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Bellomo, Eduardo; Cooke, Andrew; Hardy, James

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Chunking, conscious processing, and EEG during sequence acquisition and performance pressure:

A comprehensive test of reinvestment theory

Eduardo Bellomo^a, Andrew Cooke^a & James Hardy^a

^aInstitute for the Psychology of Elite Performance (IPEP), School of Sport, Health and Exercise Sciences, Bangor University, UK

Author Note

Correspondence concerning this article should be addressed to Eduardo Bellomo, Institute for the Psychology of Elite Performance (IPEP), School of Sport, Health & Exercise Sciences, Bangor University, Holyhead Road, Bangor, Gwynedd, UK, LL57 2PZ.

Contact: pep215@bangor.ac.uk

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Abstract

This study was designed to test the theorized link between reinvestment, motor chunks, and conscious processing, to provide a thorough examination of reinvestment theory. We measured electroencephalographic power and connectivity alongside self-reported conscious processing and behavioral indices of chunking in a 2 (group) \times 5 (block) mixed-model design. Fifty-five individuals acquired a motor sequence (blocks: A1, A2 A3, A4) via relatively explicit (errorful) or implicit (errorless) paradigms. Then they performed in a pressure condition (block: T). Results confirmed that chunking characterizes both modes of acquisition. However, explicit acquisition resulted in quicker chunking, reduced conscious processing, and increased cortical efficiency (left-temporal high-alpha power). In support of reinvestment theory, self-reported conscious processing tended to increase under pressure among explicit trainees only. In contrast to reinvestment theory, this had no adverse effect on performance. Our results endorse explicit acquisition as an effective mode of training and provide a new neurophysiological explanation why.

Keywords: chunking; cortical efficiency; explicit learning; high-alpha power; motor learning; verbal-analytic processing;

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1 **Chunking, conscious processing, and EEG during sequence acquisition and performance**
2 **pressure: A comprehensive test of reinvestment theory**

3 Acquired motor skills, ranging from everyday life actions, such as keyboard typing, to
4 skilled and specialized maneuvers typical of sport stars or expert surgeons, are essentially sequences
5 of elementary movements which with practice are progressively organized in efficient memory
6 units (Sakai, Kitaguchi, & Hikosaka, 2003). For instance, the elementary components of a golf
7 swing include gripping the shaft, initiating the backswing, rotating the hips, transferring weight
8 from one foot to the other. With practice, this sequence of separate elements is organized into a
9 single efficient technique. Indeed, classical models of motor learning (Fitts & Posner, 1967)
10 describe the progression from a verbal-analytic stage, supporting the performance of novices, to an
11 autonomous stage, which supports the performance of experts. At the verbal-analytic stage,
12 movements are performed with a high degree of conscious processing since the different
13 components of the skill need to be held in working memory (Baddeley, 2012) while the performer
14 tries to find a set of verbal-analytic rules to guide movement execution. The resulting performance
15 is jerky and errors are numerous. At the automatic stage, the elementary movement components are
16 integrated (i.e., chunked) in a single memory unit and stored in a procedural and non-verbalizable
17 format in long-term memory (Willingham, 1998). At this stage, performance is effortless and
18 consistent. In sum, practice allows a progressively quicker and more accurate execution at a reduced
19 cognitive cost (e.g., Willingham, 1998).

20 However, even after automatization, skill execution is not flawless; from time to time, so-
21 called *choking* (i.e., movement failures under pressure) can occur even in the most skilled
22 professionals (Baumeister, 1984). A motor learning-based explanation for choking under pressure is
23 offered by reinvestment theory (Masters & Maxwell, 2008). It contends that contingencies such as
24 increased psychological pressure, social evaluation, and errors during execution may prompt, in
25 some individuals, explicit action monitoring via reinvestment of the verbal-analytic rules that
26 supported skill acquisition during the early stages of learning. This results in the de-automatization

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1 of well-learned skills, characterized by the performer reverting back to a more conscious, less
2 efficient form of control, and the de-chunking of movement back to elementary components
3 (MacMahon & Masters, 1999). In other words, some of the benefits that occur with practice (e.g.,
4 increased speed and reduced cognitive cost) can be occasionally undone under pressure, causing
5 impaired motor performance.

6 **Chunking and De-chunking**

7 Evidence to support the notion that elementary movement components are “chunked”
8 together during skill acquisition is compelling (for review see Abrahamse, Ruitenberg, de Kleine, &
9 Verwey, 2013 or Shea & Wrights, 2012). For example, in a study by Sakai and colleagues (2003),
10 participants learned to press a sequence of buttons during an explicit visuomotor learning paradigm
11 called the 2×10 task. Acquisition was considered explicit because participants learned the correct
12 sequence by trial-and-error (Abrahamse et al., 2013). This promotes hypothesis-testing behavior
13 that leads performers to accumulate a bank of explicit and verbalizable rules to guide the correct
14 solution (Raab et al., 2009). Participants were required to press a sequence of ten pairs (i.e., 2×10)
15 of buttons, which illuminated in a predetermined order. Initially, while participants began
16 memorizing the sequence, execution was jerky and characterized by many elongated time gaps
17 between pairs. With practice, these gaps decreased and the execution became smoother as the
18 sequence was organized into fewer and larger motor chunks, exactly as is said to happen during the
19 acquisition of motor skills displayed in sport (Fitts & Posner, 1967). Such chunking is said to lessen
20 the load on working memory since conscious processing is needed only for retrieving the first
21 element of the chunk (Willingham, 1998).

