Neural co-activation as a yardstick of implicit motor learning and the propensity for conscious control of movement

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\textbf{A B S T R A C T}

Two studies examined EEG co-activation (coherence) between the verbal-analytical (T3) and motor planning (Fz) regions during a golf putting task. In Study 1, participants with a strong propensity to consciously monitor and control their movements, determined psychometrically by high scores on a movement specific Reinvestment Scale, displayed more alpha2 T3–Fz co-activation than participants with a weak propensity. In Study 2, participants who practiced a golf putting task implicitly (via an errorless learning protocol) displayed less alpha2 T3–Fz co-activation than those who practiced explicitly (by errorful learning). In addition, explicit but not implicit motor learners displayed more T3–Fz co-activation during golf putting under pressure, implying that verbal-analytical processing of putting movements increased under pressure. These findings provide neuropsychological evidence that supports claims that implicit motor learning can be used to limit movement specific reinvestment.

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1. Introduction

Skilled motor performance is characterized not only by biomechanical and metabolic economies (Daniels, 1985; Lay et al., 2002; Sparrow, 1983, 2000) but also by neural efficiency (Hatfield and Hillman, 2001). Extended practice is accompanied by precise allocation of processing resources (e.g., Busk and Galbraith, 1975), recognizable patterns of cortical activation (e.g., Elbert et al., 1995; Hauffer et al., 2000) and reduced cortico-cortical communication between motor and non-motor regions of the brain (e.g., Deeny et al., 2003; Hatfield et al., 2004).

Cortical activation at specific regions in the cerebral cortex can be measured by electroencephalography (EEG) power spectral analysis. Previous studies have revealed that superior marksmanship is associated with increased alpha power in the left temporal region (T3) during the initiation of shots (Hatfield et al., 1984). T3 alpha power is higher in expert marksmen than novice shooters (Hauffer et al., 2000) and has been shown to increase in response to training (Kerick et al., 2004). These findings are thought to reflect a gradual withdrawal of effortful verbal-analytical or cognitive processes as motor competence develops (Cohen, 1993; Hatfield et al., 1984; Hauffer et al., 2000; Kerick et al., 2001; Lawton et al., 1998).

Changes in co-activation (or coherence) between selected pairs of regions in the cerebral cortex may also reflect a gradual withdrawal of verbal-analytical involvement from motor performance. EEG coherence is a frequency-dependent measure of the degree of linear relatedness between signals simultaneously recorded from two separate regions on the scalp. High coherence implies ‘synched’ communication between the particular regions of the cerebral cortex, whereas low coherence indicates regional independence (Nunez, 1995; Weiss and Mueller, 2003).

In particular, measures of coherence between the left temporal region (T3) and the frontal midline region (Fz) of the cortex may allow appraisal of the contribution of verbal-analytical processes to motor performance. It is widely viewed that the left temporal region is associated with verbal-analytical processes (Hauffer et al., 2000; Kerick et al., 2001) and language processing (Cohen, 1993; Springer and Deutsch, 1998), and the frontal midline region is the premotor area of cortex that is responsible for the planning of movement (Kaufner and Lewis, 1999). Indirect support for the potential utility of EEG T3–Fz coherence is provided by work that evaluated coherence differences between expert and less skilled rifle shooters (Deeny et al., 2003). Experts exhibited lower EEG T3–Fz coherence than less skilled shooters, which Deeny et al. interpreted as evidence that verbal-analytical processes were less involved in the motor planning of experts than novice shooters. Deeny et al. found no expert-novice differences in coherence between the right temporal region (T4) and the frontal midline region (Fz). The right temporal region is thought to mediate visuospatial processes (Hauffer et al., 2000; Kerick et al., 2001; Springer and Deutsch, 1998). Deeny et al. argued that, unlike...
verbal-analytical processing, visuospatial processing is a necessary
demand of visual aiming tasks such as target shooting, so extended
practice is unlikely to result in its withdrawal.

The gradual withdrawal of verbal-analytical processes during
motor learning is thought to reflect a progression from an initial
verbal-analytical stage of learning to an autonomous stage of per-
formance (e.g., Anderson, 1983; Fitts and Posner, 1967). The verbal-
analytical stage is one in which conscious involvement is high as the
learner comes to terms with the different components of the task
and tests hypotheses about the most appropriate motor solution
available (Zhu et al., 2010). Gradually, verbal-analytical engage-
ment in the task reduces, performance becomes less attention
demanding and an autonomous stage of performance is reached.

