



## Practice makes efficient

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1 **Practice makes efficient: Cortical alpha oscillations are associated with improved golf**

2 **putting performance**

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17 Word count (main text): 6,221

18

1 **Abstract**

2 Practice of a motor skill results in improved performance and decreased movement awareness.

3 The *psychomotor efficiency* hypothesis proposes that the development of motor expertise through

4 practice is accompanied by physiological refinements whereby irrelevant processes are

5 suppressed and relevant processes are enhanced. The present study employed a test-retest design

6 to evaluate the presence of greater neurophysiological efficiency with practice and mediation

7 analyses to identify the factors accounting for performance improvements, in a golf putting task.

8 Putting performance, movement-specific conscious processing, electroencephalographic (EEG)

9 alpha power and alpha connectivity were measured from 12 right-handed recreational golfers

10 (age:  $M = 21$  years; handicap:  $M = 23$ ) before and after three practice sessions. As expected,

11 performance improved and conscious processing decreased with training. Mediation analyses

12 revealed that improvements in performance were partly attributable to increased regional gating

13 of alpha power and reduced cross-regional alpha connectivity. However, changes in conscious

14 processing were not associated with performance improvements. Increased efficiency was

15 manifested at the neurophysiological level as selective inhibition and functional isolation of task-

16 irrelevant cortical regions (temporal regions) and concomitant functional activation of task-

17 relevant regions (central regions). These findings provide preliminary evidence for the

18 development of greater psychomotor efficiency with practice in a precision aiming task.

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21 **Key words:**

22 alpha oscillations; EEG; golf putting; practice; psychomotor efficiency

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1 Practice of a motor skill typically results in improved movement execution and  
2 performance. According to the psychomotor efficiency hypothesis (Hatfield & Hillman, 2001),  
3 such improvements are accompanied by the suppression of task-irrelevant processes (e.g.,  
4 diverting resources away from cortical regions that have limited relevance for the task) and the  
5 enhancement of task-relevant processes (e.g., redirecting resources to the most important cortical  
6 regions for task-performance). At the neurophysiological level, a compelling body of research  
7 has found indirect support for this hypothesis by revealing that, while performing precision skills  
8 such as golf putting, shooting, and archery, expert athletes manifest greater neural efficiency than  
9 novices (for review see Cooke, 2013; Hatfield *et al.*, 2004). By adopting a test-retest design, the  
10 aim of the current study was to test the psychomotor efficiency hypothesis. Specifically, we  
11 examined (a) whether practice of a motor skill over time leads to neurophysiological adaptations  
12 compatible with increased psychomotor efficiency, and (b) whether such adaptations account for  
13 improvements in movement performance.

14 Most research relating to neural efficiency in precision sports has examined  
15 electroencephalographic (EEG) activity in preparation for action and during movement  
16 execution. The EEG measures time-varying changes in voltages from an array of scalp electrodes  
17 and reflects post-synaptic potentials in the pyramidal neurons of the cerebral cortex (Nunez &  
18 Srinivasan, 2006). The interplay of these potentials generates oscillations at different  
19 frequencies, including alpha oscillations (around 8-12 Hz), which are thought to play a major  
20 role in shaping the functional architecture of the cortex due to their proposed inhibitory function  
21 (Klimesch, 2012). Specifically, the magnitude of alpha oscillations – i.e., alpha power – can  
22 influence regional activation in the cortex through a gating mechanism whereby resources are  
23 diverted away from regions showing higher alpha power (i.e., more inhibition) and towards

1 regions showing lower alpha power (i.e., lower inhibition) (Jensen & Mazaheri, 2010).

2         The study of alpha oscillations in precision sports has revealed that experts display higher  
3 alpha power over the temporal regions (e.g., Haufler *et al.*, 2000; Janelle *et al.*, 2000) and lower  
4 alpha power over the central regions (e.g., Cooke *et al.*, 2014) of the cortex compared to novices  
5 while preparing for movement execution. Additionally, experts and novices show different time  
6 dynamics of alpha power. For example, Cooke *et al.* (2014) observed a biphasic pattern of alpha  
7 oscillations that was stronger for experts than novices: alpha power showed an initial increase  
8 followed by a sudden drop in the last second preceding movement initiation. Taken together  
9 these findings suggest the presence of a pattern of cortical activity across the scalp where the  
10 timely inhibition of some cortical regions (e.g., temporal) and the lack of inhibition of other  
11 regions (e.g., central) can be related to the development of motor expertise.

12         Complementing the study of the regional and temporal dynamics of alpha power, a few  
13 studies have examined the functional connectivity among alpha oscillations across different  
14 regions of the cortex. Alpha connectivity between two regions represents the extent to which the  
15 alpha activity of those regions is functionally connected (i.e., frequency-specific cortico-cortical  
16 communication between different regions). Based on the assumption that alpha reflects inhibition  
17 (Klimesch, 2012), alpha connectivity indicates the strength of the functional connection between  
18 the inhibition of one region and the inhibition of another region. For example, greater alpha  
19 connectivity could be interpreted to reflect two regions engaging in similar and consistent  
20 inhibition, whereas lower connectivity may indicate distinct inhibition profiles.

21         Research in precision sports has revealed that, compared to novices, experts display lower  
22 left temporal:frontal alpha connectivity, reflecting a functional disconnection between alpha  
23 oscillations of the left temporal region and alpha oscillations of the frontal region (e.g.,

1 Gallicchio *et al.*, 2016). Building upon the notion that the left temporal and the frontal regions  
2 are involved in language and movement planning respectively, reduced left temporal:frontal  
3 alpha connectivity has been interpreted as a marker of the selective inhibition of the left-  
4 hemisphere and decreased cognitive/verbal interference during preparation for movement  
5 execution (Deeny *et al.*, 2003).

6 More recently, a series of studies has associated left temporal:frontal alpha connectivity  
7 with the propensity to consciously monitor and control one's movements – i.e., movement-  
8 specific conscious processing – during golf putting (Gallicchio *et al.*, 2016; Zhu *et al.*, 2011).  
9 Three lines of evidence support these views. First, lower left temporal:frontal alpha connectivity  
10 in preparation for putting as well as lower putting-related conscious processing were found for  
11 expert golfers compared to novices (Gallicchio *et al.*, 2016). Second, individuals who were  
12 dispositionally less prone to engage in conscious processing displayed lower left temporal:frontal  
13 alpha connectivity prior to putting compared to individuals more prone to engage in conscious  
14 processing (Zhu *et al.*, 2011). Third, novice golfers who were trained implicitly, which was  
15 associated with lower conscious processing, showed decreased left temporal:frontal alpha  
16 connectivity when putting compared to novice golfers who were trained explicitly (Zhu *et al.*,  
17 2011).

18 Taken together, these findings suggest that decreased left temporal:frontal alpha  
19 connectivity and decreased movement-specific conscious processing are features of expertise.  
20 This is in line with classic theories of motor skill learning that argue that the development of  
21 motor expertise is accompanied by a gradual withdrawal of cognitive analysis and decreased  
22 awareness of one's movements (e.g., Fitts & Posner, 1967). These theories suggest that,  
23 following extensive practice, individuals can progress from a cognitive stage, characterized by

1 deliberate and conscious analysis of movement, to an autonomous stage, characterized by  
2 automatic control of movement.

3         While the extant literature argues for greater neural efficiency as expertise develops, some  
4 potential limitations still need to be overcome. First, the putative link between expertise and  
5 neural efficiency is mostly based on expert-novice differences seen in cross-sectional designs.  
6 These findings do not provide a direct test of the hypothesis that practice leads to greater neural  
7 efficiency because of the unfeasibility of randomly allocating participants to either the expert or  
8 the novice group. For example, it could be that, irrespectively of practice, individuals who show  
9 greater neural efficiency are more likely to become experts compared to individuals who show  
10 lower neural efficiency. To date, only two studies have examined the effects of practice on  
11 neural efficiency using a longitudinal design (Kerick *et al.*, 2004; Landers *et al.*, 1994). These  
12 studies found that performance improvements in archery (Landers *et al.*, 1994) and pistol  
13 shooting (Kerick *et al.*, 2004) after three months of training were associated with increased alpha  
14 power over the left temporal region of the cortex. However, they did not examine any practice-  
15 induced changes in cortical connectivity.