22 Importantly, chunking is not restricted to explicit learning paradigms. Implicit learning,
23 where skills are acquired with little awareness and limited accumulation of verbal-analytic rules,
24 can also support chunking (Song & Cohen, 2014; Willingham, 1998). For example, MacMahon and
25 Masters (1999) had participants acquire a sequence of button presses during a serial reaction time
26 task, which is deemed to induce a relatively implicit mode of learning (Robertson, 2007). Like

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1 Sakai and colleagues (2003), MacMahon and Masters found that with practice, the time gaps
2 between consecutive button presses decreased and execution became smoother, implying the
3 progressive organization of the sequence into fewer and larger motor chunks. Interestingly, the
4 progressive chunking observed during acquisition was followed by de-chunking (i.e., the re-
5 emergence of elongated time gaps) in a transfer phase where participants performed the same serial
6 reaction time sequence under elevated levels of social-evaluative pressure. This finding is
7 supportive of reinvestment theory's idea that pressure-induced de-chunking is a mechanism to
8 explain choking under pressure. However, it is surprising that such de-chunking was observed
9 following acquisition conditions (i.e., serial reaction time task) that are thought to promote
10 relatively implicit learning. Indeed, a core prediction of reinvestment theory is that learning in an
11 implicit fashion should reduce the possibility of de-chunking under pressure, since implicit learners,
12 compared to their explicit counterparts, have few conscious rules to reinvest. Put simply,
13 reinvestment and therefore de-chunking under pressure should be less likely after implicit than
14 explicit learning. To date, there are no experiments that directly examine this specific de-chunking
15 prediction. Addressing this void in the literature is one aim of the present experiment.

16 **Cortical Indices of Conscious Motor Processing**

17 In addition to behavioral manifestations such as chunking and, possibly, de-chunking, the
18 variations in verbal-analytic conscious processing that characterize motor learning and reinvestment
19 under pressure are said to be accompanied by changes in the EEG high-alpha (around 10-12 Hz)
20 frequency band. In brief, increased high-alpha power is viewed as an index of active inhibition of
21 non-essential neural processes (Klimesch, 2012). Accordingly, increased high-alpha power recorded
22 over the left temporal regions (T7), which are traditionally associated with verbal-analytic and
23 language processes (e.g., Springer & Deutsch, 1998), has been argued to reflect lower levels of
24 verbal-analytic activity (e.g., less conscious processing) during preparation for complex motor skills
25 (e.g., Hillman, Apparies, Janelle, & Hatfield, 2000). Researchers have also shown interest in
26 measures of connectivity between different electrode sites (e.g., magnitude squared coherence or

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1 inter-site phase clustering). Connectivity reflects the degree of similarity of activity at different
2 electrode sites, and has been interpreted to reflect the amount of functional communication between
3 different brain regions, where more connectivity reflects greater communication (Von Stein &
4 Sarnthein, 2000). Consequently, researchers have interpreted reduced high-alpha power
5 connectivity between left-temporal sites, and frontal midline sites overlaying areas deputed to motor
6 sequence planning (Ashe, Lungu, Basford, & Lu, 2006) as less verbal-analytic involvement (e.g.,
7 less conscious processing) during motor planning (e.g., Deeny, Haufler, Saffer, & Hatfield, 2009).

8 In support of these assertions, research has reported greater T7 high-alpha power and
9 reduced T7-Fz high-alpha connectivity in expert sport performers compared to less experienced
10 performers (e.g., Deeny, Hillman, Janelle, & Hatfield, 2003; Janelle et al., 2000). Research has also
11 demonstrated a progressive increase in left-temporal high-alpha power, and a reduction in T7-Fz
12 high-alpha connectivity, during motor skill training (Gallicchio, Cooke, & Ring, 2017; Kerick,
13 Douglas, & Hatfield, 2004; Landers, Han, Salazar, & Petruzzello, 1994). Moreover, Zhu, Poolton,
14 Wilson, Maxwell, and Masters (2011) found that high-alpha T7-Fz connectivity was higher in
15 individuals prone to consciously control movements, as determined by the Movement Specific
16 Reinvestment Scale (Masters, Eves, & Maxwell, 2005), than in their less prone counterparts, during
17 a golf putting task. High-alpha T7-Fz connectivity was also higher in novices after undergoing an
18 explicit learning protocol (i.e., trial-and-error condition), which fostered the accumulation of verbal-
19 analytic rules, compared to those who underwent an implicit (i.e., errorless) protocol (Zhu et al.,
20 2011). Taken together these studies endorse T7 power and T7-Fz connectivity in the high-alpha
21 band as indices that are sensitive to the reduction in conscious processing that characterizes the
22 progression from the verbal-analytic stage to the automatic stage of learning.

23 These cortical measures could also be sensitive to reinvestment under pressure. For
24 example, Zhu and colleagues (2011) found that T7-Fz high-alpha connectivity increased during
25 transfer to a high-pressure condition in their explicit learning group, but not in the implicit group.
26 This provides some tentative support for reinvestment theory's prediction that reinvestment under

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1 pressure is more likely to happen in explicit learners than implicit learners. However, these
2 differences in EEG connectivity were not accompanied by differences in putting performance,
3 thereby questioning the presumed link between connectivity, conscious processing and
4 performance. In a similar vein, Hatfield and colleagues (2013) found that pistol shooters displayed
5 decreased T7 high-alpha power and increased T7-Fz connectivity (in the 8-13 Hz alpha broadband)
6 upon transfer from low-pressure to high-pressure conditions, but again performance outcome was
7 maintained. Of note, kinematic measures obtained in this study provided some evidence that these
8 pressure-induced EEG changes were accompanied by reductions in movement efficiency (i.e.,
9 reduced fluency of aiming trajectory). This could imply increased segmentation of the action as if
10 the movement components had been de-chunked. However, since the elementary movements
11 constituting complex sport skills such as shooting are difficult to isolate, this conclusion is
12 somewhat speculative. A strength of sequence button pressing tasks such as those adopted by
13 MacMahon and Masters (1999) and Sakai and colleagues (2003) is that they permit the
14 investigation of the same basic mechanisms that underlie the acquisition of complex sport skills
15 (Abrahamse et al., 2013; Shea & Wrights, 2012), while allowing precise and objective measures of
16 chunking and de-chunking to be obtained. Button sequence practice tasks could thus be used to
17 provide a more precise examination of pressure-induced reinvestment effects (e.g., dechunking).