Just as verbal-analytical processes can be withdrawn from
motor performance, they can also return in a phenomenon
described as ‘reinvestment’ (Masters, 1992). The Theory of Rein-
vestment (see Masters and Maxwell, 2008 for a review) argues that,
“relatively automated motor processes can be disrupted if they are
run using consciously accessed, task relevant declarative knowl-
edge to control the mechanics of the movements on-line” (p. 160).
There has been consistent support for the concept of reinvestment
in a range of skills in tennis, golf, squash and soccer (e.g., Chell et
al., 2003; Kinrade et al., 2010; Masters et al., 1993; Maxwell et al.,
2006), and in people with stroke or Parkinson disease (e.g., Masters
et al., 2007; Orrell et al., 2009), as well as in elderly fallers and non-
fallers (Wong et al., 2007, 2008), musicians (Wan and Huon, 2005),
and people under postural threat (Huffman et al., 2009). Both a
general Reinvestment Scale (Masters et al., 1993) and a Movement
Specific Reinvestment Scale (Masters et al., 2005) have been devel-
oped and validated as measures of the degree to which individuals
tend to use verbal-analytical control when performing motor skills.

People with high reinvestment scores have been rated to be most
likely to be negatively impacted by pressure, and associations have
been shown between reinvestment scores and the breakdown of
skill under pressure in golf putting (Masters et al., 1993; Maxwell et
al., 2006), soccer (Chell et al., 2003) and hockey dribbling (Jackson
et al., 2006). Furthermore, learners classified as high reinvestors
report significantly more about the mechanics of a golf putt after
learning than low reinvesters (Maxwell et al., 2000, 2006), sug-
gesting that for high reinvesters verbal-analytical control processes
play a more salient role in learning.

Although there has been a great deal of behavioral support for
the predictions of the Theory of Reinvestment, cortical activity of
high and low reinvestors has not been examined. Therefore, in
Study 1 we assessed cortico-cortical communication (coherence)
in novice golf putters with a strong propensity to consciously monitor
and control their movements and in novice golf putters with a weak
propensity to consciously monitor and control their movements,
as indicated psychometrically by high and low scores respectively
on the Movement Specific Reinvestment Scale. We predicted that
novices with high scores on the Scale would exhibit more T3–Fz EEG
coherence when performing a golf putting task, than novices with
low scores, reflecting their different propensities to use verbal-
analytical control when performing the task.

In a second study, we asked whether the same task (golf
putting) could be learned in a manner that reduced the likelihood
of movement specific reinvestment by implicit motor learning
(Masters, 1992). Contemporary theories of motor learning argue
that both explicit and implicit learning processes contribute to
motor control (Gentile, 1998; Masters and Maxwell, 2004; Maxwell
et al., 2003; Willingham, 1998), but that explicit motor learning is
intentional and uses working memory (e.g., Baddeley, 1986)
to manage verbal-analytical aspects of learning, such as utiliza-
tion of verbal instructions, monitoring and control of performance,
formation and testing of hypotheses, correction of errors, and accu-
mulation, retrieval and implementation of declarative knowledge
(e.g., Masters, 1992; Masters and Maxwell, 2004; Maxwell et al.,
2003). Crucially, implicit motor learning reduces verbal-analytical
involvement in movement control by encouraging limited depen-
dence on working memory. The most blatan consequense of
implicit approaches is that the knowledge that eventually underlies
performance is difficult to consciously retrieve (e.g., Reber, 1993).

Implicit motor learning techniques specifically developed to
suppress contributions from verbal-analytical explicit processes
during motor performance (see Masters and Maxwell, 2004, for
a review) have been shown to produce performance that is more
stable in conditions of psychological stress (e.g., Hardy et al., 1996;
Lam et al., 2009; Law et al., 2003; Liao and Masters, 2001; Masters,
1992; Mullen et al., 2007), multitasking (e.g., Masters et al., 2004,
2008a,b; Maxwell et al., 2001, 2003; Poolton et al., 2006) and physi-
ological fatigue (e.g., Masters et al., 2008a,b; Poolton et al.,
2007a,b). Maxwell et al. (2001), for example, used an errorless learning tech-
nique to cause implicit learning, arguing that one of the primary
operations of explicit processes is to correct outcome errors. By
limiting the number of outcome errors committed during learn-
ing, the errorless technique therefore reduces the involvement
of verbal-analytical explicit processes in performance. Maxwell
et al. showed that novices who completed blocks of golf putts
from incrementally increasing distances from which it was virtually
impossible to miss (25 cm, 50 cm, 75 cm, etc.) were more resilient
to the demands of a concurrent cognitive task when their putting
was tested after learning. Maxwell et al. (2001; see also Poolton et
al., 2005, 2007a,b; Masters et al., 2008a,b) suggested that errorless
learning allowed the putting task to be learned without dependence
on verbal-analytical processes, leaving resources free to complete
the concurrent cognitive task.