16         Second, no study to date has examined the neurophysiological factors accounting for the  
17 development of expertise. Within-subject mediation analyses (Judd, Kenny & McClelland, 2001)  
18 can be used to examine changes in neural efficiency as a function of performance improvements  
19 and thereby shed some light on the mechanisms responsible for the improvements associated  
20 with practice.

21         Third, most studies have employed global measures of performance (e.g., hits versus  
22 misses, distance from the target) that can potentially obscure the individual contribution of  
23 distinct parameters involved in movement planning and execution. For example, the movement





1 mean golf handicap of 23.33 ( $SD = 4.62$ ). All participants provided informed consent.

## 2 **Putting task**

3 Golf balls (diameter 4.7 cm) were putted on an artificial flat putting surface (Turftiles) to  
4 a hole (diameter 10.8 cm) at a distance of 2.4 m, using a blade-style putter (length 90 cm). The  
5 participants were instructed to get each ball “*ideally in the hole, but if unsuccessful, to make them*  
6 *finish as close to the hole as possible.*”

## 7 **Training**

8 In each 1-hour training session participants practiced putting. Participants wore a cap  
9 with one frontal scalp electrode and reference and ground electrodes placed on the left and right  
10 mastoids respectively. They were instructed to try to regulate the pitch of a tone by changing  
11 their brain activity while preparing for putting and then to putt the ball when the tone was  
12 silenced. Specifically, they would stand over the ball and hear the pitch of a tone increase and  
13 decrease, and occasionally go silent for 1.5 seconds, which was a cue to putt. In reality, the tone  
14 was independent of their brain activity (i.e., sham neurofeedback), and was yoked to an  
15 experimental participant who received genuine neurofeedback: thus the sham feedback  
16 participants acted as controls in Ring *et al.* (2015). Each training session comprised twelve 5-  
17 minute blocks.

## 18 **Procedure**

19 A test-retest design was employed, with participants visiting the laboratory on five  
20 different days: putting task on day1 (i.e., test); training on days 2-4; putting task on day 5 (i.e.,  
21 retest). On average, the test-retest interval was 8.17 ( $SD = 5.24$ ) days and the final training  
22 session to retest session interval was 2.00 ( $SD = 2.59$ ) days. In the test and retest sessions,  
23 participants were instrumented for EEG recording, instructed, then completed 20 familiarisation

1 putts followed by 50 test putts. In each of the three training sessions separating the test and retest  
2 sessions, participants completed a mean of 181.25 ( $SD = 52.25$ ) practice putts. Thus, the total  
3 number of putts in training was 543.75 ( $SD = 127.01$ ). The study protocol was approved by the  
4 local research ethics committee.

## 5 **EEG Recording**

6 In the test and retest sessions 32 active electrodes were positioned on the scalp, according  
7 to the 10-20 system, at: Fp1, Fp2, AF3, AF4, F7, F3, Fz, F4, F8, FC5, FC1, FC2, FC6, T7, C3,  
8 Cz, C4, T8, CP5, CP1, CP2, CP6, P7, P3, Pz, P4, P8, PO3, PO4, O1, Oz, O2. In addition, four  
9 active electrodes were placed at the bottom and at the outer canthus of both eyes. Common mode  
10 sense and driven right leg electrodes were used to enhance the common mode rejection ratio of  
11 the signal. The signal was amplified and digitized at 512 Hz with 24-bit resolution, using the  
12 ActiveTwo recording system (Biosemi, Netherlands). Signals were down-sampled offline to 256  
13 Hz, 1-35 Hz band-pass filtered (FIR, order 512), and re-referenced to the average of all EEG  
14 channels. Channels with bad signals were removed and interpolated prior to averaging. Non-  
15 neural activity was minimized using the Artifact Subspace Reconstruction plugin for EEGLAB  
16 (Delorme & Makeig, 2004). Epochs were extracted from  $-3.25$  to  $+1.25$  s relative to the  
17 initiation of the backswing, which was triggered when the putter head broke the beam of an  
18 optical sensor interfaced with the ActiveTwo recording system.

19 Time-frequency decomposition was performed through short-time Fast Fourier  
20 Transform (FFT) on 33 overlapping segments each of the duration of 0.5 s and linearly spaced  
21 with centre points ranging from  $-3$  to  $+1$  s. Prior to FFT, each segment was also Hanning-  
22 windowed to taper both ends to 0 and then 0-padded to reach 2 s duration. This procedure  
23 generated complex-valued FFT coefficients in the time-frequency plane with a precision of 0.125

1 s and 0.5 Hz. Six Regions Of Interest (ROIs) were identified: left temporal (FC5, T7, CP5), left  
2 central (FC1, C3, CP1), frontal (F3, Fz, F4), right central (FC2, C4, CP2), right temporal (FC6,  
3 T8, CP6), and occipital (O1, Oz, O2). Signal processing was performed using the EEGLAB  
4 toolbox (Delorme & Makeig, 2004) and MATLAB (MathWorks, USA).

## 5 **Measures**

6 **Putting performance.** The number of holed putts out of 50 was recorded in the test and  
7 retest sessions. Additionally, three performance errors – radial (cm), angle (degrees), and length  
8 (cm) errors (Supplementary Material, *Figure S1*) – were computed for each putt using a camera  
9 system (Neumann & Thomas, 2008) and averaged (geometric mean) to yield measures for the  
10 test and retest sessions.

11 **Alpha power.** Power ( $\mu V^2$ ) was computed in the time-frequency plane separately for  
12 each channel and trial (i.e., putt) as the product between each FFT coefficient and its complex  
13 conjugate (i.e., equivalent to amplitude squared). Importantly, no baseline was employed.  
14 Instead, skewness and inter-individual differences in the power density distributions were dealt  
15 with by employing a median-scaled transformation: each participant's values were scaled by  
16 their median and then log-transformed ( $10 \cdot \log_{10}$ ). This procedure meant that power was normally  
17 distributed with a mean of zero for each participant, without altering within-subject relations.  
18 Power was then averaged across time (–3 to –2 s, –2 to –1 s, –1 to 0 s, 0 to +1 s, where zero  
19 represents initiation of the backswing), channels (ROIs), putts, and frequency (10-12 Hz) to yield  
20 estimates of alpha oscillatory power in each session (test, retest). Alpha is typically around 8-12  
21 Hz, however, we focused on the upper portion of this range, (i.e. 10-12 Hz) on the basis of  
22 spectral features that were evident in the current data (see Supplementary Material, Figure S4).

23 **Alpha connectivity.** Inter Site Phase Clustering (ISPC) was computed as the length of

1 the complex-valued resultant of cross-trial clustering of unitary complex vectors having as angle  
2 the phase difference between channel pairs for each point of the time-frequency plane (M.X.  
3 Cohen, 2014; Lachaux *et al.*, 1999). ISPC measures the phase lag consistency across trials (i.e.,  
4 putts) between two channels independently from their power and reflects the functional  
5 connectivity between the oscillatory activity of two underlying cortical regions, with values  
6 ranging from 0 (no connectivity) to 1 (perfect connectivity). The impact of volume conduction  
7 on connectivity was examined by taking the absolute imaginary part of the Inter Site Phase  
8 Clustering (imISPC) (cf. Nolte *et al.*, 2004). Like ISPC, imISPC reflects functional connectivity  
9 with values ranging from 0 to 1, however, imISPC is insensitive to instantaneous connectivity  
10 (i.e., 0- or  $\pi$ - lagged) and therefore values are much smaller than ISPC. No baselines were used.  
11 Instead, to normalize their density distributions, ISPC and imISPC were Fisher Z-transformed  
12 (inverse hyperbolic tangent); values could range then from 0 to  $\infty$ . Values were then averaged  
13 (arithmetic mean) across time (-3 to -2 s, -2 to -1 s, -1 to 0 s, 0 to +1 s), channel (ROI) pairs,  
14 and frequency (10-12 Hz) to yield estimates of alpha connectivity in each session (test, retest).