18 **The Present Experiment**

19 To address the limitations of previous research and to offer a comprehensive examination of
20 reinvestment theory, the present experiment was designed to be the first to examine chunking and
21 de-chunking, together with cortical measures of conscious processing, during acquisition and
22 performance under pressure, following explicit and implicit skill acquisition. Chunking was
23 expected for both explicit and implicit modes of practice. However, based on reinvestment theory,
24 we expected initially higher conscious processing (self-report, T7 high-alpha power and T7-Fz
25 high-alpha connectivity) followed by a more pronounced reduction during explicit acquisition,
26 compared to implicit acquisition. This is due to the greater hypothesis-testing and verbal-analytic

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1 processing associated with explicit compared to implicit practice (e.g., Zhu et al., 2011). Moreover,
2 we expected choking under pressure to be more likely in participants who underwent explicit rather
3 than implicit training, since this latter mode of practice should theoretically be protective against
4 reinvestment of verbal-analytic conscious processing under pressure (Masters & Maxwell, 2008).

5 **Methods**

6 **Participants**

7 Fifty-six students (male = 34, female = 21, $M_{\text{age}} = 21.87$ years, $SD_{\text{age}} = 2.56$) gave informed
8 consent and volunteered to participate in the study. They were recruited via email and posters
9 displayed across a University campus. All participants were right-handed as indicated by Edinburgh
10 Handedness Inventory (EHI; Oldfield, 1971) scores $\geq +70$ ($M = 93.27$, $SD = 11.06$). Participants
11 were assigned either to an explicit group ($N = 28$) or an implicit group ($N = 28$).

12 Previous EEG studies of reinvestment theory (Hatfield et al., 2013; Zhu et al., 2011)
13 reported medium-to-large effect sizes for group by condition interactions ($\eta_p^2 > .15$). Sensitivity
14 calculations indicated that our sample size was more than adequate to detect similar effects; our 2×5
15 mixed-model ANOVAs were powered at .80 to detect even small interaction effects ($\eta_p^2 = .02$ at
16 the 5% level of significance). Approval was granted by the Institutional Research Ethics
17 Committee.

18 **Task**

19 Two variations of a sequence learning task were employed to examine explicit and implicit
20 visuomotor sequence acquisition. The two tasks were employed to manipulate the degree of
21 conscious processing needed to perform the sequence by inducing relatively errorful (2×10 task)
22 and errorless (1×20 task) practice conditions (e.g., Zhu et al., 2011). Participants assigned to the
23 explicit group completed the 2×10 sequential button-press task (Sakai et al., 2003). This requires
24 participants to acquire, with a trial-and-error strategy, the correct order in which to press a sequence
25 of 20 buttons on a bespoke 4×4 keypad matrix (see Figure 2B). Participants were informed of the
26 existence of a sequence and asked to execute the presses as quickly and accurately as possible using

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1 the index finger of the right hand. The task started when participants pressed the “start-button”,
2 which lit-up in blue at the bottom left of the matrix. Subsequently, a pair of buttons (“a set”) lit-up
3 in green. Participants were required to press one button at a time in an attempt to learn the correct
4 order of pre-programmed button presses. If they chose the correct button to press first, the
5 associated green light was turned off and participants were able to press the remaining button. Once
6 the pair of buttons were pressed in the correct order, there was a 100 ms interval before a new pair
7 of buttons (the next set) lit-up. The above cycle then repeated. The complete sequence required
8 participants to correctly press ten pairs of buttons without error. Whenever an error occurred the
9 whole 4×4 matrix lit-up in red, and participants had to start a new trial from the beginning (Figure
10 2C). The sequence was the same in all acquisition blocks across all participants (Figure 2A). This
11 task was chosen for members of the explicit group because the extensive hypothesis-testing that
12 characterizes the task is known to prompt explicit awareness of the movement/sequence rules
13 (Sakai et al., 2003).

14 Participants assigned to the implicit group completed the 1×20 button-press task. In essence,
15 this task is the same as that performed by the explicit group insofar as the requirement to press a
16 sequence of 20 buttons with the index finger of the right hand. However, for members of the
17 implicit group, the buttons lit-up one at a time, rather than lighting up in pairs (Figure 2D). This
18 removed the hypothesis-testing that characterizes the 2×10 task and made the task akin to the
19 discrete sequence production task (DPS). Typically, in DPS tasks participants struggle to develop
20 any explicit, in-depth, verbalizable knowledge about the sequence (i.e., structural knowledge, see
21 Abrahamse, 2013; Verwey & Abrahamse, 2012), despite being informed of the presence of a
22 repeating sequence. Since in the 1×20 task participants were not told about the existence of a
23 sequence, the chances of developing of verbalizable knowledge were deemed even lower compared
24 to a typical DPS task. In short we believe that the 1×20 task limits motor awareness during training
25 and reduces the number of errors thereby creating the conditions for relatively more implicit
26 acquisition (i.e., errorless learning; Maxwell, Masters, Kerr, & Weedon, 2001).

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1 **Design**

2 We employed a mixed-model design with Group (explicit, implicit) as a between-subjects
3 factor, and Block (A1, A2, A3, A3, T) as a within-subjects factor. The Block factor represents a
4 four-block acquisition phase (A1, A2, A3, A4), followed by a transfer to a comparatively high-
5 evaluative pressure condition (T). Each block during acquisition and transfer consisted of 20
6 complete (i.e., correct) repetitions of the sequence.

7 **Measures**

8 **Manipulation Check.** In order to assess the effectiveness of the pressure manipulation used
9 in the transfer condition (see Procedure section below), we monitored self-report cognitive anxiety
10 and movement self-consciousness.

11 **Cognitive Anxiety.** Cognitive anxiety was assessed using the cognitive anxiety subscale of
12 Mental Readiness Form-3 (MRF-3; Krane, 1994). This measure consists of one statement (i.e., “my
13 mind feels...”) rated on an 11-point Likert scale (range 1-11) anchored *calm-worried*.