Consequently, in Study 2 we used an errorless technique simi-
lar to Maxwell et al. (2001) to cause implicit motor learning and
assessed co-activation between the left temporal region (T3) and
the frontal midline region (Fz) of the cortex during golf putting.
We expected reduced verbal-analytical processing to be indicated
by low T3–Fz coherence during performance compared to learn-
ers who made many errors (and consequently used a high degree
of verbal-analytical processing during performance). Additionally,
we assessed T3–Fz coherence under psychological pressure. Recent
evidence suggests that disrupted motor performance under pres-
sure is accompanied by increased T3–Fz coherence (Hatfield et
al., 2009; Chen et al., 2005), implying that verbal-analytical process-
ing increases in response to pressure, as suggested by the Theory
of Reinvestment. We expected that participants who learned the
putting task explicitly, with verbal-analytical involvement in
movement control, would display increased T3–Fz co-activation
under pressure, whereas participants who learned implicitly, with-
out verbal-analytical involvement, would display no change in
T3–Fz co-activation.

2. Study 1

Study 1 compared EEG T3–Fz (and T4–Fz) coherence levels
between participants novice to a golf putting task, and classified
as having a high or a low propensity for verbal-analytical process-
ing during motor performance. Classification was made on the basis
of scores on the conscious motor processing factor of the Movement
Specific Reinvestment Scale (Masters and Maxwell, 2008; Masters
et al., 2005).2 The factor consists of 5 statements, such as I reflect

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2 The Movement Specific Reinvestment Scale is composed of two movement rele-
vant factors, movement self-consciousness and conscious motor processing. The former
is characterized by concern about ‘style’ of movement and about making a good
impression when moving in public, whereas the latter is characterized by conscious
monitoring and control of the process of movement.
about my movement a lot or I am aware of the way my body works when I am carrying out a movement. Each statement requires a response on a 6-point Likert scale that ranges from strongly disagree to strongly agree. We predicted that performers with high conscious motor processing scores would display higher T3–Fz coherence than those with low scores. Guided by the view that visuospatial processing is unavoidable in golf putting, as in rifle shooting (Deeny et al., 2003), we expected that high and low conscious motor processing scores would not differentiate T4–Fz coherence.

2.1. Methods

2.1.1. Participants

Students (N = 204) from the University of Hong Kong completed the Movement Specific Reinvestment Scale. Students who scored 1 standard deviation (SD = 4.79) above or below the mean score on the conscious motor processing factor (mean = 19.1) were classified as high or low reinvesters respectively, suggesting a high or a low propensity to use verbal-analytical processing during motor performance. Sixteen students volunteered to participate in the study (High Reinvestment group, n = 8, M age = 23.3, SD = 3.20; Low Reinvestment group, n = 8, M age = 21.8, SD = 1.67) and provided informed consent. The participants were all right-handed with no golf experience.

2.1.2. Apparatus

The task required participants to putt standard white golf balls to a target square (size 15.2 cm × 15.2 cm) on an artificial grass putting surface that was even and level. Putts were made from a distance of 2 m using a standard golf putter. A golf ball dispenser with an infrared sensor (Hono Golf, China) was used to present each to-be-putted ball automatically. Putting performance (i.e., distance from the centre of the square) was recorded by a camera-based scoring system (for details, see Neumann and Thomas, 2008).

Electroencephalographic (EEG) activity was recorded from 7 scalp locations (Fp1, Fp2, T3, T4, Fz, Cz, Pz) referenced to linked earlobes using a stretchable electrode cap (ElectroCap Inc., USA) in accordance with the standard international 10–20 system (Jasper, 1958). The ground electrode was located at the mid forehead. EEG was recorded and stored (bandpass filter 1–45 Hz, notch filter 50 Hz, sample rate 1000 Hz) using a NeuroTop EEG system (Symtop Instruments, China). Before each measurement an impedance test ensured a sufficient signal to noise ratio. EEG artifacts caused by eye blink were removed by Independent Component Analysis (ICA, see Delorme and Makeig, 2004). An infrared sensor on the golf ball dispenser detected each ball strike and marked it in the EEG record to indicate execution of each putt. A 4-s period of continuous data prior to ball strike was selected for further processing. An experienced EEG technician visually inspected the recordings and removed any other potential biological artifacts (e.g., muscle activation or glabrous-kinetic artifacts). Artifacts were distinguished from cortical activity according to the duration, morphology, and rate of firing. A Hamming window (1024 sample and 50% overlap) was then applied to the data in preparation for coherence analysis.

Coherence was defined as \( C_{xy}(f) \) of the EEG signals at electrode sites x and y, where:

\[
C_{xy}(f) = \frac{\left| \frac{P_{xy}(f)}{P_{xx}(f)P_{yy}(f)} \right|^2}{\sum_{y=x}^{\text{other electrodes}} \left( \frac{P_{yx}(f)}{P_{xx}(f)P_{yy}(f)} \right)^2} \tag{1}
\]

and where \( P_{xx} \) and \( P_{yy} \) represent the power spectral density of x and y, respectively, and \( P_{xy} \) represents the cross power spectral density of x and y. Coherence is a function of frequency with values between 0 and 1 indicating how well x corresponds to y at each frequency.