15 **Conscious processing.** Self-reported conscious processing was measured immediately  
16 after completing the putting task in the test and retest sessions using a putting-specific version  
17 (Cooke *et al.*, 2011; Vine *et al.*, 2013) of the conscious motor processing sub-scale of the  
18 Movement Specific Reinvestment Scale (Orrell, Masters, & Eves, 2009). This scale consists of  
19 six items scored on a 5-point Likert scale (1 = *never*, 3 = *sometimes*, 5 = *always*) related to the  
20 feeling of awareness of the kinematics involved in execution of the putt and thoughts about putt  
21 outcome. The six items were averaged to generate a single scale score. Past research (Cooke *et*  
22 *al.*, 2011; Vine *et al.*, 2013) has established the reliability ( $\alpha = .81-.88$ ) and validity of the  
23 putting-specific version of the conscious motor processing sub-scale of the Movement Specific

1 Reinvestment Scale.

## 2 **Statistical Analyses**

3 **Performance and conscious processing.** Changes from test to retest in putting  
4 performance and conscious processing were examined by paired-sample *t*-tests. Within each  
5 session the relation between the number of holed putts and the three performance errors was  
6 examined through Pearson's correlations.

7 **Alpha power and connectivity.** Power was subjected to a 2 Session (test, retest) × 6 ROI  
8 (left temporal, left central, frontal, right central, right temporal, and occipital) × 4 Time (−3 to −2,  
9 −2 to −1, −1 to 0, 0 to +1 s) ANOVA. In addition, contrast analyses were performed to examine  
10 changes in power over time. ISPC and imISPC were each subjected to 2 Session × 4 Time  
11 ANOVAs, conducted separately on each of two ROI pairs (left temporal:frontal, right  
12 temporal:frontal), chosen on the basis of previous literature (Deeny *et al.*, 2003, 2009; Gallicchio  
13 *et al.*, 2016; Zhu *et al.*, 2011). The multivariate solution was reported in the ANOVAs where  
14 appropriate (Vasey & Thayer, 1988). Significant main effects were interrogated using post hoc  
15 testing. Partial eta-squared ( $\eta^2_p$ ) and  $r^2$  are reported as measures of effect size: values of .02, .13,  
16 and .26 were taken to reflect small, medium, and large effects, respectively (J. Cohen, 1992).

17 **Mediation.** Mediation analyses were conducted to test whether changes across sessions  
18 in the number of holed putts could be accounted for by changes in performance errors, conscious  
19 processing, alpha power, and alpha connectivity. We also tested whether changes in conscious  
20 processing could be attributed to changes in alpha power and connectivity. We used the  
21 procedure described by Judd *et al.* (2001) for repeated-measures designs: multiple regression  
22 was used to predict the test to retest change in the dependent variable based on the test to retest  
23 change in the potential mediator variable, while controlling for its mean-centred sum. Full

1 mediation can be inferred when the regression coefficient associated with the change in the  
2 mediator variable is significant (i.e.,  $p < .05$ ), and partial mediation is inferred when the  
3 coefficient associated with the intercept is also significant. The following strategy was adopted to  
4 reduce the likelihood of type-I errors: we first assessed whether the change in the number of  
5 holed putts was mediated by changes in any of the potential mediator variables, and only if this  
6 was the case were mediation analyses conducted on the changes in the performance errors and  
7 conscious processing.

## 8 **Results**

### 9 **Putting performance**

10 Overall, every putting performance measure improved with training from test to re-test  
11 (*Table 1*). However, there were considerable individual differences: not all participants improved  
12 equally and in fact a few got worse (Supplementary Material, *Figure S2*). The number of holed  
13 putts was highly negatively correlated with the three performance errors ( $r_s = -.77$  to  $-.92$ ,  $p_s <$   
14  $.003$ ), with angle error the highest (Supplementary Material, *Table S1*).

### 15 **Alpha power**

16 The 2 Session  $\times$  6 ROI  $\times$  4 Time ANOVA conducted on EEG power revealed a large  
17 main effect of ROI,  $F(5,7) = 105.49$ ,  $p < .001$ ,  $\eta^2_p = .987$ . Post-hoc Scheffé tests indicated ( $p <$   
18  $.001$ ) that power was higher in the occipital than left/right temporal and frontal regions, which, in  
19 turn, were higher than left/right central regions (*Figure 1A*). Power tended to be lower in the  
20 retest session than the test session (*Figure 1B*),  $F(1,11) = 0.78$ ,  $p = .40$ ,  $\eta^2_p = .066$ , in all regions  
21 (left temporal  $\Delta = -0.55$ ; left central  $\Delta = -0.40$ ; frontal  $\Delta = -0.28$ ; right central  $\Delta = -0.23$ ; right  
22 temporal  $\Delta = -0.66$ ) except the occipital region ( $\Delta = 0.40$ ). Although no clear omnibus time  
23 effect was evident,  $F(3,9) = 2.93$ ,  $p = .09$ ,  $\eta^2_p = .494$ , the effect size was large, and, therefore, we

1 performed contrast analyses to characterize the *a priori* predicted changes in power in the  
2 moments surrounding movement; a series of 4 Time ANOVAs (contrast codes: 0, 1, -2, 1) were  
3 conducted separately for each session and ROI. This quadratic trend was not displayed in the test  
4 session,  $F_s(1,11) = 0.02-0.74$ ,  $p_s = .41-.89$ ,  $\eta^2_{ps} = .002-.063$ , with the sole exception of the left  
5 temporal region,  $F(1,11) = 4.10$ ,  $p = .07$ ,  $\eta^2_p = .271$ , but was clearly evident in all regions in the  
6 retest session,  $F_s(1,11) = 12.57-4.01$ ,  $p_s = .005-.07$ ,  $\eta^2_{ps} = .267-.533$ . This implies a practice-  
7 induced time-varying change in alpha power, characterized mainly by a reduction in power  
8 during the final second before movement following practice during the retest session (*Figure*  
9 *1B*).

#### 10 **Alpha connectivity**

11 The 2 Session  $\times$  4 Time ANOVAs on the left temporal:frontal connectivity indices  
12 (*Figure 2*) revealed no main effects for session (ISPC:  $\Delta = 0.01$ ,  $F(1,11) = 1.02$ ,  $p = .34$ ,  $\eta^2_p =$   
13  $.085$ ; imISPC:  $\Delta = -0.004$ ,  $F(1,11) = 0.35$ ,  $p = .57$ ,  $\eta^2_p = .031$ ) or time (ISPC:  $F(3,9) = 0.77$ ,  $p =$   
14  $.54$ ,  $\eta^2_p = .203$ ; imISPC,  $F(3,9) = 3.46$ ,  $p = .06$ ,  $\eta^2_p = .536$ ). Similarly, no effects emerged with  
15 right temporal:frontal connectivity (*Figure 2*) as a function of session (ISPC:  $\Delta = 0.01$ ,  $F(1,11) =$   
16  $0.75$ ,  $p = .41$ ,  $\eta^2_p = .064$ ; imISPC:  $\Delta = 0.008$ ,  $F(1,11) = 2.512$ ,  $p = .14$ ,  $\eta^2_p = .186$ ) and time  
17 (ISPC:  $F(3,9) = 0.63$ ,  $p = .61$ ,  $\eta^2_p = .174$ ; imISPC:  $F(3,9) = 0.69$ ,  $p = .58$ ,  $\eta^2_p = .187$ ). No session  
18 by time interactions emerged. Finally, the results from all ROI pairs are reported in the  
19 Supplementary Material (*Figure S5*) for interested readers.