14 **Movement Self-Consciousness.** To assess movement self-consciousness during sequence
15 performance, we used the movement self-consciousness subscale of the Movement Specific
16 Reinvestment Scale (Masters et al., 2005). Although originally conceived as a trait measure, this
17 questionnaire is frequently used as a state measure where it shows high internal consistency (e.g.,
18 Gallicchio et al., 2017). Participants were asked to indicate how they felt while performing the
19 previous block in relation to four items (e.g., “I felt that I was watching myself”) rated on a 6-point
20 Likert scale (1 = strongly disagree, 6 = strongly agree). The mean Cronbach’s α coefficient was .73.

21 **Conscious processing**

22 To monitor conscious processing during both acquisition and transfer, we used the
23 conscious motor processing subscale from the Movement Specific Reinvestment Scale
24 (Gallicchio, Cooke, & Ring, 2016; Masters et al., 2005). Participants were asked to indicate how
25 they felt while performing the previous block in relation to five items (e.g., “I was aware of the way

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1 my body was working”) that were rated on a 6-point Likert scale (1 = strongly disagree, 6 =
2 strongly agree). The mean Cronbach’s α coefficient was .77.

3 **Task Performance**

4 **Percentage of sequence chunked.** The percentage of sequence chunked (*chunked%*) was
5 considered in order to explore chunking and de-chunking in the two groups. To obtain this measure
6 we first extracted all of the choice times (ChTs; time from a pair of buttons illuminating to the first
7 button being pressed) for members of the explicit group, and response times (RTs; time from a
8 single button illuminating to the button press) for members of the implicit group. These data were
9 logarithmically (Log_{10}) transformed in order to ensure a normal distribution (Sakai et al., 2003).
10 Next, the upper bound of the 95% confidence interval for $\text{Log}_{10}\text{ChTs/RTs}$ across all blocks for each
11 participant was calculated and taken as an individualized critical value to determine any
12 disproportionately long time-gaps in the execution of the sequence, which are thought to distinguish
13 temporally adjacent chunks (Sakai et al., 2003). Finally, these individual cut-offs were applied to
14 yield the number of chunks per block for each participant.

15 The maximum number of chunks (*Maxchunks*) was 10 for members of the explicit group, and
16 20 for members of the implicit group. Such scores would represent disproportionately long time-
17 gaps between every choice (explicit group) and every response (implicit group). To permit between-
18 group comparisons we express the mean number of chunks (*Meanchunks*) as a percentage using the
19 following formula:

$$20 \quad \text{chunked}\% = (\text{Mean}_{\text{chunks}} * 100) / \text{Max}_{\text{chunks}}$$

21 This ensures a consistent scale for each group (i.e., 0-100%) with a higher percentage
22 representing fewer chunks (i.e., less disproportionately long time-gaps) and signifying a more
23 holistic representation of the sequence.

24 **Movement Errors.** The mean number of errors was recorded as an additional index of
25 performance effectiveness. This measure is related to chunking, since a reduction in number of
26 chunks typically coincides with fewer errors (Sakai et al., 2003).

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1 **Cortical activity**

2 EEG activity was recorded from four scalp locations (T7, T8, Fz, Pz) using active recording
 3 electrodes and a DC amplifier (PET-4, Braininquiry EU, NL) connected to a computer running
 4 BioExplorer (CyberEvolution, Inc.) software. Reference electrodes were positioned at the mastoids
 5 (linked), and a ground electrode was located at Fpz (Jasper, 1958). Recording sites were cleaned,
 6 abraded and conductive gel (Electro-gel, ECI) was applied to ensure electrode impedances were
 7 below 10 kΩ. The signals were sampled at 1000 cycles per second. Offline signal processing was
 8 performed using EEGLAB (Delorme & Makeig, 2004) and custom scripts in MATLAB
 9 (Mathworks Inc., USA). Signals were resampled (256 Hz) and band-pass filtered (1-30 Hz). Gross
 10 muscular and ocular artefacts were then removed using the following two step process. First, data
 11 segments containing drifts exceeding $\pm 50 \mu\text{V}$ in a 250ms sliding window were identified by the
 12 Darbeliai EEGLAB extension (Baranauskas, 2008). Second, all identified data segments were
 13 reviewed by an experienced EEG analyst, and those containing artefacts were rejected.

14 Data for each block were then decomposed into their frequency representation by
 15 multiplying the power spectrum of the EEG, obtained from the fast Fourier transform, by the power
 16 spectrum of complex Morlet wavelets:

$$17 \quad e^{i2\pi t f} e^{-t^2/2\sigma^2}$$

18 where t is time, f is frequency bin, which increased from 4 to 28 Hz in 49 linearly spaced
 19 steps (thus 0.5 Hz resolution), and σ defines the width of each frequency band, set according to
 20 $4/2\pi f$ (thus, 4 cycles), and then taking the inverse fast Fourier transform. This procedure was done
 21 separately for each channel to obtain a complex signal from each convolution.

22 **Power.** From the complex signals, power at each frequency bin (f) was defined as the
 23 squared magnitude of the result of the convolution $Z \{ \text{real} [z(t)]^2 + \text{imag} [z(t)]^2 \}$ and averaged
 24 across high-alpha (10-12 Hz) frequency band. In order to ensure normal distribution all power
 25 estimates were subjected to a logarithmic (Log_{10}) transformation (Delorme & Makeig, 2004) prior
 26 to analysis.

