

Lower Left Temporal-Frontal Connectivity Characterizes Expert and Accurate Performance

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DOI:

[10.1037/spy0000055](https://doi.org/10.1037/spy0000055)

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Document Version

Peer reviewed version

Citation for published version (Harvard):

Gallicchio, G, Cooke, A & Ring, C 2016, 'Lower Left Temporal-Frontal Connectivity Characterizes Expert and Accurate Performance: High-Alpha T7-Fz Connectivity as a Marker of Conscious Processing During Movement', *Sport, Exercise, and Performance Psychology*, vol. 5, no. 1, pp. 14-24. <https://doi.org/10.1037/spy0000055>

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Gallicchio, G., Cooke, A., & Ring, C. (2016).

Lower left temporal-frontal connectivity characterizes expert and accurate performance:

Alpha-band T7-Fz as a marker of conscious processing during movement.

Sport, Exercise & Performance Psychology, 5, 14-24.

Abstract

1
2 The Theory of Reinvestment argues that conscious processing can impair motor performance. The
3 present study tested the utility of left temporal-frontal cortical connectivity as a neurophysiological
4 marker of movement specific conscious processing. Expert and novice golfers completed putts
5 while temporal-frontal connectivity was computed using high alpha Inter Site Phase Clustering
6 (ISPC) and then analyzed as a function of experience (experts versus novices), performance (holed
7 versus missed putts), and pressure (low versus high). Existing evidence shows that left temporal to
8 frontal connectivity is related to dispositional conscious processing and is sensitive to the amount of
9 declarative knowledge acquired during learning. We found that T7-Fz ISPC, but not T8-Fz ISPC,
10 was lower in experts than novices, and lower when putts were holed than missed. Accordingly, our
11 findings provide additional evidence that communication between verbal/language and motor areas
12 of the brain during preparation for action and its execution is associated with poor motor
13 performance. Our findings validate high-alpha left temporal-frontal connectivity as a
14 neurophysiological correlate of movement specific conscious processing.

15

16 Key words

17 conscious processing; Inter Site Phase Clustering (ISPC); motor control; Reinvestment Theory;
18 temporal-frontal connectivity

19

1 Classic theories of motor learning (e.g., Fitts & Posner, 1967) suggest that early in the learning
2 process novices control movements deliberately and consciously, whereas following extensive
3 practice they can learn to control movements automatically with reduced conscious awareness (i.e.,
4 they can evolve into experts). Thus, learning represents a transition from deliberate and explicit to
5 automatic and implicit control of movement. This notion has been supported by research using
6 electroencephalography (EEG) to assess cortical activity during movement tasks (for reviews see
7 Cooke, 2013; Hatfield *et al.*, 2004; Requin, Brener, & Ring, 1991). For instance, EEG research has
8 indicated that experts display greater cortical efficiency (e.g., Babiloni *et al.*, 2010), while also
9 being more sensitive to errors (e.g., Cooke *et al.*, 2015) when planning and executing movements.

10 Grounded on classic theories of motor learning and control, the *Theory of Reinvestment* (Masters,
11 1992; Masters & Maxwell, 2008) proposes that automated motor processes can be disrupted when
12 task-relevant declarative knowledge is used to consciously control movements. Specifically,
13 reinvestment of declarative knowledge de-chunks automatic motor programs into separate
14 components that require conscious control, causing a regression on the skill acquisition continuum
15 to an earlier, more primitive and less effective stage of movement control (MacMahon & Masters,
16 1999). Importantly, the theory argues that contingencies such as movement errors, or increases in
17 pressure, can create the conditions for reinvestment to occur (Lam, Masters, & Maxwell, 2010).
18 For instance, pressure – defined as "the presence of situational incentives for optimal, maximal, or
19 superior performance" – is thought to direct attention inwards and prompt individuals to become
20 self-aware of how they use declarative knowledge or rules when making movements (Baumeister &
21 Showers, 1986).

22 It has been argued that conscious processing of declarative knowledge could be reflected by
23 cortical oscillations in the alpha (8-12 Hz) frequency band (Klimesch, 2012). Indeed, reviews of
24 the literature have established that EEG alpha power distinguishes experts and novices as well as
25 accurate and inaccurate motor performance in various sport-related skills, such as gun shooting and
26 golf putting (Cooke, 2013; Hatfield *et al.*, 2004). With the aim of investigating the impact of

1 declarative information processing on preparation for action, other studies have examined the
2 functional connectivity between the left temporal area of the brain, responsible for verbal-analytic
3 and language processing, and the frontal pre-motor area, responsible for motor planning (Ashe,
4 Lungu, Basford & Lu, 2006).