#### 20 **Conscious processing**

21 Overall conscious processing decreased from test ( $M = 3.88$ ,  $SD = 0.20$ ) to retest ( $M =$   
22  $3.36$ ,  $SD = 0.24$ ),  $t(11) = 2.59$ ,  $p = .03$ ,  $r^2 = .378$ . Again, there were large individual differences  
23 in the extent of this change, with four participants opposing the trend by reporting the same or

1 greater conscious processing after training (Supplementary Material, *Figure S3*).

## 2 **Mediators of the change in putting performance**

3 Putting performance improved with practice. On average, participants holed 4.08 more  
4 balls (i.e., an 8.2% improvement) in the retest session compared to the test session. Judd *et al.*'s  
5 (2001) regression-based within-subject mediation analyses indicated that this improvement was  
6 fully mediated by the reduction in angle error from test to retest ( $b = -9.82, p = .008$ ); the  
7 intercept ( $a = 1.89, p = .21$ ) indicated that, had angle error not changed from test to retest, the  
8 improvement would have been reduced to only 1.89 additional holed putts, which represents a  
9 non-significant change in performance. Neither radial error ( $b = -0.88, p = .06$ ) nor length error  
10 ( $b = -0.81, p = .17$ ) mediated performance improvement. Further, conscious processing did not  
11 mediate the change in performance ( $b = -1.23, p = .70$ ).

12 In terms of alpha power, the improvement in putting performance was partially mediated  
13 by the change in left temporal power in the seconds surrounding backswing initiation ( $-1$  to  $0$  s:  
14  $b = 2.46, p = .04$ ;  $0$  to  $1$  s:  $b = 2.07, p = .04$ ). Since power tended to decrease with practice  
15 (*Figure 1B*), smaller reductions in left temporal power from test to retest were associated with  
16 larger improvements in performance. Based on the associated intercepts ( $-1$  to  $0$  s:  $a = 6.07, p =$   
17  $.005$ ;  $0$  to  $1$  s:  $a = 5.04, p = .01$ ), this means that an individual who increased their left temporal  
18 power from test to retest in the second before backswing initiation would be predicted to hole at  
19 least two more putts whereas someone who increased power from test to retest in the second  
20 after initiation would be predicted to hole at least one more putt. Furthermore, left temporal  
21 power within the  $-1$  to  $0$  s interval also partially mediated the reduction in angle ( $b = -0.19, p =$   
22  $.03$ ) but not radial ( $b = -1.72, p = .06$ ) or length ( $b = -1.33, p = .09$ ) errors (Supplementary  
23 Material, *Figure S6*).



1           In terms of alpha connectivity, putting performance was partially mediated by the inter-  
2 session change in left temporal:frontal ISPC within the  $-2$  to  $-1$  s interval ( $b = -120.60, p = .01$ ).  
3 Since ISPC tended to increase with practice (*Figure 2*), smaller increases in left temporal:frontal  
4 connectivity from test to retest were associated with larger improvements in putting  
5 performance. Based on the intercept ( $a = 5.88, p = .004$ ), performance would be predicted to  
6 improve by at least two more holed putts if left temporal:frontal ISPC decreased within this time  
7 interval. The same analysis conducted on imISPC also revealed a negative relation, ( $b = -53.02,$   
8  $p = .28$ ). Furthermore, left temporal:frontal ISPC within the  $-2$  to  $-1$  s interval also partially  
9 mediated the reduction in angle ( $b = 6.35, p = .05$ ), but not radial ( $b = 56.97, p = .13$ ) and length  
10 ( $b = 35.52, p = .28$ ) errors.

11           Right temporal:frontal ISPC and imISPC did not mediate the improvement in putting  
12 performance ( $ps = .19-.93$ ). Lastly, mediation analyses on all ROI pairs (Supplementary  
13 Material, *Figure S7A, B*) indicated that the relation between smaller increases in left  
14 temporal:frontal ISPC and greater performance improvement extended to a network linking the  
15 left temporal region to the other cortical regions.

### 16 **Mediators of the change in conscious processing**

17           On average, participants reported less conscious processing ( $\Delta = -0.52$ ) from test to  
18 retest. This reduction in conscious processing was fully mediated ( $a = -0.34, p = .09$ ) by the  
19 change in left temporal:frontal ISPC within the  $-2$  to  $-1$  s interval ( $b = -11.87, p = .03$ ), whereby  
20 decreases in conscious processing were associated with increases in ISPC. Finally, the mediation  
21 analyses involving all ROI pairs (Supplementary Material, *Figure S7C, D*) showed that changes  
22 in conscious processing were related to changes in connectivity across a broad network of  
23 cortical regions.

## Discussion

Performance improved from test to retest. That retention was assessed a couple of days after the end of training provided evidence for motor learning (e.g., Salmoni, Schmidt & Walter, 1984). The primary aim of this exploratory study was to identify the neurophysiological factors that mediate changes in motor performance with practice. Improvements in golf putting performance from before (test) to after (retest) completing three training sessions were mediated by EEG alpha power and alpha connectivity in preparation for putting but not by self-reported conscious processing.

### Alpha power

Spectral analyses revealed a distinct 10-12 Hz peak compatible with the alpha rhythm (see Supplementary Material, Figure S4), and therefore activity within this frequency range was interpreted as reflecting cortical alpha oscillations. Alpha activity was displayed across the different regions of the cortex in a focal pattern: power was lowest over the central regions, medium over the temporal regions, and highest over the occipital region. In line with the *gating-by-inhibition hypothesis* (Jensen & Mazaheri, 2010) the observed regional pattern suggests that neuronal resources were taken away from occipital and temporal regions (i.e., highest inhibition) and diverted towards the central regions (i.e., lowest inhibition) during movement preparation. This focal pattern, which was evident in both test and retest sessions, could reflect the prior practice history of our participants, who were all experienced golfers, and therefore had already developed a degree of psychomotor efficiency related to the putting movement.

Efficiency-based changes in alpha power due to training can be inferred from our mediation analyses. Importantly, they suggested that participants who were able to sustain a relatively higher power in the temporal regions from test to retest in the seconds surrounding

1 movement improved their putting performance the most. This effect was localized to the left  
2 (and to a lesser extent, the right) temporal region and can be interpreted in terms of alpha gating:  
3 increased inhibition in regions not directly involved in putting-relevant processing is beneficial  
4 to putting. That this effect was absent in the occipital region is most likely because occipital  
5 inhibition was already the strongest among the regions examined and tended to strengthen  
6 further with training. In other words, likely there was a ceiling effect for occipital alpha, whereby  
7 further increases did not benefit performance.

8         It is also worth noting that while a relatively higher level of temporal alpha power was  
9 beneficial, practice also prompted a decrease in power, especially at the frontal region, in the  
10 final second preceding movement. This quadratic trend for time-varying alpha power in the retest  
11 session could be interpreted as reflecting the timely allocation of resources to putting-relevant  
12 processing (Cooke *et al.*, 2015). Indeed, this quadratic pattern is consistent with previous  
13 research and has been associated with expertise and successful performance in experts (Babiloni  
14 *et al.*, 2008; Cooke *et al.*, 2014). However, as this quadratic decrease in alpha power at retest did  
15 not mediate changes in performance, the inhibition of irrelevant cortical regions seems to have  
16 been more important for performance improvement than the timely activation of relevant ones.  
17 This remains a topic for future research, which may consider variables such as task and  
18 experience as potential moderators of any effects.