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1 **Connectivity.** Functional connectivity between sites was computed in terms of inter-site
 2 phase clustering (ISPC). While most previous studies estimated functional connectivity by
 3 calculating magnitude squared coherence (e.g., Hatfield et al., 2013; Zhu et al., 2011), we report
 4 ISPC because magnitude squared coherence (a measure derived from power) could be confounded
 5 by the expected between-block differences in high-alpha power (Cohen, 2014). Moreover,
 6 Gallicchio and colleagues (2016) reported that high-alpha frontotemporal connectivity was more
 7 sensitive to experience-related differences in conscious processing when computed by ISPC
 8 compared to magnitude squared. ISPC was calculated as follows:

$$ISPC_{xy}(f) = \left| n^{-1} \sum_{t=1}^n e^{i(\theta_x(tf) - \theta_y(tf))} \right|$$

10 Where n is the number of data points, i is the imaginary operator, θ_x and θ_y are the phase
 11 angles of the recorded signal at two different scalp locations, t is the time point, and f is the
 12 frequency bin, $e^{i(\theta_x(tf) - \theta_y(tf))}$ is the complex vector with magnitude 1, $n^{-1} \sum_{t=1}^n (\cdot)$ denotes
 13 averaging over time points, and $|\cdot|$ is the magnitude of the averaged vector (Cohen, 2014). The
 14 resulting ISPC is a real number between 0 (no functional connection) and 1 (perfect functional
 15 connection), which represents the consistency of the phase angle differences across time between
 16 two electrodes. ISPC estimates were calculated and averaged for the high-alpha (10-12 Hz)
 17 frequency band. Based on our hypotheses, the main analysis focused on the electrodes pairs T7-Fz
 18 and T8-Fz, which have been argued to represent, respectively, verbal-analytic and visuospatial
 19 involvement in motor planning (e.g., Zhu et al., 2011). In accord with previous research (e.g., Zhu
 20 et al., 2011), we subjected all ISPC estimates to a Fisher's Z transformation (also known as inverse
 21 hyperbolic tangent) before conducting statistical analyses in order to reduce inter-subject variability
 22 and approximate normal distribution (Halliday et al., 1995).

23 Procedure

24 Participants individually attended a 2-hour testing session. On arrival, they were welcomed,
 25 briefed and invited to ask any questions, before providing written consent to take part. Next, the

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1 experimenter attached the EEG electrodes. Participants then underwent a familiarization block,
2 which involved pressing a simple sequence of buttons that illuminated one at a time from top left to
3 bottom right. This ensured familiarity with the force required for each button press to register and
4 allowed participants to become accustomed to pressing the buttons while instrumented for EEG
5 recordings. This was followed by the acquisition phase, which consisted of four blocks of practice
6 (A1, A2, A3, A4) on the assigned task (i.e., 2×10 task for members of the explicit group, 1×20 task
7 for members of the implicit group). Each block ended when participants successfully completed 20
8 correct repetitions of the sequence. Adjacent blocks were separated by five-minute breaks. Finally,
9 participants underwent the transfer phase (T), in which they performed a final block (20 sequence
10 repetitions) on their assigned task, while evaluative pressure was manipulated (see pressure
11 manipulation section below). Cortical activity was recorded continuously throughout each block.
12 Our self-report measure of conscious motor processing was administered at the end of each block,
13 while our manipulation check questionnaires were administered immediately before (anxiety
14 measure) and after (movement self-consciousness measure) blocks A4 (end of acquisition) and T
15 (transfer). At the end of the experiment, participants were thanked and asked not to disclose specific
16 detail about the pressure manipulation to others.

17 ***Pressure Manipulation.*** Social evaluation was manipulated based on previous research
18 deeming evaluative pressure as more likely to induce conscious processing and reinvestment than
19 outcome-based (e.g., rewards for success) pressures (DeCaro, Thomas, Albert, & Beilock, 2011). In
20 order to maximize evaluation apprehension, prior to the beginning of the transfer phase, the
21 experimenter played a scripted video where a senior academic informed participants that their
22 performance during the transfer phase would be filmed from three different locations in order for
23 students and motor control lecturers at the university to view how people perform this skill. In
24 addition, participants were told that the footage might also be used in a YouTube film on
25 visuomotor skill acquisition, which would be available worldwide for researchers and psychology
26 classes. The three cameras were placed approximately 1 m above, in front, and adjacent to the

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1 participant, and the footage was presented in real time, on a screen visible to the participant.

2 Moreover, the experimenter, who sat out of sight during the acquisition phase, repositioned to now
3 stand in very close proximity to the participant, and very obviously watch their performance.

4 **Statistical Analyses**

5 Data were un-scorable for one participant, accordingly, the sample-size retained for
6 statistical analyses was fifty-five (27 for explicit group, 28 for implicit group).

7 Cognitive anxiety and movement self-consciousness scores during the last block of
8 acquisition and transfer in the two groups were subjected to 2 Group (explicit, implicit) \times 2 Block
9 (A4, T) ANOVAs. Conscious motor processing, percentage of sequence chunked, errors, power
10 estimates at T7, T8, Fz, and Pz; and connectivity values between T7-Fz, and T8-Fz (as a control
11 analysis), were subjected to mixed-model ANOVAs with Group (explicit, implicit) as the between-
12 subject factor and Block (A1, A2, A3, A4, T) as the within-subject factor. Significant effects were
13 probed by separate ANOVAs for each Group, and by polynomial trend analyses¹.

14 The multivariate method of reporting results was adopted as it minimizes the risk of
15 violating sphericity and compound symmetry assumptions in repeated measures ANOVA (Vasey &
16 Thayer, 1987). The multivariate statistic Wilks' lambda (not reported), equals $1 - \eta_p^2$. Effect size is
17 reported with partial eta squared (η_p^2) values of .10, .25, and .40 (for repeated measures ANOVA),
18 and .02, .15, and .35 (for multivariate ANOVA) indicating relatively small, medium, and large
19 effect sizes, respectively (Cohen, 1988).

20 **Results**

21 **Manipulation Check**

¹ Although Reinvestment theory does not make specific predictions about gender, gender could be considered as an additional between-subject factor in our experiment. We analysed all our data with and without gender as a factor. There were no consistent effects relating to gender, so this factor is not included in the reported analyses. In brief, the only gender effects that emerged were a Gender \times Condition interaction for cognitive anxiety ($F(1,51) = 7.31, p < .01, \eta_p^2 = .12$; greater increase from A4 to T among females than males), and a Gender main effect for connectivity (T7-Fz: $F(1,51) = 1.67, p < .05, \eta_p^2 = .10$; T8-Fz: $F(1,51) = .58, p = .048, \eta_p^2 = .07$; marginally higher connectivity for females than males).