EEG T3–Fz and T4–Fz coherence were calculated in 0.08-Hz frequency bins and averaged across the appropriate frequencies to obtain the coherence values for alpha1 (8–10 Hz) and alpha2 (10–12 Hz) frequency bandwidths (Deeny et al., 2003). The alpha frequency bandwidth (8–12 Hz) was selected as it is more likely to reflect global cortico-cortical communication sensitive to the frontal and temporal regions, whereas coherence in higher frequency bandwidths is sensitive to more localized activation of the cortex (Nunez, 1995; Von Stein and Sarnthein, 2000). We focused the analysis still further by examining alpha1 and alpha2 bandwidths. Alpha2 is of most relevance to the current study as it is thought to be more indicative of task-specific attentional processes, whereas alpha1 is more indicative of generalized arousal (Smith et al., 1999; for a review see Klimesch, 1999). All coherence estimates were subjected to Fisher’s z transformation prior to analysis to ensure normal distribution. The processing and analysis steps described above were implemented with the EEGLAB toolbox (Delorme and Makeig, 2004) and custom scripts in MATLAB (MathWorks, USA).

2.1.3. Procedure

Participants were unaware of the purpose of the study or that they would be asked to complete a golf putting task. On arriving at the motor skill laboratory, participants’ EEG activity was assessed in a resting baseline condition designed to imitate the usual preparatory position of a golf putt. Participants quietly stood for 1 min with their feet shoulder width apart and with their eyes open, focusing on a mark on the ground between their feet. EEG activity was then recorded continuously in a golf putting condition, in which participants were asked to attempt to hit each of 10 putts into a target square (15 cm × 15 cm). The final position of each putt was visible to participants, but no other feedback was provided by the experimenter.

2.2. Results

2.2.1. Golf putting performance

Putting performance (mean distance from the centre of the target square) of the Low Reinvestment group (M = 39.0 cm, SD = 9.01) was not different from putting performance of the High Reinvestment group (M = 37.9 cm, SD = 17.99), t(14) = 0.15, P = 0.88.

2.2.2. EEG T3–Fz and T4–Fz coherence

EEG coherence estimates were computed for the T3–Fz and T4–Fz pairs in alpha1 (8–10 Hz) and alpha2 (10–12 Hz) frequency bandwidths during golf putting. These were subjected to Group × Pair (2 × 2) repeated measure ANCOVAs using T3–Fz and T4–Fz coherence during resting baseline as covariates.

\[
\text{Alpha1 (8–10 Hz)}
\]

No significant main effects were evident for Group (\( F(1,12) = 1.37, P = 0.27, \text{effect size} = 0.10 \)) or Pair (\( F(1,12) = 0.40, P = 0.84, \text{effect size} = 0.004 \)). An interaction was not evident (\( F(1,12) = 3.76, P = 0.08, \text{effect size} = 0.24 \)) (see Fig. 1).

\[
\text{Alpha2 (10–12 Hz)}
\]

No significant main effects were evident for Group (\( F(1,12) = 1.99, P = 0.18, \text{effect size} = 0.14 \)) or Pair (\( F(1,12) = 0.41, P = 0.53, \text{effect size} = 0.03 \)). A significant Group × Pair interaction was evident (\( F(1,12) = 4.96, P = 0.05, \text{effect size} = 0.29 \)) (see Fig. 2). Further analysis of the interaction revealed that T3–Fz coherence was significantly higher in the High Reinvestment group than the Low Reinvestment group (\( F(1,13) = 6.87, P < 0.05, \text{effect size} = 0.35 \)), whereas, T4–Fz coherence was not different (\( F(1,13) = 0.14, P = 0.71, \text{effect size} = 0.01 \)).

![Fig. 1.](image1)

![Fig. 2.](image2)
2.3. Discussion

Consistent with our predictions, participants with high scores on the conscious motor processing factor of the Movement Specific Reinforcement Scale displayed higher alpha2 T3–Fz coherence than participants with low scores. A similar pattern of findings was evident for alpha1 coherence (see Fig. 1) and while the interaction did not reach significance, a moderately large effect size was present (0.24).

We also found that alpha1 and alpha2 T4–Fz coherence was not different between high and low reinvesters, implying that the same degree of visuospatial processing was involved in motor planning for both groups. This finding suggests that visuospatial processing is a necessary component of motor planning in golf putting, a visuomotor aiming task (as Deeny et al., 2003).