### 19 **Alpha connectivity**

20         Functional connectivity was examined between the temporal and frontal regions using two  
21 indices based on the consistency of cross-regional phase lag across trials: ISPC and imISPC. The  
22 latter is a conservative version of the former that is not biased by volume conduction. The fact  
23 that 10-12 Hz imISPC was non-zero (Figure 2) indicated the likely presence of genuine alpha

1 connectivity. Neither connectivity index changed across the time intervals or from test to retest.  
2 However, mediation analyses suggested that greater improvements in performance from test to  
3 retest were achieved by participants displaying relatively lower left temporal:frontal connectivity  
4 a couple of seconds before putt initiation. Low left temporal:frontal alpha connectivity has been  
5 associated with expertise and successful putting performance in experts (Babiloni *et al.*, 2011;  
6 Gallicchio *et al.*, 2016). At the neurophysiological level, lower connectivity represents a stronger  
7 disconnection between the two signals – i.e., left temporal alpha and frontal alpha – provided that  
8 the two signals are not projections of the same source generator because of volume conduction  
9 within the head.

10 The additional analyses performed on a wider network of regions (Supplementary  
11 Material, Figure S7) revealed that performance improvements were not exclusively associated  
12 with a stronger disconnection of alpha activity between left temporal and frontal regions. Rather,  
13 it is evident that improved performance was associated with a functional isolation of left  
14 temporal alpha from many other regional alpha activities. Taken together, these analyses provide  
15 preliminary support for our hypothesis that improvements in performance with practice would be  
16 mediated by reduced connectivity (i.e., less cortico-cortical communication) between alpha  
17 oscillations in the left temporal region and other regions of the cortex, including the frontal  
18 region (cf., Deeny *et al.*, 2003; Gallicchio *et al.*, 2016; Zhu *et al.*, 2011).

### 19 **Conscious processing**

20 Movement-specific conscious processing decreased and performance improved with  
21 practice, in line with the classic theories of motor skill learning (e.g., Fitts & Posner, 1967).  
22 However, mediation analyses did not support the putative link between decreased conscious  
23 processing and performance improvement. Similarly, Malhotra *et al.* (2015) also found no

1 relation between improvements in putting performance and changes in conscious processing with  
2 training. It should be noted that these two null findings reflect the absence of a linear relation;  
3 however, our analyses indicate a curvilinear relationship: participants who reported a moderate  
4 decrease in conscious processing improved more than those who reported a large decrease, no  
5 change, and even a small increase in conscious processing (Supplementary Material, Figure S8).  
6 It has been increasingly recognized that conscious processing does not always negatively impact  
7 performance but can foster performance improvements in experts (Toner & Moran, 2014) and  
8 novices (Malhotra *et al.*, 2015). Given these findings it would be fruitful for future research to  
9 seek to identify optimal levels of conscious processing as a function of factors such as task,  
10 expertise and personality. Such research should also consider sub-components of conscious  
11 processing, for instance, distinguishing conscious monitoring and conscious control (Toner &  
12 Moran, 2011), particularly when they are about to putt, which should be able to paint a better  
13 picture of what individuals attend to in the moments before movement initiation.

14 Mediation analyses suggested that decreases in conscious processing from test to retest  
15 were associated with increases in alpha connectivity across a network involving all cortical  
16 regions examined (Supplementary Material, Figure S7). Higher connectivity represents a  
17 stronger connection between the alpha oscillations, and therefore suggests that decreased  
18 movement-specific conscious processing or awareness of one's movements is associated with  
19 multiple cortical regions engaging in similar and consistent inhibition (cf. Baars, 2002). This  
20 interpretation awaits confirmation.

## 21 **Performance errors**

22 The analyses of the three performance metrics – i.e., radial, angle, and length errors –  
23 revealed that improvements in the number of holed putts with practice was largely due to

1 reductions in angle error rather than radial or length errors. This finding suggests that a more  
2 precise alignment of the putter head with the ball at the moment of impact is more beneficial to  
3 putting outcome than appropriate impact velocity (Cooke *et al.*, 2010). Additionally, all of the  
4 significant associations observed between EEG activity and putting performance errors were  
5 found for angle error, suggesting that programming of movement direction is better reflected in  
6 alpha activity than movement force. Although there is evidence that movement direction and  
7 force are selectively coded by different neuronal populations (e.g., Riehle & Requin, 1995),  
8 future research is needed to clarify the relationship between alpha oscillations, on the one hand,  
9 and programming of movement parameters, on the other hand.

#### 10 **Limitations and future research**

11         The current study yielded some novel and important findings regarding the causal relations  
12 among practice, cortical efficiency, conscious processing and performance. However, their  
13 interpretation should be considered in light of potential limitations. First, although the putting  
14 task was completed under ecologically valid conditions, the training cannot be considered a form  
15 of discovery learning because participants received sham neurofeedback. Moreover, we did not  
16 employ a control group who did not receive any form of neurofeedback. We cannot determine  
17 the impact of the current training protocol and therefore future research should consider  
18 replicating our findings using other forms of training, including discovery learning, and  
19 appropriate control groups.

20         Second, we refrained from interpreting activity in different cortical regions in terms of  
21 specific cognitive processes because we did not measure nor manipulate cognition directly. We  
22 acknowledge that the presence of a certain regional activation makes some cognitive processes  
23 more likely to be involved than others, however, we avoided reverse inference (Poldrack, 2006)

1 and postponed interpretation. Indeed, it would be worth studying the relation between regional  
2 activation and cognitive processes using experimental designs where cognition is manipulated  
3 (rather than simply measured) in the context of precision aiming.

4 Third, the use of spectral decomposition on (inherently non-stationary) EEG signals  
5 implies that power is likely to be greater than 0 at any unfiltered frequency, irrespectively of the  
6 presence of actual neural generators oscillating at that frequency. The distinct 10-12 Hz power  
7 peak in the group-averaged frequency plots (see Supplementary Material, Figure S4) supported  
8 the likely presence of cortical oscillations within this frequency band. However, the use of a  
9 fixed range did not account for individual variations. Future studies could individually adjust  
10 these ranges to obtain greater specificity and sensitivity (cf. Klimesch, 1999).

11 Fourth, we considered measures of alpha as candidates to mediate the main effect of  
12 session on performance despite having non-significant main effects themselves. This strategy is  
13 in line with current guidelines recommending that mediation only requires the existence of an  
14 effect to be mediated (i.e., change in performance) for that effect to be indirectly influenced by  
15 the mediator variables (e.g., alpha power) (Preacher & Hayes, 2004). Our approach satisfies  
16 these criteria, nonetheless, we did not manipulate any of the mediator variables, and therefore the  
17 outcome variable (i.e., performance) may have influenced the mediator variables (Cooke *et al.*,  
18 2015). It would be useful to replicate these analyses in larger samples with more statistical power  
19 where the mediators are manipulated independently of the outcome variables, using, for instance,  
20 brain stimulation or neurofeedback training.

21 Fifth, the greater relative importance of the angle error over radial and length errors is  
22 potentially biased by the presence of an actual hole, which may have influenced our performance  
23 measurements, particularly in regards to length error. For example, balls can be redirected by the

1 hole (e.g., a lip out) and most balls that dropped into the hole would otherwise have rolled past  
2 the hole had the hole not been present, introducing variability that cannot be accounted for by the  
3 measurements. Future studies could use a mark on the mat instead of a hole to overcome this  
4 limitation.

5 Finally, we only tested experienced golfers that arguably lay somewhere between the  
6 cognitive and the autonomous stage of learning (cf. Fitts & Posner, 1967). Given that the  
7 particular stage of learning that the individual is in may moderate the adaptations in alpha gating  
8 and connectivity with training, future research could examine these learning-related adaptations  
9 in novices and experts as well as experienced individuals.