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1 The 2×2 mixed-model ANOVAs revealed main effects of Block for cognitive anxiety, $F(1,$
 2 53) = 17.07, $p < .001$, $\eta_p^2 = .24$, and movement self-consciousness, $F(1, 53) = 21.62$, $p < .001$, $\eta_p^2 =$
 3 .29, but no effect of Group, nor Block × Group interaction. These results confirm that the pressure
 4 manipulation was successful in inducing a relative increase in cognitive anxiety and movement self-
 5 consciousness from the final block of acquisition (A4; $M_{\text{anxiety}} = 2.72$; $M_{\text{self-consciousness}} = 2.27$) to the
 6 transfer phase (T; $M_{\text{anxiety}} = 3.71$; $M_{\text{self-consciousness}} = 2.73$) in both the explicit and the implicit group.

7 **Conscious Processing**

8 The 2×5 mixed-model ANOVA employed to examine how conscious processing changed
 9 across acquisition and transfer in the two groups revealed a significant effect of Block, $F(4, 50) =$
 10 3.50, $p = .013$, $\eta_p^2 = .22$, no effect of Group, and a significant Group × Block interaction, $F(4, 50) =$
 11 7.01, $p < .001$, $\eta_p^2 = .36$. The results of the separate repeated-measures ANOVAs conducted to
 12 probe the interaction are summarized in Table 1. The main effect of Block was apparent for the
 13 explicit group only and was best characterized by a quadratic trend ($p < .001$, $\eta_p^2 = .51$), with
 14 initially high scores decreasing during acquisition and increasing under pressure.

15 **Task performance**

16 **Chunks.** The 2×5 mixed-model ANOVA employed to examine how participants in the
 17 explicit and implicit group chunked the sequence across acquisition and transfer revealed a
 18 significant effect for Group, $F(1, 53) = 21.91$, $p < .001$, $\eta_p^2 = .29$, Block, $F(4, 50) = 143.76$, $p <$
 19 $.001$, $\eta_p^2 = .92$, and a significant Group × Block interaction, $F(4, 50) = 7.68$, $p < .001$, $\eta_p^2 = .38$. The
 20 effect of Block was significant in both groups with the percentage of sequence chunked increasing
 21 in a linear fashion (linear trend, explicit: $p < .001$, $\eta_p^2 = .93$; implicit: $p < .001$, $\eta_p^2 = .85$) during
 22 acquisition and under pressure (Table 1). The interaction reflected a significant quadratic trend that
 23 emerged for members of the explicit group only ($p < .001$, $\eta_p^2 = .47$), indicative of performance
 24 asymptote during explicit but not implicit acquisition (see Table 1).

25 **Movement Errors.** The 2×5 mixed-model ANOVA employed to examine the number of
 26 errors committed revealed a significant effect for Group, $F(1, 53) = 37.38$, $p < .001$, $\eta_p^2 = .41$,

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1 Block, $F(4, 50) = 10.18, p < .001, \eta_p^2 = .45$, and a significant Group \times Block interaction, $F(4, 50) =$
 2 $11.48, p < .001, \eta_p^2 = .48$. As shown in Table 1, the error-rate remained stable and very low
 3 throughout acquisition and transfer for members of the implicit group, while an initially high
 4 number of errors at the start of acquisition decreased sharply (quadratic trend, $p < .001, \eta_p^2 = .62$)
 5 for members of the explicit group.

6 **Cortical activity**

7 **Power.** Separate 2×5 mixed-model ANOVAs conducted for each electrode revealed main
 8 effects of Block (Fz: $F(4, 50) = 3.25, p < .05, \eta_p^2 = .21$; Pz: $F(4, 50) = 3.40, p < .05, \eta_p^2 = .21$; T8:
 9 $F(4, 49) = 3.02, p < .05, \eta_p^2 = .20$, T7: $F(4, 50) = 3.53, p < .05, \eta_p^2 = .22$). This was characterized
 10 by an increasing linear trend at all sites (Fz: $p = .001, \eta_p^2 = .18$; Pz: $p < .001, \eta_p^2 = .20$; T8: $p =$
 11 $.002, \eta_p^2 = .16$; T7: $p = .001, \eta_p^2 = .18$). There were no effects of Group. Importantly, a Group \times
 12 Block interaction emerged at the T7 electrode only, $F(4, 50) = 2.65, p < .05, \eta_p^2 = .17$. Separate
 13 repeated-measures ANOVAs conducted for each group revealed that the linear increase in high-
 14 alpha power at T7 was significant for the explicit group only ($p = .004, \eta_p^2 = .28$, Figure 1A).

15 **Connectivity.** The 2×5 ANOVA on T7-Fz high-alpha (10-12 Hz) connectivity estimates
 16 revealed a main effect for Block, $F(4, 50) = 5.26, p = .001, \eta_p^2 = .30$, but no effect for Group, nor
 17 Block \times Group interaction. As shown in Figure 1B, T7-Fz connectivity changes were best described
 18 by a linear trend ($p = .006, \eta_p^2 = .14$), reflecting an increase in connectivity from acquisition to
 19 transfer. This effect was confined to the left-hemisphere since the 2×5 ANOVA on T8-Fz
 20 connectivity revealed no main or interaction effects.

21 **Discussion**

22 Utilizing a novel multi-method approach, the present study tested whether conscious
 23 processing during motor learning and performance under pressure changed as predicted by classic
 24 models of skill acquisition (Fitts & Posner, 1967; Willingham, 1998) and reinvestment theory
 25 (Masters & Maxwell, 2008). To do so we designed the first experiment to simultaneously examine
 26 behavioral measures of chunking, alongside proposed cortical indices of conscious processing,

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1 during acquisition and pressure. Our experiment, to our knowledge, contains the largest sample and
2 the highest statistical power of any published EEG study of reinvestment theory. Our results are
3 discussed in relation to our hypotheses in the following sections.

4 **Chunking and conscious processing during acquisition**

5 The sequence learning literature suggests that chunking is a common mechanism
6 underpinning both explicit (e.g., Sakai et al., 2003) and implicit (e.g., MacMahon & Masters, 1999)
7 acquisition. Our results endorse this hypothesis. Specifically, our results showed that movements
8 were progressively chunked during both explicit and implicit practice schedules, implying that
9 verbal-analytic conscious processing is not strictly necessary for the chunking process to occur
10 during motor skill acquisition (Masters & Maxwell, 2008; Song & Cohen, 2014, Willingham,
11 1998).