Taken together, the findings suggest that a high propensity for reinvestment (conscious motor processing) is accompanied by greater verbal-analytical processing of movements, providing support for the Theory of Reinvestment (Masters, 1992; Masters and Maxwell, 2008). The extent to which verbal-analytical processes are involved in motor performance is related to personality, and may be objectively indexed by alpha2 T3–Fz coherence.3

3. Study 2

Masters and Maxwell (see 2008 for a review) have consistently argued that the propensity to involve verbal-analytical processes in motor performance (i.e., reinvestment) can be prevented by utilizing implicit motor learning to restrain the build-up of movement specific knowledge and thus reduce dependence on verbal-declarative knowledge structures during movement. In Study 2, we therefore asked whether T3–Fz coherence is modified by learning that reduces verbal-analytical involvement in motor performance. One group of participants learned to golf putt using a technique previously shown to cause implicit motor learning (i.e., errorless learning, Maxwell et al., 2001), whereas a second group of participants learned to putt using a technique that encourages explicit motor learning (errorful learning).

We assessed EEG T3–Fz coherence levels after 300 trials of learning in each group in a retention test and in a transfer test, which applied psychological pressure to perform well. Learning took place on Day 1 and testing (retention, transfer) took place on Day 2. The validity of the pressure manipulation was checked with an objective psychophysiological response measure (heart rate; Hardy and Parfitt, 1991) and self-reported anxiety (The Anxiety Thermometer; Houtman and Bakker, 1989). The extent to which the errorless learning paradigm conferred characteristics of implicit motor learning was indirectly inferred from a verbal account by each participant at the end of the study, consistent with previous research (Maxwell et al., 2001).

We hypothesized that, compared to many errors during learning, few errors during learning would reduce the involvement of verbal-analytical processes in performance and would be associated with lower T3–Fz alpha coherence when putting. Further, as implicit motor learning reduces dependence on verbal-declarative knowledge structures during performance and thus makes skill fail-ures from reinvestment less likely (see Masters and Maxwell, 2004), we tested putting performance in both groups under psychologi cal pressure to perform well. We predicted that T3–Fz coherence would increase under pressure in the explicit motor learning condition but would remain stable under pressure in the implicit motor learning condition.

3.1. Methods

3.1.1. Participants

Eighteen undergraduate students from the University of Hong Kong volunteered to participate in the study. The students provided informed consent and were randomly assigned to either an implicit motor learning treatment condition, errorless learning (n = 9, M age = 22.0, SD = 1.73) or an explicit motor learning treatment condition, errorful learning (n = 9, M age = 22.1, SD = 2.80). Participants were all right-handed with no golf experience.

3.1.2. Apparatus

During learning (Day 1), participants in the Errorless treatment condition performed each block of 50 trials from the same distance, while participants in the Errorful treatment condition performed each block of 50 practice trials (n = 300 trials) on Day 1. On Day 2, participants completed a Retention test (10 trials) and a Transfer test under psychological pressure to perform well (10 trials). EEG T3–Fz and T4–Fz coherence was assessed on Day 2 only. Throughout the experiment participants were simply instructed to putt as accurately as possible.

3.1.3. Procedure

Participants practiced golf putting in either an Errorless treatment condition that facilitated the reduction of outcome errors early in learning or an Errorful treatment condition that allowed outcome errors to occur early in learning. In both treatment conditions, participants performed 6 blocks of 50 practice trials (n = 300 trials) on Day 1. On Day 2, participants completed a Retention test (10 trials) and a Transfer test under psychological pressure to perform well (10 trials). EEG T3–Fz and T4–Fz coherence was assessed on Day 2 only. Throughout the experiment participants were simply instructed to putt as accurately as possible.

3.1.4. Data Analysis

For the Transfer test, we raised performance anxiety levels using a cover story designed to increase evaluation apprehension. Participants were informed, via a pre-recorded video message presented by the Professor leading the study, that their performance was to be filmed for later analysis so it was important that they achieve a good performance score in the test (see Masters, 1992). A video camera was then set up and switched on prior to participants beginning their 10 puts. The resting baseline measure of EEG activity was recorded as in Experiment 1 prior to the Retention test.

At the end of the study, participants were asked to report, in as much detail as possible, any rules, methods or techniques that they recalled using to perform the putting task. The statements reported by each participant were evaluated by exper imenter consensus (n = 3). The experimenters were blind to the treatment condition under which each participant performed. Scoring used the hypothesis-testing based criteria first employed by Maxwell et al. (2001). Statements that indicated that the performer had tested hypotheses related to their putting stroke were counted (e.g., “I adjusted the swing path of the putter after each missed ball” or “I tried to keep my head still throughout my putting stroke”). Retrospective statements (e.g., “I held my left hand above my right” or “My feet were shoulder width apart”) that may not have been used or thought about while putting were not counted. Statements that were irrelevant to technical performance (e.g., “The room was hot”) were also excluded.