## 10 **Conclusions**

11 This exploratory study provides preliminary evidence that practice of a motor skill leads  
12 to neurophysiological adaptations compatible with the psychomotor efficiency hypothesis  
13 (Hatfield & Hillman, 2001). Efficiency was manifested as selective inhibition and functional  
14 isolation of task-irrelevant cortical regions and concomitant functional activation of task-relevant  
15 regions. Our findings suggest that processing in broadly central regions (cf., Andersen & Buneo,  
16 2002; Desmurget *et al.*, 2009) is more important than processing in temporal regions (cf., Kerick  
17 *et al.*, 2001) while performing a precision aiming task, such as golf putting. These findings imply  
18 that larger improvements in precision aiming performance with practice may be achieved by  
19 employing training protocols that foster suppression of task-irrelevant processes.

20

21



1 **References**

- 2 Andersen, R. A., & Buneo, C. A. (2002). Intentional maps in posterior parietal cortex. *Annual*  
3 *review of neuroscience*, 25(1), 189-220.  
4 <http://dx.doi.org/10.1146/annurev.neuro.25.112701.142922>
- 5 Baars, B. J. (2002). The conscious access hypothesis: origins and recent evidence. *Trends in*  
6 *cognitive sciences*, 6(1), 47-52. [http://dx.doi.org/10.1016/S1364-6613\(00\)01819-2](http://dx.doi.org/10.1016/S1364-6613(00)01819-2)
- 7 Babiloni, C., Del Percio, C., Iacoboni, M., Infarinato, F., Lizio, R., Marzano, N., ... & Eusebi, F.  
8 (2008). Golf putt outcomes are predicted by sensorimotor cerebral EEG rhythms. *The Journal*  
9 *of physiology*, 586(1), 131-139. <http://dx.doi.org/10.1113/jphysiol.2007.141630>
- 10 Babiloni, C., Infarinato, F., Marzano, N., Iacoboni, M., Dassù, F., Soricelli, A., . . . Del Percio,  
11 C. (2011). Intra-hemispheric functional coupling of alpha rhythms is related to golfer's  
12 performance: A coherence EEG study. *International Journal of Psychophysiology*, 82, 260–  
13 268. <http://dx.doi.org/10.1016/j.ijpsycho.2011.09.008>
- 14 Cohen, J. (1992). A power primer. *Psychological Bulletin*, 112, 155-159.  
15 <http://dx.doi.org/10.1037/0033-2909.112.1.155>
- 16 Cohen, M. X. (2014). *Analyzing neural time series data: Theory and practice*. Cambridge, MA:  
17 MIT Press.
- 18 Cooke, A. (2013). Readyng the head and steadyng the heart: A review of cortical and cardiac  
19 studies of preparation for action in sport. *International Review of Sport & Exercise*  
20 *Psychology*, 6, 122-138. <http://dx.doi.org/10.1080/1750984X.2012.724438>
- 21 Cooke, A., Gallicchio, G., Kavussanu, M., Willoughby, A., McIntyre, D., & Ring, C. (2015).  
22 Premovement high-alpha power is modulated by previous movement errors: Indirect evidence  
23 to endorse high-alpha power as a marker of resource allocation during motor programming.

1        *Psychophysiology*, 52, 977-981. <http://dx.doi.org/10.1111/psyp.12414>

2        Cooke, A., Kavussanu, M., Gallicchio, G., Willoughby, A., McIntyre, D., & Ring, C. (2014).  
3        Preparation for action: Psychophysiological activity preceding a motor skill as a function of  
4        expertise, performance outcome, and psychological pressure. *Psychophysiology*, 51, 374-384.  
5        <http://dx.doi.org/10.1111/psyp.12182>

6        Cooke, A., Kavussanu, M., McIntyre, D., Boardley, I.D., & Ring, C. (2011). Effects of  
7        competitive pressure on expert performance: underlying psychological, physiological, and  
8        kinematic mechanisms. *Psychophysiology*, 48, 1146-1156. [http://dx.doi.org/10.1111/j.1469-](http://dx.doi.org/10.1111/j.1469-8986.2011.01175.x)  
9        [8986.2011.01175.x](http://dx.doi.org/10.1111/j.1469-8986.2011.01175.x)

10        Cooke, A., Kavussanu, M., McIntyre, D., & Ring, C. (2010). Psychological, muscular and  
11        kinematic factors mediate performance under pressure. *Psychophysiology*, 47, 1109-1118.  
12        <http://dx.doi.org/10.1111/j.1469-8986.2010.01021.x>

13        Deeny, S. P., Hillman, C. H., Janelle, C. M., & Hatfield, B. D. (2003). Cortico-cortical  
14        communication and superior performance in skilled marksmen: an EEG coherence analysis.  
15        *Journal of Sport and Exercise Psychology*, 25, 188-204. [http://psycnet.apa.org/psycinfo/2003-](http://psycnet.apa.org/psycinfo/2003-05573-006)  
16        [05573-006](http://psycnet.apa.org/psycinfo/2003-05573-006)

17        Deeny, S. P., Haufler, A. J., Saffer, M., & Hatfield, B. D. (2009). Electroencephalographic  
18        coherence during visuomotor performance: a comparison of cortico-cortical communication  
19        in experts and novices. *Journal of Motor Behavior*, 41, 106-116.  
20        <http://dx.doi.org/10.3200/JMBR.41.2.106-116>

21        Delorme, A., & Makeig, S. (2004). EEGLAB: an open source toolbox for analysis of single trial  
22        EEG dynamics including independent component analysis. *Journal of Neuroscience Methods*,  
23        134, 9-21. <http://dx.doi.org/10.1016/j.jneumeth.2003.10.009>

- 1 Desmurget, M., Reilly, K. T., Richard, N., Szathmari, A., Mottolese, C., & Sirigu, A. (2009).  
2 Movement intention after parietal cortex stimulation in humans. *Science*, 324(5928), 811-813.  
3 <http://dx.doi.org/10.1126/science.1169896>
- 4 Fitts, P. M., & Posner, M. I. (1967). *Human performance*. Belmont, CA: Brooks/Cole.
- 5 Gallicchio, G., Cooke, A., & Ring, C. (2016). Lower left temporal-frontal connectivity  
6 characterizes expert and accurate performance: High-alpha T7-Fz connectivity as a marker of  
7 conscious processing during movement. *Sport, Exercise & Performance Psychology*, 5(1), 14-  
8 24. <http://dx.doi.org/10.1037/spy0000055>
- 9 Hatfield, B. D., Haufler, A. J., Hung, T. M., & Spalding, T. W. (2004). Electroencephalographic  
10 studies of skilled psychomotor performance. *Journal of Clinical Neurophysiology*, 21, 144-  
11 156. <http://dx.doi.org/10.1097/00004691-200405000-00003>
- 12 Hatfield, B. D., & Hillman, C. H. (2001). The psychophysiology of sport: A mechanistic  
13 understanding of the psychology of superior performance. In R. N. Singer, H. A. Hausenblas,  
14 & C. M. Janelle (Eds.), *Handbook of sport psychology* (2nd ed., pp. 362-386). New York:  
15 Wiley.
- 16 Haufler, A. J., Spalding, T. W., Santa Maria, D. L., & Hatfield, B. D. (2000). Neuro-cognitive  
17 activity during a self-paced visuospatial task: comparative EEG profiles in marksmen and  
18 novice shooters. *Biological Psychology*, 53(2), 131-160. [http://dx.doi.org/10.1016/S0301-](http://dx.doi.org/10.1016/S0301-0511(00)00047-8)  
19 [0511\(00\)00047-8](http://dx.doi.org/10.1016/S0301-0511(00)00047-8)
- 20 Janelle, C. M., Hillman, C. H., Apparies, R. J., Murray, N. P., Meili, L., Fallon, E. A., &  
21 Hatfield, B. D. (2000). Expertise differences in cortical activation and gaze behavior during  
22 rifle shooting. *Journal of Sport and Exercise psychology*, 22, 167-182.
- 23 Jensen, O., & Mazaheri, A. (2010). Shaping functional architecture by oscillatory alpha activity:

1 gating by inhibition. *Frontiers in Human Neuroscience*, 4, 1-8.  
2 <http://dx.doi.org/10.3389/fnhum.2010.00186>