5 For instance, Deeny *et al.* (2003), assessed functional connectivity prior to trigger pull in
6 experienced marksmen. They computed magnitude squared coherence between electrode sites over
7 the left temporal area (T3) and the frontal midline area (Fz) of the cortex. Magnitude squared
8 coherence reflects the degree of co-variation between the levels of cortical activity (or spectral
9 density) between two electrode sites over time, with high values indicative of a strong and active
10 information pathway between the two underlying brain areas. Alpha band T3-Fz coherence was
11 lower in expert marksmen than in their less skilled counterparts, suggesting that reduced cognitive-
12 motor interference (i.e., conscious processing) was a characteristic of highly-skilled expert
13 performance. Further support for this finding has emerged from a study of cortical activity during
14 golf putting in experts. Specifically, Babiloni *et al.* (2011) found that high-alpha magnitude
15 squared coherence between the left temporal (T3) and left frontal (F3) cortical areas decreased more
16 compared to a pre-movement baseline for holed putts than missed putts in expert golfers. However,
17 Dyke *et al.* (2014) reported no coherence differences between the best and worst putts of novices,
18 suggesting disruption of movement by conscious processing is more likely to be a feature of
19 expertise. Overall, these findings suggest that cognitive-motor interference is lower in experts than
20 novices, and that low left temporal to frontal connectivity distinguishes accurate and inaccurate
21 movements in experts.

22 Building on these observations, Masters and colleagues have conducted a series of experiments
23 designed to examine more closely the putative association between left temporal to frontal
24 functional connectivity and the conscious control of movements. First, they revealed that
25 individuals prone to consciously monitor and control their movements – based on high scores on a
26 dispositional movement reinvestment scale – displayed greater T3-Fz high-alpha (10-12 Hz) band

1 magnitude squared coherence than individuals less prone to reinvest (Zhu *et al.*, 2011). Second, in
2 a follow-up training study, they evaluated the functionality of high-alpha band magnitude squared
3 coherence during motor learning (Zhu *et al.*, 2011). Novices learned to putt golf balls using
4 implicit (without conscious control) or explicit (with conscious control) training protocols. In
5 retention tests, implicit learners displayed less T3-Fz high-alpha band coherence while putting than
6 explicit learners.

7 Taken together, these connectivity findings suggest that reduced verbal-analytic involvement in
8 movement preparation may underlie expert (versus novice) and accurate (versus inaccurate)
9 movement control. They also indicate that left temporal to frontal high-alpha band connectivity
10 could represent a neurophysiological marker of movement-related conscious processing associated
11 with reinvestment of declarative knowledge during the planning and execution of a movement.
12 However, while existing evidence linking left temporal-frontal connectivity to conscious motor
13 processing is compelling, some caveats remain that need to be addressed.

14 First, based on the Theory of Reinvestment, one would expect high-pressure situations – with
15 elements of social evaluation and comparison or reward and punishment – to increase conscious
16 processing and left temporal-frontal cortical connectivity. Available evidence is limited in this
17 regard. Hatfield *et al.* (2013) reported that alpha band coherence between frontal (Fz) and other
18 cortical (including temporal) areas was greater when marksmen performed during a head-to-head
19 competition than a solo do-your-best situation. Moreover, Zhu *et al.* (2011) reported that high-
20 alpha T3-Fz coherence increased during social evaluation in explicit learners only, although this
21 was not accompanied by any pressure-induced changes in performance as would be predicted by the
22 Theory of Reinvestment. Accordingly, further pressure-based research paying specific attention to
23 localised connectivity between the temporal and frontal regions, and its link to performance
24 outcome, is clearly warranted.

25 Second, researchers should also be aware of the potential impact that variations in the EEG power
26 can have on their connectivity measures. Magnitude squared coherence, which has been the

1 connectivity measure of choice in this field to date, is influenced by absolute power and could be
2 confounded by overall power differences between experimental conditions and/or groups (Cohen,
3 2014). This is noteworthy because recent research has demonstrated substantial within and
4 between-group variations in absolute levels of pre-movement alpha power (Babiloni *et al.*, 2008;
5 Cooke *et al.*, 2014). Accordingly, such variations could have influenced the results of some of the
6 previously described connectivity studies. To address this issue, connectivity can be computed
7 using Inter Site Phase Clustering (ISPC, Cohen, 2014; Lachaux *et al.*, 1999). Unlike magnitude-
8 squared coherence, ISPC is computed using just EEG phase angles and therefore measures the
9 degree of interrelation between two neural time series independently of variations in EEG power.
10 This approach to assessing cortical connectivity in sport was adopted for the first time in the present
11 experiment.