3 To determine whether the level of cortical activation at the verbal-analytical region (T3) and the visuospatial region (T4) was different between low and high reinvesters, EEG power at each region during golf putting in the alpha1 (8–10 Hz) and alpha2 (10–12 Hz) frequency bandwidths was analyzed separately with Group × Region (2 × 2) repeated measure ANCOVAs (relevant power during the resting baseline was used as a covariate for each analysis). The analyses revealed no difference in T3 or T4 alpha power between groups, suggesting that independent cortical activation at the verbal-analytical region (T3) and the visuospatial region (T4) may not index the involvement of verbal-analytical processes in motor performance.

4 Maxwell et al.'s work (2001) showed that an analogous random treatment condition promoted explicit dependence on verbal-analytical processes.
3.2. Results

3.2.1. Day 1: outcome errors during learning

An independent t-test showed that significantly fewer putting outcome errors \((t(16) = -2.46; P < 0.05)\) were made during the 300 trials of learning by participants in the Errorless treatment condition (\(M = 80.4, SD = 11.82\)) than by participants in the Errorful treatment condition (\(M = 94.7, SD = 12.69\)).

3.2.2. Day 2: putting performance

Putting performance (mean distance from the centre of the target hole) was analyzed by computing Group \( \times \) Test (2 \( \times \) 2) ANOVAs with repeated measures on the latter factor. No main effect of Test (\(F(1,16) = 0.02, P = 0.89\), effect size < 0.01) or Group \( \times \) Test interaction (\(F(1,16) = 0.09, P = 0.76\), effect size < 0.01) was evident. A significant main effect of Group was evident (\(F(1,16) = 5.00, P < 0.05\), effect size = 0.24). Observation of the means indicates that participants in the Errorless treatment condition put more accurately than participants in the Errorful treatment condition in both the Retention test (Errorless: \(M = 17.35, SD = 8.72\); Errorful: \(M = 27.37, SD = 13.71\)) and the Transfer test (Errorless: \(M = 17.91, SD = 6.41\); Errorful: \(M = 25.88, SD = 13.62\)).

3.2.3. Day 2: pressure intervention

Heart rate and Anxiety Thermometer measures were subjected to Group \( \times \) Test (2 \( \times \) 2) ANOVAs with repeated measures on the latter factor. The analysis of heart rate revealed a significant main effect of Test (\(F(1,16) = 21.49, P < 0.001\), effect size = 0.57), but neither a main effect of Group (\(F(1,16) = 0.32, P = 0.58\), effect size = 0.02) nor a Group \( \times \) Test interaction (\(F(1,16) = 0.01, P = 0.92\), effect size = 0.001). As expected, heart rate in both treatment conditions was higher immediately prior to the Transfer test than the Retention test (see Table 1). Analysis of the Anxiety Thermometer measure also revealed a significant main effect of Test (\(F(1,16) = 23.84, P < 0.001\), effect size = 0.60), but no Group effect (\(F(1,16) = 0.32, P = 0.58\), effect size = 0.02) or interaction (\(F(1,16) = 0.39, P = 0.54\), effect size = 0.02). Self reported anxiety was higher immediately prior to the Transfer test than the Retention test (see Table 1).

3.2.4. Day 2: E EG T3–Fz and T4–Fz coherence

EGG coherence estimates were computed for the T3–Fz and T4–Fz pairs during the Retention test and the pressured Transfer test in alpha1 (8–10 Hz) and alpha2 (10–12 Hz) frequency band-widths. These were subjected to Group \( \times \) Test \( \times \) Pair (2 \( \times \) 2 \( \times \) 2) repeated measure ANCOVAs using T3–Fz and T4–Fz coherence during resting baseline as covariates.

Alpha1 (8–10 Hz). The analysis only revealed a significant main effect of Group (\(F(1,14) = 5.40, P = 0.04\), effect size = 0.28). As illustrated in Fig. 3, participants in the Errorless treatment condition exhibited lower overall coherence than participants in the Errorful treatment condition.

Alpha2 (10–12 Hz). A significant Group \( \times \) Test \( \times \) Pair interaction was evident (\(F(1,14) = 5.43, P = 0.04\), effect size = 0.28). Further analyses separated the T3–Fz and T4–Fz pairs and computed two Group \( \times \) Test (2 \( \times \) 2) repeated measure ANCOVAs using T3–Fz and T4–Fz coherence during resting baseline as covariates, respectively. The analysis of T3–Fz coherence showed a significant main effect of Group (\(F(1,15) = 5.20, P < 0.05\), effect size = 0.26) and a Group \( \times \) Test interaction (\(F(1,15) = 5.55, P < 0.05\), effect size = 0.27), but no significant main effect of Test (\(F(1,15) = 0.35, P = 0.56\), effect size = 0.02). As illustrated in Fig. 4, participants in the Errorless treatment condition displayed lower T3–Fz coherence than participants in the Errorful treatment condition. Follow-up analysis revealed that T3–Fz coherence increased significantly from retention to transfer in the Errorful treatment condition (\(P < 0.05\)), but not the Errorless treatment condition (\(P = 0.56\)). The analysis of T4–Fz coherence also showed a significant main effect of Group (\(F(1,15) = 5.30, P < 0.05\), effect size = 0.26), but no significant main effect of Test (\(F(1,15) = 2.83, P = 0.11\), effect size = 0.16) and no Group \( \times \) Test interaction (\(F(1,15) = 0.18, P = 0.68\), effect size = 0.02). As illustrated in Fig. 4, participants in the Errorless treatment condition displayed lower T4–Fz coherence than participants in the Errorful treatment condition.