12 We expected that conscious processing would progressively decrease during explicit skill
13 acquisition, reflecting a reduction in hypothesis testing as the rules that govern successful
14 performance become automatized with practice (e.g., Fitts & Posner, 1967). On the contrary, when
15 acquisition was comparatively implicit, we expected stable levels of conscious processing, due to
16 low error rates and the removal of the decision-making component from our sequence learning task
17 (e.g., Maxwell et al., 2001). Our measures of conscious processing provided mixed support for this
18 hypothesis. On the one hand, self-reported data supported our hypothesis, with stable conscious
19 processing scores throughout implicit acquisition and initially higher scores that progressively
20 reduced during explicit acquisition. On the other hand, of our cortical measures of conscious
21 processing, only T7 high-alpha power appeared sensitive to the different levels of verbal-analytic
22 conscious processing required by explicit versus implicit acquisition. Specifically, high-alpha power
23 measured at the left-temporal site, overlying verbal-analytic areas (Springer & Deutsch, 1998),
24 increased during acquisition in the explicit group only, implying that left-temporal cortical activity
25 progressively decreased with explicit but not implicit training. However, since T7 high-alpha power
26 was initially similar in the two groups, our results do not offer neurophysiological support for the

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1 idea that conscious processing should be higher during the early stages of explicit compared to
2 implicit training.

3 Interestingly, our T7 high-alpha power findings more closely mirror performance than our
4 self-report measure of conscious processing. Specifically, both T7 high-alpha power and chunking
5 performance were initially similar in the two groups, then participants practicing the explicit
6 schedule showed steeper increases than their implicit counterparts. Similar performance effects
7 have been reported before (e.g., Masters & Maxwell, 2008). Our accompanying T7 high-alpha
8 power data provide new evidence that the superior performance associated with explicit acquisition
9 could be explained by explicit acquisition fostering more rapid increases in cortical efficiency (i.e.,
10 progressively lower left-temporal activation) than implicit acquisition.

11 In contrast to our findings for T7 high-alpha power, T7-Fz high-alpha connectivity was
12 similar for both groups, and increased rather than decreased during acquisition. This contradicts
13 previous research and could reflect an increase in communication between verbal-analytic areas and
14 motor planning areas as participants transitioned from a novice stage to a more advanced stage of
15 learning (Gallicchio et al., 2017; Kerick et al., 2004). For example, our participants may have
16 evolved from pure novices, possessing no verbalizable knowledge, to moderately skilled
17 performers, who had developed some verbal strategies to guide execution (e.g., Deeny et al. 2009).
18 However, if we accepted this explanation it would not be clear why, in the present study, left-
19 temporal connectivity increased following both explicit and implicit practice schedules, and in spite
20 of decreases in self-reported conscious processing and left-temporal activity among members of the
21 explicit group.

22 An alternative interpretation of this cortical measure can be offered when one considers the
23 following two features. First, it is important to recognize that connectivity simply measures the
24 similarity between signals recorded at two different sites, with any relations drawn to neural
25 communication pathways being inferred rather than directly assessed (Cohen, 2014). Second, it is
26 important to remember that activity in the high-alpha frequency band is said to have an inverse

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1 relationship with cortical activity (Klimesch, 2012). Based on these two points, one would expect
2 that the functional interpretation of any changes in high-alpha connectivity over time should
3 consider whether absolute high-alpha power increased or decreased during the same time period. In
4 previous studies simultaneously measuring power and connectivity, high-alpha power decreased
5 (Gallicchio et al., 2017; Hatfield et al., 2013; Kerick et al., 2004), and, hence, the simultaneous
6 increase in high-alpha connectivity that those studies reported could indeed represent more similar
7 *co-activation* of the two sites. However, if high-alpha power increased, as in the present study,
8 increased high-alpha connectivity could represent more similar *co-inhibition* of two sites.
9 Consequently, our finding of increased left-frontotemporal connectivity with practice could reflect a
10 progressively stronger inhibitory communication between left-temporal and frontal electrode sites
11 that characterized both types of training. It would be interesting for future studies to scrutinize this
12 interpretation by comparing connectivity between tasks or regions known to be associated with
13 practice-induced increases versus decreases in power, or to examine connectivity when power has
14 been experimentally manipulated (e.g., via neurofeedback training).

15 **Conscious processing and performance during pressure**

16 Our second set of predictions concerned psychological pressure. Specifically, based on
17 reinvestment theory (Masters & Maxwell, 2008), we expected that an increase in pressure would
18 elicit increases in conscious processing and possibly de-chunking of the movements in explicit
19 trainees. In contrast, we expected this to be less likely for implicit trainees since implicit training
20 should limit the accrual of verbal-analytic rules that would be needed for reinvestment to occur.
21 Although manipulation check data suggested that cognitive anxiety and movement self-
22 consciousness increased significantly from the last block of acquisition to transfer (A4 to T), our
23 results indicate that choking did not occur. Rather, performance improved in both groups, alongside
24 further changes in self-report and EEG measures characteristic of those already observed during the
25 acquisition phase. As a consequence, it was not possible to conclusively support or refute

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1 reinvestment theory's prediction that de-chunking and increased conscious processing cause
2 choking under pressure among explicit learners and not among implicit learners.

3 The absence of choking might be attributed to the high number of trials during the transfer
4 block diluting the effect of our pressure manipulation, and resulting in moderate levels of conscious
5 processing which did not impair performance (e.g., Cooke et al., 2014). With fewer trials the
6 pressure manipulation would likely have been stronger (cf., Woodman & Davis, 2008), providing a
7 greater chance for choking and, possibly, de-chunking to occur. However, simply reducing the
8 number of trials is problematic as it compromises the EEG signal-to-noise ratio (Cohen, 2014). An
9 alternative solution to this issue would be to employ multiple, potentially more impactful stressors
10 (e.g., a live audience), and/or recruit participants with dispositionally high-levels of anxiety and/or
11 self-consciousness (e.g., Zhu et al., 2011). Future investigations on choking under pressure should
12 consider these methodological practicalities.