12 To extend the research discussed above, the current study was designed to investigate **time**
13 **varying** functional connectivity between the temporal and frontal cortical areas in preparation for
14 golf putting as a function of experience (experts versus novices), performance outcome (holed
15 versus missed putts), and pressure (low versus high pressure). Importantly, this is the first study to
16 our knowledge to adopt ISPC, rather than magnitude squared coherence, as a measure of cortical
17 connectivity during preparation for action in sport. Based on the Theory of Reinvestment (Masters
18 & Maxwell, 2008) we formulated the following hypotheses. First, we expected both self-reported
19 conscious processing and T7-Fz ISPC to be lower in expert compared to novice golfers. Second,
20 we expected T7-Fz ISPC to be lower preceding holed compared to missed putts. Third, we
21 expected both self-reported conscious processing and T7-Fz ISPC to be lower preceding low
22 compared to high-pressure putts. **The interactions between experience, performance outcome, and**
23 **pressure were considered to explore possible moderating effects (e.g., functional connectivity**
24 **affecting putting performance differently in experts and novices, and under different pressure**
25 **conditions).** Our hypotheses were tested using new analyses performed on an existing dataset (see
26 Anon *et al.*, year).

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Methods

Participants

Ten expert ($M = 11.25$ years golf experience; $M = 1.50$ golf handicap) and ten novice ($M = 1.85$ years golf experience; no formal golf handicap) right-handed male golfers were recruited. The study protocol was approved by our university research ethics committee and all participants gave informed consent.

Task

Participants putted golf balls on a flat putting mat to a 2.4 m distant hole with a diameter of 5.4 cm (experts) and 10.8 cm (novices). The different hole size ensured a similar percentage of putts holed for the two groups (see the Results section), allowing us to include the outcome of the putt (holed, missed) as a within-subjects factor in our analyses (cf. Babiloni *et al.*, 2008). Movement onset (i.e., initiation of the backswing of the putting stroke) was detected when the putter head broke the beam of an optical sensor that was interfaced to a computer running ActiView (Biosemi) software. Participants were instructed to try to get putts “*ideally in the hole, but if unsuccessful, to make them finish as close to the hole as possible.*” The outcome of each putt was recorded, and then the ball was replaced on the start position by the experimenter; the interval between putts was approximately 20 seconds.

Procedure

Participants attended a single session. Following instrumentation, instruction, and practice, each participant completed 60 putts under each of two counterbalanced pressure conditions: low and high. The low-pressure condition was a non-competitive climate and involved a cover story that informed participants that one aim of the study was to compare Titleist ProV1 and Titleist ProV1x golf balls. They were randomly assigned one of these balls to putt in the low-pressure condition

1 and were advised that their individual score would not be assessed as data would be pooled among
2 all participants to compute general scores for the two balls. In reality the two golf balls were not
3 compared since the real aim of the cover story was solely to minimize competitive pressure (cf.
4 Cooke, Kavussanu, McIntyre, Boardley, & Ring, 2011). In the high-pressure condition, designed to
5 maximize competitive pressure and reward incentives, participants were informed that they would
6 be individually ranked based on their putting performance, with the leader board emailed to all
7 participants, and with a cash prize being awarded to the top three performers (£100, £50, and £30).
8 The pressure manipulation was successful in increasing heart rate ($M_{\text{low pressure}} = 87$ beats per
9 minute; $M_{\text{high pressure}} = 91$ beats per minute) and perceived pressure ($M_{\text{low pressure}} = 2.90$; $M_{\text{high pressure}} =$
10 3.70), measured after each pressure condition using the pressure/tension subscale of the Intrinsic
11 Motivation Inventory (Ryan, 1982). Participants were thanked and debriefed at the end of their
12 testing session.

13

14 Design

15 We employed a mixed-multifactorial design, with group (expert, novice) as a between-subjects
16 factor, and pressure (low, high), outcome (holed, missed), and epoch (-4 to -3 s, -3 to -2 s, -2 to $-$
17 1 s, -1 to 0 s, 0 to $+1$ s), as within-subjects factors. Epoch describes the time windows around
18 movement (relative to onset of the backswing) during which cortical activity was assessed.

19

20 Measures

21 **Conscious Processing.** The level of self-reported conscious processing was assessed after each
22 pressure condition using a putting specific version (Cooke, Kavussanu, McIntyre, Boardley, &
23 Ring, 2011; Vine *et al.*, 2013) of the conscious motor processing subscale of the Movement
24 Specific Reinvestment Scale (Orrell, Masters, & Eves, 2009). Participants were asked to indicate
25 how they felt while putting in relation to six items, including, “*I thought about bad putts*” and “*I*
26 *tried to figure out why I missed putts*”. Each item was scored on a 5-point Likert scale, with

1 anchors of 1 (*never*), 3 (*sometimes*), and 5 (*always*). Participants completed the scale after each
 2 pressure condition and the mean of the six items was computed to yield the scale score. Past
 3 research has established the validity and internal reliability of the scale, with coefficient alphas of
 4 .81 to .86 (Cooke *et al.*, 2011) and .84 to .88 (Vine *et al.*, 2013). Alpha coefficients in this study
 5 were very good (.82 and .86 for low and high-pressure conditions, respectively).