3.2.5. Day 2: declarative knowledge

As expected, participants in the Errorless treatment condition reported fewer hypothesis testing statements regarding the putting stroke (\(M = 0.72, SD = 0.44\)) than participants in the Errorful treatment condition (\(M = 1.67, SD = 1.12\), \(\chi(16) = -2.36, P = 0.03\).

3.3. Discussion

The results are consistent with previous findings that errorless learning encourages a bias towards implicit motor learning (Maxwell et al., 2001; Poolton et al., 2005, 2007a,b). Participants in the Errorful treatment condition made fewer errors than participants in the Errorful treatment condition during the learning phase. As predicted, this resulted in fewer statements that indicated that the performer had tested hypotheses related to their putting stroke, implying reduced verbal-analytical involvement in performance.
More compelling evidence of differences in verbal-analytical involvement was provided by the EEG T3–Fz coherence measures taken on Day 2, during the retention and transfer tests. Participants in the Errorless treatment condition exhibited lower overall alpha2 T3–Fz coherence levels than participants in the Errorful treatment condition, suggesting that implicit and explicit motor learning techniques cause different adaptations at a neural level. Compared to explicit motor learning, implicit motor learning appears to be characterized by attenuated communication between the verbal-analytical region (T3) and the motor planning region (Fz). Furthermore, although both groups displayed significantly elevated heart rates and self-reported anxiety levels following the pressure intervention, only participants in the explicit, Errorful treatment condition revealed significantly increased levels of alpha2 T3–Fz coherence. This finding supports predictions from the Theory of Reinvestment that stress increases verbal-analytical interference in motor performance and planning. Moreover, the finding supports predictions that implicit motor learning techniques that reduce conscious access to task relevant declarative knowledge protect against reinvestment in stressful conditions.

Participants in the Errorful treatment condition also revealed significantly higher levels of alpha2 T4–Fz coherence than participants in the Errorless treatment condition across the test session, implying enhanced visuospatial involvement involved in motor performance. This could be a result of differences in the design of the practice schedules. Participants in the Errorful treatment condition practiced eight blocks in a pseudo-random sequence (i.e., 125, 100, 25, 75, 50, and 150 cm) during the learning phase on Day 1, which required substantial recalibration of the parameter values assigned to the putting stroke compared to that needed to adjust to moving 25 cm further from the hole in the Errorless treatment condition. Visuospatial processes may have facilitated this recalibration. Alternatively, enhanced involvement of verbal-analytical processing suggests a greater awareness of the body and how it interacts with the environment (e.g., the ball, the club and the target), which may also involve visuospatial processing.

Although EEG T3–Fz coherence data supports the prediction from the Theory of Reinvestment that stress increases verbal-analytical interference in motor performance, the prediction that putting performance would be worse as a consequence was not supported. One possible explanation is that despite our pressure intervention being strong enough to provoke a physiological (heart rate) and psychological (Anxiety Thermometer) stress responses, as well as changes in cognitive processing of motor performance (T3–Fz), it was not strong enough to impact on our basic performance measure. Landau et al. (2004) found that the decreases in brain fMRI signal were not accompanied by improved behavioral performance, suggesting that practice influences particular neural processes which may not be captured by performance measures. It appears that the relationship between sensitive cortical measures and less sensitive behavioral measures is not linear. Rather, the relationship between cortical activity and behavioral performance might better be captured in terms of psychomotor efficiency (i.e., ratio of motor performance to allocated neural resource, Hatfield and Hillman, 2001). Thus in Study 2, the pressure manipulation may have caused a reduction in the psychomotor efficiency of participants in the Errorful treatment condition, while not affecting participants in the Errorless treatment condition.

