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Sport, Exercise, and Performance Psychology

DOI:
10.1037/spy0000055

Published: 01/02/2016

Peer reviewed version

Cyswllt i'r cyhoeddiad / Link to publication

Dyfyniad o'r fersiwn a gyhoeddwyd / Citation for published version (APA):
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*, *5*(1), 14-24. https://doi.org/10.1037/spy0000055

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19. Apr. 2024

ACCEPTED MANUSCRIPT

To appear in ***Sport, Exercise and Performance Psychology***

Accepted: 25th September 2015

Lower left temporal-frontal connectivity characterizes expert and accurate performance: High-alpha T7-Fz connectivity as a marker of conscious processing during movement

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Abstract

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

Key words

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Design

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

Measures

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

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

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

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

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

Statistical Analyses

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

Results

Putting Performance

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

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

Conscious Processing

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

Cortical Activity

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

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

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

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

Discussion

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

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

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

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

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

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

The analyses of ISPC over the left / right temporal and frontal areas revealed that the expertise and outcome effects discussed above were localized to the left hemisphere. The relative stability of right temporal-frontal functional connectivity across different levels of expertise and pressure has been observed previously (e.g., Deeny *et al.*, 2003; Zhu *et al.*, 2011) and could reflect visuo-spatial processing, typically lateralized in the right hemisphere, playing a crucial and sustained role in the execution of aiming movements, even in later stages of motor learning (Deeny *et al.*, 2003). However it should be noted that one previous study of marksmen revealed less right-hemispheric temporal to frontal connectivity in experts compared to novices (Deeny *et al.*, 2009), so this interpretation remains speculative and awaits further investigations, perhaps including a wider array of channel pairs. Additional channel pairs were examined in the present investigation for exploratory purposes – their results can be viewed in the online supplementary material accompanying this submission. In brief, they revealed that left temporal (T7) to right frontal (F4) ISPC was marginally the strongest discriminator of skilled versus unskilled motor performance (compared to other temporal-frontal channel pairs). This further supports the view that left-temporal to frontal strip (e.g., F3, Fz, F4) connectivity is a key discriminator of movement performance, likely related to the amount of conscious knowledge used to control movement. Future research could employ high-density EEG recording while enhancing the spatial resolution (e.g. by means of source estimation analyses or spatial filtering) to better understand the underlying neural generators of these scalp-recorded signals (Schoffelen & Gross, 2009).