6 **Cortical Activity.** EEG activity was recorded from 16 silver/silver chloride pin electrodes (Fp1,
 7 Fp2, F4, Fz,F3, T7, C3, Cz, C4, T8, P4, Pz, P3, O1, Oz, O2) positioned using the 10–20 system
 8 (Jasper, 1958). Common mode sense and driven right leg electrodes were used to enhance the
 9 common mode rejection ratio of the signals. Electrodes were placed over the mastoids to allow
 10 offline referencing. Signals were amplified and digitized at 512 Hz with 24-bit resolution
 11 (ActiveTwo, BioSemi) using ActiView (BioSemi) software.

12 Signal pre-processing was performed using the EEGLAB toolbox for MATLAB (Delorme &
 13 Makeig, 2004). Signals were resampled (256 Hz), filtered (1-50 Hz), and referenced to the average
 14 mastoid, and windows spanning 4 s before to 1 s after the initiation of each putt were identified for
 15 further analyses. Gross artefacts (potentials >100 μ V within the -4 to +1 s windows) were removed.
 16 The Runica Infomax algorithm (Makeig *et al.*, 1996) computed independent components, and non-
 17 neural components were removed using ADJUST (Mognon *et al.*, 2011). The cleaned signals were
 18 then divided into five one-second epochs (-4 to -3 s, -3 to -2 s, -2 to -1 s, -1 to 0 s, 0 to +1 s)
 19 relative to backswing initiation, and the channel-to-channel functional connectivity was computed
 20 for each epoch, with 0.5 Hz resolution, as the Inter Site Phase Clustering (ISPC) over trials. ISPC
 21 was computed over the fast Fourier transform spectral estimation of 0.5 s long, Hanning-windowed
 22 segments with 75% overlap (Welch, 1967), 0-padded to reach 2 s length, using bespoke MATLAB
 23 scripts. $ISPC(f) = \left| n^{-1} \sum_{t=1}^n e^{i(\theta_x(t,f) - \theta_y(t,f))} \right|$, where i is the imaginary operator; θ_x and θ_y are
 24 the phase angles of the recorded signal at two different scalp locations at trial t and frequency f ;
 25 $e^{i(\theta_x(t,f) - \theta_y(t,f))}$ denotes a complex vector with magnitude 1 and angle $\theta_x - \theta_y$; $n^{-1} \sum_{t=1}^n (\cdot)$

1 denotes averaging across trials; and $|\cdot|$ is the module of the averaged vector (Cohen, 2014; Lachaux
 2 *et al.*, 1999). ISPC measures the consistency of phase angle differences across trials between two
 3 time series, with values ranging from zero (no functional connection) to one (perfect functional
 4 connection). Following previous research and our a priori hypotheses, we focused on left temporal
 5 (T7) - frontal (Fz) ISPC in the high-alpha (10-12 Hz) frequency band for our statistical analyses.
 6 We also analysed right temporal (T8) - frontal (Fz) high-alpha ISPC to verify the extent to which
 7 any expertise and/or outcome and/or pressure based-connectivity effects were localised to the left-
 8 temporal region, and thereby determine the discriminant validity of our putative marker of
 9 conscious processing.¹ High-alpha ISPC was Z-transformed (i.e. inverse hyperbolic tangent) to
 10 ensure normal distribution before statistical analyses were performed.

11

12 **Statistical Analyses**

13 The temporal-frontal functional connectivity indices (see **Supplementary Files**), computed for
 14 the left (T7-Fz) and right (T8-Fz) temporal cortex, were subjected to 2 Group (expert, novice) \times 2
 15 Pressure (low, high) \times 2 Outcome (holed, missed) \times 5 Epoch (- 4 to -3 s, -3 to -2 s, -2 to -1s, -1
 16 to 0 s, 0 to +1 s) ANOVA. Epoch-related effects were corrected using Huyn-Feldt epsilon (ϵ) and
 17 further examined using polynomial trend analyses and *t*-tests. Partial eta-squared (η_p^2) is reported as
 18 a measure of effect size: values of .02, .15, and .25 represent small, medium, and large effects,
 19 respectively (Cohen, 1992).

20

Results

21 **Putting Performance**

22 A 2 Group \times 2 Pressure ANOVA conducted on the percentage of putts holed revealed no effects
 23 for Group, $F(1,18) = 1.79, p = .20, \eta_p^2 = .090$ ($M_{\text{experts}} = 63\%, M_{\text{novices}} = 71\%$), Pressure, $F(1,18) =$
 24 $3.47, p = .08, \eta_p^2 = .162$ ($M_{\text{low}} = 64\%, M_{\text{high}} = 70\%$), nor Group \times Pressure, $F(1,18) = 0.11, p = .75,$
 25 $\eta_p^2 = .006$ (experts: $M_{\text{low}} = 59\%, M_{\text{high}} = 66\%$; novices: $M_{\text{low}} = 69\%, M_{\text{high}} = 74\%$). This indicates

1 that our hole-size manipulation was successful in ensuring a similar number of holed putts among
 2 novices and experts.