4. General discussion

Two experiments assessed the extent to which verbal-analytical processes were involved in motor output in a golf putting task, by assessing the degree of EEG co-activation (coherence) between the left temporal region (T3) and the frontal midline region (Fz). In Study 1, we found that novices with high scores on the conscious motor processing factor of the Movement Specific Reinvestment Scale displayed higher alpha2 T3–Fz coherence during a golf putting task than novices with low scores. The left temporal region is thought to play a salient role in verbal-analytical processing (Haufler et al., 2000; Kerick et al., 2001), and the frontal midline region is the premotor area of cortex that is responsible for motor planning (Deeny et al., 2003). Therefore, we suggested that our finding supports the view that high reinvesters adopt more verbal, conscious control of their movements during motor performance than low reinvesters. The result provides the first psychophysiological evidence for the Theory of Reinvestment (Masters and Maxwell, 2008) and fortifies the claim that the propensity to monitor and consciously control movements on-line is a characteristic of individual personality (Masters et al., 1993). It also provides additional support for the validity of the Movement Specific Reinvestment Scale (Masters et al., 2005).

In Study 2, we found that participants who practiced a golf putting task implicitly by errorless learning had lower alpha2 T3–Fz coherence and reported less declarative knowledge than those who practiced explicitly by errorful learning. The findings imply that implicit, errorless learners used less verbal-analytical control of their movements than explicit, errorful learners. We also found that alpha2 T3–Fz coherence remained stable in implicit, errorless learners under pressure, but increased significantly in explicit, errorful learners under pressure. Together, the findings provide the first neuropsychological evidence that implicit motor learning techniques which reduce the involvement of verbal-analytical processing in motor performance provide a practical solution by which to prevent reinvestment under pressure.

Although no significant effects were evident for alpha1 T3–Fz coherence in either study, medium to large effect sizes were evident and the pattern of findings in both studies shadows alpha2 T3–Fz
coherence. While the physiological function of alpha rhythms is not fully clear, at least for cognitive tasks, the alpha1 (8–10 Hz) component is thought to be sensitive to changes in general arousal whereas the alpha2 (10–12 Hz) component is thought to be more indicative of task-specific processes (Smith et al., 1999; for a review see Klimesch, 1999). The lower level of alpha2 co-activation at the T3–Fz region in both low reinvaders (Study 1) and implicit motor learners (Study 2) suggests, enticingly, that communication between the motor planning regions and the verbal-analytical regions during the motor task was more refined, with greater attenuation of non-essential cortico-cortical co-activation. Hatfield and colleagues (e.g., Deeny et al., 2003; Hatfield et al., 2004; Hatfield et al., 2009; Haufler et al., 2000) have shown that this phenomenon is present in expert performers but not novice performers, so we speculate, on the basis of our data, that low reinvaders and implicit motor learners are potentially further along the road to expertise than high reinvaders and explicit motor learners.5 This finding goes some way to supporting claims by Masters and colleagues (e.g., Masters and Maxwell, 2004; Masters et al., 2008a,b) that implicit motor learning techniques may circumvent effortful, cognitive stages of skill that are typical of unskilled performers and promote more expert-like procedural stages of performance.

Future studies should examine the utility of alternative implicit motor learning paradigms in limiting reinvestment by measuring EEG T3–Fz coherence to assess the involvement of verbal-analytical processes in motor output. For example, analogy learning (Liao and Masters, 2001; Poolton et al., 2007a,b) promotes implicit motor learning by re-packing consciously accessible, task-relevant ‘rules’ and knowledge into a single chunk, which may reduce the contribution of verbal-analytical processes to motor performance. Therefore, T3–Fz coherence is predicted to be lower in analogy learners compared to explicit motor learners during motor performance.

Our findings also provide a rationale for the use of EEG biofeedback or neurofeedback in motor learning and performance. Self-regulation of cortical activity via EEG biofeedback or neurofeedback technology has been used in golf (Landers et al., 1991; Arns et al., 2007), dance (Raymond et al., 2005) and microsurgical skills (Ros et al., 2009). Methods which train low EEG T3–Fz co-activation that is stable in the face of contingencies such as psychological pressure may potentially help people who must deal with stress (e.g., athletes, musicians or surgeons) or who must deal with movement disruptions or disorders that cause them to be more conscious of their movements, and thus use more verbal-analytical processing than normal (e.g., stroke, Orrell et al., 2009; cerebral palsy, Steenbergen et al., 2010).

In this study cortico-cortical communication between the verbal-analytical region and the motor planning region was derived using the EEG signal from two separate electrodes; however, volume conduction may have meant that the single electrode recordings contained activity from adjacent cortical areas. To improve the spatial resolution of EEG measurement, future studies should consider deriving surface-Laplacian or current source density (CSD) from the recordings (Perrin et al., 1989). This requires denser electrode arrays (e.g., 64 or 128 channels) than the set-up used in this study.

To conclude, the present studies represent the first attempt to provide neuropsychological evidence for the concept of reinvest-

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5 The role of verbal-analytical processes in the development of expertise is not well understood, but recent interest in the moderating effect of verbalization (especially inner speech) on response execution and inhibition during childhood development suggests that such processes may play an important part in the development of expertise (see, for example, Miyake et al., 2004 or Kray et al., 2009).

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