13 **Limitations and future directions**

14 Our results should be interpreted in light of certain methodological limitations. First, we
15 concede that our task lacked ecological validity, with participants using only their index finger to
16 make movements. While this task was chosen, based on previous research (e.g., Sakai et al., 2003),
17 due to its suitability for evaluating chunking/de-chunking, we recommend that future investigations
18 employ more complex motor tasks involving the coordination of multiple joints such as occurs in
19 sport. Indeed, it is possible that movements involving more degrees of freedom than we investigated
20 here would encourage the accrual of even more verbal-analytic rules during explicit acquisition, and
21 provide an increased likelihood of choking under pressure (Zhu et al., 2010).

22 Second, although in our study participants reached a high-degree of proficiency, there was
23 still scope for further improvement since the movements were not fully chunked at the end of
24 acquisition. Thus, we cannot rule out the possibility that had we trained participants for longer, the
25 sequence would have likely become even more automatized, and a reinvestment related de-
26 chunking under pressure more probable. Future endeavours aiming to further examine reinvestment

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1 theory's prediction that de-chunking causes choking under pressure among explicit learners would
2 do well to ensure that participants are trained to an extremely high-level of proficiency before the
3 undertaking the pressure test. This is because, according to reinvestment theory de-chunking occurs
4 in movements that are highly automated (Masters & Maxwell, 2008). In contrast, contingencies that
5 increase conscious processing (e.g., pressure) among performers at cognitive and associative stages
6 of acquisition may enhance performance (e.g., Beilock, Carr, MacMahon, & Starkes, 2002; Gray,
7 2004; Malhotra et al., 2015). In addition to extending the acquisition phase, future studies could
8 also introduce a period of sleep consolidation, which has been argued to further automatize skills
9 (e.g., Mazza et al., 2016; Walker & Stickgold, 2006), prior to delayed retention and pressure tests.
10 Delayed retention tests in particular would allow assessment of the extent to which participants
11 truly learned the sequence, rather than their proficiency at acquiring and memorising it in a single
12 day, as we tested here.

13 Third, although the two tasks employed here induced relatively errorful and errorless forms
14 of training, it is possible that participants in our so-called implicit group still used some degree of
15 conscious processing to perform the task. We are confident that our tasks provided appropriate
16 conditions to foster relatively high (explicit) and low (implicit) levels of hypothesis testing (see
17 Abrahamse et al., 2013, Sakai et al., 2003), but future investigations could design different tasks
18 that further dichotomize explicit and implicit training to their extremes.

19 Fourth, it is important to recognize that EEG is limited by poor spatial resolution. Thus,
20 despite being frequently advocated in the literature, the assumption that electrical activity recorded
21 by T7 and Fz electrodes reflects verbal-analytic and motor planning processes, respectively, is
22 overly simplistic (Cooke, 2013). Although resolving the *inverse problem* with certainty is
23 mathematically impossible, applying spatial filters such as surface Laplacian, independent
24 component analyses (ICA), or generalized Eigen decomposition (GED) could all improve the
25 spatial resolution of EEG and allow more confident assertions about the underlying generators of
26 the signals recorded on the scalp to be made (Cohen, 2014; Delorme & Makeig, 2004; Perrin,

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1 Pernier, Bertrand, & Echallier, 1989). However, all these solutions would require a higher number
2 of electrodes than were employed here. It is important for future research to adopt denser electrode
3 arrays and apply spatial analyses such as these to gain much greater insight into the underlying
4 cortical dynamics of explicit versus implicit learning and performance under pressure.

5 Fifth, in light of the inconsistencies between our self-report and cortical measures of
6 conscious processing, it is possible that both high-alpha T7 power and T7-Fz connectivity are
7 influenced by a broader range of processes than simply verbal-analytic conscious processing. For
8 example, motivational self-talk may involve some activation of the language regions, without
9 involving conscious motor processing (cf., Hardy, 2006). Accordingly, within and between-person
10 variability in the use of motivational self-talk could confound our interpretation of left temporal
11 high-alpha power and connectivity. Assessing how power and connectivity change based on the
12 direct manipulation of instructional versus motivational self-talk during motor skill acquisition and
13 performance under pressure would facilitate further understanding of our cortical markers. This
14 would be a fruitful avenue for future research.

15 Finally, we would also encourage future research to more closely examine individual
16 differences variables in addition to the practice schedule (i.e., explicit versus implicit) factor
17 employed here. For instance, personality traits such as reinvestment or neuroticism are likely to
18 moderate the relationship between chunking, conscious processing, and performance under pressure
19 (e.g, Barlow, Woodman, Gorgulu, & Voyzey, 2016). Such designs might be better equipped to test
20 reinvestment theory's specific de-chunking prediction, because anecdotal evidence indicates that
21 de-chunking (choking) under pressure does not occur uniformly for all individuals during all
22 pressure situations.

23 In conclusion, by simultaneously examining chunking and a combination of self-report and
24 psychophysiological measures of conscious processing during both explicit and implicit acquisition,
25 and transfer (pressure), this large-scale EEG experiment is the first to specifically investigate
26 reinvestment theory's pivotal dechunking hypothesis and provides the most comprehensive test of

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1 the theory to date. Our results confirmed that chunking is a general mechanism underpinning both
2 explicit and implicit motor sequence acquisition (e.g., Hikosaka et al., 1999; Song & Cohen, 2014;
3 Willingham, 1998). They also provide new neurophysiological evidence that explicit training can
4 support quicker chunking than implicit training by promoting the active inhibition of the left-
5 hemisphere, and a more pronounced increase in cortical efficiency. While the specific de-chunking
6 hypothesis of reinvestment theory warrants further scrutiny, our results add support to the literature
7 endorsing explicit learning as a means of accelerating movement acquisition, and provide a new
8 neurophysiological explanation why.

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1 Acknowledgements

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