3 **Conscious Processing**

4 A 2 Group \times 2 Pressure ANOVA performed on the putting specific reinvestment scale revealed
 5 that conscious processing was moderately lower in experts ($M = 2.80$, $SD = 0.93$) than novices ($M =$
 6 3.50 , $SD = 0.77$), $F(1, 18) = 3.55$, $p = .07$, $\eta_p^2 = .165$. Analyses of the individual items of the
 7 subscale indicated that experts ($M = 1.80$) “*thought about bad putts*” less than novices ($M = 3.25$),
 8 $F(1, 18) = 13.30$, $p = .002$, $\eta_p^2 = .425$, and experts ($M = 3.05$) “*thought about their stroke*” less than
 9 novices ($M = 3.85$), $F(1, 18) = 3.25$, $p = .09$, $\eta_p^2 = .153$. Neither the pressure main effect, $F(1, 18) =$
 10 0.00 , $p = 1.00$, $\eta_p^2 = .000$ ($M_{\text{low}} = 3.15$, $M_{\text{high}} = 3.15$), nor the group by pressure interaction effect,
 11 $F(1, 18) = 0.52$, $p = .48$, $\eta_p^2 = .028$, were significant.

12

13 **Cortical Activity**

14 **Left temporal-frontal connectivity.** *Figure 1* displays the time-varying left (and right) temporal-
 15 frontal connectivity as a function of Group (panel A), Pressure (panel B), and Outcome (panel C).
 16 The Group \times Pressure \times Outcome \times Epoch ANOVA on T7-Fz ISPC revealed medium-to-large
 17 main effects for Group, $F(1,18) = 3.89$, $p = .06$, $\eta_p^2 = .178$, ($M_{\text{experts}} = .39 < M_{\text{novices}} = .48$), Outcome,
 18 $F(1,18) = 5.71$, $p = .03$, $\eta_p^2 = .241$, ($M_{\text{holed}} = .40 < M_{\text{misses}} = .46$), and Epoch, $F(4,72) = 3.13$, $\epsilon =$
 19 1.00 , $p = .02$, $\eta_p^2 = .148$, ($M_{-4/-3 \text{ s}} = .43$, $M_{-3/-2 \text{ s}} = .45$, $M_{-2/-1 \text{ s}} = .48$, $M_{-1/0 \text{ s}} = .40$, $M_{0/1 \text{ s}} = .40$), but
 20 not Pressure, $F(1,18) = 1.08$, $p = .31$, $\eta_p^2 = .056$, ($M_{\text{low}} = .42$, $M_{\text{high}} = .45$). Epoch-based analyses
 21 confirmed that experts exhibited progressively less connectivity than novices with the approach of
 22 movement onset: $-4/-3 \text{ s}$ ($\Delta_{\text{experts-novices}} = -.04$, $p = .39$, $\eta_p^2 = .042$), $-3/-2 \text{ s}$ ($\Delta_{\text{experts-novices}} = -.06$, $p =$
 23 $.33$, $\eta_p^2 = .053$), $-2/-1 \text{ s}$ ($\Delta_{\text{experts-novices}} = -.09$, $p = .21$, $\eta_p^2 = .085$), $-1/0 \text{ s}$ ($\Delta_{\text{experts-novices}} = -.12$, $p = .04$,
 24 $\eta_p^2 = .209$), and $0/1 \text{ s}$ ($\Delta_{\text{experts-novices}} = -.12$, $p = .04$, $\eta_p^2 = .225$). **The main effect showed that**
 25 **functional connectivity was lower for successful compared to unsuccessful outcomes: subgroup**

1 analyses indicated that this effect was somewhat more evident for experts, $F(1,9) = 5.03, p = .05, \eta_p^2$
 2 $= .358, (M_{\text{holed}} = .37, M_{\text{misses}} = .41)$, compared to novices, $F(1,9) = 2.58, p = .14, \eta_p^2 = .223, (M_{\text{holed}} =$
 3 $.44, M_{\text{misses}} = .51)$.