3 Judd, C. M., Kenny, D. A., & McClelland, G. H. (2001). Estimating and testing mediation and  
4 moderation in within-subject designs. *Psychological Methods*, 6(2), 115-134.  
5 <http://dx.doi.org/10.1037/1082-989X.6.2.115>

6 Kerick, S. E., Douglass, L. W., & Hatfield, B. D. (2004). Cerebral cortical adaptations associated  
7 with visuomotor practice. *Medicine and Science in Sports and Exercise*, 36(1), 118-129.  
8 <http://dx.doi.org/10.1249/01.MSS.0000106176.31784.D4>

9 Kerick, S. E., McDowell, K., Hung, T. M., Santa Maria, D. L., Spalding, T. W., & Hatfield, B.  
10 D. (2001). The role of the left temporal region under the cognitive motor demands of shooting  
11 in skilled marksmen. *Biological Psychology*, 58(3), 263-277.  
12 [http://dx.doi.org/10.1016/S0301-0511\(01\)00116-8](http://dx.doi.org/10.1016/S0301-0511(01)00116-8)

13 Klimesch, W. (1999). EEG alpha and theta oscillations reflect cognitive and memory  
14 performance: a review and analysis. *Brain Research Reviews*, 29, 169-195.  
15 [http://dx.doi.org/10.1016/S0165-0173\(98\)00056-3](http://dx.doi.org/10.1016/S0165-0173(98)00056-3)

16 Klimesch, W. (2012). Alpha-band oscillations, attention, and controlled access to stored  
17 information. *Trends in Cognitive Sciences*, 16, 606-617.  
18 <http://dx.doi.org/10.1016/j.tics.2012.10.007>

19 Landers, D. M., Han, M., Salazar, W., Petruzzello, S. J., Kubitz, K. A., & Gannon, T. L. (1994).  
20 Effect of learning on electroencephalographic patterns in novice archers. *International*  
21 *Journal of Sport Psychology*, 22, 56-71.

22 Lachaux, J. P., Rodriguez, E., Martinerie, J., & Varela, F. J. (1999). Measuring phase synchrony  
23 in brain signals. *Human Brain Mapping*, 8, 194-208. [http://dx.doi.org/10.1002/\(SICI\)1097-](http://dx.doi.org/10.1002/(SICI)1097-)

1 [0193\(1999\)8:4%3C194::AID-HBM4%3E3.0.CO;2-C](http://dx.doi.org/10.1016/j.neuroimage.2014.11.008)

2 Malhotra, N., Poolton, J. M., Wilson, M. R., Omuro, S., & Masters, R. S. (2015). Dimensions of  
3 movement specific reinvestment in practice of a golf putting task. *Psychology of Sport and*  
4 *Exercise, 18*, 1-8. <http://dx.doi.org/10.1016/j.psychsport.2014.11.008>

5 Neumann, D. L., & Thomas, P. R. (2008). A camera-based scoring system for evaluating  
6 performance accuracy during a golf putting task. *Behavior Research Methods, 40*(3), 892-897.  
7 <http://dx.doi.org/10.3758/BRM.40.3.892>

8 Nolte, G., Bai, O., Wheaton, L., Mari, Z., Vorbach, S., & Hallett, M. (2004). Identifying true  
9 brain interaction from EEG data using the imaginary part of coherency. *Clinical*  
10 *Neurophysiology, 115*(10), 2292-2307. <http://dx.doi.org/10.1016/j.clinph.2004.04.029>

11 Nunez, P. L., & Srinivasan, R. (2006). *Electric fields of the brain: the neurophysics of EEG*.  
12 Oxford University Press, USA.

13 Orrell, A. J., Masters, R. S. W., & Eves, F. F. (2009). Reinvestment and movement disruption  
14 following stroke. *Neurorehabilitation and Neural Repair, 23*, 177–183.  
15 <http://dx.doi.org/10.1177/1545968308317752>

16 Poldrack, R. A. (2006). Can cognitive processes be inferred from neuroimaging data? *Trends in*  
17 *Cognitive Sciences, 10*(2), 59-63. <http://dx.doi.org/10.1016/j.tics.2005.12.004>

18 Preacher, K.J. & Hayes, A.F. (2004). SPSS and SAS procedures for estimating indirect effects in  
19 simple mediation models. *Behavior Research Methods, Instruments Computers, 36*, 717-731.  
20 <http://dx.doi.org/10.3758/BF03206553>

21 Riehle, A., & Requin, J. (1995). Neuronal correlates of the specification of movement direction  
22 and force in four cortical areas of the monkey. *Behavioural Brain Research, 70*, 1-13.  
23 [http://dx.doi.org/10.1016/0166-4328\(94\)00180-N](http://dx.doi.org/10.1016/0166-4328(94)00180-N)

- 1 Ring, C., Cooke, A., Kavussanu, M., McIntyre, D.B., & Masters, R.S.W. (2015). Investigating  
2 the efficacy of neurofeedback training for expediting expertise and excellence in sport.  
3 *Psychology of Sport & Exercise*, 16(1), 118-127.  
4 <http://dx.doi.org/10.1016/j.psychsport.2014.08.005>
- 5 Salmoni, A. W., Schmidt, R. A. & Walter, C. B. (1984). Knowledge of results and motor  
6 learning: a review and critical appraisal. *Psychological Bulletin*, 95, 335-386. 10.1037/0033-  
7 2909.95.3.355 <http://dx.doi.org/10.1037/0033-2909.95.3.355>
- 8 Toner, J., & Moran, A. (2011). The effects of conscious processing on golf putting proficiency  
9 and kinematics. *Journal of Sports Sciences*, 29(7), 673-683.  
10 <http://dx.doi.org/10.1080/02640414.2011.553964>
- 11 Toner, J., & Moran, A. (2015). In praise of conscious awareness: a new framework for the  
12 investigation of “continuous improvement” in expert athletes. *Frontiers in Psychology*, 5, 1-5.  
13 <http://dx.doi.org/10.3389/fpsyg.2014.00769>
- 14 Vasey, M. W., & Thayer, J. F. (1987). The continuing problem of false positives in repeated  
15 measures ANOVA in psychophysiology: A multivariate solution. *Psychophysiology*, 24, 479-  
16 486. <http://dx.doi.org/10.1111/j.1469-8986.1987.tb00324.x>
- 17 Vine, S.J., Moore, L.J., Cooke, A., Ring, C., & Wilson, M.R. (2013). Quiet eye training: a means  
18 to implicit motor learning. *International Journal of Sport Psychology*, 44, 367-386.
- 19 Zhu, F. F., Poolton, J. M., Wilson, M. R., Maxwell, J. P., & Masters, R. S. W. (2011). Neural co-  
20 activation as a yardstick of implicit motor learning and the propensity for conscious control of  
21 movement. *Biological Psychology*, 87, 66-73.  
22 <http://dx.doi.org/10.1016/j.biopsycho.2011.02.004>
- 23

*Table 1.* Descriptive statistics of putting performance as a function of session together with the results of the paired-sample t-tests.