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

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

Limitations and Directions for Future Research

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

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

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

Conclusion

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

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Notes

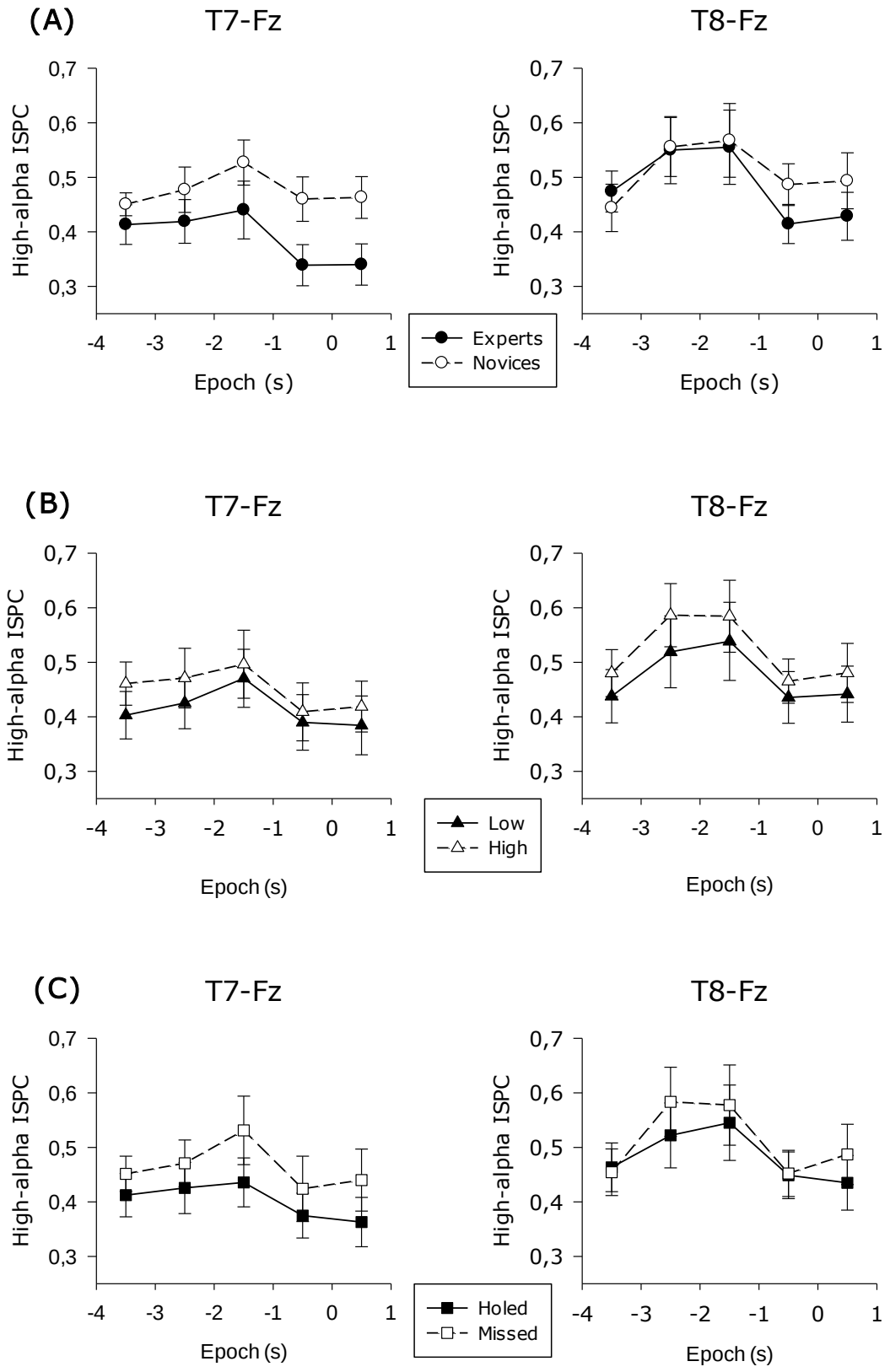
1. The terms “T3” and “T7” are used interchangeably in EEG literature, denoting the same electrode position in older and newer EEG recording systems, respectively. The same consideration applies to “T4” and “T8”.

2. Functional connectivity was additionally assessed with magnitude squared coherence. $Coh_{xy}^2(f) = \frac{|S_{xy}(f)|^2}{S_{xx}(f)S_{yy}(f)} = \frac{\left|n^{-1}\sum_{t=1}^{n}|X(t,f)||Y(t,f)|e^{i\left(\theta_X(t,f)-\theta_Y(t,f)\right)}\right|^2}{\left(n^{-1}\sum_{t=1}^{n}|X(t,f)|^2\right)\left(n^{-1}\sum_{t=1}^{n}|Y(t,f)|^2\right)}$, 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 × Pressure × Outcome × Epoch ANOVAs revealed Time effects, Fs(4,72) = 6.08 – 7.95, ps< .001, η_p^2s = .253 - .306, for both T7-Fz and T8-Fz magnitude squared coherence. No effects emerged for Group, Fs(1,18) = .987 - .229, ps = .192 - .638, η_p^2s = .093 - .013 (Ms$_{experts}$ = .621 - .734, Ms$_{novices}$ = .720 - .785), Outcome, Fs(1,18) = .208 - .011, ps = .654 - .916, η_p^2s = .011 - .001 (Ms$_{holed}$ = .672 - .760, Ms$_{misses}$ = .669 - .759), or Pressure, Fs(1,18) = 1.538 - 3.213, ps = .231 - .090, η_p^2s = .079 - .151 (Ms$_{low}$ = .643 - .728, Ms$_{high}$ = .698 - .792).

Figure Caption

Figure 1. Mean left / right temporal-frontal (T7-Fz / T8-Fz) inter site phase clustering (ISPC) as a 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 novices) (panel A), Pressure (low versus high) (panel B), and Outcome (holed versus missed) (panel C). Vertical bars indicate standard error of the means.

Figure 1:


(A)
T7-Fz
T8-Fz
High-alpha ISPC
0,7
0,6
0,5
0,4
0,3
-4
-3
-2
-1
0
1
Epoch (s)
Experts
Novices
(B)
Low
High
(C)
Holed
Missed