4 **Right temporal-frontal connectivity.** The Group \times Pressure \times Outcome \times Epoch ANOVA on T8-
 5 Fz ISPC yielded a main effect for Epoch only, $F(4,72) = 7.99, \epsilon = .984, p < .001, \eta_p^2 = .307, (M_{-4/-3 \text{ s}}$
 6 $= .46, M_{-3/-2 \text{ s}} = .55, M_{-2/-1 \text{ s}} = .56, M_{-1/0 \text{ s}} = .45, M_{0/1 \text{ s}} = .46)$. Connectivity was characterized by a
 7 temporally varying quadratic pattern, increasing and then decreasing just before the onset of the
 8 movement. No effects were noted for Group, $F(1,18) = 0.15, p = .70, \eta_p^2 = .01, (M_{\text{experts}} =$
 9 $.48, M_{\text{novices}} = .51)$, Outcome, $F(1,18) = 2.07, p = .17, \eta_p^2 = .103, (M_{\text{holed}} = .48, M_{\text{misses}} = .51)$, or
 10 Pressure, $F(1,18) = 3.43, p = .08, \eta_p^2 = .160, (M_{\text{low}} = .48, M_{\text{high}} = .52)$. The right temporal-frontal
 11 connectivity data are depicted in **Figure 1**.

12 Please note that while our main focus was on ISPC-based connectivity analyses, we also
 13 computed magnitude squared coherence connectivity estimates to allow comparison across
 14 methodologies and with the previous coherence-based literature. The magnitude squared coherence
 15 results are presented in footnote 2.

16

17

Discussion

18 The current study evaluated the utility of left temporal-frontal functional connectivity – namely,
 19 high-alpha Inter Site Phase Clustering, ISPC – as an index of conscious processing during golf
 20 putting (Zhu *et al.*, 2011). This research project was designed to evaluate three predictions derived
 21 from *Reinvestment Theory* (Masters, 1992; Masters & Maxwell, 2008) that might be considered
 22 important characteristics of candidate indices of conscious processing. Our results indicated that
 23 self-reported conscious processing and T7-Fz ISPC **both tended to be** lower in experts than novices
 24 (hypothesis one), and that T7-Fz ISPC was lower for holed than missed putts (hypothesis two).

1 However, the data failed to demonstrate that self-reported conscious processing and T7-Fz ISPC
2 were lower in low compared to high-pressure situations (hypothesis three).

3 Our finding that the amount of self-reported conscious processing and T7-Fz ISPC **tended to be**
4 lower in experts compared to novices is compatible with the classic stage models of motor learning
5 and control (e.g., Fitts & Posner, 1967). The lower left temporal-frontal connectivity displayed by
6 experts versus novices was particularly evident during the final stages of movement preparation and
7 during movement execution, where the most crucial movement-related processes take place (e.g.,
8 Keele, 1968). Overall these findings suggest that our autonomous experts thought less about
9 movement mechanics and bad putts than our cognitive novices.

10 Our finding that missed putts were preceded by higher T7-Fz ISPC compared to holed putts,
11 **indirectly** supports one of the key predictions of *Reinvestment Theory* (Masters, 1992; Masters &
12 Maxwell, 2008), namely, that performance is impaired by conscious processing. This evidence
13 indicates that mistakes, particularly among experts, can be attributed to conscious verbal / analytic
14 interference with movement preparation. The current findings are also in broad agreement with
15 those of Babiloni *et al.* (2011) and Dyke *et al.* (2014), who reported that left temporal-frontal
16 coherence was greater on missed than holed putts among expert golfers only.

17 Left temporal to frontal connectivity tended to increase with pressure (Δ T7-Fz ISPC = .03), with
18 a small-to-medium effect size but our hypothesis that elevated pressure would elicit significantly
19 higher T7-Fz ISPC was not supported by our statistical analyses. **It is worth noting that putting**
20 **performance did not decline under pressure, making it impossible to test a core prediction of**
21 ***Reinvestment Theory* (Masters, 1992; Masters & Maxwell, 2008), namely that declines in**
22 **performance under pressure are due to higher conscious processing. Further, additional analyses**
23 **conducted on the same dataset did not detect any significant effects of pressure on EEG high-alpha**
24 **power (Anon *et al.*, year). These null findings may be attributable to a number of factors. First, the**
25 **experts might have acquired a repertoire of thought strategies to deal with pressure in performance**
26 **situations whereas the novices might have a **less organized and qualitatively different** pool of**

1 declarative knowledge to regress back to when faced with pressure. Second, it is possible that our
2 pressure manipulation was not sufficiently provocative, even though heart rates and
3 pressure/tension ratings were greatest under the high-pressure condition. Third, the methodological
4 requirement to include a large number of trials in order to obtain reliable [estimates of the cortical](#)
5 [activity](#) (e.g., Cohen, 2014) could have diluted any disrupting effects of pressure on putting
6 performance and cortical activity. To overcome this limitation, future studies should develop more
7 provocative and alternative pressure manipulations that employ as few trials as possible.