	<b>Test</b> <i>M (SD)</i>	<b>Retest</b> <i>M (SD)</i>	<b><i>t</i>(11)</b>	<b><i>p</i></b>	<b><i>r</i><sup>2</sup></b>
holed putts (0-50)	12.17 (2.39)	16.25 (2.97)	2.18	.05	.301
radial error (cm)	10.95 (1.59)	8.05 (1.23)	2.26	.04	.317
angle error (degrees)	1.39 (0.12)	1.17 (0.14)	1.74	.11	.215
length error (cm)	8.80 (1.27)	6.42 (0.95)	2.22	.05	.310

Figures

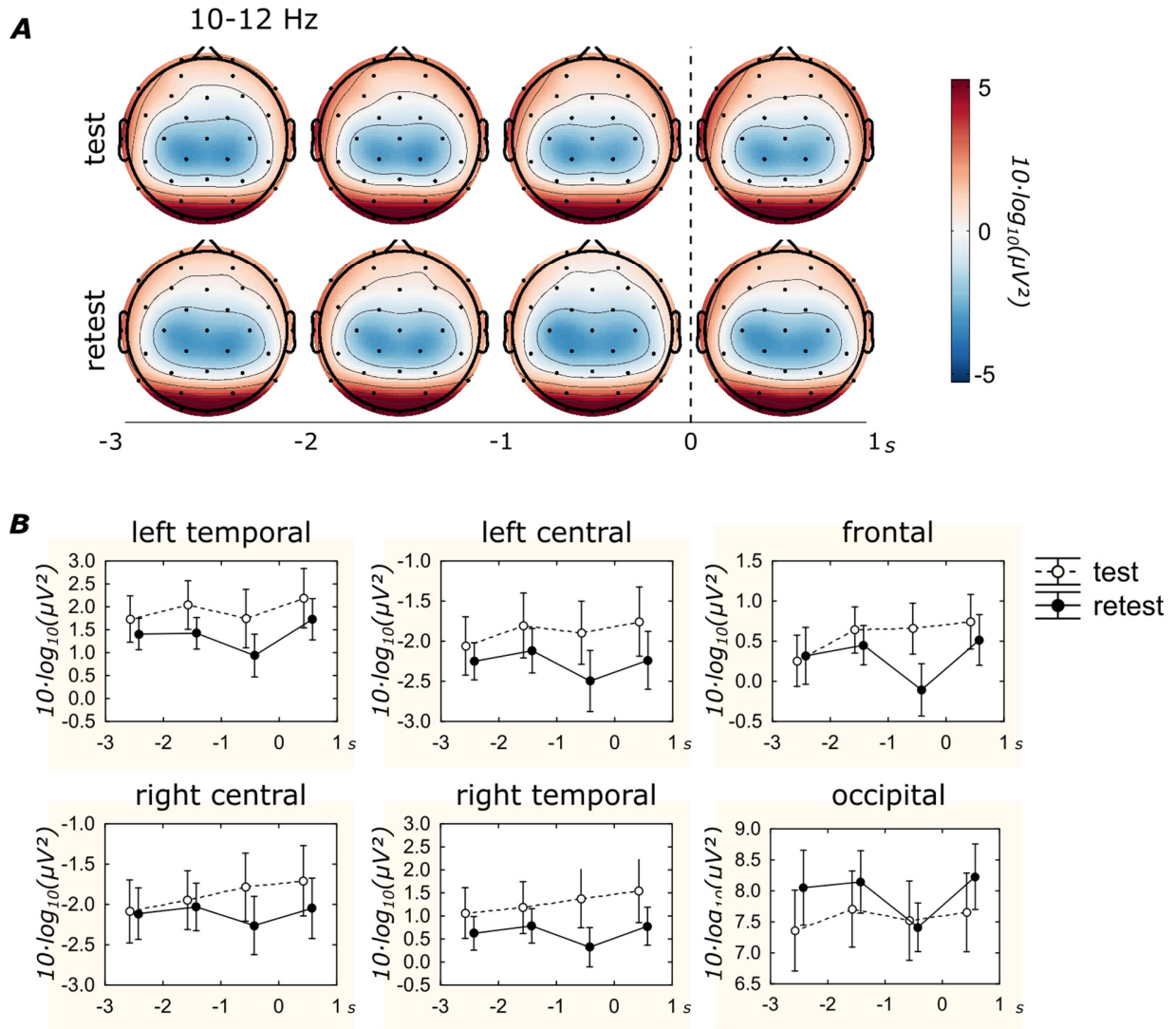


Figure 1. **A:** Scalp maps representing alpha power ( $10 \cdot \log_{10}(\mu V^2)$ ) averaged across participants, as a function of session (test, retest), time ( $-3$  to  $+1$  s), and channel. **B:** Alpha power ( $10 \cdot \log_{10}(\mu V^2)$ ) averaged across participants, as a function of session (test, retest) and time ( $-3$  to  $+1$  s) in the six regions. Error bars represent the standard error of the mean.



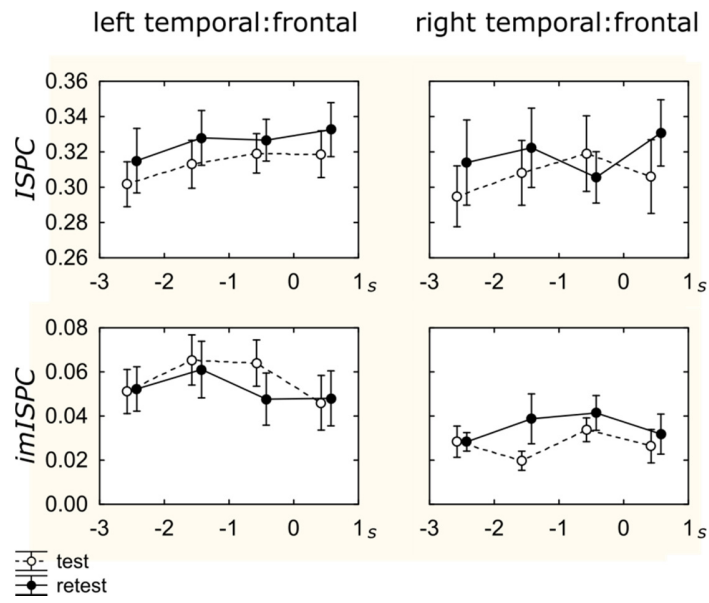
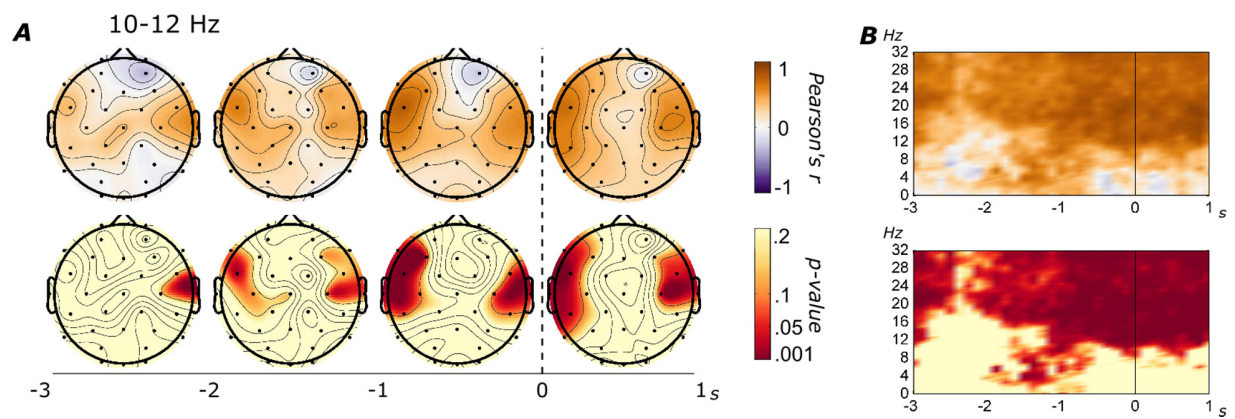


Figure 2. Left / right temporal:frontal alpha ISPC and imISPC averaged across participants as a function of session (test, retest) and time (-3 to +1 s). Error bars represent the standard error of the mean.



*Figure 3. A:* Scalp maps representing Pearson's correlations conducted on the inter-session change scores between the number of holed putts and alpha power, as a function of time (−3 to +1 s) and channel. **B:** Time-frequency plots representing Pearson's correlations conducted on the inter-session change scores between the left temporal alpha power ( $10 \cdot \log_{10}(\mu V^2)$ ) and the number of holed putts, as a function of time (−3 to +1 s) and frequency (0 to 32 Hz).