8 The analyses of ISPC over the left / right temporal and frontal areas revealed that the expertise
9 and outcome effects discussed above were localized to the left hemisphere. [The relative stability of](#)
10 [right temporal-frontal functional connectivity across different levels of expertise and pressure has](#)
11 [been observed previously \(e.g., Deeny *et al.*, 2003; Zhu *et al.*, 2011\) and could reflect visuo-spatial](#)
12 [processing, typically lateralized in the right hemisphere, playing a crucial and sustained role in the](#)
13 [execution of aiming movements, even in later stages of motor learning \(Deeny *et al.*, 2003\).](#)

14 However it should be noted that one previous study of marksmen revealed less right-hemispheric
15 temporal to frontal connectivity in experts compared to novices (Deeny *et al.*, 2009), so this
16 interpretation remains speculative and awaits further investigations, perhaps including a wider array
17 of channel pairs. Additional channel pairs were examined in the present investigation for
18 exploratory purposes – their results can be viewed in the online supplementary material
19 accompanying this submission. In brief, they revealed that left temporal (T7) to right frontal (F4)
20 ISPC was marginally the strongest discriminator of skilled versus unskilled motor performance
21 (compared to other temporal-frontal channel pairs). This further supports the view that left-
22 temporal to frontal strip (e.g., F3, Fz, F4) connectivity is a key discriminator of movement
23 performance, likely related to the amount of conscious knowledge used to control movement.
24 Future research could employ high-density EEG recording while enhancing the spatial resolution
25 (e.g. by means of source estimation analyses or spatial filtering) to better understand the underlying
26 neural generators of these scalp-recorded signals ([Schoffelen & Gross, 2009](#)).

1 In addition to being compatible with Reinvestment Theory, it should be noted that the present
2 results could be alternatively interpreted through the *Psychomotor Efficiency* hypothesis (e.g.,
3 Hatfield *et al.*, 2004). This contends that expert performance is characterized by the activation of
4 task-relevant cortical areas in relative independence of other task-irrelevant areas. Our findings
5 lend broad support to the view that a relative independence of motor processes from other cognitive
6 processes (e.g., verbal / analytic) constitutes a feature of skilled performance and that non-motor
7 inputs during movement preparation could add task-irrelevant noise to motor processes resulting in
8 a poorer performance. Additionally, our findings suggest that not all non-motor processes (e.g.,
9 visuo-spatial) are disruptive to movement performance, as testified by the relative stability of right
10 temporal-frontal connectivity.

11 Finally, it is worth noting that our comparison of the ISPC and the magnitude squared coherence
12 methodologies for computing functional connectivity indicated that ISPC was more sensitive to
13 experience and outcome-related differences. This is likely due to additional variability introduced
14 in the magnitude squared coherence estimates by the large variations in power (e.g., alpha
15 desynchronisation) that occur in the pre-movement period (e.g., Babiloni *et al.*, 2008; Cooke *et al.*,
16 2014). Since ISPC is independent of the magnitude and power of cortical oscillations it is immune
17 from this limitation. To our knowledge this is the first study in the sport domain to highlight the
18 advantages of ISPC over magnitude-squared coherence in assessing EEG-based functional
19 connectivity.

20

21 **Limitations and Directions for Future Research**

22 While expert and novice comparisons can be informative, we concede that there are also some
23 limitations with this approach. First, experts and novices differ on multiple levels, most notably
24 skill *experience* and skill *level*, both higher in the experts. Being the two variables naturally
25 confounded in the expert-novice classification, the present study cannot assess the differential
26 influence of skill experience and skill level on movement performance and conscious processing.

1 Future research could address this point by independently manipulating individual skill experience
2 and skill level or by recruiting participants with similar skill experience and different skill level.
3 Second, differences in skill experience and skill level may regard not just the *quantitative* plane
4 (i.e., same processes in different proportions), but also the *qualitative* one (i.e., different processes)
5 (Ericsson *et al.*, 1993). Since this study aimed to investigate the quantity rather than the quality of
6 conscious processing, we cannot rule out the possibility that experts and novices interpreted
7 differently the inquiries on their movement-related conscious processing. Future research should
8 devote specific attention to examine the qualitative nature and the content of reinvestment,
9 considering that the type of explicit knowledge that is reinvested may have a different impact on
10 movement execution.

11 The results of the present experiment suggest that left temporal-frontal functional connectivity
12 during movement preparation decreases as expertise increases. It would be interesting for future
13 research to further evaluate this interpretation by adopting a longitudinal study design that measures
14 the relations between motor performance, cortical connectivity and conscious processing during
15 learning. Future research could also use these results as a basis for informing neurofeedback
16 training protocols designed to expedite motor learning and to promote an implicit form of learning
17 that is robust to the potential deleterious effects of increased pressure (e.g., Masters, 1992).
18 Specifically, training individuals to reduce the degree of high-alpha band connectivity between their
19 left temporal (verbal) and frontal (motor) cortical areas during motor learning could be an effective
20 way to prevent the formation of movement-related declarative knowledge. Ring, Cooke,
21 Kavussanu, McIntyre, and Masters (2015) have recently demonstrated the efficacy of
22 neurofeedback training in teaching individuals to alter selective features of their cortical activity
23 during the acquisition of a motor skill. It would be particularly interesting for future research to
24 compare the effectiveness of a connectivity-based neurofeedback training protocol with more
25 traditional methods to minimize intrusions of declarative knowledge during movement preparation
26 via psychological skill training or implicit learning (e.g., Masters & Poolton, 2012).

1 **Conclusion**

2 Diminished communication between the left temporal and frontal cortical areas, as measured by
3 Inter Site Phase Clustering (ISPC; Cohen, 2014; [Lachuax et al., 1999](#)) computed in the high-alpha
4 (i.e. 10-12 Hz) frequency band, was identified as a characteristic of expertise and successful motor
5 performance in a golf putting task. The current findings help establish the construct validity of left-
6 temporal to frontal connectivity: expert-novice and holed-missed differences providing evidence for
7 the concurrent and convergent validity of T7-Fz as a marker of conscious processing, whereas the
8 lack of effects for T8-Fz provide evidence for discriminant validity. Our findings provide [indirect](#)
9 support for *Reinvestment Theory*'s prediction that the performance of well-learned motor skills is
10 impaired by conscious motor processing (Masters & Maxwell, 2008). Previous research has
11 indicated that golfers should maximise the amount of cortical resources devoted to programming
12 movement parameters (e.g., direction and force) to achieve putting success (e.g., Babiloni *et al.*,
13 2008; Cooke *et al.*, 2014; 2015). When taken alongside the current findings, the advice for golfers
14 would be to concentrate, but not take conscious control of movements, when preparing for crucial
15 putts.

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13

Notes

1. The terms “T3” and “T7” are used interchangeably in EEG literature, denoting the same electrode position in older and newer EEG recording systems, respectively. The same consideration applies to “T4” and “T8”.

2. Functional connectivity was additionally assessed with magnitude squared coherence.

$$Coh_{xy}^2(f) = \frac{|S_{xy}(f)|^2}{S_{xx}(f)S_{yy}(f)} = \frac{\left| \frac{n^{-1} \sum_{t=1}^n |X(t,f)||Y(t,f)|e^{i(\theta_x(t,f)-\theta_y(t,f))}}{(n^{-1} \sum_{t=1}^n |X(t,f)|^2)(n^{-1} \sum_{t=1}^n |Y(t,f)|^2)} \right|^2}{S_{xx}(f)S_{yy}(f)},$$

where S_{xy} denotes the cross-spectral density of the two signals and S_{xx} and S_{yy} their respective auto-spectral densities. Similarly to ISPC, phase angle differences are clustered across trials. Differently from ISPC, phase angle differences are additionally weighted on the EEG spectral amplitudes of the two signals (i.e., $|X(t, f)|$ and $|Y(t, f)|$) and, after averaging across trials, this quantity is further scaled on the EEG power measured at the two scalp locations (i.e., $|X(t, f)|^2$ and $|Y(t, f)|^2$). The Group \times Pressure \times Outcome \times Epoch ANOVAs revealed Time effects, $F_s(4,72) = 6.08 - 7.95$, $p_s < .001$, $\eta_p^2_s = .253 - .306$, for both T7-Fz and T8-Fz magnitude squared coherence. No effects emerged for Group, $F_s(1,18) = .987 - .229$, $p_s = .192 - .638$, $\eta_p^2_s = .093 - .013$ ($M_{S_{experts}} = .621 - .734$, $M_{S_{novices}} = .720 - .785$), Outcome, $F_s(1,18) = .208 - .011$, $p_s = .654 - .916$, $\eta_p^2_s = .011 - .001$ ($M_{S_{holed}} = .672 - .760$, $M_{S_{misses}} = .669 - .759$), or Pressure, $F_s(1,18) = 1.538 - 3.213$, $p_s = .231 - .090$, $\eta_p^2_s = .079 - .151$ ($M_{S_{low}} = .643 - .728$, $M_{S_{high}} = .698 - .792$).

Figure Caption

1

2 Figure 1. Mean left / right temporal-frontal (T7-Fz / T8-Fz) inter site phase clustering (ISPC) as a
3 function of Epoch (-4 to -3 s, -3 to -2 s, -2 to -1 s, -1 to 0 s, 0 to +1 s) and Group (experts versus
4 novices) (panel A), Pressure (low versus high) (panel B), and Outcome (holed versus missed) (panel
5 C). Vertical bars indicate standard error of the means.

6

Figure 1:

