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A psychophysiological examination of concept conscious processing of movements

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- A PSYCHOPHYSIOLOGICAL EXAMINATION OF CONCEPT OF CONSCIOUS PROCESSING OF MOVEMENTS

by

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Abstract

The aim of this thesis was to clarify the neurophysiological mechanisms underpinning the concept of movement *conscious processing*. This concept represents the core of reinvestment theory (Masters, 1992) which is a motor-control based explanation of motor-skill failures (i.e., choking) under psychological pressure, and whose predictions are relevant to the sporting world, the performing arts, and the motoric rehabilitation. The four experimental chapters that come discuss mixed-model design experiments in which participants extensively practiced a variety of motor tasks under different training conditions (between-participant factor), practice blocks and psychological climates (within-participant factor). Specifically, I manipulated training conditions in order for my participants to execute the motor tasks with either a comparatively *high* versus *low* degree of *conscious processing*. After an initial acquisition phase, they performed the tasks under *high* versus *low* evaluative and competitive psychological climates (*psychological pressure*). In all studies, alongside fine-grained measures of motor performance (e.g., movement chunking and kinematics), I monitored self-reports of conscious processing, and recorded electroencephalographic (EEG) activity during and/or in preparation for the tasks. In particular, I centred my analysis on two measures connected to representative of alpha frequency neuroelectric oscillations, namely power and connectivity. Specifically, based on previous research I focused my analyses around temporal power and frontotemporal connectivity in the left-hemisphere, as they have been identified as putative measures of conscious processing (Hatfield et al., 2013), and within the high-alpha band, as it is deemed to be more sensitive to the task related changes (Babiloni et al., 2011).

Chapter 2 describes a study (Bellomo, Cooke, & Hardy, 2018) which was planned to offer a comprehensive test of the predictions of reinvestment theory and enable us to understand how conscious processing is linked to the concept of motor chunking. Participants used the index finger

of their dominant hand to perform a sequence learning task either following an explicit/trial-and-error (high-conscious processing) or implicit/errorless (low-conscious processing) practice schedule. After an acquisition phase, they performed the task under high-psychological pressure. Results showed that explicit acquisition resulted in quicker sequence acquisition, reduced conscious processing, and increased cortical efficiency (left-temporal high-alpha power). Moreover, 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. However, this might have been due to either the motor-simplicity of the task, or due to movements not being fully automatized. In addition, since we observed a disconnect between self-reports and EEG measures of conscious processing, we questioned the specific sensitivity of these neurophysiological measures.

Chapter 3 describes a study that attempted to address the limitations of the previous study by increasing the motoric complexity of the sequence learning task (i.e., participants used four fingers on their non-dominant hand), introducing an over-night sleep period to foster movement automatization, and dichotomising the training schedule based on the amount of movement-specific declarative knowledge. This decision was taken in the hope of clarifying whether these EEG measures are actually sensitive to verbal activity functional to movement execution. Specifically, a to-be-learned repeating sequence was alternated with random button presses. This was unbeknownst to the members of the implicit group, in order to prevent any explicit processing. On the contrary, participants of the explicit group were showed the repeating sequence and given the possibility of verbalising it with an acronym (since buttons were labelled with letters). As in the previous study, participants underwent an acquisition phase on a first day. However, this was followed by an overnight sleep before they returned to complete the retention, and the low and high- pressure conditions on a second day. Results questioned the specific sensitivity of left-temporal EEG measures to movement-specific verbal activity. However, the additional consideration of other sites and pairs contributed to improving our understanding of the electroencephalographic features of movement-specific declarative knowledge.

Chapter 4 and 5 describe the results of a study which was designed to scrutinise the specific sensitivity of the aforementioned left-temporal EEG measures to the semantic content of verbal activity happening prior to movement execution. Specifically, via a self-talk intervention, participants were induced into rehearsing either movement-relevant (i.e., instructional self-talk) or movement-irrelevant (i.e., motivational self-talk) verbalisations prior to movement execution. Chapter 4 focused specifically on left-temporal alpha power and left-frontotemporal alpha connectivity and provided evidence against the idea of a specific sensitivity of these EEG measures to movement-relevant verbalisations. Chapter 5 tested additional hypotheses linked to putative mechanisms underpinning the effects of instructional and motivational self-talk on motor performance. Results showed that the instructional group was characterised by more top-down control of action, while the motivational group was characterised by increased bodily arousal and effort, which, as suggested by performance data, was not fully matching the fine control requirements of the putting task.

Taken together these studies, provided evidence against the idea of a left-temporal power and left-frontotemporal connectivity as measures of verbal processes relevant for motor behaviour typical of conscious processing. However, they also put the base for a re-discussion of the concept of conscious processing as a cognitive phenomenon which might consist of an explicit control of movement implemented in modalities other than the verbal one, such as visual or kinaesthetic.

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List of publications

Published manuscripts

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Submitted manuscripts

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Manuscripts in preparation

Bellomo, E., Cooke, A., Gallicchio, G., Ring, C., Hardy, J. (in preparation). Examining the cortical effects of explicit versus implicit motor sequence learning, retention and pressure: Implications for the conscious processing literature.

Bellomo, E., Cooke, A., Gallicchio, G., Ring, C., Hardy, J. (in preparation). Effects of skill-relevant vs -irrelevant self-talk on high-alpha left-temporal (T7) power and (T7-Fz) connectivity.

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Bellomo, E., Cooke, A., Hardy, J. (2016). Underneath the hood: an exploratory study of the cortical underpinnings of explicit and implicit motor learning and performance under pressure. BASES student conference (British Association for Sport and Exercises Sciences) 18th March 2016. Bangor University, Bangor (UK).

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CHAPTER ONE

General Introduction

Motor learning is arguably one of the most crucial processes for life as it frees us from spatial constraint and enables a dynamic interaction with the environment around us. Learning a motor skill involves a series of complex processes in our brain, which are developed and consolidated with practice and experience. The successful execution of a motor skill requires the integration of information from the visual, somatosensory, and motor channels in order to generate the movement plan which best suits our strategic goal (Willingham, 1998). For example, when learning to walk, a child has to establish a final destination, refine balance and lower limb control, use the sensory information to generate a model of the surrounding space, integrate and continuously re-evaluate this information until all the movements are completed and the goal is reached. Given its importance, it is no surprise that the acquisition of complex motor skills has attracted the attention of researchers.

Motor Learning: explicit and implicit routes

The foundation bricks of research in this area were laid by Fitts and Posner (1967) and their model of motor learning that describes skill acquisition as a practice dependent transition across three stages: cognitive, associative, and autonomous. During the cognitive stage, characteristic of novices, performers apply explicit hypothesis-testing strategies to work out the *how-to* of a movement. This typically involves a high number of errors and verbally-mediated conscious adjustments to find the rules for the best execution, which result in the accumulation of movement-relevant declarative knowledge. At the associative stage, typical of intermediate performers, an initial understanding of the movement has been achieved, performance is progressively smoothed out, errors are reduced, and so is verbally mediated hypothesis-testing. At the autonomous stage, observed in experts, movement is completely consolidated, performance is accurate, effortless, and automatic. In other words, the transition from the cognitive to the autonomous stage is characterised by a progression from a declarative to a procedural execution of movements (cf., Anderson, 1982). The backbone of this model is still accepted today, and it has been endorsed by computational simulations (Adaptive Control of Thought; Anderson, 1982), and integrated in neuropsychological models (Hikosaka et al., 1999; Willingham, 1998).

While most researchers endorse Fitts and Posner's (1967) seminal model, many have also reported occasions where the acquisition of a motor skill happens in the absence of awareness, without working memory mediated conscious control of movements, with limited accumulation of declarative knowledge, and through a procedural mechanism from the earliest stages (cf., Hikosaka et al., 1999; Masters & Maxwell, 2008; Nissen & Bullemer, 1987; Willingham, 1998). This type of learning, which, because of its nature was labelled as implicit, was first discussed in the seminal work on sequence learning by Nissen and Bullemer (1987). These authors introduced a paradigm, the serial reaction time task (SRTT), in which participants are required to press buttons mapped to visual stimuli (usually four) appearing on a screen at spatially distinct locations. The visual stimulus disappears after the response; then, and after a short response-stimulus interval (~200-500 ms), another stimulus appears. Unbeknownst to participants, the signals might follow a repeating sequential (e.g., 4-2-3-1-3-2-4-3-2-1; Nissen & Bullemer sequence) or a pseudorandom (no immediate repetition of the same position) pattern. Crucially, because in each block beginning and end are not designated, the task cycles with no breaks, alternating sequential and pseudorandom patterns until the block is completed (6 to 10 cycles). The authors noticed that reaction times (RTs) improved with practice, with a progressively faster and smoother execution, that they interpreted as indicative of sequence learning. Notably, this learning happens despite little measurable explicit knowledge of the sequence. They therefore suggested that learning occurred in a so-called implicit way. This argument was further supported by neuropsychological evidence showing double dissociations (for a review see Curran, 1995). For instance, individuals with explicit memory deficits such as amnesic patients, who typically have damage to the medial temporal lobe, including hippocampus or the diencephalon (Parkin & Leng, 1993; Squire, Amaral, & Press, 1990), or

Alzheimer's disease patients, who have neurofibrillary tangles and neurotic plaques in limbic, temporal, and frontal regions (Arnold, Hyman, Flory, Damasio, & Van Hoesen, 1991), still demonstrated SRTT learning. Conversely, impaired SRTT learning has been observed in Huntington's and Parkinson's disease (HD and PD) patients, who are characterised by disfunctions to the basal ganglia, the brain structure that is critical for using sequential information to guide performance. Meanwhile their ability to learn explicitly (i.e., awareness of the sequence; Jackson et al., 1995; Willingham & Koroshetz, 1993) is preserved.

In sum, the most up-to-date models of motor learning suggest that the acquisition of complex movements can follow two routes which are not mutually exclusive and are initially activated in parallel (Hikosaka et al., 1999; Masters et al., 1993; Willingham, 1998). On the one side, the explicit route consists of a series of conscious, deliberate, top-down efforts to control movement execution, which require the allocation of cognitive resources in working memory and end with the development of movement-specific declarative knowledge. On the other, the implicit route to movement acquisition takes place without consciousness, in a bottom-up fashion which by-passes working memory.

Although at the beginning of learning these two routes are activated in parallel, because of conscious hypothesis-testing, the explicit route initially grants a faster skill acquisition (Curran, 1995; Hikosaka et al., 1999). However, with extensive practice, these explicit processes progressively decrease and execution gravitates towards a more implicit mode (Fitts & Posner, 1967; Hikosaka et al., 1999; Masters & Maxwell, 2008; Willingham, 1998).

The conscious processing hypothesis

Based on the idea that the explicit route tends, with practice, to merge with the implicit route (Fitts & Posner, 1967), and that sometimes, skills acquired without initial awareness can become conscious (Curran, 1995), several authors hypothesised these two modalities of skill acquisition to be at the extremes of a continuum characterised by high versus low levels of *conscious processing* (Hardy, Mullen & Jones, 1996; Masters & Maxwell, 2008; Masters, Polman, & Hammond, 1993).

An individual engaging in hypothesis testing or making conscious effort to control movement would be at the high-conscious end of the continuum whereas individuals executing movements with limited declarative knowledge of the movements executed would be at the low-conscious end of the continuum (cf., Masters & Maxwell, 2008).

The concept of a conscious processing continuum is pivotal to reinvestment theory (Masters, 1992; Masters & Maxwell, 2008). The theory argues that conscious processing levels during the initial stages of movement acquisition play a crucial role for learning and subsequent performance under pressure. As mentioned above, high-conscious processing of movements, which is often triggered by explicit instructions, rules, or feedback (i.e., from a coach/instructor) seems to initially benefit learning, by granting a faster movement acquisition (Curran, 1995; Fitts & Posner, 1967; Hikosaka et al., 1999). However, according to the theory, these benefits that emerge early in learning can leave an individual susceptible to performance problems later on, especially when they encounter competitive and/or evaluative conditions that elicit high-psychological pressure to perform well (for reviews see De Caro, Thomas, Albert, & Beilock, 2005; Masters & Maxwell, 2008).

More specifically, reinvestment theory argues that while explicit learners do become automated and effortless after extensive practice, the movement-relevant declarative knowledge accrued when they were a novice exposes them to the risk of reinvesting focus on the sub-components of the movement, recalling the accumulated declarative rules for movement execution, and thereby undoing automaticity and damaging their performance as an expert. This reinvestment/de-automatization process is especially likely to occur (often as a well-intentioned coping strategy) under conditions of increased incentive to do well, such as under high-competitive pressure. In this way, reinvestment theory provides a motor-control based explanation for incidences whereby experts choked under pressure (e.g., the penalty missed by the Ballon D’Or, Roberto Baggio, at USA ’94). Specifically, it suggests that the experts choke because (paradoxically) their well-intentioned attempts to produce their best execution of a highly automated skill triggers conscious processing and that promotes a more novice-like and inefficient execution. Importantly, the theory also argues that if the initial stages of movement acquisition limit movement awareness and conscious processing (i.e., implicit route), performance under pressure would be more robust, since reinvestment of declarative knowledge would be less likely (Hardy et al., 1996; Masters & Maxwell, 2008).

The predictions of reinvestment theory are corroborated by a large body of evidence accumulated in the last twenty-five years. For example, Masters (1992) showed that after an initial acquisition phase, only participants who were equipped with declarative knowledge on how to best execute a golf-putt (i.e., explicit group) showed deterioration of performance (lack of improvement) in a subsequent high psychological pressure condition. In contrast, performance under pressure was robust (continuous improvement) in participants who did not receive any explicit instruction and were asked to perform a random letter generation task at specific intervals (i.e., implicit group). Crucially, this additional task was assigned to the implicit group in order to limit any type of verbally mediated putting-related declarative processing. These core finding were confirmed by Hardy and colleagues (1996) in a follow-up study and have been replicated extensively since. For instance, reinvestment effects have been observed for complex motor skills in sports (e.g., trampolining, golf putting, soccer and hockey dribbling, basketball free-throwing, rugby passing, table tennis, baseball batting; for a review see Masters & Maxwell, 2008), surgery (e.g., simulated laparoscopy; Zhu et al., 2011), rehabilitation and balance (Orrell, Eves, Masters, 2006) and sensorimotor eye-hand mapping tasks such as typing (Langer & Imber, 1979), video games (Baumeister, 1984), or sequence learning (MacMahon & Masters, 1999).

In essence, this research supports the idea that the likelihood for this phenomenon, commonly known as reinvestment of conscious processing (Hardy et al., 1996, Masters & Maxwell, 2008), is associated with the amount of task-relevant declarative knowledge accumulated early in learning (Maxwell, Masters, & Eves, 2000), and the degree of movement automatization, since conscious processing is initially beneficial for movement learning and would be harmful only once the movement is automated (see Masters & Maxwell, 2008).

While on the one side research has highlighted the long-term costs of acquiring movements via the explicit route, on the other side, it has tried to identify ways of limiting hypothesis-testing and triggering the implicit route early in learning (e.g., Liao & Masters, 2001). These methods include articulatory suppression during practice (Masters, 1992), reduced feedback paradigms (Maxwell, Masters, & Eves, 2003), subliminal feedback (Masters, Maxwell, & Eves, 2009), errorless practice (Maxwell, Masters, Kerr, & Weedon, 2001), and analogy learning (Masters & Liao, 2001).

Articulatory suppression (see Masters, 1992) consists of performing a random letter generation task concurrently to the to-be-learned movement with the rationale that by keeping the articulatory-loop busy, the performer will not be able to verbalise in working memory the different steps required to best execute the movement and would have had to rely on the implicit route. The reduced feedback paradigm (Maxwell et al., 2003) consists of withholding performance outcome feedback (most likely visual) from the performer, in order to prevent the learner from distinguishing success from failure and therefore avoid corrective hypothesis testing. The subliminal feedback paradigm consists of giving feedback, but at an unconscious level (e.g., through a tachistoscope; Masters, Maxwell, et al., 2009). Errorless learning consists of providing sensory feedback but in an environment that prevents chance for errors (e.g., by increasing putting distance gradually, Maxwell et al., 2001; Zhu et al., 2011). Finally, analogy learning (Liao & Masters, 2001) represents an attempt to reduce the number of explicit rules accrued by evoking an image that summarises the important aspects of the skill without overflooding the system with unstructured explicit instructions. The use of analogies would have the advantage of efficiently packaging (or chunking) movement-relevant declarative knowledge and, possibly, triggering a less verbal and more visuospatial form of movement processing (cf., Liao & Masters, 2001). Similar to analogy learning, the use of holistic process-goals (Kingston & Hardy, 1997) would offer a cognitively efficient way to consciously process movement by focusing on the whole movement rather than breaking it into sub-actions.

Crucially, all these methods resulted in a lower number of declarative rules compared to explicit learners as well as continued improvements, rather than a plateau, of performance under pressure (Masters & Maxwell, 2008). In other words, the implicit learning methods identified by the literature represent can limit conscious processing by directly or indirectly manipulating movement-related verbal processes (cf., Masters & Maxwell, 2008), and are associated with robust performance under pressure.

Neuroscience of conscious processing

What stands out from the literature discussed so far is that the construct of conscious processing is functionally theorised as a series of movement-relevant verbal processes that decrease with practice through the explicit route; are limited during learning via the implicit route; and are recalled, for movements acquired via the explicit route only, during pressure-induced reinvestment (Masters & Maxwell, 2008). The following sections describe pioneering studies measuring electroencephalography (EEG) in complex movements in an attempt to understand the neurophysiological consequences of conscious processing. Most highlighted effects mainly localised in the left-hemisphere and in particular in the temporal regions. Since activity in these regions plays a role in language-related processing and in working-memory function (D’Esposito et al., 1998; Galin & Ornstein,1972; Hellige, 1990; Sauseng, Klimesch, Schabus, & Doppelmayr, 2005; Springer & Deutsch, 1998), several authors hypothesised these left-temporal effects could represent cortical indices associated with conscious processing of movements (cf., Hatfield et al., 2013; Zhu et al., 2011). Before presenting this evidence in the following paragraphs, a brief introduction to the EEG methodology is provided.

Introduction to EEG

EEG is a technique that consists of deriving a measure of the brain’s electro-neural activity via the application of electrodes over the scalp of an individual and the subsequent amplification and digitisation of the signal obtained. The principle at the core of this technique is the differential amplification, which is defined as: $(S - G) - (R - G) = S - R$; where S is a signal electrode, R is reference, G is ground; and in essence consists of measuring electro-neural activity from electrodes of interest (i.e., signal) relative to a reference, in order to obtain measures of scalp level potentials (measured in microvolts: mV). In the vast majority of cognitive neuroscience investigations, the electrodes are arranged according to the standard and extended 10-20 system (Jasper, 1958; American Electroencephalographic Society, 1994; see Figure 1) whereby different labels, codifying scalp region and laterality (format region-laterality), are applied based on the topographical location. The letters *F-*, *C-*, *P-*, *O-*, *T-* are used for electrodes above the frontal, central, parietal, occipital, and temporal regions of the scalp; these letters are coupled with, *-odd*, and *-even* digits to identify laterality (left- and right-hemisphere respectively) and distance from the sagittal-midline (codified as *-z*), with the magnitude of the digit itself increasing as the distance increased (i.e., *Pz* midline parietal, *P3* left-medial parietal, *P7* left-lateral parietal).

EEG is a measure of scalp level voltages corresponding to electric fields (dipoles; Figure 2) generated by the summation of membrane (post-synaptic) potentials and dependent on the synchronous activity of a population of neurons (Luck, 2015). More precisely, EEG is a measure of spatial coherence of membrane potential, and as such it is direct measure of neural activity[1] with an exquisite temporal resolution (Cohen, 2014). This synchronous activity has oscillatory characteristics which can be described in terms of frequency, which is how fast an oscillation is (cycles per second; measured in Hz); power, which represents the strength of an oscillation (measured in μV^2); and phase, which represents the points in the oscillatory cycle (measured in radians).

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[1] EEG is advantageous for studying neurocognitive processes compared to MRI-based techniques (cf., Cohen, 2014), which make indirect assumptions on brain activity based on slow brain haemodynamic responses (BOLD; blood oxygenation level dependent).

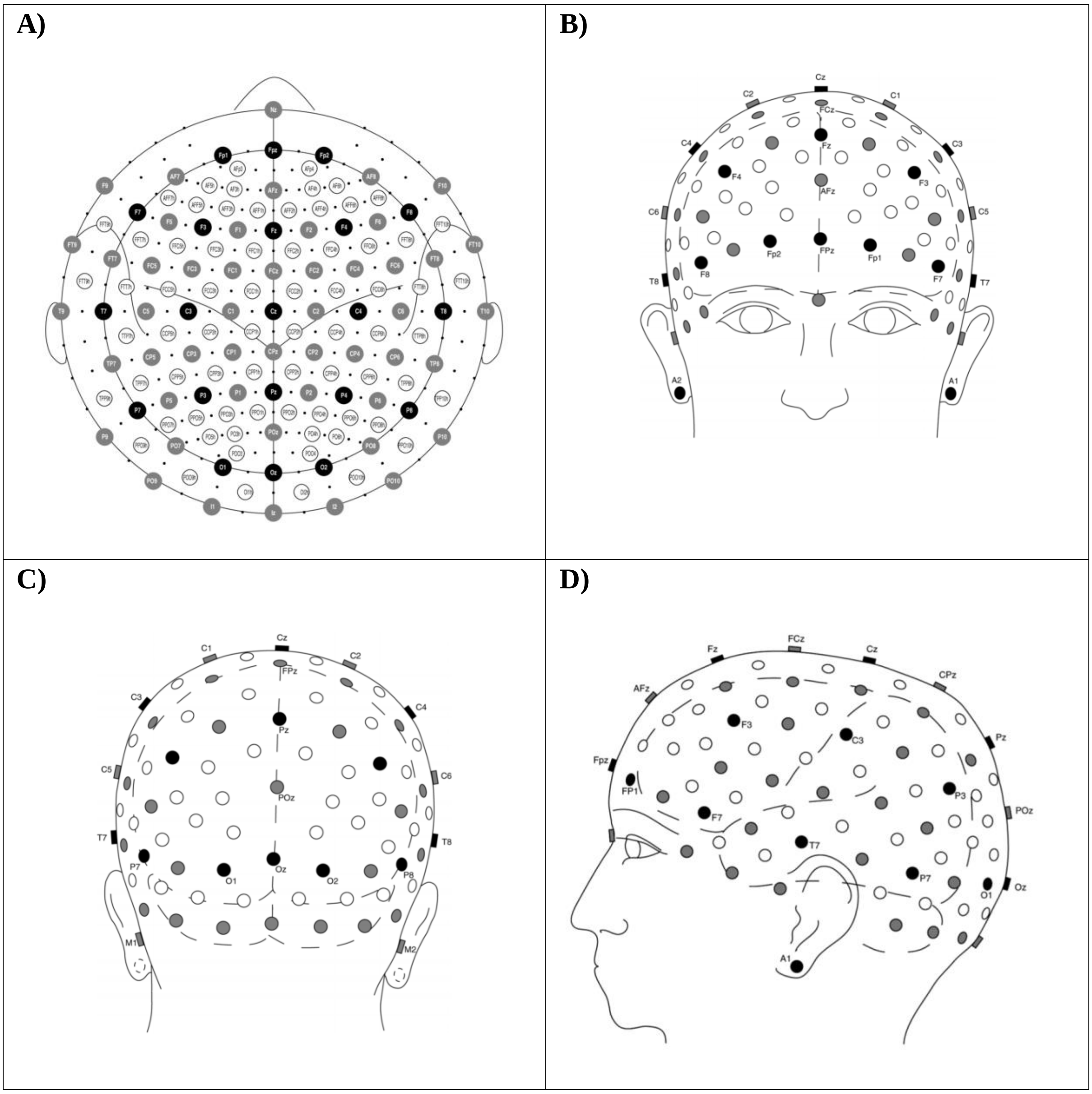

Figure 1. Electrode positions in the 10-20 system (black circles) and its extension (grey circles): A) standard layout; B), C), D) representation on a realistic head drawing. Adapted from Oostenveld and Praamstra (2001).

EEG in its raw form carries little information since it is a mixture of both neural (and non-neural) activity at multiple frequencies. By means of signal-processing techniques, such as time-frequency decomposition[2], it is possible to identify the time course of activity at specific

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[2] Time-frequency decomposition enables investigation of both the time and frequency domain characteristics of the EEG signal (Cohen, 2014). As such, it represents an evolution of the analysis in the frequency domain, which looks at the spectral characteristics of the signal, ignoring the time dimension; and of the time domain, which looks at the evolution of the trace over time, ignoring the frequency dimension. The most classical time-domain analysis applied to EEG signal is the estimation of the event-related potentials (ERP), which consists of averaging several segments of the EEG trace time-locked to a specific event (i.e., a stimulus, a movement, etc.) under the assumption that the averaging would zero out random signal fluctuations, and highlight event-related activity only (for a detailed explanation see Luck, 2014).

frequencies and make predictions about their functional meaning based on the neural and cognitive functions discussed in the literature (see Cohen, 2014 for a detailed description of these techniques). Typically, time-frequency analysis involves identifying, from the neural time-series, segments (commonly labelled as trials or epochs) time-locked to specific events (i.e., movement initiation); and then performing an averaging across trials, so that random activity is dampened and consistent activity across trials is highlighted. Please refer to Figure 3 for a graphical representation of this process.

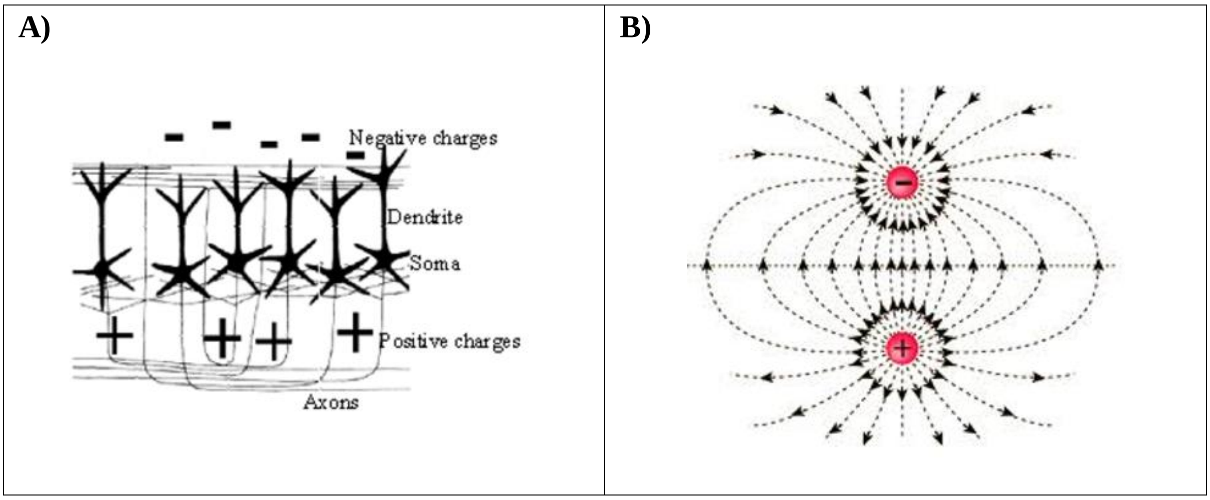

Figure 2. Diagram of the summation of post-synaptic potentials (A) and the correspondent theoretical representation of the physical phenomenon also known as derived equivalent dipole (B). The generation of electric fields of opposite polarities depends on the summation of positive/negative charges in the post-synaptic space. Adapted from Luck (2015).

Power analyses are typically employed to quantify the amount of frequency-specific activity in the EEG signal. Phase information has instead been mostly employed to derive frequency-specific inter-electrode connectivity measures. Widely used phase-based connectivity measures are magnitude-squared coherence and inter-site phase clustering (ISPC). While magnitude squared coherence is influenced by absolute fluctuations in power, ISPC uses only phase information. As discussed by Cohen (2014) both connectivity measures can be calculated by first averaging the time-series values either over time (connectivity across time) or over trials (connectivity across trials). Averaging over time is advantageous for high-frequencies (i.e., gamma) and for long lasting events (several seconds), while averaging over trials is better for slower frequencies (such as alpha) and for detecting task-related modulations (Cohen, 2014). More details on these specific measures is provided in the methodological sections of each of my experimental chapters below.

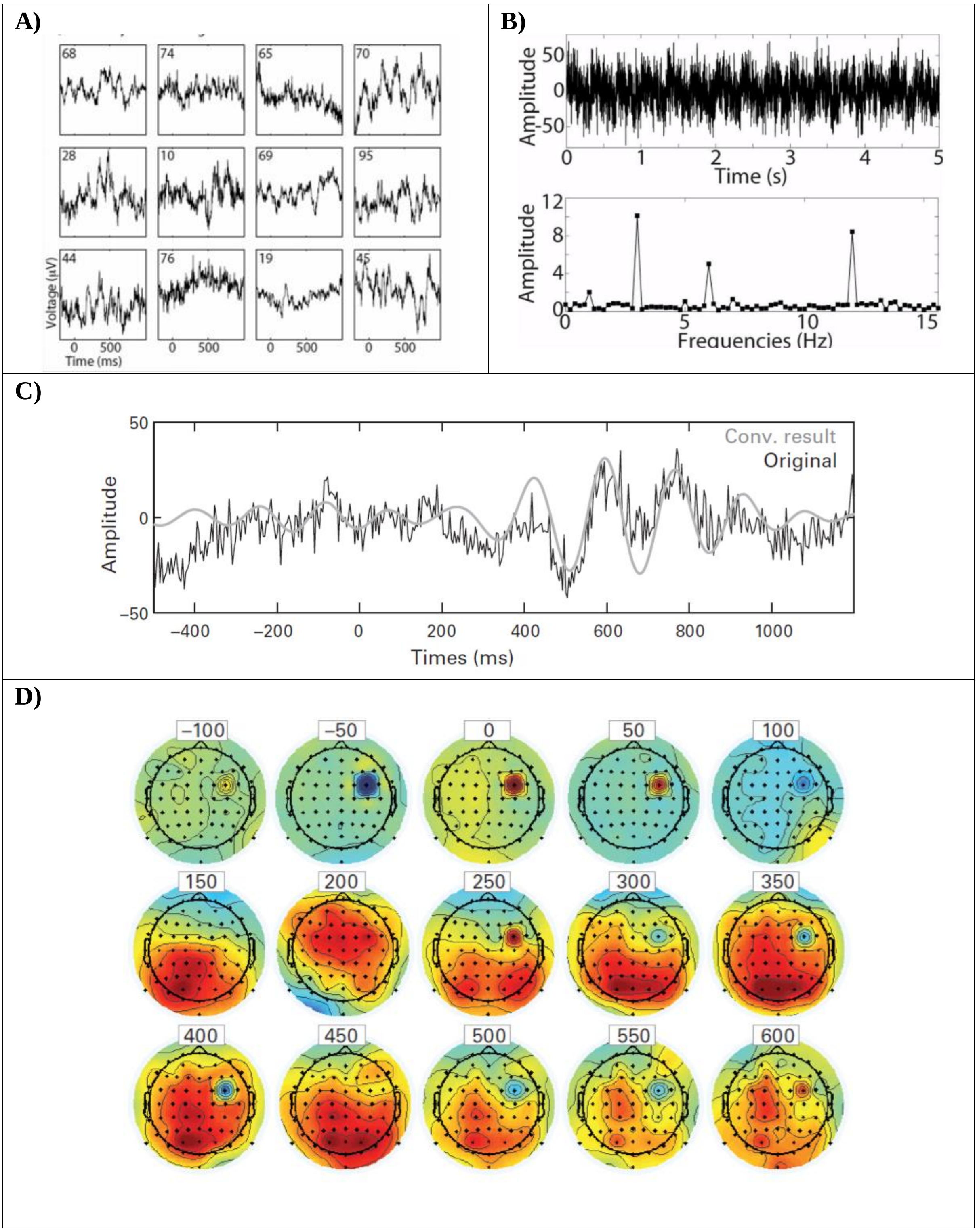

Figure 3. Simplified overview of the process that goes from raw EEG to time-frequency representation of the signal. Panel A) several segments (epochs) of the EEG time series are extracted based on a specific event (e.g., beginning of the trial, presentation of a stimulus). Panel B) time domain and frequency domain representation of the EEG time series. Panel C) example of a wavelet band-passed epoch of EEG time series to extract frequency specific information. Panel D) topographic maps of frequency-specific activity at specific time points. Adapted from Cohen (2014).

Alpha activity and complex movements.

Most of the EEG research relevant to motor learning reports results in the so-called alpha (around 10 Hz) frequency band (Cooke, 2013). Alpha was the first frequency of brainwave to be identified (Berger, 1929), hence it being named by the first letter of the Greek alphabet and is widely acknowledged as the predominant frequency in the adult human brain (Klimesch, 2012). From a functional point of view, alpha oscillatory activity represents inhibition of task-irrelevant areas (Jensen & Mazaheri, 2010; Klimesch, 2012; Klimesch, Sauseng & Hanslmayr, 2007). Within the alpha band it is possible to additionally distinguish between low- and high-alpha frequencies (Klimesch et al., 2007). While the low-alpha frequency band (around 8-10 Hz) is generally thought to reflect more global brain alertness regulation, the high-alpha frequency band (around 10-12 Hz) is considered to be more sensitive to task-related oscillations related to sensory and motor information processing. For this reason, most of the studies, including the current experimental work, focused on the high-alpha band.

The literature on complex movements consistently reported that both high-alpha power and connectivity are sensitive to expertise; quality of movement outcome; and levels of performance-pressure, as shown by topographical changes and event-related differences highlighted by expert-novice comparison and longitudinal motor-skill training studies (e.g. Cooke et al., 2014, 2015; Gallicchio et al., 2016, 2017). Some of the key studies are reviewed next.

Expertise and practice

High-alpha power shows a dynamic event-related decrease prior to movement initiation (usually ~2 seconds before), which is generally interpreted as timely increase in activity functional to movement because the effect is strongest around frontocentral regions which are deputed to movement planning and execution (Babiloni et al., 1999; Cooke et al., 2014; Hillman, Apparies, Janelle, & Hatfield, 2000; Janelle et al., 2000; Kerick, Iso-Ahola, & Hatfield, 2000; Loze, Collins, & Holmes, 2001; Pfurtscheller & Aranibar, 1979; Salazar et al., 1990). Notably, this effect is strengthened by expertise and is sensitive to performance quality (Babiloni et al., 2008; Cooke et al., 2014, 2015; Gallicchio et al., 2016). In fact, experienced performers (i.e., experts or amateurs undergoing intensive training) typically show a more dramatic pre-movement high-alpha power decrease (Babiloni et al., 2008; Cooke et al., 2014; Gallicchio et al., 2016). Moreover, when this process fails (less dramatic reduction), performance suffers (i.e., missed putt, Cooke et al., 2014; aborted shots, Hillman et al., 2000).

High-alpha power also shows changes in topographical distribution as a function of expertise (Gallicchio et al., 2017; Gallicchio, Finkenzeller, Sattlecker, Lindiger, & Hoedlmoser, 2016; Gallicchio & Ring, 2018). Specifically, power increases at sites that with practice become redundant for the task, and, conversely, decreases at sites which are important for the task. This phenomenon, also known as *alpha-gating (*see gating-by-inhibition hypothesis; Jensen & Mazaheri, 2010) seems to be at the root of those changes that enable our brain to achieve an efficient task-specific processing via an intelligent distribution of resources (see *psychomotor efficiency,* Hatfield & Hillman, 2001; or *neural efficiency*, Babiloni et al., 2011; Del Percio et al., 2011).

Despite some task-specific effects, the motor control literature consistently showed that with training and expertise left-hemisphere processing is progressively reduced. Since left-hemispheric function is strongly associated with verbal–analytical cognitive processes (D’Esposito et al., 1998; Galin & Ornstein,1972; Hellige, 1990; Kinsbourne, 1982; Springer & Deutsch, 1998), the expertise-dependent reduction in activity has therefore been interpreted a shift from a verbally-mediated mode, typical of the cognitive stage of learning, to a procedural and effortless mode of movement execution, typical of the automatic stage (*psychomotor efficiency*, Hatfield & Hillman, 2001). For example, Haufler, Spalding, Santa Maria, and Hatfield (2000) showed that expert marksmen, compared to novices, displayed more high-alpha (10-11 Hz) power in the left-hemisphere, at central (C3), temporal (T7) and parietal (P3) sites in preparation to the shot. Similarly, Landers and colleagues (1994) showed that following 35 hours of archery training, high-alpha power in preparation to the shot increased at the left-temporal (T7) compared to the right-temporal (T8) site. These findings were partially replicated with golf putting by Gallicchio and colleagues (2017) which reported an increase in left-temporal (average of T7, FC5, CP5) power in intermediate golfers after a three-day long intensive putting training. Interestingly, these changes were also accompanied by decreased high-alpha power at centroparietal (C3, Cz, C4, CP3, CP4) sites, which are in all likelihood important for aiming tasks such as putting (Gallicchio et al., 2017).

Alongside high-alpha power changes, expertise in complex movements seems to be also characterised by a refinement of the connectivity network supporting movement planning and execution, whereby stronger connectivity is observed between regions important for the task, while connectivity is reduced for those that become redundant. For example, frontoparietal and frontoccipital connectivity is strengthened for better performances (successful putts; Babiloni et al., 2011) and is more stable prior to movements in experts compared to novices (Del Percio et al., 2011). Del Percio and colleagues (2011) suggested that this effect represented a refinement of causal top-down control of spatial attention (Corbetta & Shulman, 2002; Serences & Yantis, 2006) functional to task execution, since frontal regions are associated with executive, attentional, and motor planning functions, whereas posterior (i.e., parietal and occipital) regions are associated with sensorimotor integration and visuospatial processing. Moreover, the authors discussed that a strengthening of high-alpha connectivity between frontal, central and parietal regions during movements matches the main nodes of the neural substrate identified for motor sequence learning and production (primary motor, posterior parietal cortex, medial motor areas and dorsolateral prefrontal cortex; Ashe et al., 2006; Lu & Ashe, 2005; Bischoff-Grethe, Goedert, Willingham, & Grafton, 2004; Haaland, Elsinger, Mayer, Durgerian, & Rao, 2004).

Alongside these strengthened connections, the literature showed reduced connectivity between frontal motor regions and associative/non-motor regions, in particular the left-temporal region (cf., Deeny, Haufler, Saffer, & Hatfield, 2009; Gallicchio et al., 2016). Since left-temporal activity is reduced with practice, researchers have reasoned that a reduction in left-frontotemporal connectivity (usually measured at T7-Fz or T7-F3) could represent the isolation of the left-temporal site, due to a practice-induced redundancy of verbal processing for movements (cf., Zhu et al., 2011). Indeed, left-frontotemporal (T7-Fz) connectivity is weaker in more experienced performers than it is in novices (Babiloni et al., 2011; Deeny, Haufler, Saffer, & Hatfield, 2009;[3] Gallicchio et al., 2016, 2017). For example, Gallicchio and colleagues (2016, 2017) reported that weaker T7-Fz high-alpha connectivity (ISPC across trials) is characteristic of experts versus novices; of accurate versus inaccurate putts; and is connected to greater performance improvements during training[4].

The conceptual link between left-frontotemporal high-alpha connectivity and movement-relevant verbal processing is additionally supported by the fact that it discriminated individuals based on their likelihood of relying on explicit control of movements via verbal declarative rules (Zhu et al., 2011; Zhu, Poolton, Wilson, Hu et al., 2011). Specifically, in Zhu and colleagues (2011), stronger T7-Fz connectivity (magnitude squared coherence) prior to or during movement execution (i.e., golf putting; laparoscopic simulator) was observed in individuals with high propensity to consciously control movements (determined by the Movement Specific Reinvestment Scale; Masters, Eves, & Maxwell, 2005) compared to their low-propensity counterparts. The study also showed stronger T7-Fz connectivity among individuals who underwent an explicit, trial-and-error learning protocol compared to those who underwent implicit, errorless training.

In summary, decreases in left-temporal high-alpha power and connectivity are observed as learning progresses and for this reason have been interpreted as indexes of movement-relevant verbal processing (cf., Deeny et al., 2009; Hatfield et al., 2013; Zhu et al., 2011).

Competitive pressure

In addition to the evidence regarding expertise and practice, extant literature shows that left-temporal high-alpha power and left-frontotemporal high-alpha connectivity might be also sensitive to competitive pressure (both power and connectivity, Hatfield et al., 2013; only connectivity, Chen et al., 2005; Zhu et al., 2011). Hatfield and colleagues (2013) reported that under competitive

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[3] It is worth mentioning that in both the studies of Babiloni and colleagues (2011) and Deeny and colleagues (2009), the weaker left-frontotemporal alpha connectivity observed in expert performers compared to novices, was not supported by statistical significance.

[4] Gallicchio and colleagues (2017) reported that this effect was not specific to the left-frontotemporal pair but consisted in a more general isolation of the left-temporal site (T7).

pressure experienced pistol-shooters displayed less T7 power, stronger T7-Fz connectivity (in the 8-13 Hz alpha broadband), and less efficient aiming behaviour (although this did not impact shooting performance). In a subsequent phase of the aforementioned study by Zhu and colleagues (2011), individuals who underwent explicit (but not implicit) skill training showed an increase of T7-Fz connectivity once under competitive pressure. However, as in Hatfield's study, performance outcome was unaffected by the increase in T7-Fz connectivity.

Two additional studies do provide direct and indirect links between performance outcome and left-frontotemporal connectivity. Deeny, Hillman, Janelle and Hatfield (2003) reported stronger T7-Fz connectivity in expert marksmen with a history of poor performance in competition, compared to experts who performed consistently well. Chen and colleagues (2005) reported that increases in T7-Fz connectivity induced by a competitive and evaluative environment, were directly associated with anxiety and inversely associated with dart-throwing performance. Taken together these changes suggest a pressure-induced increase in left-temporal processing may be interpreted as a dysfunctional increase of movement-relevant verbal processing due to conscious processing of movement (Hatfield et al., 2013; Masters & Maxwell, 2008; Zhu et al., 2011).

High-alpha activity and conscious processing

The literature discussed above consistently reports that during preparation for self-paced aiming tasks (e.g., golf-putting or shooting), left-temporal high-alpha power (usually measured at T7) and left-frontotemporal high-alpha connectivity (usually measured at the T7-Fz pair) discriminate expertise level (i.e., novices vs experts), type (i.e., trial-and-error versus errorless practice) and amount of practice (i.e., amateurs undergoing training), and high versus low psychological pressure conditions (e.g., Gallicchio et al., 2016, 2017; Landers et al., 1994; Hatfield et al., 2013; Haufler et al., 2000; Zhu et al., 2011). Because of their left-temporal localisation, these effects have been conceptually associated to the changes in movement-related verbal activity due to conscious processing predicted by the theories of motor learning (stages of learning, Fitts & Posner, 1967) and of performance under pressure (reinvestment theory, Masters & Maxwell, 2008). In other words, left-temporal high-alpha power and left-frontotemporal connectivity have often been considered as neurophysiological measures of conscious processing (cf., Hatfield et al., 2013; Zhu et al., 2011).

Limitations of Extant Research

The literature discussed left-temporal high-alpha power and left-frontotemporal high-alpha connectivity as putative and objective measures of movement-related verbal processing representative of conscious processing. While these conclusions are extremely intriguing, they are limited by a series of factors. Indeed, rather than coming from a single and comprehensive study, they are based on a series of separate studies, some of which only partially supported reinvestment theory’s hypotheses. For example, the left-frontotemporal connectivity differences observed by Zhu and colleagues (2011) during the pressure phase (i.e., more connectivity for the explicit practice group) were not accompanied by the expected changes in performance (i.e., decrease in performance for the explicit practice group). Moreover, it is not clear how left-temporal high-alpha power and left-frontotemporal high-alpha connectivity interact with each other, since most of the studies fail to report both of these indices (e.g., Hillman et al., 2000; Landers et al., 1994, Zhu et al., 2011). Additionally, despite some longitudinal efforts (e.g., Gallicchio et al., 2017; Landers et al., 1994), little is understood of how, based on training conditions, these measures change with practice. It is a shame that when these conditions were manipulated (Zhu et al., 2011; Zhu, Poolton, Wilson, Hu et al., 2011), no EEG data from the acquisition phase were reported. Crucially, although these studies interpreted the observed changes as representative of differences in conscious processing in terms of movement-relevant verbal processing and declarative knowledge, none of the experimental manipulations employed attempted to directly target these processes.

In light of these considerations, we cannot exclude the possibility that processes other than verbally mediated conscious processing of movements contributed to the left-hemisphere expert-novice or errorful-errorless differences observed in some studies (e.g., Haufler et al., 2000; Gallicchio et al., 2016; Zhu et al., 2011). As such, left-temporal high-alpha power and left-frontotemporal connectivity may be linked to additional factors other than movement-related verbal activity due to conscious processing. For example, the pressure related changes in left-temporal high-alpha power and connectivity (i.e., Hatfield et al., 2013; Zhu et al., 2011) might have been induced by a generalised emotional arousal (e.g., worrisome thoughts) induced by the increased performance pressure. Similarly, verbal processes unrelated to conscious motor processing (e.g., motivational self-talk) may also occur during learning and especially under pressure, adding a further potential confound to our interpretation of left-temporal activity.

The present experimental work

The studies described in the experimental chapters of this thesis aimed at improving our understanding of reinvestment theory, of the concept of conscious processing, and of its neurophysiological underpinnings. To do so, three mixed-model design experiments simultaneously compared explicit versus implicit training conditions (between-participant factor) during practice and under performance pressure (within-participant factor). These experiments employed a multi-measure approach which included fine-grained measures of performance (e.g., chunking, movement kinematics), self-reported conscious processing, as well as EEG high-alpha power and connectivity.

Chapter 2 was the first investigation to employ such a layered approach and by doing so offered the most comprehensive test of reinvestment theory to date. The main goals were to test whether reinvestment of explicit knowledge is linked to a de-chunking of movement sequences in their original sub-components; and to verify whether conscious processing, left-temporal high-alpha power and left-frontotemporal high-alpha connectivity changed as predicted by reinvestment theory. Results evidenced quicker sequence acquisition, reduced conscious processing, and increased cortical efficiency (increased left-temporal high-alpha power) in the explicit (trial-and-error) versus the implicit (errorless) group. Moreover, self-reported conscious processing increased under pressure for the explicit group only, but this had no adverse effect on performance. Given the absence of behavioural reinvestment effects (i.e., no de-chunking) under pressure and in light of a disconnect between self-reports and EEG measures of conscious processing, a series of methodological limitations were discussed and doubts on the specific sensitivity of these left-temporal neurophysiological measures were raised.

Chapter 3 attempted to address these methodological limitations in order to provide an even tighter multi-measure test of reinvestment theory. In order to create more chance for reinvestment effects (i.e. de-chunking), the motoric complexity of the sequence learning task was increased, the acquisition phase was extended, and followed by an overnight-sleep phase to ensure movement consolidation as well as to enable a retention phase to assess learning. In order to ensure a strict dichotomization into explicit versus implicit groups, only participants with *full*- versus *null*-movement relevant declarative knowledge (through an assessment at the end of the study) were retained for analysis. In order to strengthen the pressure manipulation, a mixture of social-evaluation, competition, and potential monetary rewards-losses was introduced. In order to improve our EEG measurements, a denser array of electrodes (i.e., 32 vs the 4 of the previous study) was used and event-related analyses of the motor preparation period were employed. In line with Chapter 2, results failed to show behavioural reinvestment under pressure and additionally strengthened the doubts on the specific sensitivity of left-temporal EEG measures to verbal-analytic conscious processing. Nevertheless, based on the additional effects observed at other electrode pairs, this chapter identified new cortical networks (mainly frontal and parietal regions) that might be related to conscious processing, and further discusses the possibility that verbal processing during movement could encompass other non-movement focused cognitions (e.g., motivational self-talk).

The final two experimental chapters pursue this latter suggestion by describing the first study[5] that assessed the effects of instructional versus motivational self-talk interventions on cortical activity. In doing so, these final experimental chapters provide a bridge between motor learning/stress and performance theory (i.e., reinvestment) and applied interventions (i.e., self-talk).

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[5] Please note that chapter 4 and 5 discuss data coming from the same investigation. Chapter 4 focused on a direct test-of the link between pre-movement verbalizations and left-temporal EEG measures. Chapter 5 focused on a larger scale investigation of additional psychophysiological correlates of self-talk type.

By controlling the amount of verbal-related activity that participants used while manipulating the type (i.e., movement-relevant instructions versus movement irrelevant motivations) they are the first experiments to test whether previously identified EEG indices of conscious processing uniquely reflect movement-related thoughts. I am aware that no self-talk literature has been covered in this General Introduction, however, detailed introduction to the self-talk literature is offered in Chapters 4 and 5.

The self-talk manipulation employed in Chapter 4 enabled a tight scrutiny of the specific sensitivity of left-temporal high-alpha power and left-frontotemporal high-alpha connectivity to the semantic content (i.e., movement-relevant versus -irrelevant) of verbal activity during motor preparation in low- and high-pressure conditions. Results failed to highlight any difference between groups at any stage for either of these two EEG measures. This implies that left-temporal activity might be sensitive to any general (and not movement-relevant) verbal processing happening during movements and offers important implications that can re-shape our interpretations of much of the previous EEG and conscious processing literature.

In Chapter 5 the same self-talk manipulation enabled a wider test of mechanisms discussed by the self-talk literature in order to explain the differential effects of instructional versus motivational self-talk on motor performance. Notably, results showed that high-alpha power and connectivity at frontal and parietal regions distinguished the two groups and supported the idea of an attentional mechanism to explain how instructional self-talk can encourage motor learning.

Finally, in Chapter 6 (General Discussion) all the findings are consolidated to form the basis of a new neuropsychological model of conscious processing. Importantly, this new model broadens the conceptualization of conscious processing beyond movement-related cognitions and extends neurophysiological bases beyond the narrow focus on the left-temporal regions that has pervaded much literature to date.

References

American Electroencephalographic Society (1994). American Electroencephalographic Society. Guideline thirteen: Guidelines for standard electrode position nomenclature. *Journal of Clinical Neurophysiology, 11,* 111-113.

Anderson, J. R. (1982). Acquisition of cognitive skill. *Psychological Review, 89*, 369-406. http://dx.doi.org/10.1037/0033-295X.89.4.369

Arnold, S. E., Hyman, B. T., Flory, J., Damasio, A. R., & Van Hoesen, G. W. (1991). The topographical and neuroanatomic distribution of neurofibrillary tangles and neuritic plaques in the cerebral cortex of patients with Alzheimer's disease. Cerebral Cortex, 1, 103-116.

Ashe, J., Lungu, O. V., Basford, A. T., & Lu, X. (2006). Cortical control of motor sequences. *Current Opinion in Neurobiology*, *16*, 213-221. https://doi.org/10.1016/j.conb.2006.03.008

Babiloni, C., Del Percio, C., Iacoboni, M., Infarinato, F., Lizio, R., Marzano, N., ... & Eusebi, F. (2008). Golf putt outcomes are predicted by sensorimotor cerebral EEG rhythms. *The Journal of Physiology, 586*, 131-139. https://doi.org/10.1113/jphysiol.2007.141630

Babiloni, C., Infarinato, F., Marzano, N., Iacoboni, M., Dassù, F., Soricelli, A., ... & Del Percio, C. (2011). Intra-hemispheric functional coupling of alpha rhythms is related to golfer's performance: A coherence EEG study. *International Journal of Psychophysiology, 82,* 260-268. https://doi.org/10.1016/j.ijpsycho.2011.09.008

Baumeister, R. F. (1984). Choking under pressure: Self-consciousness and paradoxical effects of incentives on skillful performance. *Journal of Personality and Social Psychology, 46,* 610–620. http://dx.doi.org/10.1037/0022-3514.46.3.610

Berger, H. (1929). Über das elektrenkephalogramm des menschen. *European Archives of Psychiatry and Clinical Neuroscience, 87,* 527-570.

Bischoff-Grethe, A., Goedert, K. M., Willingham, D. T., & Grafton, S. T. (2004). Neural substrates of response-based sequence learning using fMRI. *Journal of Cognitive Neuroscience, 16*, 127-138. https://doi.org/10.1162/089892904322755610

Chen, J., Hung, T.-M., Lin, J. H., Lo, L. C., Kao, J. F., Hung, C.-L., … Lai, Z.-S. (2005). *Effects of anxiety on EEG coherence during dart throw*. In T. Morris & P. Terry (Eds.), 11th World Congress of Sport Psychology (pp. 2–5). Sydney, AUS.

Cohen, M. X. (2014). *Analyzing neural time series data: Theory and practice.* Cambridge, MA: MIT Press.

Cooke, A. (2013). Readying the head and steadying the heart: a review of cortical and cardiac studies of preparation for action in sport. *International Review of Sport and Exercise Psychology, 6*. http://doi.org/10.1080/1750984X.2012.724438

Cooke, A., Gallicchio, G., Kavussanu, M., Willoughby, A., McIntyre, D., & Ring, C. (2015). Premovement high-alpha power is modulated by previous movement errors: Indirect evidence to endorse high-alpha power as a marker of resource allocation during motor programming. *Psychophysiology, 5*, 977-981.https://doi.org/10.1111/psyp.12414

Cooke, A., Kavussanu, M., Gallicchio, G., Willoughby, A., Mcintyre, D., & Ring, C. (2014). Preparation for action: Psychophysiological activity preceding a motor skill as a function of expertise, performance outcome, and psychological pressure. *Psychophysiology, 51*. http://doi.org/10.1111/psyp.12182

Curran, T. (1995). On the neural mechanisms of sequence learning. *Psyche, 2*.

DeCaro, M. S., Thomas, R. D., Albert, N. B., & Beilock, S. L. (2011). Choking under pressure: Multiple routes to skill failure. *Journal of Experimental Psychology: General, 140*, 390-406. http://dx.doi.org/10.1037/a0023466

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

Deeny, S. P., Hillman, C. H., Janelle, C. M., & Hatfield, B. D. (2003). Cortico-cortical communication and superior performance in skilled marksmen: An EEG coherence analysis. *Journal of Sport & Exercise Psychology*, *25*, 188–204. https://doi.org/10.1123/jsep.25.2.188

Del Percio, C., Iacoboni, M., Lizio, R., Marzano, N., Infarinato, F., Vecchio, F., ... & Babiloni, C. (2011). Functional coupling of parietal alpha rhythms is enhanced in athletes before visuomotor performance: a coherence electroencephalographic study. *Neuroscience*, *175*, 198-211. https://doi.org/10.1016/j.neuroscience.2010.11.031

D'Esposito, M., Aguirre, G. K., Zarahn, E., Ballard, D., Shin, R. K., & Lease, J. (1998). Functional MRI studies of spatial and nonspatial working memory. *Cognitive Brain Research*, *7*, 1-13. https://doi.org/10.1016/S0926-6410(98)00004-4

Fitts, P. M., & Posner, M. I. (1967). *Human Performance*. Belmont, CA: Brooks/Cole.

Galin, D., & Ornstein, R. (1972). Lateral specialization of cognitive mode: *An EEG study. Psychophysiology*, *9*, 412-418. https://doi.org/10.1111/j.1469-8986.1972.tb01788.x

Gallicchio, G., & Ring, C. (2018). Don’t look, don’t think, just do it! Toward an understanding of alpha gating in a discrete aiming task. *Psychophysiology*, e13298. https://doi.org/10.1111/psyp.13298

Gallicchio, G., Cooke, A., & Ring, C. (2016). Lower left temporal-frontal connectivity characterizes expert and accurate performance: High-alpha t7-fz connectivity as a marker of conscious processing during movement. *Sport, Exercise, and Performance Psychology*, *5*, 14–24. http://doi.org/10.1037/spy0000055

Gallicchio, G., Cooke, A., & Ring, C. (2016). Lower left temporal-frontal connectivity characterizes expert and accurate performance: High-alpha t7-fz connectivity as a marker of

conscious processing during movement. *Sport, Exercise, and Performance Psychology, 5,* 14–24. http://doi.org/10.1037/spy0000055

Gallicchio, G., Cooke, A., & Ring, C. (2017). Practice makes efficient: cortical alpha oscillations are associated with improved golf putting performance. *Sport, Exercise, and Performance Psychology, 6,* 89–102. http://doi.org/10.1037/spy0000077

Gallicchio, G., Cooke, A., & Ring, C. (2017). Practice makes efficient: cortical alpha oscillations are associated with improved golf putting performance. *Sport, Exercise, and Performance Psychology, 6,* 89–102. http://doi.org/10.1037/spy0000077

Gallicchio, G., Finkenzeller, T., Sattlecker, G., Lindinger, S., & Hoedlmoser, K. (2016). Shooting under cardiovascular load: Electroencephalographic activity in preparation for biathlon shooting. *International Journal of Psychophysiology, 109*, 92-99. https://doi.org/10.1016/j.ijpsycho.2016.09.004

Haaland, K. Y., Elsinger, C. L., Mayer, A. R., Durgerian, S., & Rao, S. M. (2004). Motor sequence complexity and performing hand produce differential patterns of hemispheric lateralization. *Journal of Cognitive Neuroscience, 16*, 621-636. https://doi.org/10.1162/089892904323057344

Hardy, L., Mullen, R., & Jones, G. (1996). Knowledge and conscious control of motor actions under stress. *British Journal of Psychology, 87,* 621-636. https://doi.org/10.1111/j.2044-8295.1996.tb02612.x

Hatfield, B. D., Costanzo, M. E., Goodman, R. N., Lo, L.-C., Oh, H., Rietschel, J. C., … Haufler, A. (2013). The influence of social evaluation on cerebral cortical activity and motor performance: a study of “Real-Life” competition. *International Journal of Psychophysiology, 90*, 240–9. http://doi.org/10.1016/j.ijpsycho.2013.08.002

Haufler, A. J., Spalding, T. W., Santa Maria, D. L., & Hatfield, B. D. (2000). Neuro-cognitive activity during a self-paced visuospatial task: comparative EEG profiles in marksmen and novice shooters. *Biological Psychology, 53*, 131-160. https://doi.org/10.1016/S0301-0511(00)00047-8

Hellige, J. B. (1990). Hemispheric asymmetry. *Annual Review of Psychology, 41*, 55-80. https://doi.org/10.1146/annurev.ps.41.020190.000415

Hikosaka, O., Nakahara, H., Rand, M. K., Sakai, K., Lu, X., Nakamura, K., Miyachi, S., & Doya, K. (1999). Parallel neural networks for learning sequential procedures. *Trends in Neurosciences, 22*, 464–471. https://doi.org/10.1016/S0166-2236(99)01439-3

Hillman, C. H., Apparies, R. J., Janelle, C. M., & Hatfield, B. D. (2000). An electrocortical comparison of executed and rejected shots in skilled marksmen. *Biological Psychology, 52*, 71–83. http://doi.org/10.1016/S0301-0511(99)00021-6

Jackson, G. M., Jackson, S. R., Harrison, J., Henderson, L., & Kennard, C. (1995). Serial reaction time learning and Parkinson's disease: Evidence for a procedural learning deficit. Neuropsychologia, 33, 577-593.

Janelle, C. M., Hillman, C. H., Apparies, R. J., Murray, N. P., Meili, L., Fallon, E. A., & Hatfield, B. D. (2000). Expertise differences in cortical activation and gaze behavior during rifle shooting. *Journal of Sport and Exercise Psychology, 22*, 167-182. https://doi.org/10.1123/jsep.22.2.167

Jasper, H. H. (1958). The ten-twenty electrode system of the International Federation. *Electroencephalography and Clinical Neurophysiology*, *17*, 37–46.

Jensen, O., & Mazaheri, A. (2010). Shaping functional architecture by oscillatory alpha activity: gating by inhibition. *Frontiers in Human Neuroscience*, *4*, 186. https://doi.org/10.3389/fnhum.2010.00186

Kerick, S. E., Douglas, L. W., & Hatfield, B. D. . (2004). Cerebral cortical adaptations associated with visuomotor practice. *Medicine & Science in Sports & Exercise*, *36*, 118–129.

http://doi.org/10.1249/01.MSS.0000106176.31784.D4

Kingston, K. M., & Hardy, L. (1997). Effects of different types of goals on processes that support performance. *The Sport Psychologist, 11*, 277-293. https://doi.org/10.1123/tsp.11.3.277

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

Klimesch, W., Sauseng, P., & Hanslmayr, S. (2007). EEG alpha oscillations: the inhibition–timing hypothesis. *Brain Research Reviews, 53,* 63-88. https://doi.org/10.1016/j.brainresrev.2006.06.003

Landers, D. M. Han, M., Salazar, W., & Petruzzello, S. J. (1994). Effects of learning on encephalographic and electrocardiographic patterns in novice archers. *International Journal of Sport Psychology, 25,* 313-330.

Langer, E. J., & Imber, L. G. (1979). When practice makes imperfect: Debilitating effects of overlearning. *Journal of Personality and Social Psychology, 37*, 2014-2024. http://dx.doi.org/10.1037/0022-3514.37.11.2014

Liao, C. M., & Masters, R. S. (2001). Analogy learning: A means to implicit motor learning. *Journal of Sports Sciences, 19*, 307-319. https://doi.org/10.1080/02640410152006081

Loze, G. M., Collins, D., & Holmes, P. S. (2001). Pre-shot EEG alpha-power reactivity during expert air-pistol shooting: a comparison of best and worst shots. *Journal of Sports Sciences, 19*, 727-733. https://doi.org/10.1080/02640410152475856

Lu, X., & Ashe, J. (2005). Anticipatory activity in primary motor cortex codes memorized movement sequences. *Neuron, 45,* 967-973. https://doi.org/10.1016/j.neuron.2005.01.036

Luck, S. J. (2014). *An introduction to the event-related potential technique*. MIT press.

MacMahon, K., & Masters, R. (1999). From novice to expert and back again: Chunking and dechunking in motor skills. *Journal of Sports Sciences, 17,* 527–609.

Masters, R. S. (1992). Knowledge, knerves and know-how: The role of explicit versus implicit knowledge in the breakdown of a complex motor skill under pressure. *British Journal of Psychology, 83*, 343-358. https://doi.org/10.1111/j.2044-8295.1992.tb02446.x

Masters, R. S. W., & Maxwell, J. (2008). The theory of reinvestment. *International Review of Sport and Exercise Psychology*, *1,* 160–183. http://doi.org/10.1080/17509840802287218

Masters, R. S. W., Eves, F. F., & Maxwell, J. P. (2005). Development of a movement specific Reinvestment Scale. In & P. T. Morris, P. Terry, S. Gordon, S. Hanrahan, L. Ievleva, G. Kolt & Tremayne (Eds.), *Proceedings of the ISSP 11th World Congress of Sport Psychology*. Sidney, Australia.

Masters, R. S. W., Polman, R. C., & Hammond, N. V. (1993). 'Reinvestment': A dimension of personality implicated in skill breakdown under pressure. *Personality and individual differences, 14*, 655-666. https://doi.org/10.1016/0191-8869(93)90113-H

Masters, R. S., Maxwell, J. P., & Eves, F. F. (2009). Marginally perceptible outcome feedback, motor learning and implicit processes. *Consciousness and Cognition, 18*, 639-645. https://doi.org/10.1016/j.concog.2009.03.004

Maxwell, J. P., Masters, R. S. W., & Eves, F. F. (2000). From novice to no know-how: A longitudinal study of implicit motor learning. *Journal of Sports Sciences, 18*, 111-120. https://doi.org/10.1080/026404100365180

Maxwell, J. P., Masters, R. S. W., & Eves, F. F. (2003). The role of working memory in motor learning and performance. *Consciousness and Cognition*, 12, 376-402. https://doi.org/10.1016/S1053-8100(03)00005-9

Maxwell, J. P., Masters, R. S. W., Kerr, E., & Weedon, E. (2001). The implicit benefit of learning without errors. *The Quarterly Journal of Experimental Psychology Section A, 54*, 1049-1068. https://doi.org/10.1080/713756014

Nissen, M. J., & Bullemer, P. (1987). Attentional requirements of learning: Evidence from performance measures. *Cognitive Psychology, 19*, 1-32. https://doi.org/10.1016/0010-0285(87)90002-8

Oostenveld, R., & Praamstra, P. (2001). The five percent electrode system for high-resolution EEG and ERP measurements. *Clinical Neurophysiology*, *112*, 713-719. https://doi.org/10.1016/S1388-2457(00)00527-7

Orrell, A. J., Eves, F. F., & Masters, R. S. (2006). Motor learning of a dynamic balancing task after stroke: implicit implications for stroke rehabilitation. *Physical Therapy, 86*, 369-380. https://doi.org/10.1093/ptj/86.3.369

Parkin, A. J., & Leng, N. R. C. (1993). Neuropsychology of the amnesic syndrome. Hillsdale, NJ: Lawrence Erlbaum Associates.

Pfurtscheller, G., & Aranibar, A. (1979). Evaluation of event-related desynchronization (ERD) preceding and following voluntary self-paced movement. *Electroencephalography and Clinical Neurophysiology, 46*, 138-146. https://doi.org/10.1016/0013-4694(79)90063-4

Salazar, W., Landers, D. M., Petruzzello, S. J., Hanm M., Crews, D. J., & Kubitz, K. A. (1990) Hemispheric Asymmetry, Cardiac Response, and Performance in Elite Archers, *Research Quarterly for Exercise and Sport, 61*, 351-359. https://doi.org/10.1080/02701367.1990.10607499

Sauseng, P., Klimesch, W., Schabus, M., & Doppelmayr, M. (2005). Fronto-parietal EEG coherence in theta and upper alpha reflect central executive functions of working memory. *International Journal of Psychophysiology, 57*, 97-103. https://doi.org/10.1016/j.ijpsycho.2005.03.018

Springer, S. P., & Deutsch, G. (1998). Left brain, right brain: Perspective from cognitive neuroscience (5th ed.). New York, NY: Freeman.

Squire, L. R., Amaral, D. G., & Press, G. A. (1990). Magnetic resonance imaging of the hippocampal formation and mammilary nuclei distinguish medial temporal lobe and diencephalic amnesia. The Journal of Neuroscience, 10, 3106-3117.

Willingham, D. B. (1998). A neuropsychological theory of motor skill learning. *Psychological Review*, *105*, 558. http://dx.doi.org/10.1037/0033-295X.105.3.558

Willingham, D. B., & Koroshetz, W. J. (1993). Evidence for dissociable motor skills in Huntington's disease patients. Psychobiology, 21, 173-182.

Zhu, F. F., Poolton, J. M., Wilson, M. R., Hu, Y., Maxwell, J. P., & Masters, R. S. (2011). Implicit motor learning promotes neural efficiency during laparoscopy. *Surgical Endoscopy*, *25*, 2925-2950. https://doi.org/10.1007/s00464-011-1647-8

Zhu, F. F., Poolton, J. M., Wilson, M. R., Maxwell, J. P., & Masters, R. S. W. (2011). Neural co-activation as a yardstick of implicit motor learning and the propensity for conscious control of movement. *Biological Psychology*, *87*, 66–73. http://doi.org/10.1016/j.biopsycho.2011.02.004

CHAPTER TWO

Bellomo, E., Cooke, A., Hardy, J. (2018). Chunking, conscious processing, and EEG during sequence acquisition and performance pressure: A comprehensive test of reinvestment theory. *Journal of Sport and Exercise Psychology*. https://doi.org/10.1123/jsep.2017-0308

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) × 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;

Introduction

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

However, even after automatization, skill execution is not flawless; from time to time, so-called *choking* (i.e., movement failures under pressure) can occur even in the most skilled professionals (Baumeister, 1984). A motor learning-based explanation for choking under pressure is offered by reinvestment theory (Masters & Maxwell, 2008). It contends that contingencies such as increased psychological pressure, social evaluation, and errors during execution may prompt, in some individuals, explicit action monitoring via reinvestment of the verbal-analytic rules that supported skill acquisition during the early stages of learning. This results in the de-automatization of well-learned skills, characterized by the performer reverting back to a more conscious, less efficient form of control, and the de-chunking of movement back to elementary components (MacMahon & Masters, 1999). In other words, some of the benefits that occur with practice (e.g., increased speed and reduced cognitive cost) can be occasionally undone under pressure, causing impaired motor performance.

Chunking and De-chunking

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

Importantly, chunking is not restricted to explicit learning paradigms. Implicit learning, where skills are acquired with little awareness and limited accumulation of verbal-analytic rules, can also support chunking (Song & Cohen, 2014; Willingham, 1998). For example, MacMahon and Masters (1999) had participants acquire a sequence of button presses during a serial reaction time task, which is deemed to induce a relatively implicit mode of learning (Robertson, 2007). Like Sakai and colleagues (2003), MacMahon and Masters found that with practice, the time gaps between consecutive button presses decreased and execution became smoother, implying the progressive organization of the sequence into fewer and larger motor chunks. Interestingly, the progressive chunking observed during acquisition was followed by de-chunking (i.e., the re-emergence of elongated time gaps) in a transfer phase where participants performed the same serial reaction time sequence under elevated levels of social-evaluative pressure. This finding is supportive of reinvestment theory's idea that pressure-induced de-chunking is a mechanism to explain choking under pressure. However, it is surprising that such de-chunking was observed following acquisition conditions (i.e., serial reaction time task) that are thought to promote relatively implicit learning. Indeed, a core prediction of reinvestment theory is that learning in an implicit fashion should reduce the possibility of de-chunking under pressure, since implicit learners, compared to their explicit counterparts, have few conscious rules to reinvest. Put simply, reinvestment and therefore de-chunking under pressure should be less likely after implicit than explicit learning. To date, there are no experiments that directly examine this specific de-chunking prediction. Addressing this void in the literature is one aim of the present experiment.

Cortical Indices of Conscious Motor Processing

In addition to behavioral manifestations such as chunking and, possibly, de-chunking, the variations in verbal-analytic conscious processing that characterize motor learning and reinvestment under pressure are said to be accompanied by changes in the EEG high-alpha (around 10-12 Hz) frequency band. In brief, increased high-alpha power is viewed as an index of active inhibition of non-essential neural processes (Klimesch, 2012). Accordingly, increased high-alpha power recorded over the left temporal regions (T7), which are traditionally associated with verbal-analytic and language processes (e.g., Springer & Deutsch, 1998), has been argued to reflect lower levels of verbal-analytic activity (e.g., less conscious processing) during preparation for complex motor skills (e.g., Hillman, Apparies, Janelle, & Hatfield, 2000). Researchers have also shown interest in measures of connectivity between different electrode sites (e.g., magnitude squared coherence or inter-site phase clustering). Connectivity reflects the degree of similarity of activity at different electrode sites, and has been interpreted to reflect the amount of functional communication between different brain regions, where more connectivity reflects greater communication (Von Stein & Sarnthein, 2000). Consequently, researchers have interpreted reduced high-alpha power connectivity between left-temporal sites, and frontal midline sites overlaying areas deputed to motor sequence planning (Ashe, Lungu, Basford, & Lu, 2006) as less verbal-analytic involvement (e.g., less conscious processing) during motor planning (e.g., Deeny, Haufler, Saffer, & Hatfield, 2009).

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

These cortical measures could also be sensitive to reinvestment under pressure. For example, Zhu and colleagues (2011) found that T7-Fz high-alpha connectivity increased during transfer to a high-pressure condition in their explicit learning group, but not in the implicit group. This provides some tentative support for reinvestment theory's prediction that reinvestment under pressure is more likely to happen in explicit learners than implicit learners. However, these differences in EEG connectivity were not accompanied by differences in putting performance, thereby questioning the presumed link between connectivity, conscious processing and performance. In a similar vein, Hatfield and colleagues (2013) found that pistol shooters displayed decreased T7 high-alpha power and increased T7-Fz connectivity (in the 8-13 Hz alpha broadband) upon transfer from low-pressure to high-pressure conditions, but again performance outcome was maintained. Of note, kinematic measures obtained in this study provided some evidence that these pressure-induced EEG changes were accompanied by reductions in movement efficiency (i.e., reduced fluency of aiming trajectory). This could imply increased segmentation of the action as if the movement components had been de-chunked. However, since the elementary movements constituting complex sport skills such as shooting are difficult to isolate, this conclusion is somewhat speculative. A strength of sequence button pressing tasks such as those adopted by MacMahon and Masters (1999) and Sakai and colleagues (2003) is that they permit the investigation of the same basic mechanisms that underlie the acquisition of complex sport skills (Abrahamse et al., 2013; Shea & Wrights, 2012), while allowing precise and objective measures of chunking and de-chunking to be obtained. Button sequence practice tasks could thus be used to provide a more precise examination of pressure-induced reinvestment effects (e.g., de-chunking).

The Present Experiment

To address the limitations of previous research and to offer a comprehensive examination of reinvestment theory, the present experiment was designed to be the first to examine chunking and de-chunking, together with cortical measures of conscious processing, during acquisition and performance under pressure, following explicit and implicit skill acquisition. Chunking was expected for both explicit and implicit modes of practice. However, based on reinvestment theory, we expected initially higher conscious processing (self-report, T7 high-alpha power and T7-Fz high-alpha connectivity) followed by a more pronounced reduction during explicit acquisition, compared to implicit acquisition. This is due to the greater hypothesis-testing and verbal-analytic processing associated with explicit compared to implicit practice (e.g., Zhu et al., 2011). Moreover, we expected choking under pressure to be more likely in participants who underwent explicit rather than implicit training, since this latter mode of practice should theoretically be protective against reinvestment of verbal-analytic conscious processing under pressure (Masters & Maxwell, 2008).

Methods

Participants

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

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

Task

Two variations of a sequence learning task were employed to examine explicit and implicit visuomotor sequence acquisition. The two tasks were employed to manipulate the degree of conscious processing needed to perform the sequence by inducing relatively errorful (*2×10 task*) and errorless (*1×20 task*) practice conditions (e.g., Zhu et al., 2011). Participants assigned to the explicit group completed the *2×10* sequential button-press task (Sakai et al., 2003). This requires participants to acquire, with a trial-and-error strategy, the correct order in which to press a sequence of 20 buttons on a bespoke 4×4 keypad matrix (see Figure 2B). Participants were informed of the existence of a sequence and asked to execute the presses as quickly and accurately as possible using the index finger of the right hand. The task started when participants pressed the “start-button”, which lit-up in blue at the bottom left of the matrix. Subsequently, a pair of buttons (“a set”) lit-up in green. Participants were required to press one button at a time in an attempt to learn the correct order of pre-programmed button presses. If they chose the correct button to press first, the associated green light was turned off and participants were able to press the remaining button. Once the pair of buttons were pressed in the correct order, there was a 100 ms interval before a new pair of buttons (the next set) lit-up. The above cycle then repeated. The complete sequence required participants to correctly press ten pairs of buttons without error. Whenever an error occurred the whole 4×4 matrix lit-up in red, and participants had to start a new trial from the beginning (Figure 2C). The sequence was the same in all acquisition blocks across all participants (Figure 2A). This task was chosen for members of the explicit group because the extensive hypothesis-testing that characterizes the task is known to prompt explicit awareness of the movement/sequence rules (Sakai et al., 2003).

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

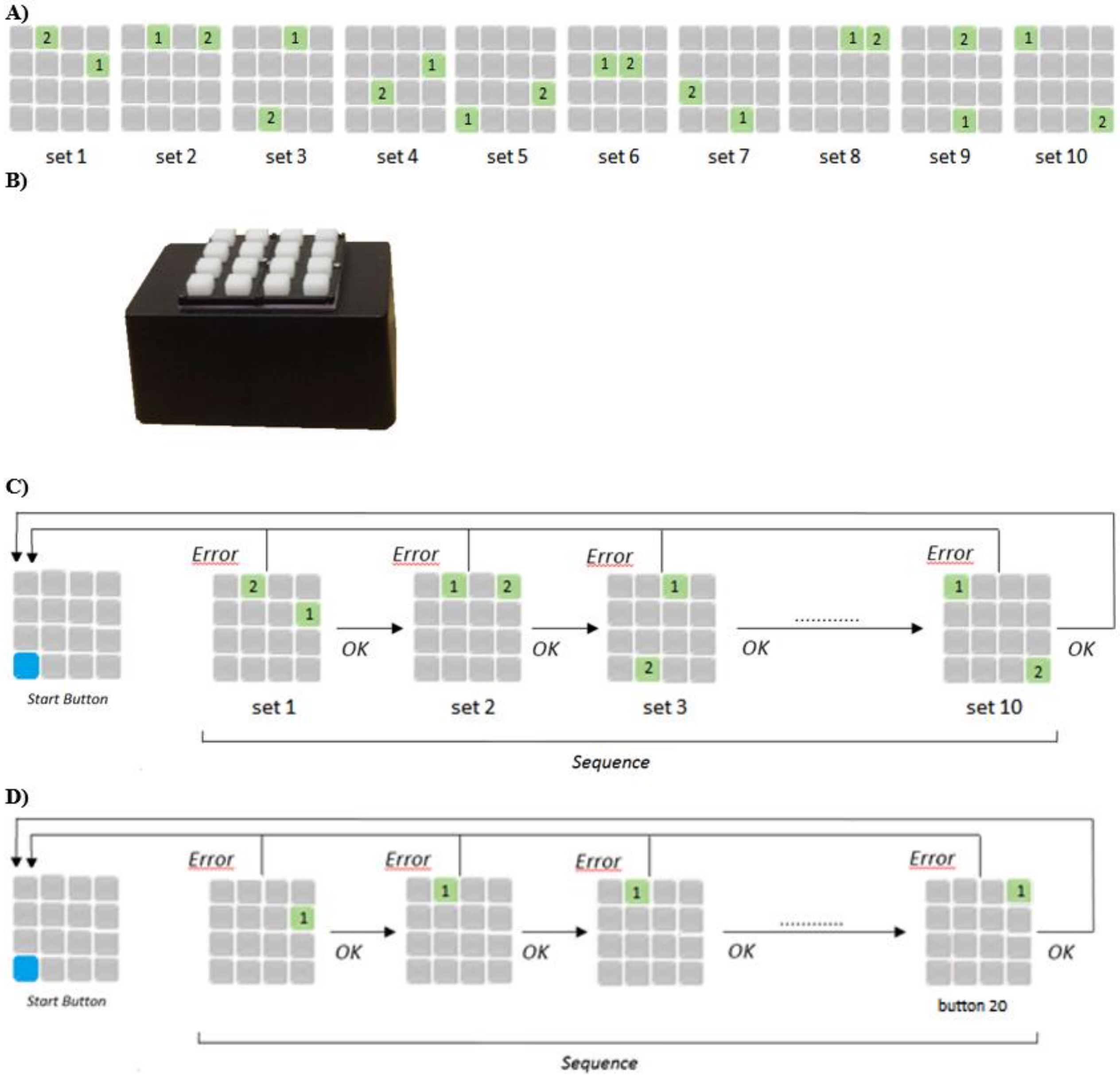

Figure 2. A) Pre-programmed sequence of buttons performed by participants. B) Button-press device used in this study. C) Schematic representation of the sequential button-press task: 2×10 task. D) Schematic representation of the 1x20 task.

Design

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

Measures

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

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

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

Conscious processing

To monitor conscious processing during both acquisition and transfer, we used the conscious motor processing subscale from a the Movement Specific Reinvestment Scale (Gallicchio, Cooke, & Ring, 2016; Masters et al., 2005). Participants were asked to indicate how they felt while performing the previous block in relation to five items (e.g., "I was aware of the way my body was working") that were rated on a 6-point Likert scale (1 = strongly disagree, 6 = strongly agree). The mean Cronbach's α coefficient was .77.

Task Performance

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

The maximum number of chunks (Max_{chunks}) was 10 for members of the explicit group, and 20 for members of the implicit group. Such scores would represent disproportionately long time-gaps between every choice (explicit group) and every response (implicit group). To permit between-group comparisons we express the mean number of chunks ($Mean_{chunks}$) as a percentage using the following formula:

$$chunked\% = \ (Mean_{chunks} * 100)/Max_{chunks}$$

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

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

Cortical activity

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

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

$$e^{i2\pi tf}e^{-t^2/2\sigma^2}$$

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

Power. From the complex signals, power at each frequency bin (f) was defined as the squared magnitude of the result of the convolution Z {real $[z(t)]^2$ + imag $[z(t)]^2$} and averaged across high-alpha (10-12 Hz) frequency band[6]. In order to ensure normal distribution all power estimates were subjected to a logarithmic (Log_{10}) transformation (Delorme & Makeig, 2004) prior to analysis.

Connectivity. Functional connectivity between sites was computed in terms of inter-site phase clustering (ISPC). While most previous studies estimated functional connectivity by calculating magnitude squared coherence (e.g., Hatfield et al., 2013; Zhu et al., 2011), we report ISPC because magnitude squared coherence (a measure derived from power) could be confounded by the expected between-block differences in high-alpha power (Cohen, 2014). Moreover,

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[6] Although the manuscript focussed on the high-alpha frequency band, the interested reader may refer to the Supplementary Material for additional analyses on the theta (4-8 Hz), low-alpha (8-10 Hz), low-beta (12-20Hz), and high-beta (20-28 Hz) frequency bands.

Gallicchio and colleagues (2016) reported that high-alpha frontotemporal connectivity was more sensitive to experience-related differences in conscious processing when computed by ISPC compared to magnitude squared. ISPC was calculated as follows:

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

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

Procedure

Participants individually attended a 2-hour testing session. On arrival, they were welcomed, briefed and invited to ask any questions, before providing written consent to take part. Next, the experimenter attached the EEG electrodes. Participants then underwent a familiarization block, which involved pressing a simple sequence of buttons that illuminated one at a time from top left to bottom right. This ensured familiarity with the force required for each button press to register and allowed participants to become accustomed to pressing the buttons while instrumented for EEG recordings. This was followed by the acquisition phase, which consisted of four blocks of practice

(A1, A2, A3, A4) on the assigned task (i.e., *2×10 task* for members of the explicit group, *1×20 task* for members of the implicit group). Each block ended when participants successfully completed 20 correct repetitions of the sequence. Adjacent blocks were separated by five-minute breaks. Finally, participants underwent the transfer phase (T), in which they performed a final block (20 sequence repetitions) on their assigned task, while evaluative pressure was manipulated (see pressure manipulation section below). Cortical activity was recorded continuously throughout each block. Our self-report measure of conscious motor processing was administered at the end of each block, while our manipulation check questionnaires were administered immediately before (anxiety measure) and after (movement self-consciousness measure) blocks A4 (end of acquisition) and T (transfer). At the end of the experiment, participants were thanked and asked not to disclose specific detail about the pressure manipulation to others.

Pressure Manipulation. Social evaluation was manipulated based on previous research deeming evaluative pressure as more likely to induce conscious processing and reinvestment than outcome-based (e.g., rewards for success) pressures (DeCaro, Thomas, Albert, & Beilock, 2011). In order to maximize evaluation apprehension, prior to the beginning of the transfer phase, the experimenter played a scripted video where a senior academic informed participants that their performance during the transfer phase would be filmed from three different locations in order for students and motor control lecturers at the university to view how people perform this skill. In addition, participants were told that the footage might also be used in a YouTube film on visuomotor skill acquisition, which would be available worldwide for researchers and psychology classes. The three cameras were placed approximately 1 m above, in front, and adjacent to the participant, and the footage was presented in real time, on a screen visible to the participant. Moreover, the experimenter, who sat out of sight during the acquisition phase, repositioned to now stand in very close proximity to the participant, and very obviously watch their performance.

Statistical Analyses

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

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

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

Results

Manipulation Check

The 2×2 mixed-model ANOVAs revealed main effects of Block for cognitive anxiety, $F(1, 53) = 17.07$, $p < .001$, $\eta_p^2 = .24$, and movement self-consciousness, $F(1, 53) = 21.62$, $p < .001$, $\eta_p^2 = .29$, but no effect of Group, nor Block × Group interaction. These results confirm that the pressure manipulation was successful in inducing a relative increase in cognitive anxiety and movement self-

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[7] 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 × 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).

consciousness from the final block of acquisition (A4; $M_{\text{anxiety}} = 2.72$; $M_{\text{self-consciousness}} = 2.27$) to the transfer phase (T; $M_{\text{anxiety}} = 3.71$; $M_{\text{self-consciousness}} = 2.73$) in both the explicit and the implicit group.

Conscious Processing

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

Task performance

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

Movement Errors. The 2×5 mixed-model ANOVA employed to examine the number of errors committed revealed a significant effect for Group, $F(1, 53) = 37.38$, $p < .001$, $\eta_p^2 = .41$, Block, $F(4, 50) = 10.18$, $p < .001$, $\eta_p^2 = .45$, and a significant Group × Block interaction, $F(4, 50) = 11.48$, $p < .001$, $\eta_p^2 = .48$. As shown in Table 1, the error-rate remained stable and very low throughout acquisition and transfer for members of the implicit group, while an initially high number of errors at the start of acquisition decreased sharply (quadratic trend, $p < .001$, $\eta_p^2 = .62$) for members of the explicit group.

Table 1. *Mean (SD) of the Measures in each Block (A1, A2, A3, A4, T)*

	Block						
	A1	A2	A3	A4	T		
Measure (range)	M(SD)	M(SD)	M(SD)	M(SD)	M(SD)	*Main effect of Block*	η_p^2
			Conscious Processing				
MSRS-S Motor Proc. (1-6)							
Explicit	4.30(.77)	3.56 (.97)**a**	3.17 (1.12)**a**	3.12(1.08)	3.32(1.16)	F(4,23) 7.95**	.58
Implicit	3.72(.93)	3.89(1.07)	3.91(1.12)	3.96(1.26)	3.93(1.23)	F(4,24) .45	.07
			Performance				
Chunked (%)							
Explicit	7.04(8.23)	37.41 (19.33)**a**	59.63 (21.75)**a**	73.70 (14.45)**a**	80.37(13.15)**a**	F(4,23) = 118.13***	.95
Implicit	10.71(13.03)	25.71(13.99)**a**	38.39(12.33)**a**	57.14(15.18)**a**	66.96(17.76)**a**	F(4,24) = 42.02***	.87
Errors							
Explicit	41.30(28.31)	6.81 (4.03)**a**	4.85(2.86)**a**	4.81(4.66)	4.26(4.74)	F(4,23) = 9.68***	.63
Implicit	3.25(4.54)	4.03(4.91)	4.78(3.83)	5.25(4.59)	4.25(3.92)	F(4,24) = 1.06	.15

Note: Letter "a" in bold indicates a significant difference from the previous block. *p<.05; **p<.01; ***p<.001

Cortical activity

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

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

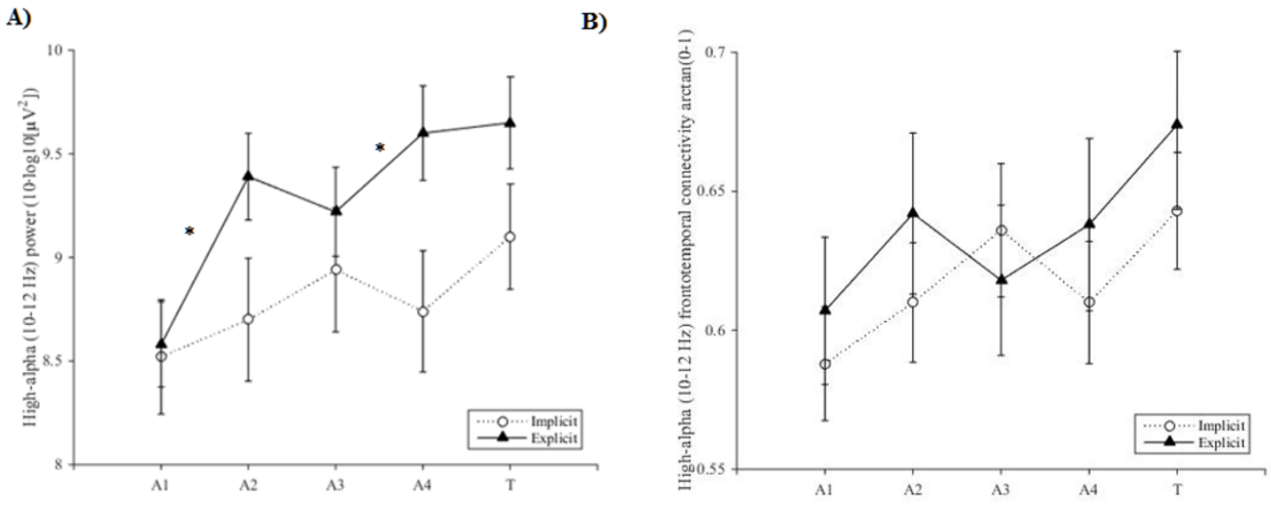

Figure 1. A) High-alpha (10-12 Hz) power (10·log10[µV^2]) at T7 (Y-axis) across Blocks (X-axis). Error bars depict standard error of the mean. Power increased more in the explicit than in the implicit group across acquisition and transfer. B) High-alpha (10-12 Hz) T7-Fz connectivity (Y-axis) across different blocks (X-axis). Error bars depict standard error of the mean. In both groups, we observed a linear increase in T7-Fz connectivity.

Discussion

Utilizing a novel multi-method approach, the present study tested whether conscious processing during motor learning and performance under pressure changed as predicted by classic models of skill acquisition (Fitts & Posner, 1967; Willingham, 1998) and reinvestment theory (Masters & Maxwell, 2008). To do so we designed the first experiment to simultaneously examine behavioral measures of chunking, alongside proposed cortical indices of conscious processing, during acquisition and pressure. Our experiment, to our knowledge, contains the largest sample and the highest statistical power of any published EEG study of reinvestment theory. Our results are discussed in relation to our hypotheses in the following sections.

Chunking and conscious processing during acquisition

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

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

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

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

An alternative interpretation of this cortical measure can be offered when one considers the following two features. First, it is important to recognize that connectivity simply measures the similarity between signals recorded at two different sites, with any relations drawn to neural communication pathways being inferred rather than directly assessed (Cohen, 2014). Second, it is important to remember that activity in the high-alpha frequency band is said to have an inverse relationship with cortical activity (Klimesch, 2012). Based on these two points, one would expect that the functional interpretation of any changes in high-alpha connectivity over time should consider whether absolute high-alpha power increased or decreased during the same time period. In previous studies simultaneously measuring power and connectivity, high-alpha power decreased (Gallicchio et al., 2017; Hatfield et al., 2013; Kerick et al., 2004), and, hence, the simultaneous increase in high-alpha connectivity that those studies reported could indeed represent more similar *co-activation* of the two sites. However, if high-alpha power increased, as in the present study, increased high-alpha connectivity could represent more similar *co-inhibition* of two sites.

Consequently, our finding of increased left-frontotemporal connectivity with practice could reflect a progressively stronger inhibitory communication between left-temporal and frontal electrode sites that characterized both types of training. It would be interesting for future studies to scrutinize this interpretation by comparing connectivity between tasks or regions known to be associated with practice-induced increases versus decreases in power, or to examine connectivity when power has been experimentally manipulated (e.g., via neurofeedback training).

Conscious processing and performance during pressure

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

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

Limitations and future directions

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

Second, although in our study participants reached a high-degree of proficiency, there was still scope for further improvement since the movements were not fully chunked at the end of acquisition. Thus, we cannot rule out the possibility that had we trained participants for longer, the sequence would have likely become even more automatized, and a reinvestment related de-chunking under pressure more probable. Future endeavours aiming to further examine reinvestment theory’s prediction that de-chunking causes choking under pressure among explicit learners would do well to ensure that participants are trained to an extremely high-level of proficiency before the undertaking the pressure test. This is because, according to reinvestment theory de-chunking occurs in movements that are highly automated (Masters & Maxwell, 2008). In contrast, contingencies that increase conscious processing (e.g., pressure) among performers at cognitive and associative stages of acquisition may enhance performance (e.g., Beilock, Carr, MacMahon, & Starkes, 2002; Gray, 2004; Malhotra et al., 2015). In addition to extending the acquisition phase, future studies could also introduce a period of sleep consolidation, which has been argued to further automatize skills (e.g., Mazza et al., 2016; Walker & Stickgold, 2006), prior to delayed retention and pressure tests.

Delayed retention tests in particular would allow assessment of the extent to which participants truly learned the sequence, rather than their proficiency at acquiring and memorising it in a single day, as we tested here.

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

Fourth, it is important to recognize that EEG is limited by poor spatial resolution. Thus, despite being frequently advocated in the literature, the assumption that electrical activity recorded by T7 and Fz electrodes reflects verbal-analytic and motor planning processes, respectively, is overly simplistic (Cooke, 2013). Although resolving the *inverse problem* with certainty is mathematically impossible, applying spatial filters such as surface Laplacian, independent component analyses (ICA), or generalized Eigen decomposition (GED) could all improve the spatial resolution of EEG and allow more confident assertions about the underlying generators of the signals recorded on the scalp to be made (Cohen, 2014; Delorme & Makeig, 2004; Perrin, Pernier, Bertrand, & Echallier, 1989). However, all these solutions would require a higher number of electrodes than were employed here. It is important for future research to adopt denser electrode arrays and apply spatial analyses such as these to gain much greater insight into the underlying cortical dynamics of explicit versus implicit learning and performance under pressure.

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

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

In conclusion, by simultaneously examining chunking and a combination of self-report and psychophysiological measures of conscious processing during both explicit and implicit acquisition, and transfer (pressure), this large-scale EEG experiment is the first to specifically investigate reinvestment theory’s pivotal dechunking hypothesis and provides the most comprehensive test of the theory to date. Our results confirmed that chunking is a general mechanism underpinning both explicit and implicit motor sequence acquisition (e.g., Hikosaka et al., 1999; Song & Cohen, 2014; Willingham, 1998). They also provide new neurophysiological evidence that explicit training can support quicker chunking than implicit training by promoting the active inhibition of the left-hemisphere, and a more pronounced increase in cortical efficiency. While the specific de-chunking hypothesis of reinvestment theory warrants further scrutiny, our results add support to the literature endorsing explicit learning as a means of accelerating movement acquisition, and provide a new neurophysiological explanation why.

References

Abrahamse, E. L., Ruitenberg, M. F. L., de Kleine, E., & Verwery, W. B., (2013). Control of automated behavior: Insights from the discrete sequence production task. *Frontiers In Human Neuroscience, 7,* 1-16. http://doi.org/10.3389/fnhum.2013.00082

Ashe, J., Lungu, O. V., Basford, A. T., & Lu, X. (2006). Cortical control of motor sequences. *Current Opinion in Neurobiology*, *16*, 213–221. http://doi.org/10.1016/j.conb.2006.03.008

Baddeley, A. (2012). Working memory: Theories, models, and controversies. *Annual Review of Psychology, 63*, 1–29. http://doi.org/10.1146/annurev-psych-120710-100422

Baranauskas, M. (2008). *Darbeliai: Multiple files renaming, processing, epoching, ERP properties, spectral power calculation*. Retrieved from https://sccn.ucsd.edu/wiki/EEGLAB_Extensions_and_plug-ins

Barlow, M., Woodman, T., Gorgulu, R., & Voyzey, R. (2016). Ironic effects of performance are worse for neurotics. *Psychology of Sport and Exercise*, *24*, 27–37. http://doi.org/10.1016/j.psychsport.2015.12.005

Baumeister, R. F. (1984). Choking under pressure: Self-consciousness and paradoxical effects of incentives on skillful performance. *Journal of Personality and Social Psychology*, *46*, 610–620. http://dx.doi.org/10.1037/0022-3514.46.3.610

Beilock, S. L., Carr, T. H., MacMahon, C., & Starkes, J. L. (2002). When paying attention becomes counterproductive: Impact of divided versus skill-focused attention on novice and experienced performance of sensorimotor skills. *Journal of Experimental Psychology: Applied, 8,* 6-16. http://dx.doi.org/10.1037/1076-898X.8.1.6

Cohen, J. (1988). *Statistical power analysis for the behavioral sciences* (2nd ed.). Hillsdale, NJ: Erlbaum. http://doi.org/10.1234/12345678

Cohen, M. X. (2014). *Analyzing neural time series data: Theory and practice.* Cambridge, MA:

MIT Press.

Cooke, A. (2013). Readying the head and steadying the heart: a review of cortical and cardiac studies of preparation for action in sport. *International Review of Sport and Exercise Psychology*, *6*. http://doi.org/10.1080/1750984X.2012.724438

Cooke, A., Kavussanu, M., Gallicchio, G., Willoughby, A., Mcintyre, D., & Ring, C. (2014). Preparation for action: Psychophysiological activity preceding a motor skill as a function of expertise, performance outcome, and psychological pressure. *Psychophysiology*, *51*. http://doi.org/10.1111/psyp.12182

DeCaro, M. S., Thomas, R. D., Albert, N. B., & Beilock, S. L. (2011). Choking under pressure: Multiple routes to skill failure. *Journal of Experimental Psychology: General*, *140*, 390–406. http://doi.org/10.1037/a0023466

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

Deeny, S. P., Hillman, C. H., Janelle, C. M., & Hatfield, B. D. (2003). Cortico-cortical communication and superior performance in skilled marksmen: An EEG coherence analysis. *Journal of Sport & Exercise Psychology*, *25*, 188–204. https://doi.org/10.1123/jsep.25.2.188

Delorme, A., & Makeig, S. (2004). EEGLAB: An open source toolbox for analysis of single-trial EEG dynamics including independent component analysis. *Journal of Neuroscience Methods*, *134*(1), 9–21. http://doi.org/10.1016/j.jneumeth.2003.10.009

Fitts, P. M., & Posner, M. I. (1967). *Human Performance*. Belmont, CA: Brooks/Cole.

Gallicchio, G., Cooke, A., & Ring, C. (2016). Lower left temporal-frontal connectivity characterizes expert and accurate performance: High-alpha t7-fz connectivity as a marker of conscious processing during movement. *Sport, Exercise, and Performance Psychology*, *5*, 14–24. http://doi.org/10.1037/spy0000055

Gallicchio, G., Cooke, A., & Ring, C. (2017). Practice makes efficient: cortical alpha oscillations are associated with improved golf putting performance. *Sport, Exercise, and Performance Psychology*, *6*, 89–102. http://doi.org/10.1037/spy0000077

Halliday, D. M., Rosenberg, J. R., Amjad, A. M., Breeze, P., Conway, B. A., & Farmer, S. F. (1995). A framework for the analysis of mixed time series/point process data-theory and application to the study of physiological tremor, single motor unit discharges and electromyograms. *Progress in Biophysics and Molecular Biology*, *64*, 237–278. http://doi.org/10.1016/S0079-6107(96)00009-0

Hardy, J. (2006). Speaking clearly: A critical review of the self-talk literature. *Psychology of Sport and Exercise*, *7*, 81–97. http://doi.org/10.1016/j.psychsport.2005.04.002

Hatfield, B. D., Costanzo, M. E., Goodman, R. N., Lo, L.-C., Oh, H., Rietschel, J. C., … Haufler, A. (2013). The influence of social evaluation on cerebral cortical activity and motor performance: a study of "Real-Life" competition. *International Journal of Psychophysiology*, *90*, 240–9. http://doi.org/10.1016/j.ijpsycho.2013.08.002

Hikosaka, O., Nakahara, H., Rand, M. K., Sakai, K., Lu, X., Nakamura, K., Miyachi, S., & Doya, K. (1999). Parallel neural networks for learning sequential procedures. *Trends in Neurosciences*, *22*, 464–471. https://doi.org/10.1016/S0166-2236(99)01439-3

Hillman, C. H., Apparies, R. J., Janelle, C. M., & Hatfield, B. D. (2000). An electrocortical comparison of executed and rejected shots in skilled marksmen. *Biological Psychology*, *52*, 71–83. http://doi.org/10.1016/S0301-0511(99)00021-6

Janelle, C. M., Hillman, C. H., Apparies, R. J., Murray, N. P., Meili, L., Fallon, E. A., & Hatfield, B. D. (2000). Expertise differences in cortical activation and gaze behavior during rifle shooting. *Journal of Sport and Exercise Psychology*, *22*, 167-182.

https://doi.org/10.1123/jsep.22.2.167

Jasper, H. H. (1958). The ten-twenty electrode system of the International Federation. *Electroencephalography and Clinical Neurophysiology*, *17*, 37–46.

Kerick, S. E., Douglas, L. W., & Hatfield, B. D. . (2004). Cerebral cortical adaptations associated with visuomotor practice. *Medicine & Science in Sports & Exercise*, *36*, 118–129. http://doi.org/10.1249/01.MSS.0000106176.31784.D4

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

Krane, V. (1994). The Mental Readiness Form as a measure of competitive state anxiety. *The Sport Psychologist*, *8*, 189–202.

MacMahon, K., & Masters, R. (1999). From novice to expert and back again: Chunking and dechunking in motor skills. *Journal of Sports Sciences*, *17*, 527–609.

Masters, R. S. W., Eves, F. F., & Maxwell, J. P. (2005). Development of a movement specific Reinvestment Scale. In & P. T. Morris, P. Terry, S. Gordon, S. Hanrahan, L. Ievleva, G. Kolt & Tremayne (Eds.), *Proceedings of the ISSP 11th World Congress of Sport Psychology*. Sidney, Australia.

Masters, R. S. W., & Maxwell, J. (2008). The theory of reinvestment. *International Review of Sport and Exercise Psychology*, *1*, 160–183. http://doi.org/10.1080/17509840802287218

Maxwell, J. P., Masters, R. S. W., Kerr, E., & Weedon, E. (2001). The implicit benefit of learning without errors. *The Quarterly Journal of Experimental Psychology*, *54*, 1049–1068. http://doi.org/10.1080/713756014

Mazza, S., Gerbier, E., Gustin, M. P., Kasikci, Z., Koenig, O., Toppino, T. C., & Magnin, M. (2016). Relearn faster and retain longer: Along with practice, sleep makes perfect. *Psychological Science*, *27*, 1321-1330. http://doi.org/10.1177/0956797616659930

Oldfield, R. C. (1971). The assessment and analysis of handedness: The Edinburgh Inventory. *Neuropsychologia*, *9*, 71–113. http://dx.doi.org/10.1016/0028-3932(71)90067-4

Perrin, F., Pernier, J., Bertrand, O., & Echallier, J. F. (1989). Spherical splines for scalp potential and current density mapping. *Electroencephalography and Clinical Neurophysiology*, *72*, 184–187. http://doi.org/10.1016/0013-4694(89)90180-6

Raab, M., Masters, R. S. W., Maxwell, J. P., Arnold, A., Schlapkohl, N., & Poolton, J. M. (2009). Discovery learning in sports: implicit or explicit processes? *International Journal of Sport and Exercise Psychology*, *7*, 413–430. https://doi.org/10.1080/1612197X.2009.9671917.

Robertson, E. M. (2007). The serial reaction time task: Implicit motor skill learning? *The Journal of Neuroscience, 27*, 10073–10075. http://doi.org/10.1523/JNEUROSCI.2747-07.2007

Sakai, K., Kitaguchi, K., & Hikosaka, O. (2003). Chunking during human visuomotor sequence learning. *Experimental Brain Research*, *152*, 229–242. http://doi.org/10.1007/s00221-003-1548-8

Shea, C. H., & Wrights, D. L. (2012). The representation, production, and transfer of simple and complex movement sequences. In N. Hodges & M. A. Williams (Eds.), *Skill Acquisition in Sport: Research, Theory and Practice* (pp. 131-147). Abingdon, UK: Routledge.

Song, S., & Cohen, L. (2014). Impact of conscious intent on chunking during motor learning. *Learning & Memory, 21*, 449–51. http://doi.org/10.1101/lm.035824.114

Springer, S. P., & Deutsch, G. (1998). *Left brain, right brain: Perspective from cognitive neuroscience* (5th ed.). New York, NY: Freeman.

Vasey, M. W., & Thayer, J. F. (1987). The continuing problem of false positives in repeated measures ANOVA in psychophysiology: a multivariate solution. *Psychophysiology*, *24*, 479–486. http://doi.org/10.1111/j.1469-8986.1987.tb00324.x

Verwey, W., & Abrahamse, E. L. (2012). Distinct modes of executing movement sequences:

Reacting, associating, and chunking. *Acta Psychologica*, *140*, 274–282. http://doi.org/10.1016/j.actpsy.2012.05.007

Von Stein, A. U., & Sarnthein, J. (2000). Different frequencies for different scales of cortical integration: from local gamma to long range alphartheta synchronization. *International Journal of Psychophysiology*, *38*, 301–313. http://doi.org/10.1016/S0167-8760(00)00172-0

Willingham, D. B. (1998). A neuropsychological theory of motor skill learning. *Psychological Review, 105*, 558–584. http://dx.doi.org/10.1037/0033-295X.105.3.558

Woodman, T., & Davis, P. A. (2008). The role of repression in the incidence of ironic effects. *The Sport Psychologist*, *22*, 183–196. https://doi.org/10.1123/tsp.22.2.183

Zhu, F. F., Maxwell, J. P., Hu, Y., Zhang, Z. G., Lam, W. K., Poolton, J. M., & Masters, R. S. W. (2010). EEG activity during the verbal-cognitive stage of motor skill acquisition. *Biological Psychology*, *84*, 221–7. http://doi.org/10.1016/j.biopsycho.2010.01.015

Zhu, F. F., Poolton, J. M., Wilson, M. R., Maxwell, J. P., & Masters, R. S. W. (2011). Neural co-activation as a yardstick of implicit motor learning and the propensity for conscious control of movement. *Biological Psychology*, *87*, 66–73. http://doi.org/10.1016/j.biopsycho.2011.02.004

Supplementary Material

Additional frequency bands

For exploratory purposes, activity in the theta (4-8 Hz), low-alpha (8-10 Hz), low-beta (12-20 Hz), and high-beta (20-28 Hz) was analyzed with 2 (Group) × 5 (Block) ANOVAs.

For the theta band, significant main effects of Block (*F*s(4,50) = 2.29-4.46, *p*s = .073-.004, η_p^2 =.15-.26), characterized by quadratic trends (*p*s = .028-.053, η_p^2 = .09)) emerged for power at Pz and Fz.

For the low-alpha band, significant main effects of Block (*F*s(4,50) = 2.56-2.62, *p*s = .005-.033, η_p^2 =.13-.27), characterized by quadratic trends (*p*s = .004-.007, η_p^2 = .13-.15)) emerged for power at T7, Fz, and Pz. Moreover, a significant main effect of Block (*F*(4,50) = 3.71, *p* = .01, η_p^2 = .23), characterized by an incremental linear trend (*p* = .006, η_p^2 = .14) emerged for T7-Fz connectivity.

For the low-beta band, significant main effects of Block (*F*s(4,50) = 2.86-4.18., *p*s = .005-.033, η_p^2 =.19-.25), characterized by incremental linear trends (*p*s = .004-.008, η_p^2 = .14-.25) emerged for power at T7, T8, Fz, and Pz. Group × Block interactions also emerged for T7 and T8 (*F*s(4,50) = 2.61-2.53, *p*s = .046-.053, η_p^2 = .17). Follow-up repeated-measures ANOVAs per each group failed to reveal any other significant effect, except for a main effect of Block (*F*(4,23) = 2.35, *p* = .047, η_p^2 = .33) with a quadratic trend (*p* = .020, η_p^2 = .19) in the implicit group for T8., Finally, we observed significant main effects of Block for both T7-Fz and T8-Fz connectivity, (*F*s(4,50) = 2.44-8.16, *p*s = .001-.014, η_p^2 = .16-.36) characterized by incremental linear trends (*p* = .002-.008, η_p^2 = .12-.17).

For the high-beta band, significant main effects of Block (*F*s(4,50) = 3.46-5.20., *p*s = .001-.014, η_p^2 =.22-.29), characterized by linear trends (*p*s = .001-.006, η_p^2 = .14-.23) emerged for power at T7, T8, Fz, and Pz. Trends for Group × Block interactions (*F*s(4,50) = 2.37-2.45, *p*s = .058-.065, η_p^2 = .16-.17) also emerged for T7 and T8. Follow-up repeated-measures ANOVAs at T7 revealed main effects of Block (*Fs*(4,23) = 1.06-3.10, *p*s = .006-.034, η_p^2 = .17-.23) with quadradic trends (*p*s = .026, η_p^2 = .17) for both the explicit and the implicit group. The same analysis at T8 revealed a significant main effect of Block (*F*(4,23) = 3.93, *p* = .014, η_p^2 = .41) described by a quadratic trend (p = .002, ηp2 = .31) for the implicit group only. Finally, we observed significant main effects of Block for both T7-Fz and T8-Fz (*F*s(4,50) = 4.07-7.82, *p*s = .001-.006, η_p^2 = .25-.39), characterized by incremental linear trends (*p* = .001-002, η_p^2 = .17-.21).

CHAPTER THREE

Bellomo, E., Cooke, A., Gallicchio, G., Ring, C., Hardy, J. (in preparation). Examining the cortical effects of explicit versus implicit motor sequence learning, retention and pressure: Implications for the conscious processing literature.

Abstract

The study was designed to provide a direct test of the link between the phenomenon of movement chunking, the concept of conscious motor processing, and its putative neurophysiological markers (in the high-alpha EEG frequency). We integrated this multi-measure approach in a group × block mixed-model design. Participants were randomized to training conditions that fostered (explicit group) versus prevented (implicit group) the development of movement-specific declarative knowledge while performing a repeated motor sequence. On day-1, they acquired sequence (4 blocks); and on day-2 they underwent retention, high-pressure, and low-pressure (3 blocks). Results showed that explicit learning resulted in comparatively quicker chunking and more robust performance under pressure. Neither left-temporal high-alpha power nor left frontal-temporal connectivity distinguished explicit from implicit learners, therefore questioning the validity of these putative neurophysiological indices of conscious processing. However, group differences did emerge at frontal and parietal sites. High-alpha activity of explicit learners was characterized by increased activation of parietal areas, decreased activation of the frontal-midline, and suppressed connectivity between frontal and parietal sites, compared to their implicit counterparts. These results emphasize the importance of considering more than just left-temporal sites in neurophysiological studies of conscious processing. The implications of our new frontal and parietal conscious processing measures, and suggestions for how they can be used in future motor learning and stress and performance research, are discussed.

Keywords: reinvestment theory; conscious processing; T7 power; T7-Fz connectivity; sequence learning;

Introduction

Observing how visuomotor sequences are learned and then performed in evaluative conditions can shed light on neurocognitive mechanisms that underpin skill acquisition and performance under pressure. Unravelling these mechanisms could lead to new methods of enhancing motor performance in a range of domains including sport, music and movement rehabilitation. According to well established theories of motor learning (Hikosaka et al., 1999; Masters, 1992; Willingham, 1998), complex movements can be acquired either via an explicit route, where top-down, conscious processes are utilized to chunk the sub-components of the movement together via the development of movement specific declarative knowledge (i.e., verbal-analytic rules, cf., Fitts & Posner, 1967); or via an implicit route, where the sub-components of the movement are chunked together in a more bottom-up and barely conscious manner (Curran & Keele, 1993; Song & Cohen, 2014). The purpose of this experiment is to examine the comparative effects of these two routes of learning on cortical activity and performance under pressure, guided by the predictions of Reinvestment Theory (Masters & Maxwell, 2008).

Implicit versus Explicit Motor Learning and Reinvestment Theory

The explicit route to motor learning is thought to grant expedited improvement in the early stages of skill acquisition (Bellomo et al., 2018; Curran & Keele, 1993; Hikosaka et al., 1999). However, with extensive practice, the explicit route naturally converges with the implicit route, as the elementary movement components are integrated (i.e., chunked) in a single memory unit, enabling a more procedural (i.e., unconscious) execution and marking the achievement of the automatic stage of performance (Hikosaka et al., 1999; Willingham, 1998). Masters and Maxwell's (2008) reinvestment theory places emphasis on the differential effects of explicit versus implicit motor learning on performance under stress. It argues that skills acquired via the explicit route are susceptible to de-automatization under pressure. Specifically, as a well-intentioned strategy, experts who acquired their skill via the explicit route could re-focus on the sub-components of the movement, recall the execution rules accumulated as a beginner, and thereby revert to a more primitive form of movement control. In contrast, reinvestment theory argues that if the learning conditions limit movement awareness and conscious processing from the outset (i.e., implicit route), performance under pressure should be more robust, since no declarative knowledge would be available to reinvest. In sum, the amount of conscious processing during the initial stages of movement acquisition is theorized to play a crucial role for subsequent performance under pressure.

Chunking and De-chunking

Chunking and de-chunking are thought to underpin the effects predicted by reinvestment theory (Masters & Maxwell, 2008). Surprisingly, the reinvestment literature lacks studies which directly attempted to measure these variables. Sequence learning tasks, which involve performing a series of separate movements (i.e., finger oppositions or button presses) in a serial fashion, afford the possibility of assessing chunking and de-chunking. Typically, the time gaps between each sub-component of the sequence are initially large but decrease with practice as execution becomes smoother and these movement sub-components are efficiently organized in fewer and larger motor chunks (Sakai, Kitaguchi, & Hikosaka, 2003), exactly as is said to happen during the acquisition of more complex motor skills (Fitts & Posner, 1967). Chunking is said to reduce the load on working memory since conscious processing is needed only for retrieving the first element of the chunk (Willingham, 1998). Chunking occurs as a result of both explicit and implicit training (see Abrahamse, Ruitenberg, de Kleine, & Verwey, 2013; Song & Cohen, 2014). However, only one study has demonstrated pressure-induced de-chunking, as predicted by reinvestment theory. Surprisingly, that study documented de-chunking after participants acquired a sequence via the implicit route[8] (MacMahon & Masters, 1999), thereby failing to provide full support for the predictions of reinvestment theory.

To address this gap, in a previous investigation (Bellomo et al., 2018), we attempted to scrutinize the de-chunking hypotheses of reinvestment theory by observing participants as they

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[8] The serial reaction time task adopted in that study is generally considered to promote implicit learning (Curran, 1995; Nissen & Bullmeier, 1999)

acquired a set sequence of button presses on a 4 × 4 matrix (*n* × *m* task; Hikosaka et al., 1995) while following either the explicit (errorful) or implicit (errorless) routes of movement processing. Importantly, when participants were transferred to a high-pressure condition, we observed a selective increase in self-reported conscious processing among explicit learners only. However, neither group showed any evidence of de-chunking, with pressure instead promoting further chunking of the sequence. Thus, we still lack evidence to support reinvestment theory's pivotal dechunking hypothesis.

Several limitations could have constrained the opportunity for dechunking to emerge in that study. For instance, movement is unlikely to have been fully automatized prior to the pressure test due to the relatively short acquisition phase and the absence of an overnight-sleep phase to encourage motor consolidation. The task could have been too simple, due to a relatively low number of motoric degrees of freedom. Sequence declarative knowledge was not assessed, so we cannot guarantee that the two groups were fully dichotomized in terms of access to conscious rules. Finally, although the manipulation check confirmed that pressure was induced, the pressure manipulation might not have been sufficiently intense to provoke dechunking. The present study is designed to address all of these limitations to further examine the de-chunking hypothesis of reinvestment theory.

Putative Neurophysiological Indexes of Conscious Motor Processing

In addition to behavioral manifestations of reinvestment (e.g., de-chunking), neurophysiological measures implicated in conscious processing can also be employed to test reinvestment theory. Conscious processing is thought to involve a series of working memory-based movement control processes including action-awareness, action-monitoring, hypothesis-testing, and error-analysis (Masters, Eves, & Maxwell, 2005). These processes promote the development of declarative (i.e., verbalizable) rules on how to execute the movement (Masters, 1992; Hardy, Mullen, Jones, 1996, Zhu et al., 2011). At a neurophysiological level, such verbal-analytic processes attuned to working-memory function and language-related processing have been mainly associated to the left-temporal area of the brain (Springer & Deustch, 1998; Zhu et al., 2015, 2011). Importantly, pioneering electroencephalographic (EEG) studies of complex movements (e.g., golf-putting, archery, gun shooting, simulated surgery) report effects in these left-temporal areas (Gallicchio, Cooke, & Ring, 2016; Hatfield et al., 2013; Zhu et al., 2015, 2011). For example, in preparation for self-paced aiming tasks (e.g., golf-putting or shooting), left-temporal power within the 10-12 Hz high-alpha frequency band (usually measured at T7) was reduced, and left-frontotemporal connectivity (usually measured at the T7-Fz pair) was increased in novices compared to experts (Gallicchio et al., 2016) and in high compared to low psychological pressure conditions (Hatfield et al., 2013).

EEG alpha power is involved in cortical inhibition, with more power reflecting increased inhibition and less power reflecting as a release from inhibition (Klimesch, 2012; Klimesch, Sauseng & Hanslmayr, 2007). EEG alpha connectivity measures long-range cortico-cortical communication, whereby the more synchronous the activity, the stronger the connectivity, and vice versa (Cohen, 2014; Lachaux, Rodriguez, Marinerie, & Varela, 1999). Accordingly, the studies above argue that the lower left-temporal high-alpha power and stronger left-frontotemporal alpha connectivity that characterized novices and emerged in high-pressure conditions indicate increased conscious processing via movement-related verbal activity and communication between left-temporal (verbal) and frontal midline (motor planning) sites (Deeny, Haufler, Saffer, & Hatfield, 2009; Hatfield et al., 2013).

However, while left-temporal power and left-frontotemporal connectivity in the high-alpha band could represent conscious processing in the form of verbal activity related to movement execution, it is important to note that this conclusion is generally based on post-hoc explanations of cross-section effects (e.g., expert and novice comparisons) rather than theory driven tests. Currently, only two studies (Bellomo et al., 2018; Zhu et al., 2011) appear to have been designed to directly test the hypothesized link between cortical activity and conscious processing. First, Zhu and colleagues (2011) employed a golf putting task and manipulated practice conditions in order to elicit high versus low levels of conscious processing (explicit versus implicit group) before introducing a performance pressure phase. Results showed that left-frontotemporal high-alpha connectivity (but not left-temporal high alpha power) was stronger after training in the explicit (i.e., trial-and-error practice) compared to the implicit (i.e., errorless practice) group. Moreover, under pressure connectivity strength further increased, as expected, in the explicit group only, but this was not accompanied by any regression in performance. Second, Bellomo and colleagues (2018) employed a sequence learning task and manipulated practice conditions to encourage either explicit (errorful) or implicit (errorless) acquisition, before transferring participants to a high-pressure condition. Results showed that left-temporal high-alpha power increased during acquisition in the explicit group only, suggesting a progressive reduction in activity which matched the superior rate of improvement that was achieved by the explicit group. However, left frontotemporal connectivity did not distinguish the two groups during acquisition, and neither left-temporal power or left frontotemporal connectivity distinguished the two groups under pressure.

Taken together, these findings question the theorized links between left-temporal high-alpha power, left-frontotemporal high-alpha connectivity, conscious processing, and performance. However, both previous studies were limited by a small number of recording electrodes (Zhu et al., 2011 = 7; Bellomo et al., 2018 = 4), thereby preventing a more extended scalp analyses of regions and connectivity paths that might be additionally implicated in conscious processes. The studies were also limited by rather large recording epochs (frequency analyses or averaging over blocks), preventing fine grained (e.g., millisecond resolution), time-locked analysis of power and connectivity in preparation for movement (e.g., Gallicchio et al., 2017). These limitations are addressed in the present study to provide a better test of the validity of left-temporal high-alpha power and left-frontotemporal high-alpha connectivity as neurophysiological measures of conscious processing.

The Present Experiment

By building upon the methodology of our previous investigation (Bellomo et al., 2018), the current study is designed to provide the most rigorous multi-measure test of reinvestment theory to date. We adopt a complex sequence learning task with an extended acquisition phase and with overnight-sleep consolidation followed by a retention phase to assess learning. We directly manipulate the chance for sequence declarative knowledge to be developed and we directly assess it at the end of the experiment to exclude participants not fully dichotomized into either *full*- (explicit route) or *null*- (implicit route) declarative knowledge groups. Moreover, to strengthen the pressure manipulation, we introduce a mixture of social-evaluation, competition, and potential monetary rewards-losses. Finally, to improve our EEG measurements, we employ a denser array of electrodes and focus our analyzes on the preparatory period time locked to the beginning of the sequence. Based on previous research (Bellomo et al., 2018), we hypothesized that participants in both groups would display chunking of the sequence during acquisition, but the explicit group would improve more rapidly. Based on reinvestment theory (Masters & Maxwell, 2008) we predicted that under pressure, de-chunking would be more likely in the explicit group, while the implicit group would be immune. Third, if left-temporal alpha power and left-frontotemporal alpha connectivity are truly linked to conscious processing, we expected high-conscious processing (e.g., explicit group in the initial stages of learning) to manifest as low levels of left-temporal power and high-levels of left-frontotemporal connectivity. Finally, to advance electrocortical studies of motor learning and pressure beyond focusing on frontal and left-temporal electrodes, we conduct exploratory scalp-level analysis analyses of activity and whole scalp communication pathways to shed new light on the concept of conscious processing across the whole brain.

Methods

Participants

Participants were 40 (18 male, 22 female), right-handed (Edinburgh Handedness Inventory ≥ +70, Oldfield, 1971), volunteers, aged 22.37 (*SD* = 4.45) years. This sample size was powered at

.80 to detect up to small interaction effects (η_p^2 = .040 and .034) in a 2 × 3 and 2 × 4 mixed-model analysis of variance (ANOVA) at the 5% level of significance. All participants were native speakers of a language based on a Latin alphabet, had normal/corrected to normal vision, were free from color-blindness, refrained from consuming alcohol, drugs (24 hours before) and caffeine (3 hours before), and reported more than 6 hours of sleep during the night preceding each days of testing. Participants provided informed consent before taking part and were paid £10 when the experiment was completed. The protocol was approved by the local research ethics committee.

Design

We employed a mixed-model. Participants were randomly allocated to a *full*-declarative (explicit) or a *null*-declarative (implicit) group (between-participant factor). Moreover, all participants performed the task across different blocks (within-participant factor): four blocks on day-1 (acquisition) and three blocks on day-2 (retention, high-pressure, low-pressure).

Task and Explicit versus Implicit Manipulation

We used a modified version of the serial reaction time task (Nissen & Bullmeier, 1987) in combination with a S1-S2 paradigm (Brunia, van Boxtel, Bocker, 2011), which enabled us to examine action preparation during visuomotor sequence learning. Participants sat on a comfortable chair and positioned their left-hand index, medium, ring, and little finger on four standard keyboard-buttons, which were mapped to four grey circular stimuli displayed on a computer screen (47 cm from their eyes). The stimuli were disposed horizontally and equally spaced on a grey background (Figure 1). Participants were instructed to: 1) press any button to start the trial; 2) “get ready” – a “beep” sound accompanied the appearance of four stimuli on the screen, with either an orange or a gold contour (S1; warning-stimulus); 3) press the button corresponding to each stimulus that flashes green as quickly as possible (S2; imperative-stimulus). Each trial was structured as follows (Figure 2): 1000 ms after participants decided to press any of the four keyboard-buttons (self-initiated start event), four grey circular stimuli with a colored (gold versus orange) outline appeared on the screen. After 3000ms (preparation-period), the outline of the stimuli would turn black again, and, at the same time, one of the four stimuli would flash in green for 200ms (imperative-stimulus). At this point, if the participant pressed the correct button, a second and different stimulus would flash in green for 200ms. If no errors were committed, this cycle would repeat for a total of 12 stimuli, with the only difference that once the 12th correct button press was executed, the stimuli would stay on the screen for 1000ms and after the four circles disappeared from the screen and the trial ended. In case of errors, the same would happen but straight after the incorrect press.

The task consisted of two types of trial. Specifically, within each block, 50% of the trials were a random 12-button sequence (random-trials), while the other 50% contained a pre-programmed 12-button sequence (sequence-trials). Random-trials were introduced to disguise the implicit learners from noticing the repeating pattern of sequence-trials. Each block terminated when participants completed 40 correct trials. Additional task instructions were provided dependent on the group to which participants had been assigned.

Explicit Group. For members of the explicit group the four circular stimuli were inscribed with verbalizable Latin letters (A, D, F, M) (see Figure 1), and they were told that half of the trials would contain the same repeated sequence (FAFMDMFADMAD), and that the color of the warning signal contours would indicate whether each trial contained the sequence (gold warning) or was random (orange warning). Finally, having shown participants the sequence (FAFMDMFADMAD), we asked them to verbally rehearse it for 2 minutes prior to beginning acquisition.

Implicit Group. For members of the implicit group the four circular stimuli were inscribed with Coptic and Hebrew characters (Ϫ, ב, Γ, וו)[9] which are arguably hard to verbalize for participants whose mother tongue was a language based on the Latin alphabet [10]. Members of this group were not told about the two types of trial (i.e., sequence versus random), nor were they told about the different information carried by the gold versus orange warning signals. Naturally, we did

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[9] These stimuli were selected since their visual complexity level roughly approximated the letters A, D, F, M.

[10] A screening procedure carried on before the beginning of the experiment, confirmed that none of the participants assigned to the implicit group could verbalize them.

not show the sequence (ΓꓫΓבוובΓꓫבווꓫב) to the members of the implicit group, nor did we provide time to rehearse it.

The intermixing of sequence and random trials and the withholding of information about the existence of a repeating sequence served to minimize the likelihood of members of the implicit group from becoming explicitly aware of the repeating sequence-trials. Since our hypotheses did not directly concern random trials, we focused our analysis on sequence trials only.

Retention and Pressure Tests

After completing four acquisition blocks of trials on day-1, participants returned to the laboratory on day-2 to complete retention and pressure tests. The task performed was identical to day-1, except the Explicit versus Implicit instructions were not repeated on day-2. A 40-trial retention test was completed first, followed by a 40-trial high-pressure test, and then a final 40-trial low-pressure / second retention test. To induce pressure, at the end of the first retention block, participants were informed, via instructions displayed in red on the computer screen and reinforced viva voce by the experimenter, they were about to begin the "test-phase", whereby their performance would be evaluated and compared to other participants, and there would be the chance

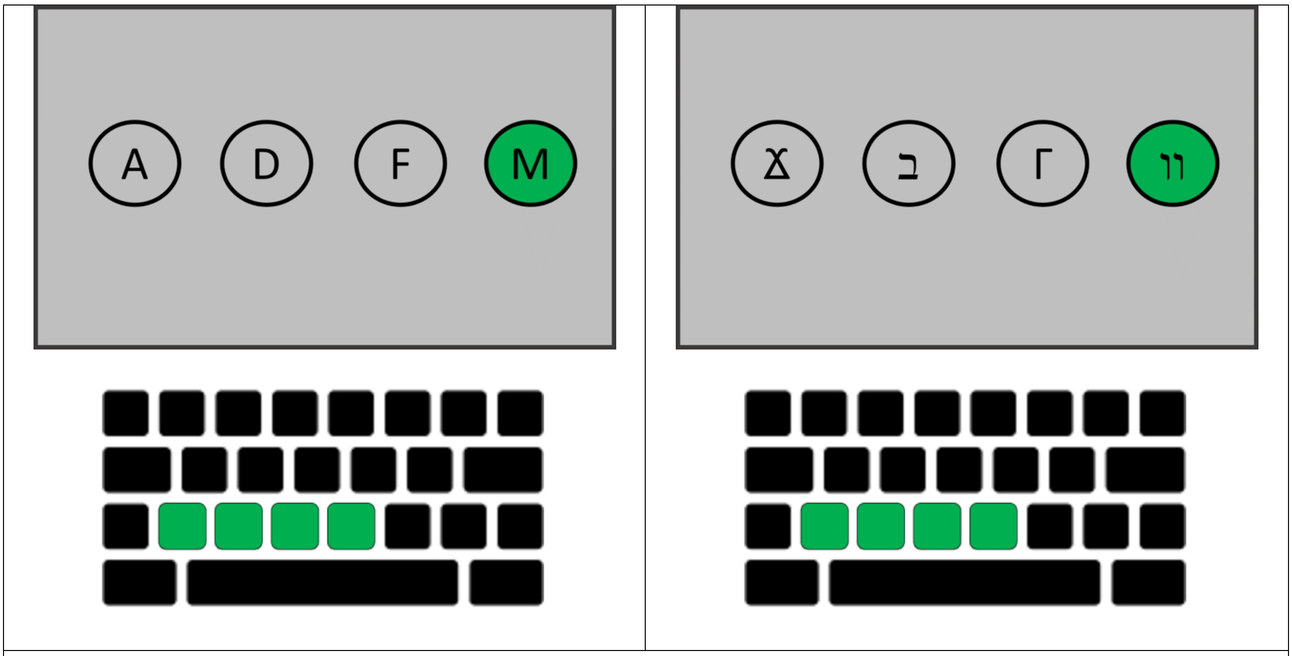


Figure 1. Example of the stimuli and the correspondent keyboard-buttons used for the explicit group (left panel) and implicit group (right panel). Note that the only difference is the type of character inscribed in the circles. More details in explanation below.

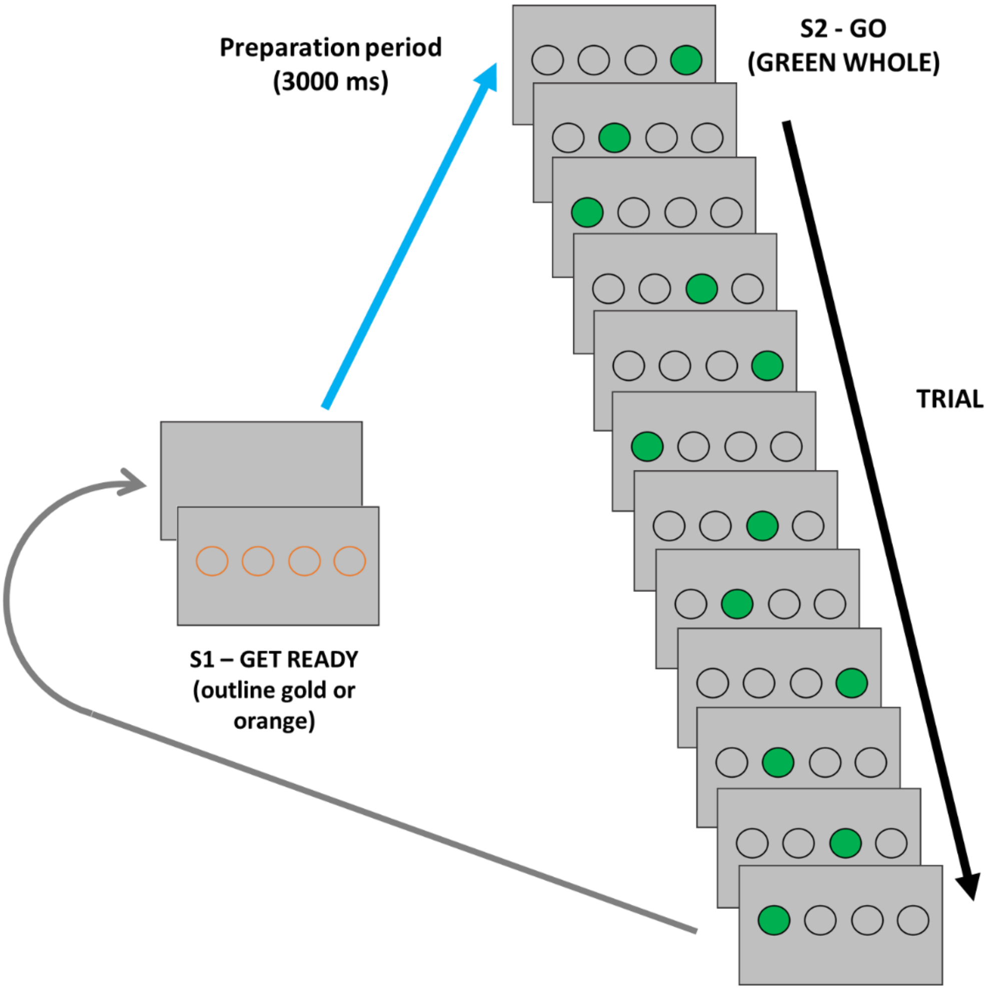


Figure 2. Task schematic. Once participants decided to start a new trial, with a delay of 1000 ms five grey circles inscribed with characters (Latin or Coptic/Hebrew depending on the experimental condition) for 3000 ms. Notably, the colour of the outline (gold or orange; S1-warning) informed participants to get ready for the type of trial. After a preparation period (S1-S2 interval) the whole of one of the four circles flashed green (S2-target) for 200 ms. If the participant correctly pressed the correspondent button, the whole of a new circle flashed green for 200 ms. If all the presses were correct, the same cycle would repeat for a total of 12 button presses. If at any point in the sequence an error was committed, the trial ended prematurely and the cycle was restarted.

to earn additional money or lose everything. First, they were informed that based on their performance on day-1, they had accumulated a total of £10 (same for all participants) but their payment was contingent on their performance in the “test phase”. Second, they were informed that the top three performers in the test phase would receive an additional monetary prize (£30, £15, £5). Third, participants were told that data from the worst 30% of the sample would be of no use for the study and would be discarded. They were further told that participants in this lower 30% would not be paid and had effectively wasted their own time and the time of the experimenter. Fourth, non-contingent feedback was provided. Specifically, the experimenter briefly exited the laboratory under the guise that he was checking in with a second experimenter who had been processing the participant's performance score during their previous block. After returning, the experimenter entered a false performance-score in the experiment-computer, and a message appeared on the screen informing participants that their performance currently placed them within the bottom 30% of the sample. Finally, participants were told the video-camera placed above them was set to record their movements and that the footage was broadcasted live to the room next door, where the second experimenter would further evaluate their performance. After the high-pressure test, participants completed a final 40-trial block where they were simply asked to do their best, with no pressure-inciting rewards or consequences attached. At the end of the experiment participants were fully debriefed, thanked and asked not to disclose specific detail about the pressure manipulation to others.

Procedure

Participants successfully screened for the exclusion/inclusion criteria individually attended two 2-hour testing session on consecutive days. The first day consisted of an acquisition phase, (day-1), while the second day consisted of a retention and pressure phase (day-2).

On the first day, after participants provided written consent to take part, the experimenter proceeded with the EEG montage. Next, resting EEG was recorded for 1 minute with eye-closed in order to calculate the individual alpha peak (IAF, see Bazanova & Vernon, 2014; Corcoran, Alday, Schlesewsky, Bornkessel-Schlesewsky, 2018) and subsequently calculate individual frequency bands. Then participants underwent a familiarization phase (simplified version of the task - no letters inscribed, only random trials - until 5 successful trials). This was followed by the explicit versus implicit manipulation (see above). Finally, they began the acquisition-phase, during which they practiced the task for across four blocks. Each block was considered completed after a total of 40 successful trials, 20 sequence-trials and 20 random-trials, respectively. Blocks were separated by five-minute breaks. Once this phase was completed, the electrodes were removed, and participants were thanked and reminded to return for the second phase of the study. On the second day, after the welcome, EEG montage and resting EEG recording, participants underwent the test-phase, which comprised a retention block, followed by a performance-pressure transfer block, and by an additional low-pressure block. The criterion for block completion was the same as in the acquisition phase. Retention assessed learning, therefore participants performed the task in absence of any manipulation. Conversely, in the transfer block, participants performed the task under conditions designed to create a mixture of incentives and punishments to increase evaluative pressure (see pressure manipulation section above). In the second low-pressure retention, participants performed the task once again, with no incentives or punishments. Once this final block terminated, we assessed sequence awareness. At the end of the experiment participants were thanked and asked not to disclose specific detail about the pressure manipulation to others.

EEG was recorded continuously throughout each block, while our pressure manipulation check questionnaires were administered immediately before each block.

Measures

Pressure manipulation. The effectiveness of the pressure manipulation was assessed by monitoring self-report cognitive and somatic anxiety. We administered the cognitive and somatic anxiety subscales of the Mental Readiness Form-3 (MRF-3; Krane, 1994) which consist of two statements (i.e., cognitive anxiety: "*my thoughts are…*"; somatic anxiety: "*my body feels…*") rated on a 11-point Likert scale (range 1-11) respectively anchored *not worried-worried, not tense-tense*.

Movement declarative knowledge. To verify the nature of our training manipulation, at the end of the task, we assessed sequence awareness ("did you notice a repeating sequence?") and sequence knowledge ("if yes, could you please write it down?"). Based on the percentage of correct button presses recalled, we computed a sequence knowledge score (expressed as a percentage). A button press was considered as correct if a specific button label was identified in the correct ordinal position. This enabled us to fully dichotomize the two groups since only participants that correctly reported the 100% of the sequence in the explicit group, and the 0% of the sequence in the implicit group, were retained.

Performance. The percentage of sequence chunked (chunked %) was considered to explore chunking and dechunking in the two groups. To obtain this measure, we first extracted all of the response times (RTs - time interval between the green flash of one of the circular stimuli on the screen and the following button press), which represent the time taken for stimulus identification, response programming, and movement time (Schmidt & Lee, 2011). This measure was computed as follows. We derived the number of chunks per each trial based on subject-specific cut-offs. First, RTs across all blocks were square-root transformed to approximate a normal distribution of the data (Sakai, Kitaguchi, & Hikosaka, 2003). Second, for each participant the upper bound of the 97.5% confidence interval for sequence-trials root-transformed RTs was calculated and taken as an individualized critical value to determine any disproportionately long time-gaps in the execution of the sequence and therefore distinguish temporally adjacent chunks (Sakai et al., 2003). Third, these individual cut-offs were applied to sequence-trials to yield the number of chunks per block for each participant. Fourth, we identified the number of chunks both types of trials and we calculated the percentage of trial chunked normalized by the minimum and maximum number of chunks across the whole dataset (blocks × trial types × group matrix) as $\%chunked = (1 - chunks - chunks_{min}/chunks_{max} - chunks_{min}) \times 100$; where $chunks$ is the number of chunks for a specific subject at a specific block, $chunks_{min}$ and $chunks_{max}$ are respectively the minimum and the maximum value across the whole dataset. This normalization ensured that the two groups were fully comparable.

Cortical activity. EEG activity was recorded from thirty-two (32) active electrodes at Fp1, Fp2, AF3, AF4, F7, F3, Fz, F4, F8, FC5, FC1, FC2, FC6, T7, C3, Cz, C4, T8, CP5, CP1, CP2, CP6, P7, P3, Pz, P4, P8, PO3, PO4, O1, Oz, O2 (10-20 system, Jasper, 1958). Additional, active electrodes were positioned on each mastoid, at the outer canthus and below each eye to record vertical and horizontal electrooculogram (EOG). All channels were recorded in monopolar. The signal sampled at 1024 Hz, with no online filter, using an ActiveTwo amplifier (Biosemi, The Netherlands). Electrode offset was kept below 15 mV. E-Prime was used for stimulus presentation.

Offline signal processing was performed using EEGLAB (Delorme & Makeig, 2004), ERPLAB (Lopez-Calderon, & Luck, 2014) and bespoke scripts in MATLAB (Mathworks Inc., USA). Data were down-sampled to 250 Hz, re-referenced to the average of all 32 EEG channels, and filtered .01 to 30 Hz (Butterworth, 12dB/40roll-off order2 non-causal). Segments/epochs were extracted from -4000 ms to +1000 ms relative to the onset of S2 (first stimulus of the sequence) and baseline subtraction (-200 ms to 0 ms) was then applied. Epochs were visually inspected and rejected if they contained gross artefacts. No bad channels were identified. Independent component analysis (ICA) weights were obtained through the RunICA informax algorithm (Makeig, Bell, Jung, & Sejnowski, 1996) running on these same EEG data (32 channels, yielding the same number of independent components) that, however, were instead high-pass filtered to 1 Hz (FIR [finite impulse response] filter, filter order 826) and concatenated across all blocks (separately for each day) within each participant. Then ICA weights for day-1 and day-2 were applied to the respective original 0.1-30 Hz filtered signals. Artefactual components (e.g., eye or muscle related) flagged by automated procedures (SASICA plugin; Chaumon, Bishop, Busch, 2015) and then visually inspected were manually rejected.

Time-frequency analysis. Time-frequency analysis was applied by convolving the fast-fourier (FFT) power spectrum of each EEG artefact-free epoch with a family of complex Morlet wavelets, defined as a Gaussian-windowed complex sine wave: $e^{i2\pi tf}e^{-t^2/2\sigma^2}$; where t is time, f is frequency bin, which increased from 4 to 30 Hz in 30 logarithmically steps, and σ defines the width of each frequency band (set to $\mathit{cycles}/2\pi f$, with *cycles* ranging from 3 and 6), and then taking the inverse FFT. From the convolution we obtained: (1) estimates of instantaneous power (squared magnitude of the analytic signal); and (2) phase (phase angle of the analytic signal) which was then used to compute inter-site connectivity.

IAF. Following the approach advocated by Bazanova and Veron (2014), the individual frequency bands were calculated based on the individual alpha peak (IAF, Kilmesh, 1996; 1999, Klimesh et al., 1998). IAF was calculated with the IAF toolbox (Corcoran et al., 2018) based on a

60s segment of eye-closed EEG recording taken before the beginning of the task, which were processed in the same way as task-related data (excluding the epoching). Accordingly, the IAF-adjusted high-alpha frequency bands was determined as high-alpha IAF to IAF+2. The IAF estimates (explicit$_{\text{day1}}$ = 9.94 ± .75 explicit$_{\text{day2}}$ = 10.07 ± .79; implicit$_{\text{day1}}$ = 9.51 ± .82, implicit$_{\text{day2}}$ = 9.61 ± .911) were not statistically different, as revealed by the 2 × 2 (Day, Group) mixed-model ANOVA.

Power. Changes in instantaneous power were calculated from the complex signal for each frequency bin (f) as the squared magnitude of the result of the convolution defined as Z_t (power time series: $p_t = real(z_t)^2 + imag(z_t)^2$. Crucially, no classical baseline normalisation was employed. Following the approach of Gallicchio and colleagues (Gallicchio, Finkenzeller et al., 2016, Gallicchio, Cooke et al., 2018) to control for skewness and interindividual differences, trial-averaged absolute alpha power was median-scaled log transformed, whereby values for each participant were scaled by the median of all values (electrode × points × block matrix) per each wavelet (representing a frequency bin) within that participant, and then subjected to a 10·log$_{10}$ transformation. Power was then averaged across IAF-adjusted frequency bands, and time bins (-100ms to +100ms, +900ms to +1100ms, +1900ms to +2100ms, +2900ms to +3100ms).

Connectivity. Functional connectivity between sites was computed in terms of inter-site phase clustering (ISPC) based on the phase angle time series, $\phi_t = imag(z_t)^2/real(z_t)^2$. This measure was preferred to other (e.g., magnitude squared coherence) as, being based on phase angle differences, it is independent of absolute power variations (Cohen, 2014). ISPC$_{\text{trials}}$ measures consistency of phase angle differences at specific time points across trials and is calculated with the following formula: $ISPC_{xy}(f) = \left|n^{-1}\sum_{t=1}^{n} e^{i(\theta_x(tf)-\theta_y(tf))}\right|$; where n is the number of trials, i is the imaginary operator, θ_x and θ_y are the phase angles of the recorded signal at two different scalp locations, t is trial, and f is the frequency bin, $e^{i(\theta_x(tf)-\theta_y(tf))}$ is the complex vector with magnitude, $n^{-1}\sum_{t=1}^{n}(.)$ denotes averaging over trials (for ISPC$_{\text{trials}}$), and $|.|$ is the magnitude of the averaged vector (Cohen, 2014; Lachaux et al., 1999). The resulting ISPC is a real number between

0 (no functional connection) and 1 (perfect functional connection). ISPC values were Z-transformed (i.e., inverse hyperbolic tangent; MATLAB transformation *atanh*) which extends the upper bound of ISPC to values larger than 1) to ensure normal distribution before statistical analyzes were performed (Halliday et al., 1995).

Statistical Analyses

We removed 17 participants (10 explicit, 7 implicit) due to not having *full*- vs *null*-declarative knowledge, respectively (knowledge score 100% vs 0%). Therefore, statistical analyses were conducted on 23 participants.

Self-report and performance data were analyzed using 2 Group (explicit, implicit) × 4 Block (acquisition 1-4) for day-1 and a 2 Group (explicit, implicit) × 3 Block (low-pressure retention 1, high-pressure transfer, low-pressure retention 2) ANOVAs for day-2.

Event-related power was analyzed Group × Site × Block × Bin (-100ms to +100ms, +900ms to +1100ms, +1900ms to +2100ms, +2900ms to +3100ms) ANOVAs for day-1 and day2, followed by separate ANOVAs at specific sites. Based on our study aims the factor Site included the following subset of the electrode sites: frontal (Fz, F3, F4), central (Cz, C3, C4), parietal (Pz, P3, P4), occipital (Oz, O1, O2), and temporal (T7, T8).

Event-related connectivity was analyzed with separate Group × Pair × Block × Bin ANOVAs to explore connectivity between the all the electrodes measures. To focus our analyses, we report the connectivity patterns anchored at two midline sites, Fz and Pz, deputed to motor planning and sensorimotor integration, respectively, as well as the key left-temporal site, T7, and its counterpart in the right-hemisphere, T8.

For brevity of reporting, and to ensure consistency with our experimental hypothesis, only significant main or interaction effects involving Group or Block are reported in the results section. These represent the factors that we manipulated, and the most important factors in terms of our theory derived predictions. Additional exploratory effects of Bin, Site and Pair are reported in the supplementary material.

Significant main effects and interactions were probed by separate ANOVAs for each Group, and Block, and by Bonferroni corrected pairwise comparisons, as described in the respective sections (Block). The multivariate method of reporting results was adopted as it minimizes the risk of violating sphericity and compound symmetry assumptions in repeated measures ANOVA (Vasey & Thayer, 1987). The multivariate statistic Wilks' lambda (not reported), equals $1 - \eta_p^2$. Effect size is reported with partial ηp2 squared (η_p^2) values of .10, .25, and .40 (for repeated measures ANOVA), and .02, .15, and .35 (for multivariate ANOVA) indicating relatively small, medium, and large effect sizes, respectively (Cohen, 1988).

Results

Pressure manipulation.

A Block × Group mixed-model ANOVA performed on the test-phase anxiety scores revealed main effects of Block, $F\text{s}(2, 20) = 10.91$ to 13.25, $p\text{s} < .001$, $\eta_p^2\text{s} = .52$ to $.57$, characterized by a pressure-induced increase in scores (Table 1). This indicates that our pressure manipulation successfully induced heightened levels of cognitive and somatic anxiety in both groups.

Performance.

Percentage chunked.

Acquisition (day-1). The Block × Group mixed-model ANOVA revealed main effects of Block, $F(3, 19) = 22.77$, $p < .001$, $\eta_p^2 = .78$, and Group, $F(1, 21) = 7.16$, $p = .014$, $\eta_p^2 = .25$. Post-hoc tests indicated that performance improved with practice early in acquisition (linear trend, $p < .001$, $\eta_p^2 = .78$), and was superior in the explicit group ($M = 75.3\%$, $SD = 15.2\%$) versus implicit group ($M = 62.9\%$, $SD = 11.0\%$).

Retention and pressure (day-2). The Block × Group mixed-model ANOVA revealed a main effects of Block, $F(2, 20) = 8.80$, $p = .002$, $\eta_p^2 = .47$, and Group, $F(1, 21) = 17.87$, $p < .001$, $\eta_p^2 = .46$. Post-hoc tests revealed that performance improved from retention to transfer and was maintained at the second retention test (quadratic trend, $p = .001$, $\eta_p^2 = .44$), and was superior for the explicit group ($M = 92.8\%$, $SD = .6$) versus implicit group ($M = 82.4\%$, $SD = .6\%$).

***Table 1.* Mean (SD) of self-report and performance measures in each Block and each Group.**

	Acquisition (day-1)				Retention and Pressure (day-2)		
Meas. (range)	**A1**	**A2**	**A3**	**A4**	**R1**	**T**	**R2**
MRF-3 (1-11)							
Cognitive Anx.							
Explicit	2.70(1.25)	3.30(1.57)	3.20(1.40)	2.80(1.55)	2.00(.94)	4.10(1.91)	2.90(2.18)
Implicit	3.38(2.29)	3.38(1.80)	3.54(1.94)	3.08(2.14)	2.31(1.49)	5.92(2.53)	3.08(1.93)
Somatic Anx.							
Explicit	4.20(.73)	5.00(3.46)	4.10(3.07)	3.50(2.88)	2.70(1.49)	4.40(2.46)	3.60(.3.50)
Implicit	5.08(2.53)	4.92(2.60)	5.31(2.43)	4.62(2.53)	3.46(2.50)	5.46(2.57)	3.77(2.35)
% chunked							
Explicit	53(25)	77(18)	84(10)	86(8)	90(8)	94(4)	94(6)
Implicit	41(15)	66(11)	69(10)	74(7)	79(7)	85(5)	82(7)

EEG activity

Power.

Acquisition (day 1). Results are illustrated in Figure 3A. The Group × Site × Block × Bin ANOVA revealed revealed a main effect of Block, $F(3, 19) = 3.76$, $p = .028$, $\eta_p^2 = .37$, characterized by a linear ($p = .022$, $\eta_p^2 = .22$) increase in power over the blocks. Main effects also emerged for Site and Bin, these effects do not speak to our central hypotheses so are reported in the supplementary material. No other effects emerged.

Separate ANOVAs were also performed for each electrode, these results are reported in full in the supplementary material (see Supplementary Material Table 1). Effects pertaining to our key Group and Block factors were as follows: ANOVA revealed a main effect of group characterized by more power for the explicit group at Fz and T8, and less power for the explicit group at F3, P3, P4, Moreover, the practice-related increase in power (main effect of Block), characterized frontal midline, right-frontal, midline central, midline occipital, and bilateral temporal sites (Fz, F4, Cz, Oz, T7, T8).

Retention and pressure (day 2). Results are summarized in Figure 3B. The Group × Site × Block × Bin ANOVA revealed main effects of Block, $F(2, 20) = 18.64$, $p < .001$, $\eta_p^2 = .65$, suggesting a pressure-related decrease in power at transfer, with no differences between retention 1 and retention 2. Main effects also emerged for Site and Bin (see supplementary material).

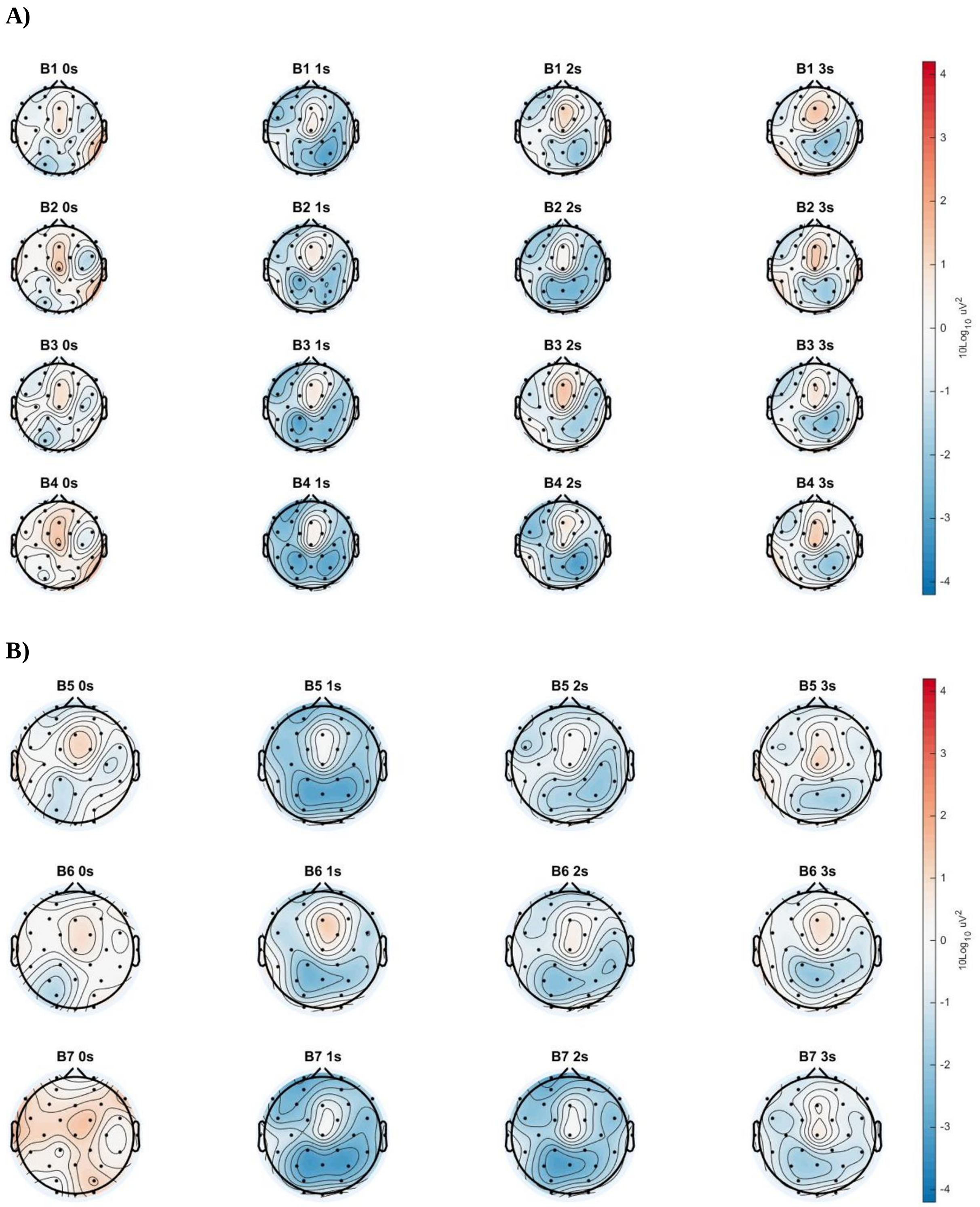


Figure 3. Difference maps (explicit – implicit) of the topographic distribution of median scaled power A) at day-1 B) at day-2. Red colors indicate more power for the explicit group (and less for the implicit group), blue colors indicate less power for the explicit group (and more for the implicit group).

Separate ANOVAs were also performed for each electrode (see Supplementary Material Table 1). Pertaining to our key Group and Block factors, these analyses revealed that the main effect of Group was characterized by more power for the explicit group at Fz and T8, and less power for the explicit group at F3, Pz, P3, P4. They revealed main effects of Block consisting of reduced power during the high-pressure condition compared to the retention conditions at all sites (Fz, F3, F4, Cz, C4, P3, P4, Pz, T7, T8, Oz, O1, O2).

Connectivity. We conducted separate analyses to specifically assess connectivity with the frontal-midline (Fz), the parietal-midline (Pz), the left-temporal (T7) and right-temporal (T8) sites. Results are summarized in Figure 4.

Acquisition (day-1).

Fz connectivity. The Group × Pair × Block × Bin mixed-model ANOVA, conducted to assess Fz connectivity revealed main effects for Pair and Bin (see supplementary material) but these effects were interspersed by Group × Pair interactions, F(9, 13) = 2.70, p = .051, η_p^2 = .65, which were probed with separate Block × Bin × Group ANOVAs for each pair. This analysis revealed group differences (main effect of Group, Fs(1, 21) = 4.54 - 6.34, ps = .045 - .20, η_p^2s = .18 - .23) whereby connectivity with the right-temporal site (Fz-T8) was stronger in explicit group while connectivity with the parietal midline (Fz-Pz) was weaker in the explicit group.

Pz connectivity. The Group × Pair × Block × Bin mixed-model ANOVA, conducted to assess Pz connectivity revealed a main effect for Pair (see supplementay material), and a main effect of Group, F(1, 21) = 7.48, p = .012, η_p^2 = .26, indicating weaker connectivity in the explicit group). Importantly, this effect was superseded by Group × Pair interactions, F(9, 13) = 3.46, p = .021, η_p^2 = .66, which were probed with separate Block × Bin × Group ANOVAs for each pair. This analysis revealed group differences (main effect of Group F(1,21) = 6.07 - 6.58, p = .018 - .022, η_p^2 = .22 - .24) whereby connectivity with left-frontal (Pz-F3), right-central (Pz-C4) and the occipital midline (Pz-Oz) site was weaker for the explicit group.

T7 connectivity. The Group × Pair × Block × Bin mixed-model ANOVA, conducted to assess T7 connectivity failed to reveal any Group or Block effect but revealed a main effect of Pair (see supplementary material).

T8 connectivity. The Group × Pair × Block × Bin mixed-model ANOVA, conducted assess T8 connectivity failed to reveal any Group or Block effect but revealed a main effect of Pair (see supplementary material).

Retention and transfer (day-2).

Fz connectivity. The Group × Pair × Block × Bin mixed-model ANOVA, conducted to assess Fz connectivity revealed a main effect of Block, F(2, 20) = 3.56, $p = .047$, $\eta_p^2 = .26$, whereby Fz connectivity reduced from retention to the high-pressure condition, although these comparisons were only approaching significance (Bonferroni $p \sim .08$). The main ANOVA also revealed main effects of Pair and Bin (see supplementary material).

Pz connectivity. The Group × Pair × Block × Bin mixed-model ANOVA, conducted to assess Pz connectivity revealed a main effect of Group, F(1, 21) = 4.46, $p = .047$, $\eta_p^2 = .17$, where connectivity was weaker for members of the explicit group. The analysis also revealed a main effect of Pair (see supplementary material).

T7 connectivity. The Group × Pair × Block × Bin mixed-model ANOVA, conducted to assess T7 connectivity did not reveal any effect of Block or Group but revealed effects for Pair and Bin (see the supplementary material).

T8 connectivity. The Group × Pair × Block × Bin mixed-model ANOVA, conducted to assess T8 connectivity revealed a main effects of Pair and Bin (see supplementary material), and a Group × Pair × Bin interaction, F(15, 7) = 4.57, $p = .025$, $\eta_p^2 = .91$. Follow-up ANOVAs for each Group revealed that connectivity with the parietal-midline, and with the right-frontal site (Pz-T8, T8-F4) was lower under pressure (Block, Fs(2, 20) = 3.53-6.68, $ps = .002$-$.049$, η_p^2s = .26-.40). No Group differences emerged.

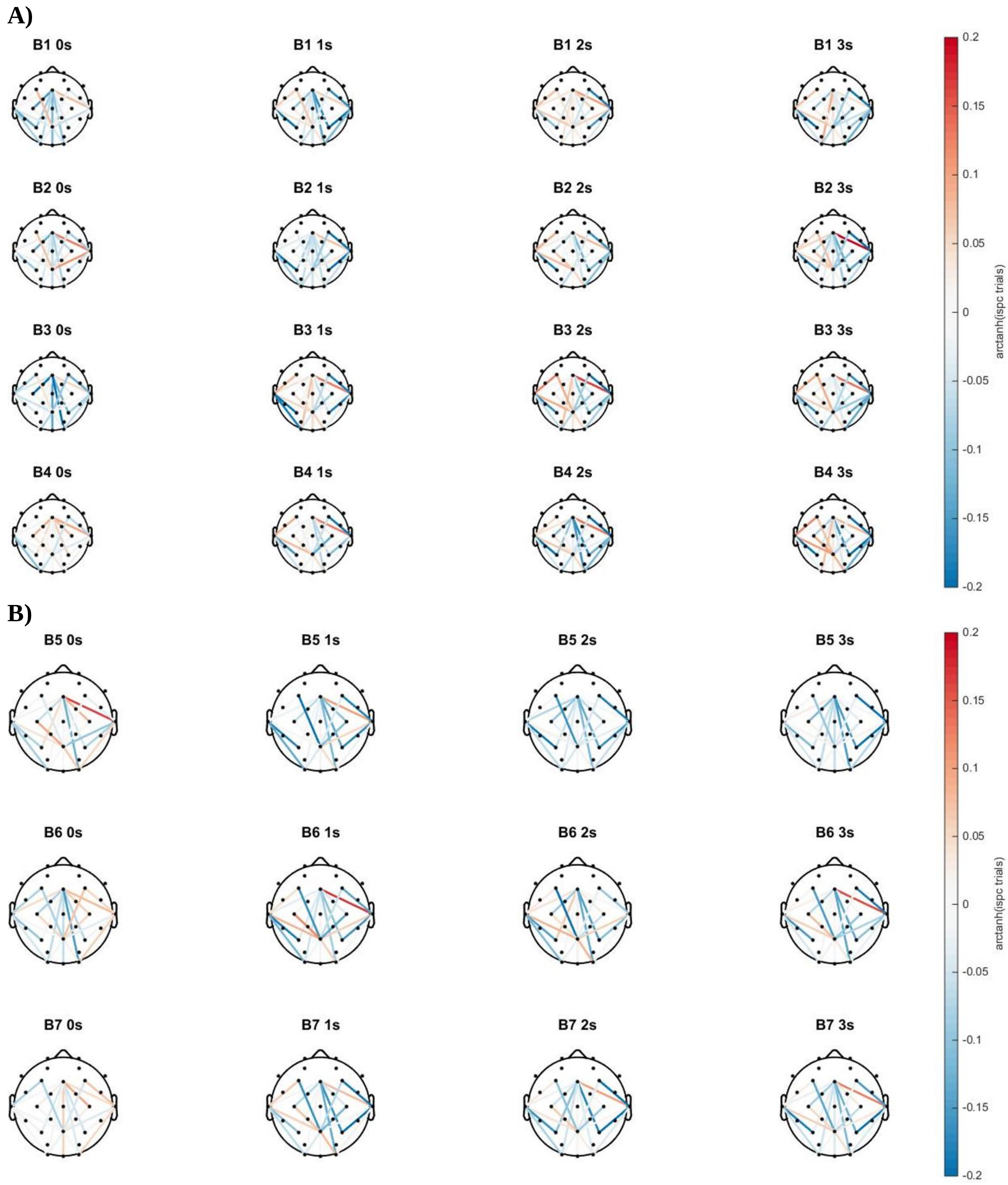


Figure 4. Difference maps (explicit – implicit) of the topographic distribution of connectivity A) at day-1; B) at day-2. Red colors indicate more connectivity for the explicit group (and less for the implicit group), blue colors indicate less connectivity for the explicit group (and more for the implicit group).

Discussion

This study aimed at improving our understanding of the mechanisms underpinning the explicit and implicit acquisition of complex movements and their subsequent execution in conditions of high-psychological pressure. The design and methodology employed represent an evolution of our previous investigation (Bellomo et al., 2018), and makes the current study the most comprehensive multi-measure test of reinvestment theory (Masters & Maxwell, 2008). Alongside the direct manipulation of participants access to movement-specific declarative knowledge in order to create pure explicit versus implicit conditions, this multi-measure approach included an assessment of motor chunking and measures of whole-scalp electroencephalographic (EEG) power and inter-electrode connectivity during acquisition (day-1) and during retention, high-pressure, and low-pressure phases (day-2). Our predictions were based on reinvestment theory (Masters & Maxwell, 2008), and are discussed in turn, alongside our results, in the following paragraphs.

Effects of Explicit versus Implicit Acquisition on Chunking and Dechunking

Based on the findings of Bellomo and colleagues (2018), we hypothesized that both our explicit and our implicit learning groups would improve performance by chunking the motor sequence over the course of acquisition. Moreover, following reinvestment theory (Masters & Maxwell, 2008), we predicted that under pressure, de-chunking would be more likely in the explicit group, while the implicit group would be immune. As expected, with practice both groups showed performance improvements and by the end of the acquisition phase they had chunked ~80% of the sequence, with an additional improvement to ~85% of the sequence after an overnight sleep. This resulted in a smooth and relatively flawless execution which is considered a characteristic of the automatic stage of learning (Fitts & Posner, 1967). Notably, the explicit group also demonstrated superior performance throughout the study. This effect emerged from the first acquisition blocks and thus provides additional support for research highlighting the early learning advantages of the explicit route of motor acquisition (Bellomo et al., 2018; Curran, 1995; Hikosaka et al., 1999).

However, in contrast to our hypothesis, both groups improved their performance from retention to the high-pressure block, and then maintained this high performance-level in the subsequent low-pressure block. As such it was not possible to verify whether de-chunking is a mechanistic explanation of movement failures under pressure. This finding replicated what was previously observed by Bellomo and colleagues (2018).

Two potential explanations for the absence of pressure-induced performance decrements are as follows. First, it is possible that participants in the explicit group still relied on movement-specific declarative knowledge to perform the sequence and therefore had not yet reached a level of performance automaticity sufficient enough to have scope to regress to a less efficient form of movement execution (cf., Masters & Maxwell, 2008). However, if this were the case, it is surprising that MacMahon and Masters (1999) observed de-chunking with an acquisition phase that was considerably shorter compared to both the current study and Bellomo and colleagues' (2018). Therefore, a second explanation, related to the nature of the task, might apply. Specifically, since the task required participants to react to externally presented cues, it might have triggered an external focus of attention, which has consistently been shown to benefit both learning and performance under pressure by freeing-up the motor system from internally generated (i.e., internal focus) constraints (Wulf, 2015). We recommend that future studies aiming to study reinvestment in the context of sequence learning ensure that focus of attention is controlled for (e.g., using finger tapping sequences). It would also be fruitful for future research to directly assess the neurophysiological differences induced by external versus internal attentional foci during motor tasks.

Effects of Explicit versus Implicit Acquisition on existing EEG Measures of Conscious Processing

A large body of previous literature has identified decreased left-temporal high-alpha power and increased left-frontotemporal high-alpha connectivity to reflect increasing levels of conscious processing during preparation for movement (Hatfield et al., 2013; Gallicchio et al., 2016; Zhu et al., 2011), but few studies have scrutinized these neurophysiological measures in longitudinal explicit versus implicit learning paradigms. As explicit learning confers high-levels of conscious processing, while implicit learning confers low-levels of conscious processing (Masters & Maxwell, 2008), we expected our left-temporal EEG measures to distinguish the explicit and implicit groups in our experiment. Despite our experimental manipulation establishing clear differences in movement-relevant declarative knowledge (i.e., distinct explicit versus implicit groups), neither of these left-temporal measures discriminated the two groups during practice (day-1) or at retention and pressure (day-2). This result challenges previous evidence discussing these two measures as putative indexes of conscious processing (e.g., Hatfield et al., 2013; Gallicchio et al., 2016; Zhu et al., 2011). The different effects observed here compared to those observed in previous studies may be attributed to methodological differences in how high versus low conscious processing conditions were operationalized. In previous studies, conscious processing differences were indirectly assumed, based, for example, on experience level (Deeny et al., 2009), or number of performance errors allowed by the task (Zhu et al., 2011). In contrast, the group dichotomization implemented in the current study was directly based on the definition of explicit versus implicit learning (i.e., *full-* versus *null*-levels of movement relevant declarative knowledge), therefore making it a more valid characterization of high versus low conscious processing conditions. Accordingly, the differences in left-temporal activity reported by previous studies may reflect cross-sectional differences in experience or proficiency rather than being pure indices of conscious processing.

Overall, these findings contrast reinvestment theory’s predictions that conscious processing would be greater for explicit versus implicit learners and would decrease during acquisition and then increase again under pressure for explicit learners, while remaining low and stable for implicit learners. However, since our data question the validity of left-temporal EEG measures as reliable indices of conscious motor processing, we do not wish to challenge the theory based on these measures alone. Importantly, by moving beyond the study of left-temporal and frontal electrodes, researchers might reveal stronger neurophysiological correlates of conscious motor control. In this experiment we identify some potential new indices that could provide stronger tests of the theoretical predictions, these are discussed next.

Conscious processing: Moving Beyond Left-Temporal Measures

A final and important aim of this experiment was to conduct exploratory scalp-level analyses of activity and communication pathways across a wider array of electrodes to shed new light on the concept of conscious processing across the whole brain. By moving beyond the study of T7 and Fz sites, we revealed several group, practice, and pressure related effects that could have important implications for future neurophysiological studies of conscious processing during learning.

More precisely, we revealed a range of complementary power and connectivity effects, principally at frontal and parietal sites, which can be interpreted via Ashe and colleagues' (2006) frontoparietal network model. In brief, Ashe and colleagues argue that activity of the frontal and partietal brain-circuits reflect the extent to which we are engaged in feedforward/top-down versus feedback/bottom-up modes of movement control. Activation of frontal areas is deputed to decision making and strategic planning, activation of parietal areas is deputed to integration of visual and somatosensory information, and communication between the two areas reflects the extent to which these distinct processes are influencing one another (Murata & Ishida, 2007). In the present experiment, we revealed that the explicit group showed comparatively more activity (less alpha power) at parietal sites (P3, P4) during acquisition, and after overnight consolidation (P3, P4, Pz). They also displayed comparatively less activity (more alpha power) at the frontal-midline (Fz), and also the right-temporal site (T8), which is responsible for attentional visuospatial processes (cf., Hatfield et al., 2013). Lastly, connectivity analyses revealed that the explicit group was characterized by an isolation (comparatively less connectivity) of the parietal-midline (Pz) especially from frontal (Fz, F3) sites.

These findings fit the frontal-parietal network model. Specifically, increased activity at parietal sites alongside reduced activity at frontal and right-temporal sites suggests that participants in the explicit group engaged in comparatively more multi-modal (visual, somatic, proprioceptive) sensorimotor integration processes and less strategic and visuomotor planning than their implicit counterparts. Moreover, the reduced frontal and parietal communication evident in the explicit group suggests that their sensorimotor processing was relatively isolated from the influence of frontally-generated plans. This pattern makes sense when one considers the externally cued-nature of our task. Since our task was preceded by a warning signal that informed members of the explicit group about the upcoming trial (i.e., gold contours = sequence; orange contours = random), it is likely that the explicit group employed their movement-relevant declarative knowledge to prime the parietal areas to attend the sequence cues in the moments prior to the beginning of the trials. In other words, thanks to the valid warning signal and their explicit knowledge of the sequence, the event-certainty enjoyed by the explicit group likely reduced the need for strategic planning (i.e., less frontal activation) and increased activation of parietal areas concerned with integrating the various systems (e.g., visual, proprioceptive) needed to execute the known movement. Conversely, the absence of movement-relevant declarative knowledge may have augmented the need for such frontally-generated planning among members of the implicit group, who were not aware of the meaning attached to the warning stimulus, and therefore would have been more reliant on a reactive-mode of movement execution (cf., Abrahamse et al., 2013).

These findings emphasize the importance of considering more than just left-temporal brain areas to gain a wider appreciation of the neurophysiological pathways implicated in conscious motor processing. They also highlight the potential for task to interact with putative neurophysiological conscious processing measures. For example, the combination of the frontal-parietal network and the externally-cued nature of the current task means that that a relative activation and isolation of parietal areas, as evident in the explicit group, likely reflects conscious top-down programming. However, in a self-paced task, one might expect the same relative activation and isolation of parietal areas to be associated with a less conscious form of control, since in self-paced tasks it seems likely that conscious decisions about action would emanate from more frontal areas, while partial activity would be synonymous with more automatic proprioceptive motor control (Abrahamse et al., 2013). This theme is developed further in the final experimental chapter of this thesis.

There were two noteworthy EEG findings outside the boundaries of the frontal-parietal network. First, that despite showing reduced power at T8 and Fz, the explicit group displayed stronger T8-Fz connectivity than the implicit group during acquisition. Power and connectivity (as calculated in this study) are orthogonal to each other (cf., Cohen, 2014) and, in short, respectively represent activation and cooperation. Therefore, although possessing movement-relevant declarative knowledge required less activation of visuospatial processing and motor planning sites (power data), it appears that these areas needed to be more synchronized (connectivity data), during the initial stages of movement acquisition. However, this group difference in T8-Fz connectivity disappeared on day two. This could reflect a reduction of movement-relevant visuospatial communication after the overnight sleep, and increased similarity between the explicit and the implicit group. This is in accord with models of skill acquisition predicting that sleep consolidation can encourage a convergence of the two groups into a more implicit-procedural mode of execution (Hikosaka et al., 1995; Masters & Maxwell, 2008).

Second, while activation at the Fz site was lower for explicit than implicit learners, activation at the neighboring F3 site was greater for members of the explicit group. While this is not entirely consistent with the frontal-parietal network interpretation of findings offered above, it does offer some indirect support for previous literature. Specifically, Zhu and colleagues (2015) showed that inhibitory stimulation (cathodal transcranial direct current stimulation - tDCS) over the left-dorsolateral prefrontal cortex suppressed verbal working memory activity and reduced movement conscious processing prior to golf putting. If Zhu et al.'s (2015) conclusion was that decreased activation around F3 reduces conscious processing, it seems reasonable that our finding of increased F3 activation in explicit versus implicit learners may be associated with increased conscious processing. This prediction can be tested more directly by future research.

Limitations and future directions

Methodological limitations should be mentioned when interpreting our results. First, although the task required the use of four fingers of the dominant hand, and this represented an evolution from Bellomo and colleagues' (2018) study, each movement was guided by external stimulus thereby reducing task complexity. This might have contributed to the absence of a de-chunking effect. However, our externally cued-task was integral to ensuring that we obtained a pure dichotomization of the two groups. It is a challenge for future studies to develop new tasks that still allow group dichotomization and measures of chunking and dechunking, but that also require a more internal generation of the movement. Second, in the current study, rather than having explicit group participants progressively develop movement-specific declarative knowledge by trial-and-errors, we supplied them with the knowledge directly before the beginning of the acquisition phase. This might have prevented them from accruing a large and complex pool of personal and idiosyncratic movement rules, as might occur in more naturalistic environments. Since the goal was to obtain a full dichotomization of the groups, we could not afford such an environment in the current study. To address this issue, future studies could include a discovery learning group.

Conclusions

The study was designed to enrichen our understanding of the complex relationship between the concept of conscious motor processing, its putative neurophysiological markers, and movement chunking. Results supported the idea that both explicit and implicit learning pathways foster chunking (Bellomo et al., 2018), but did not support the idea of pressure-induced dechunking (Masters & Maxwell, 2008). Results also questioned the validity of high-alpha T7 power and T7-Fz connectivity as neurophysiological measures conscious processing because these measures could not distinguish explicit from implicit learning groups. However, an extended analysis of neurophysiological activity identified new frontal and parietal EEG measures that speak to conscious motor processing and can be employed in the future to enhance understanding of conscious processes in the motor learning and stress and performance fields. Such an investigation as indeed the potential of identifying objective neurophysiological measures that could be used to evaluate the success of particular training regimes (e.g., analogy learning), or sport skills intervention (e.g., self-talk, imagery), and potentially be directly targeted with neuromodulation interventions such as neurofeedback (see Ring et al., 2015) or transcranial direct current stimulation (tDCS; see Zhu et al., 2015),

References

Abrahamse, E. L., Ruitenberg, M. F. L., de Kleine, E., & Verwery, W. B., (2013). Control of automated behavior: Insights from the discrete sequence production task. *Frontiers In Human Neuroscience, 7,* 1-16. http://doi.org/10.3389/fnhum.2013.00082

Ashe, J., Lungu, O. V., Basford, A. T., & Lu, X. (2006). Cortical control of motor sequences. *Current Opinion in Neurobiology, 16*, 213–221. http://doi.org/10.1016/j.conb.2006.03.008

Babiloni, C., Carducci, F., Cincotti, F., Rossini, P. M., Neuper, C., Pfurtscheller, G., & Babiloni, F. (1999). Human movement-related potentials versus desynchronization of EEG alpha rhythm: a high-resolution EEG study. *Neuroimage, 10,* 658-665. https://doi.org/10.1006/nimg.1999.0504

Babiloni, C., Del Percio, C., Iacoboni, M., Infarinato, F., Lizio, R., Marzano, N., ... & Eusebi, F. (2008). Golf putt outcomes are predicted by sensorimotor cerebral EEG rhythms. *The Journal of Physiology, 586*, 131-139. https://doi.org/10.1113/jphysiol.2007.141630

Babiloni, C., Infarinato, F., Marzano, N., Iacoboni, M., Dassù, F., Soricelli, A., ... & Del Percio, C. (2011). Intra-hemispheric functional coupling of alpha rhythms is related to golfer's performance: A coherence EEG study. *International Journal of Psychophysiology, 82*, 260-268. https://doi.org/10.1016/j.ijpsycho.2011.09.008

Bazanova, O. M., & Vernon, D. (2014). Interpreting EEG alpha activity. *Neuroscience & Biobehavioral Reviews, 44*, 94-110. https://doi.org/10.1016/j.neubiorev.2013.05.007

Bellomo, E., Cooke, A., & Hardy, J. (2018). Chunking, Conscious Processing, and EEG During Sequence Acquisition and Performance Pressure: A Comprehensive Test of Reinvestment Theory. *Journal of Sport and Exercise Psychology, 40*, 135-145. https://doi.org/10.1123/jsep.2017-0308

Brunia, C. H. van Boxtel, G. J. & Böcker, K. B. (2011). Negative Slow Waves as Indices of Anticipation: The Bereitschaftspotential, the Contingent Negative Variation, and the Stimulus-

Preceding Negativity. In Luck, S. J., & Kappenman, E. S. (Eds.). *The Oxford handbook of event-related potential components*. Oxford University Press. https://doi.org/ 10.1093/oxfordhb/9780195374148.013.0108

Callan, D. E., & Naito, E. (2014). Neural processes distinguishing elite from expert and novice athletes. *Cognitive and Behavioral Neurology, 27*, 183-188. http://doi.org/10.1097/WNN.0000000000000043

Chaumon, M., Bishop, D. V., & Busch, N. A. (2015). A practical guide to the selection of independent components of the electroencephalogram for artifact correction. *Journal of Neuroscience Methods, 250*, 47-63. https://doi.org/10.1016/j.jneumeth.2015.02.025

Cohen, J. (1988). *Statistical power analysis for the behavioral sciences* (2nd ed.). Hillsdale, NJ: Erlbaum. http://doi.org/10.1234/12345678

Cohen, M. X. (2014). *Analyzing neural time series data: Theory and practice.* Cambridge, MA: MIT Press.

Cooke, A., Kavussanu, M., Gallicchio, G., Willoughby, A., Mcintyre, D., & Ring, C. (2014). Preparation for action: Psychophysiological activity preceding a motor skill as a function of expertise, performance outcome, and psychological pressure. *Psychophysiology, 51*. http://doi.org/10.1111/psyp.12182

Corcoran, A. W., Alday, P. M., Schlesewsky, M., & Bornkessel-Schlesewsky, I. (2018). Toward a reliable, automated method of individual alpha frequency (IAF) quantification. *Psychophysiology*, e13064. https://doi.org/10.1111/psyp.13064

Curran, T. (1995). On the neural mechanisms of sequence learning. *Psyche, 2*.

Curran, T., & Keele, S. W. (1993). Attentional and nonattentional forms of sequence learning. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *19*, 189. https://doi.org/10.1037/0278-7393.19.1.189

Davidson, R. J., Chapman, J. P., Chapman, L. J., & Henriques, J. B. (1990). Asymmetrical brain electrical activity discriminates between psychometrically-matched verbal and spatial cognitive tasks. *Psychophysiology, 27*, 528-543. https://doi.org/10.1111/j.1469-8986.1990.tb01970.x

De Caro, M. S., Thomas, R. D., Albert, N. B., & Beilock, S. L. (2011). Choking under pressure: Multiple routes to skill failure. *Journal of Experimental Psychology: General*, *140*, 390–406. http://doi.org/10.1037/a0023466

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

Del Percio, C., Iacoboni, M., Lizio, R., Marzano, N., Infarinato, F., Vecchio, F., ... & Babiloni, C. (2011). Functional coupling of parietal alpha rhythms is enhanced in athletes before visuomotor performance: a coherence electroencephalographic study. *Neuroscience*, 175, 198-211. https://doi.org/10.1016/j.neuroscience.2010.11.031

Delorme, A., & Makeig, S. (2004). EEGLAB: An open source toolbox for analysis of single-trial EEG dynamics including independent component analysis. *Journal of Neuroscience Methods*, *134*(1), 9–21. http://doi.org/10.1016/j.jneumeth.2003.10.009

Eysenck, M. W., Derakshan, N., Santos, R., & Calvo, M. G. (2007). Anxiety and cognitive performance: attentional control theory. *Emotion, 7*, 336-353. https://doi.org/10.1037/1528-3542.7.2.336

Fitts, P. M., & Posner, M. I. (1967). *Human Performance*. Belmont, CA: Brooks/Cole.

Gallicchio, G., Cooke, A., & Ring, C. (2016). Lower left temporal-frontal connectivity characterizes expert and accurate performance: High-alpha t7-fz connectivity as a marker of conscious processing during movement. *Sport, Exercise, and Performance Psychology*, *5*, 14–

24. http://doi.org/10.1037/spy0000055

Gallicchio, G., Cooke, A., & Ring, C. (2017). Practice makes efficient: cortical alpha oscillations are associated with improved golf putting performance. *Sport, Exercise, and Performance Psychology, 6,* 89–102. http://doi.org/10.1037/spy0000077

Gallicchio, G., Finkenzeller, T., Sattlecker, G., Lindinger, S., & Hoedlmoser, K. (2016). Shooting under cardiovascular load: Electroencephalographic activity in preparation for biathlon shooting. *International Journal of Psychophysiology, 109*, 92–99. https://doi.org/10.1016/j.ijpsycho.2016.09.004

Gentili, R. J., Bradberry, T. J., Oh, H., Costanzo, M. E., Kerick, S. E., Contreras-Vidal, J. L., & Hatfield, B. D. (2015). Evolution of cerebral cortico-cortical communication during visuomotor adaptation to a cognitive-motor executive challenge. *Biological psychology*, *105*, 51-65. https://doi.org/10.1016/j.biopsycho.2014.12.003

Halliday, D. M., Rosenberg, J. R., Amjad, A. M., Breeze, P., Conway, B. A., & Farmer, S. F. (1995). A framework for the analysis of mixed time series/point process data-theory and application to the study of physiological tremor, single motor unit discharges and electromyograms. *Progress in Biophysics and Molecular Biology*, *64*, 237–278. http://doi.org/10.1016/S0079-6107(96)00009-0

Hardy, L., Mullen, R., & Jones, G. (1996). Knowledge and conscious control of motor actions under stress. *British Journal of Psychology, 87,* 621-636. https://doi.org/10.1111/j.2044-8295.1996.tb02612.x

Hatfield, B. D., Costanzo, M. E., Goodman, R. N., Lo, L.-C., Oh, H., Rietschel, J. C., … Haufler, A. (2013). The influence of social evaluation on cerebral cortical activity and motor performance: a study of “Real-Life” competition. *International Journal of Psychophysiology*, *90*, 240–9. http://doi.org/10.1016/j.ijpsycho.2013.08.002

Hafield B. D., & Hillman C. H. (2001). *The psychophysiology of sport: A mechanistic* *understanding of the psychology of superior performance*. In Singer R. N., Hausenblas H. A., & Janelle C. M. (Eds.), Handbook of Sport Psychology (2nd ed., pp. 362–386). New York, NY: Wiley.

Hikosaka, O., Nakahara, H., Rand, M. K., Sakai, K., Lu, X., Nakamura, K., Miyachi, S., & Doya, K. (1999). Parallel neural networks for learning sequential procedures. *Trends in Neurosciences*, *22*, 464–471. https://doi.org/10.1016/S0166-2236(99)01439-3

Hikosaka, O., Rand, M. K., Miyachi, S., & Miyashita, K. (1995). Learning of sequential movements in the monkey–process of learning and retention of memory. *Journal of Neurophysiology*, *74*, 1652–1661. http://doi.org/ 10.1152/jn.1995.74.4.1652

Hillman, C. H., Apparies, R. J., Janelle, C. M., & Hatfield, B. D. (2000). An electrocortical comparison of executed and rejected shots in skilled marksmen. *Biological Psychology*, *52*, 71–83. http://doi.org/10.1016/S0301-0511(99)00021-6

Jasper, H. H. (1958). The ten-twenty electrode system of the International Federation. *Electroencephalography and Clinical Neurophysiology*, *17*, 37–46.

Kim, W., Chang, Y., Kim, J., Seo, J., Ryu, K., Lee, E., ... & Janelle, C. M. (2014). An fMRI study of differences in brain activity among elite, expert, and novice archers at the moment of optimal aiming. *Cognitive and Behavioral Neurology*, *27*, 173-182. http://dx.doi.org/ 10.1097/WNN.0000000000000042

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

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

Klimesch, W. (1996). Memory processes, brain oscillations and EEG synchronization. *International Journal of Psychophysiology*, *24*, 61-100. https://doi.org/10.1016/S0167-8760(96)00057-8

Klimesch, W., Sauseng, P., & Hanslmayr, S. (2007). EEG alpha oscillations: the inhibition–timing hypothesis. *Brain Research Reviews, 53*, 63-88. https://doi.org/10.1016/j.brainresrev.2006.06.003

Krane, V. (1994). The Mental Readiness Form as a measure of competitive state anxiety. *The Sport Psychologist*, *8*, 189–202.

Lachaux, J. P., Rodriguez, E., Martinerie, J., & Varela, F. J. (1999). Measuring phase synchrony in brain signals. *Human Brain Mapping*, *8*, 194-208. https://doi.org/10.1002/(SICI)1097-0193(1999)8:4<194::AID-HBM4>3.0.CO;2-C

Lopez-Calderon, J., & Luck, S. J. (2014). ERPLAB: an open-source toolbox for the analysis of event-related potentials. *Frontiers in Human Neuroscience*, 8, 213. https://doi.org/10.3389/fnhum.2014.00213

Makeig, S., Bell, A.J., Jung, T.P., Sejnowski, T.J., 1996. *Independent component analysis of electroencephalographic data*. In: Touretzky, D., Mozer, M., Hasselmo, M. (Eds.), Advances in Neural Information Processing Systems Vol. 8. MIT Press, Cambridge, MA.

Masters, R. S. (1992). Knowledge, knerves and know-how: The role of explicit versus implicit knowledge in the breakdown of a complex motor skill under pressure. *British Journal of Psychology, 83*, 343-358. https://doi.org/10.1111/j.2044-8295.1992.tb02446.x

Masters, R. S. W., & Maxwell, J. (2008). The theory of reinvestment. *International Review of Sport and Exercise Psychology*, *1*, 160–183. http://doi.org/10.1080/17509840802287218

Masters, R. S. W., Eves, F. F., & Maxwell, J. P. (2005). Development of a movement specific Reinvestment Scale. In & P. T. Morris, P. Terry, S. Gordon, S. Hanrahan, L. Ievleva, G. Kolt & Tremayne (Eds.), *Proceedings of the ISSP 11th World Congress of Sport Psychology*.

Sidney, Australia.

Mazza, S., Gerbier, E., Gustin, M. P., Kasikci, Z., Koenig, O., Toppino, T. C., & Magnin, M. (2016). Relearn faster and retain longer: Along with practice, sleep makes perfect. *Psychological Science, 27,* 1321-1330. http://doi.org/10.1177/0956797616659930

Norman J. (2002). "Two visual systems and two theories of perception: An attempt to reconcile the constructivist and ecological approaches". Behavoral Brain Science, 25, 73–144. https://doi.org/10.1017/s0140525x0200002x

Nissen, M. J., & Bullemer, P. (1987). Attentional requirements of learning: Evidence from performance measures. *Cognitive Psychology, 19,* 1-32. https://doi.org/10.1016/0010-0285(87)90002-8

Oldfield, R. C. (1971). The assessment and analysis of handedness: The Edinburgh Inventory. *Neuropsychologia*, *9*, 71–113. http://dx.doi.org/10.1016/0028-3932(71)90067-4

Pfurtscheller, G., & Aranibar, A. (1979). Evaluation of event-related desynchronization (ERD) preceding and following voluntary self-paced movement. *Electroencephalography and Clinical Neurophysiology*, *46*, 138-146. https://doi.org/10.1016/0013-4694(79)90063-4

Rozengurt, R., Barnea, A., Uchida, S., & Levy, D. A. (2016). Theta EEG neurofeedback benefits early consolidation of motor sequence learning. *Psychophysiology*, *53*, 965-973. https://doi.org/10.1111/psyp.12656

Sakai, K., Kitaguchi, K., & Hikosaka, O. (2003). Chunking during human visuomotor sequence learning. *Experimental Brain Research*, *152*, 229–242. http://doi.org/10.1007/s00221-003-1548-8

Schmidt, R. A., & Lee, T. D., (2011). *Motor control and learning: A behavioral emphasis*. Human Kinetics.

Song, S., & Cohen, L. (2014). Impact of conscious intent on chunking during motor learning.

Learning & Memory, 21, 449–51. http://doi.org/10.1101/lm.035824.114

Springer, S. P., & Deutsch, G. (1998). *Left brain, right brain: Perspective from cognitive neuroscience* (5th ed.). New York, NY: Freeman.

Vasey, M. W., & Thayer, J. F. (1987). The continuing problem of false positives in repeated measures ANOVA in psychophysiology: a multivariate solution. *Psychophysiology*, *24*, 479–486. http://doi.org/10.1111/j.1469-8986.1987.tb00324.x

Walker, M. P., & Stickgold, R. (2006). Sleep, memory, and plasticity. *Annual Review of Psychology, 57*, 139-166. https://doi.org/10.1146/annurev.psych.56.091103.070307

Vine, S. J., Moore, L., & Wilson, M. R. (2011). Quiet eye training facilitates competitive putting performance in elite golfers. *Frontiers in Psychology, 2*, 8. https://doi.org/10.3389/fpsyg.2011.00008

Vine, S. J., & Wilson, M. R. (2010). Quiet eye training: Effects on learning and performance under pressure. Journal *of Applied Sport Psychology, 22*, 361-376. https://doi.org/10.1080/10413200.2010.495106

Willingham, D. B. (1998). A neuropsychological theory of motor skill learning. *Psychological Review*, *105,* 558–584. http://dx.doi.org/10.1037/0033-295X.105.3.558

Wilson, M. R., Vine, S. J., & Wood, G. (2009). The influence of anxiety on visual attentional control in basketball free throw shooting. *Journal of Sport and Exercise Psychology, 31*, 152-168. https://doi.org/10.1123/jsep.31.6.761

Wulf, G. (2013). Attentional focus and motor learning: a review of 15 years. *International Review of Sport and Exercise Psychology*, *6*, 77-104. https://doi.org/10.1080/1750984X.2012.723728

Zhu, F. F., Poolton, J. M., Wilson, M. R., Maxwell, J. P., & Masters, R. S. W. (2011). Neural co-activation as a yardstick of implicit motor learning and the propensity for conscious control of movement. *Biological Psychology*, *87*, 66–73. http://doi.org/10.1016/j.biopsycho.2011.02.004

Zhu, F. F., Yeung, A. Y., Poolton, J. M., Lee, T. M., Leung, G. K., & Masters, R. S. (2015). Cathodal transcranial direct current stimulation over left dorsolateral prefrontal cortex area promotes implicit motor learning in a golf putting task. *Brain stimulation, 8*, 784-786. https://doi.org/10.1016/j.brs.2015.02.005

Supplementary Material

Additional analyses

Power.

Acquisition (day 1). The analysis additionally revealed revealed main effects of Site, F(13, 9) = 23.07, $p < .001$, $\eta_p^2 = .97$, and Bin, F(3, 19) = 16.82, $p < .001$, $\eta_p^2 = .73$. Event-related changes in power during the preparatory period were evident (main effect of Bin, linear trend $p < .001$, $\eta_p^2 = .68$), with a decrease between S1 and S2. We also observed a specific topographic (see Figure 2) distribution with highest power at occipital (Oz, O1, O2) and midline and right-parietal (Pz, P4) and lowest at right-frontal, right-central, right-temporal (F4, C4, T8 and left-central (C3).

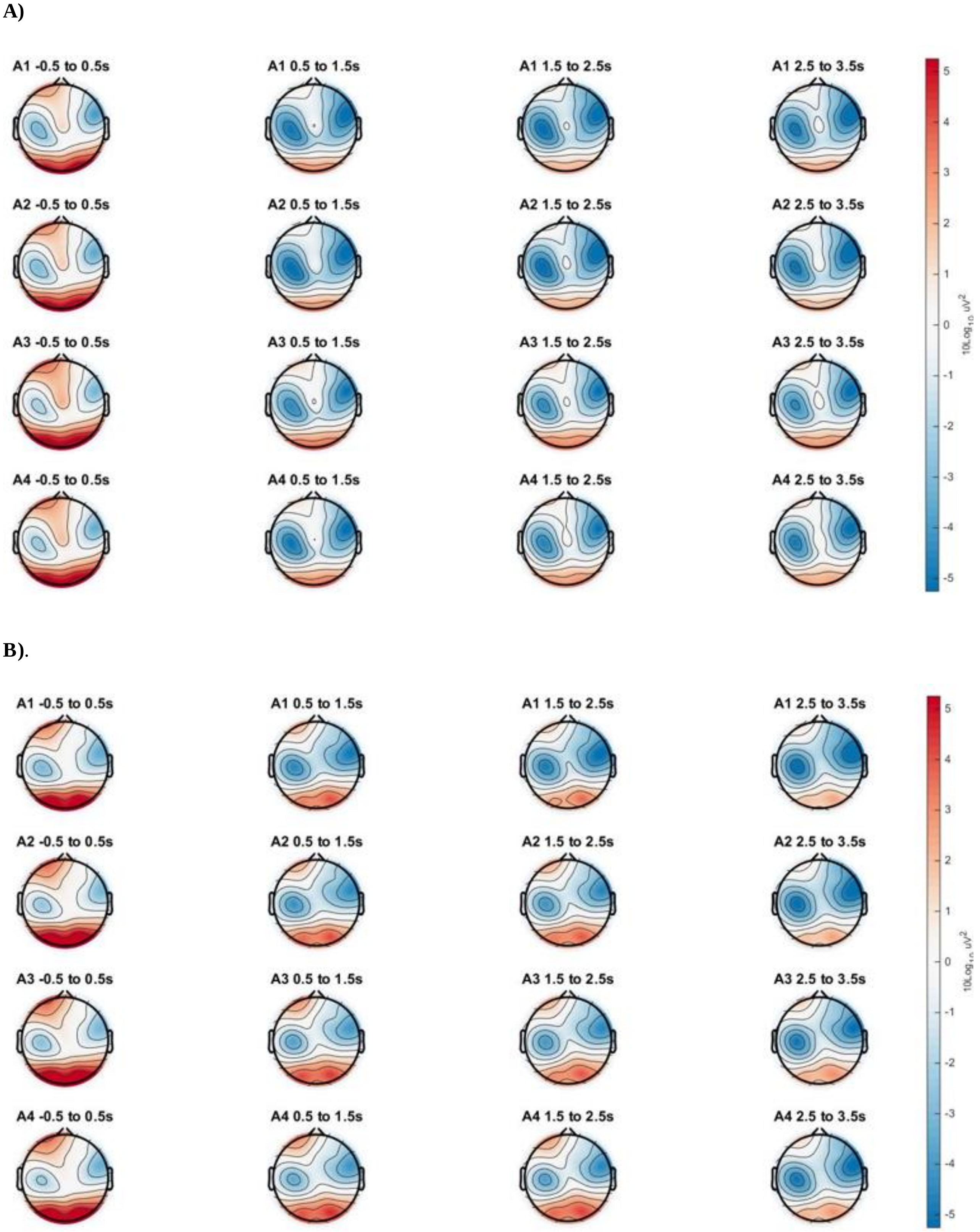
Retention and pressure (day 2). The analysis additionally revealed revealed main effects of Site, F(13, 9) = 35.29, $p < .001$, $\eta_p^2 = .98$, and Bin, F(3, 19) = 13.45, $p < .001$, $\eta_p^2 = .68$. Event-related changes in power during the preparatory period were evident (main effect of Bin, linear trend $p < .001$, $\eta_p^2 = .62$), with a decrease between S1 and S2. Moreover, we also observed topographic distribution similar to acquisition (see Figure 3) with highest power at occipital (Oz, O1, O2) and midline/right-parietal (Pz, P4) and lowest at right-frontal, right-central, right-temporal (F4, C4, T8), and left-central (C3) sites.

Summary. In sum, power was had a characteristic topographical distribution since it was highest at occipital sites bilaterally, and, in the right-hemisphere, lowest at frontal, central, temporal, and parietal sites, while at central sites only in the left-hemisphere. Moreover, power showed a whole scalp event-related decrease in preparation to movement during all phases (acquisition, retention, pressure).

Separate ANOVAs per each site

Table 1. Power

Site	**Acquisition (day-1)**	**Retention and pressure (day-2)**
Fz	Block, F(3, 19) = 4.47, $p = .015$, $\eta_p^2 = .41$, Bin, F(3, 19) = 12.33, $p < .001$, $\eta_p^2 = .66$, Group, F(1, 21) = 4.53, $p = .045$, $\eta_p^2 = .18$ (explicit more)	Block, F(2, 20) = 7.16, $p = .005$, $\eta_p^2 = .42$, Bin, F(3, 19) = 10.19, $p < .001$, $\eta_p^2 = .62$, Group, F(1, 21) = 4.53, $p = .045$, $\eta_p^2 = .18$ (T<R2)
F3	Block, F(3, 19) = 3.23, $p = .046$, $\eta_p^2 = .34$, Bin, F(3, 19) = 17.02, $p < .001$, $\eta_p^2 = .73$, Group, F(1, 21) = 8.83, $p = .006$, $\eta_p^2 = .30$ (explicit less)	Block, F(2, 20) = 9.98, $p = .001$, $\eta_p^2 = .50$, Bin, F(3, 19) = 15.84, $p < .001$, $\eta_p^2 = .71$, Group, F(1, 21) = 7.05, $p = .015$, $\eta_p^2 = .25$ (R1>T<R2)
F4	Bin, F(3, 19) = 13.99, $p < .001$, $\eta_p^2 = .69$	Block, F(2, 20) = 10.04, $p = .001$, $\eta_p^2 = .50$, Bin, F(3, 19) = 10.55, $p < .001$, $\eta_p^2 = .62$ (R1>T<R2)
Cz	Block, F(3, 19) = 4.21, $p = .019$, $\eta_p^2 = .40$, Bin, F(3, 19) = 12.41, $p < .001$, $\eta_p^2 = .66$,	Block, F(2, 20) = 6.01, $p = .009$, $\eta_p^2 = .37$, Bin, F(3, 19) = 14.24, $p < .001$, $\eta_p^2 = .69$, (T<R2)
C3,	Bin, F(3, 19) = 8.92, $p < .001$, $\eta_p^2 = .58$, Bin*group, F(3, 19) = 3.98, $p = .023$, $\eta_p^2 = .39$	Bin, F(3, 19) = 8.24, $p = .001$, $\eta_p^2 = .57$
C4	Bin, F(3, 19) = 17.34, $p < .001$, $\eta_p^2 = .73$	Block, F(2, 20) = 7.88, $p = .003$, $\eta_p^2 = .44$, Bin, F(3, 19) = 9.71, $p < .001$, $\eta_p^2 = .60$, bin*group, 3,10 = 3.37, .040, .35 (T<R2)
Pz	Bin, F(3, 19) = 4.42, $p = .016$, $\eta_p^2 = .41$	Block, F(2, 20) = 9.87, $p = .001$, $\eta_p^2 = .50$, Bin, F(3, 19) = 3.58, $p = .033$, $\eta_p^2 = .36$, Group 1,21 = 3.92, .061, .16 (R1>T<R2)
P3	Bin, F(3, 19) = 20.16, $p < .001$, $\eta_p^2 = .76$, Group, F(1, 21) = 7.03, $p = .015$, $\eta_p^2 = .25$ (explicit less)	Block, F(2, 20) = 6.27, $p = .008$, $\eta_p^2 = .39$, Bin, F(3, 19) = 11.62, $p < .001$, $\eta_p^2 = .65$, Group, F(1, 21) = 4.75, $p = .041$, $\eta_p^2 = .18$ (T<R2)
P4	Bin, F(3, 19) = 11.82, $p < .001$, $\eta_p^2 = .65$, Group, F(1, 21) = 8.16, $p = .009$, $\eta_p^2 = .28$ (explicit less)	Block, F(2, 20) = 16.22, $p < .001$, $\eta_p^2 = .62$, Bin, F(3, 19) = 7.87, $p = .001$, $\eta_p^2 = .55$, Group, F(1, 21) = 5.85, $p = .025$, $\eta_p^2 = .22$ (R1>T<R2)
Oz	Block, F(3, 19) = 3.03, $p = .054$, $\eta_p^2 = .32$, Bin, F(3, 19) = 16.66, $p < .001$, $\eta_p^2 = .72$	Block, F(2, 20) = 8.96, $p = .002$, $\eta_p^2 = .47$, Bin, F(3, 19) = 23.59, $p < .001$, $\eta_p^2 = .79$ (R1>T<R2)
O1	Bin, F(3, 19) = 20.19, $p < .001$, $\eta_p^2 = .76$	Block, F(2, 20) = 9.58, $p = .001$, $\eta_p^2 = .49$, Bin, F(3, 19) = 22.67, $p < .001$, $\eta_p^2 = .78$ (R1>T<R2)
O2	Bin, F(3, 19) = 21.55, $p < .001$, $\eta_p^2 = .77$, Bin*Group, F(3, 19) = 3.16, $p = .048$, $\eta_p^2 = .33$	Block, F(2, 20) = 12.30, $p = .000$, $\eta_p^2 = .47$, Bin, F(3, 19) = 21.91, $p < .001$, $\eta_p^2 = .77$ (R1>T<R2)
T7	Block, F(3, 19) = 4.10, $p = .021$, $\eta_p^2 = .39$, Bin, F(3, 19) = 6.95, $p = .002$, $\eta_p^2 = .66$	Block, F(2, 20) = 6.00, $p = .009$, $\eta_p^2 = .37$, Bin, F(3, 19) = 9.05, $p = .001$, $\eta_p^2 = .59$ (T<R2)
T8	Block, F(3, 19) = 6.07, $p = .004$, $\eta_p^2 = .49$, Bin, F(3, 19) = 7.98, $p = .001$, $\eta_p^2 = .56$, Bin*group, F(3, 19) = 4.03, $p = .022$, $\eta_p^2 = .39$, Block*Bin, F(9, 13) = 2.73, $p = .049$, $\eta_p^2 = .65$, Group, F(1, 21) = 3.92, $p = .061$, $\eta_p^2 = .16$ (explicit more)	Block, F(2, 20) = 5.47, $p = .013$, $\eta_p^2 = .35$, Bin, F(3, 19) = 6.45, $p = .003$, $\eta_p^2 = .50$, Block*Bin, F(6, 16) = 2.64, $p = .056$, $\eta_p^2 = .50$, Group, F(1, 21) = 3.90, $p = .062$, $\eta_p^2 = .16$ (explicit more) (T<R2)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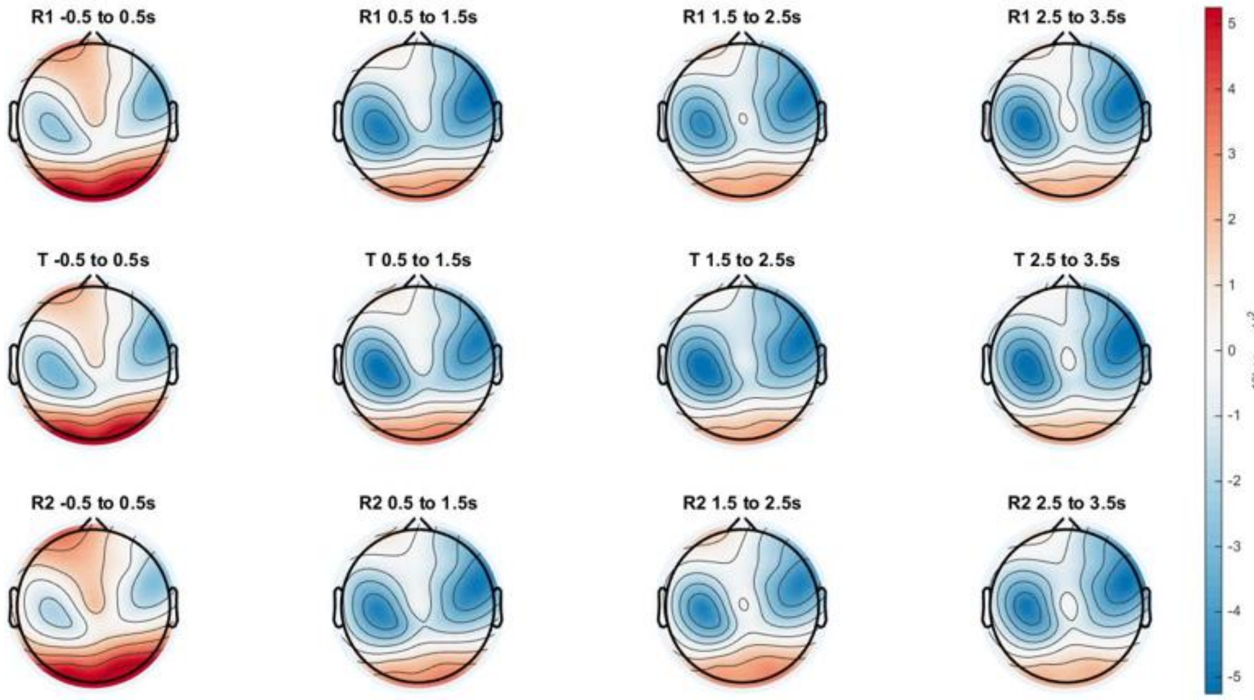

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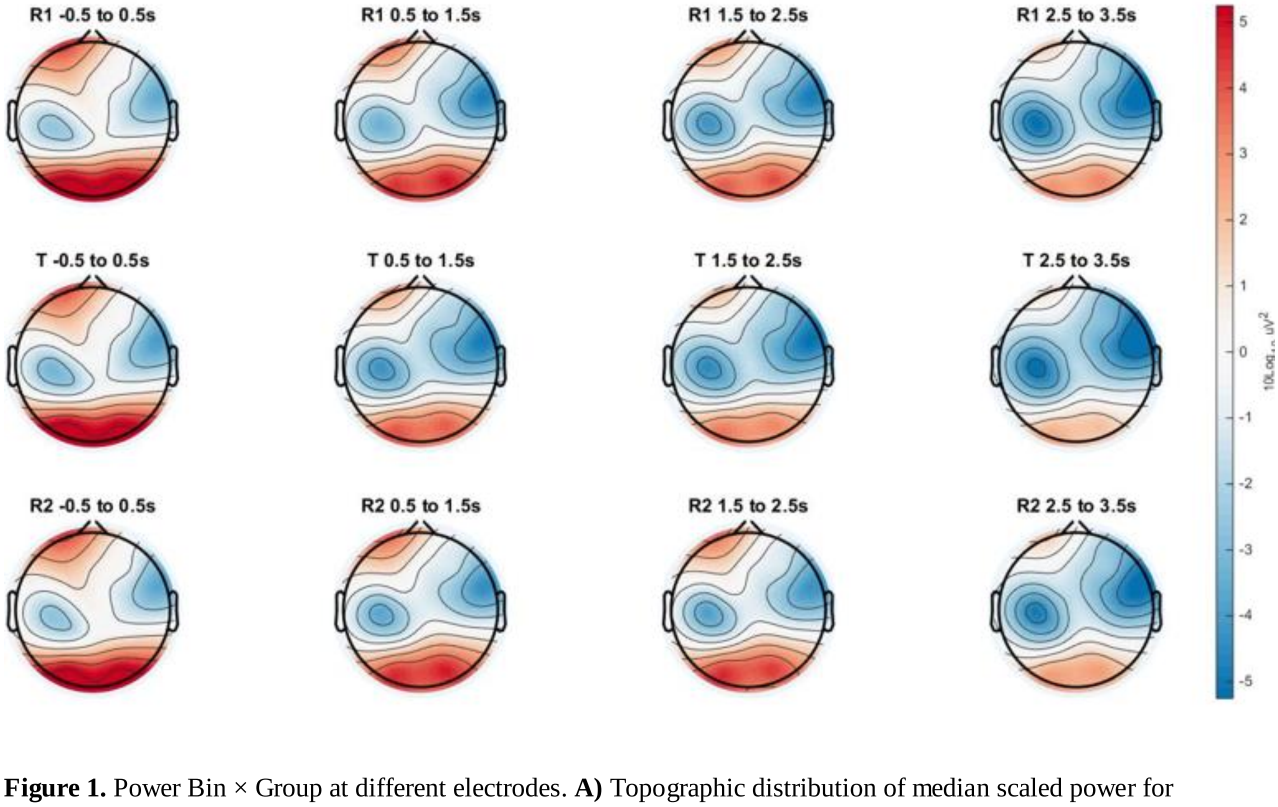


Figure 1. Power Bin × Group at different electrodes. **A)** Topographic distribution of median scaled power for sequence trials in the explicit group at day-1; **B)** Topographic distribution of median scaled power for sequence trials in the implicit group at day-1; C) Topographic distribution of median scaled power for sequence trials in the explicit group at day-2; **D)** Topographic distribution of median scaled power for sequence trials in the implicit group at day-2.

Connectivity

Acquisition (day-1).

Fz connectivity. The analysis additionally revealed a decrease in connectivity in preparation to movement (Bin, F(3, 19) = 7.53, p = .002, η_p^2 = .54; linear p < .001, η_p^2 = .51); and confirmed that connectivity was strongest with occipital (Fz-Oz, Fz-O1, FzO2) and parietal (Fz-P4, Fz-P3, Fz-Pz) sites (Pair, F(9, 13) = 52.77, p < .001, η_p^2 = .97).

Pz connectivity. The analysis additionally revealed that connectivity was strongest with the left-frontal and left-temporal sites (Pz-F3, Pz-T7; Pair, F(8, 14) = 77.23, p < .001, η_p^2 = .98).

T7 connectivity. The analysis additionally revealed that connectivity towards the left-temporal site (T7) revealed that connectivity was strongest with the parietal midline and the left-lateral frontal site (PzT7, T7-F3, Pair, F(5, 17) = 34.71, p < .001, η_p^2 = .91).

Connectivity towards T8. The analysis additionally revealed that connectivity was strongest with the frontal-midline (FzT8, Pair, F(5, 17) = 16.49, p < .001, η_p^2 = .83).

Retention and transfer (day-2).

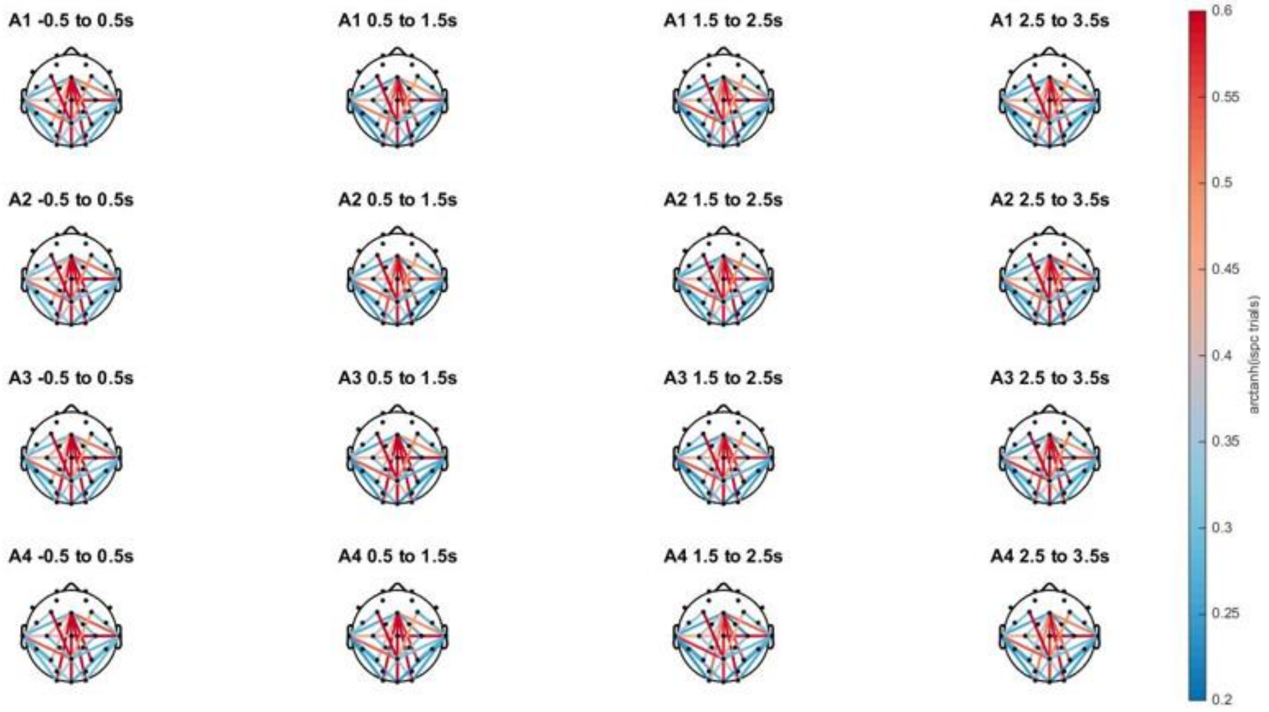
Fz connectivity. The analysis additionally revealed a main effect of Pair, F(5, 17) = 69.66, p < .001, η_p^2 = .98, which consisted in stronger connectivity with occipital sites and right-parietal (Fz-O2, Fz-Oz, Fz-O1, Fz-P4) and revealed a main effect of Bin, F(3, 19) = 7.27, p = .002, η_p^2 = .53, characterized by a decrease in connectivity (linear p < .001, η_p^2 = .53) prior to movement.

Pz connectivity. The analysis additionally revealed a main effect of Pair, F(8, 14) = 55.78, p < .001, η_p^2 = .97, whereby connectivity was strongest with left-frontal and left-temporal sites (Pz-F3, Pz-T7) and lowest with central sites (Pz-C3, Pz-C4).

T7 connectivity. The analysis additionally revealed a main effect of Pair, F(5, 17) = 18.16, p < .001, η_p^2 = .84, whereby connectivity was strongest with midline parietal and left-frontal sites (PzT7, T7-F3). Moreover it revealed a main effect of Bin, F(5, 17) = 3.15, p = .042, η_p^2 = .34, consisting of a decrease in connectivity prior to movement execution (linear p = .013, η_p^2 = .26).

T8 connectivity. The analysis additionally revealed a main effect of Pair, F(5, 17) = 30.91, p < .001, η_p^2 = .90, whereby connectivity was strongest with frontal and parietal midline (Fz-T8, Pz-T8); and a main effect of Bin, F(3, 19) = 4.55, p = .014, η_p^2 = .42, with a reduction prior to movement (quadratic p = .013, η_p^2 = .26).

A)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arctanh(ispc trials)

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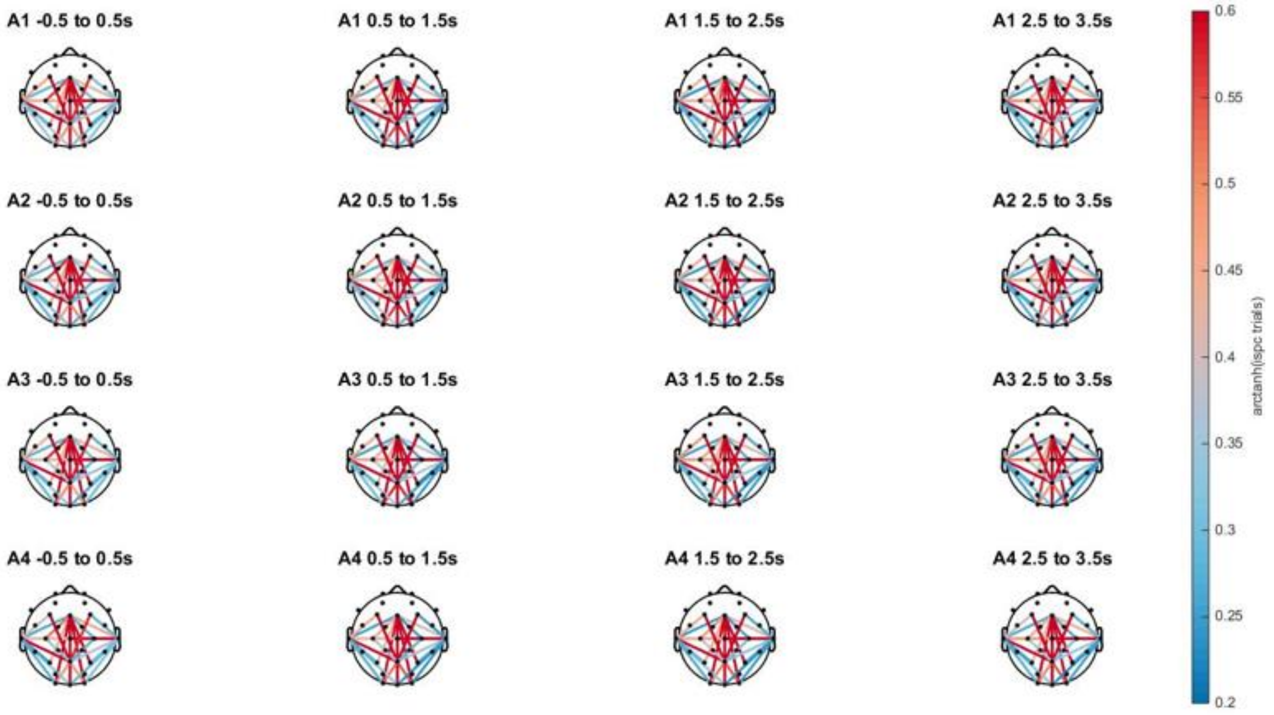
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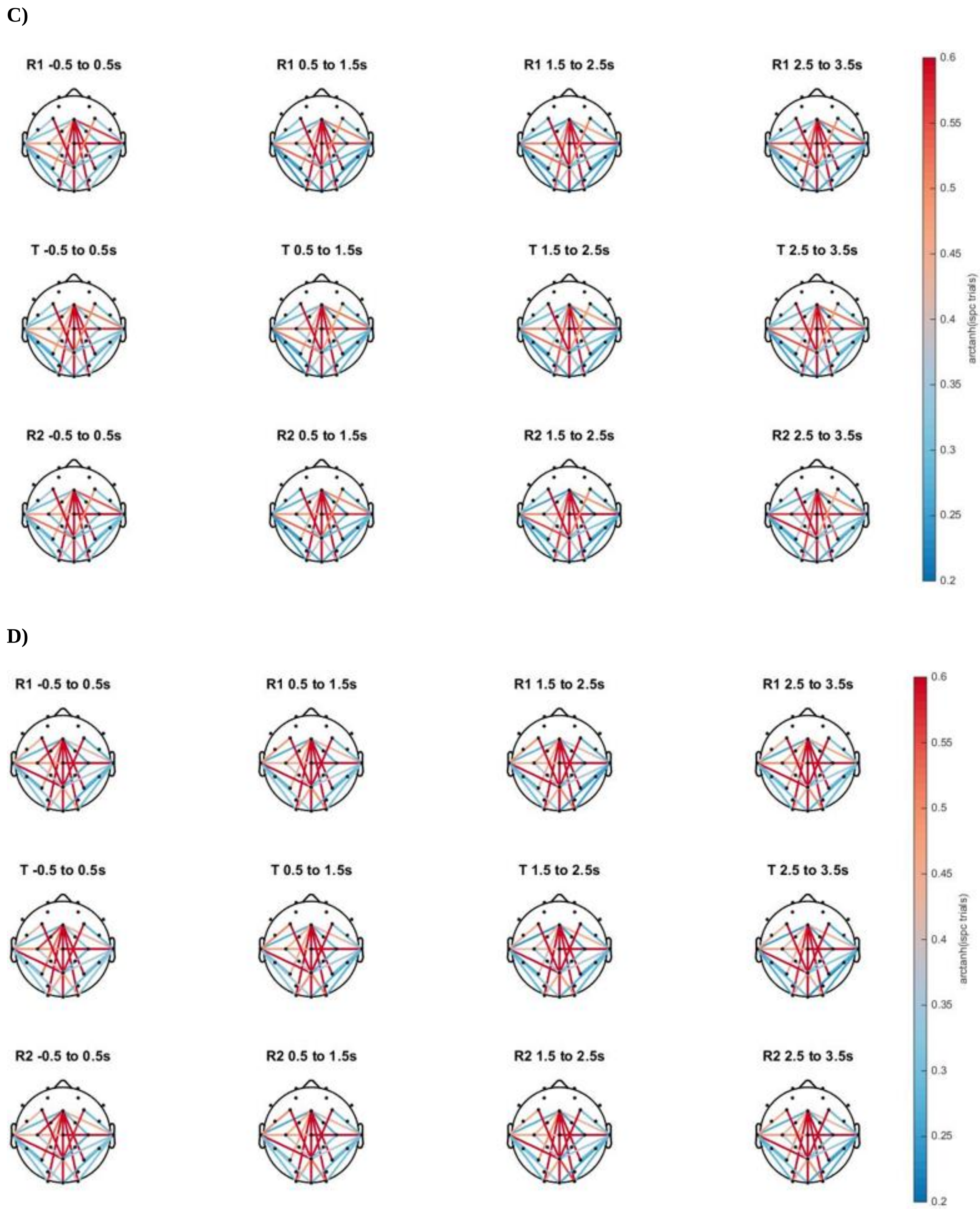

Figure 2. Connectivity Bin × Group at different electrodes. A) Topographic distribution of atanh($\mathrm{ISPC}_{\mathrm{trials}}$) for sequence trials in the explicit group at day-1; B) Topographic distribution of atanh($\mathrm{ISPC}_{\mathrm{trials}}$) for sequence trials in the implicit group at day-1; C) Topographic distribution of atanh($\mathrm{ISPC}_{\mathrm{trials}}$) for sequence trials in the explicit group at day-2; D) Topographic distribution of atanh($\mathrm{ISPC}_{\mathrm{trials}}$) for sequence trials in the implicit group at day-2.

Summary. In sum, the analyzes revealed that the frontal midline was strongly connected with posterior (parietal and occipital) sites (Fz-Oz, Fz-Oz); the parietal midline was strongly connected with left-frontal and left-temporal sites (Pz-F3, Pz-T7); the left-temporal site was more connected with left-frontal and parietal sites (T7-F3, T7-Pz); and the right-temporal site was more connected with the frontal midline (T8-Fz).

Moreover, it revealed event-related reduction in preparatory connectivity with the frontal-midline (Fz) was apparent at all phases (acquisition, retention, pressure). Interestingly, during retention and pressure this effect emerged for connectivity with the both left and right temporal sites (T7, T8).

Additional results: discussion

Topographic distribution. This paragraph contains a discussion on results that are not directly related to our hypotheses but nevertheless contribute to our understanding of the neurophysiological processes underpinning the execution of movement sequences. In fact, in both groups, power and connectivity displayed a comparable topographical distribution that might be related to common processes implemented when performing the task. On the one hand, power was lowest in the right-hemisphere, at frontal, central, temporal, and parietal sites; while in the left-hemisphere only at the central site. Considering that the task required to quickly respond with the left-hand to a series of stimuli appearing on a screen, activation of the contralateral areas responsible for left-hand control and for visuospatial attention it is not surprising. On the contrary, activation of the left-central sites might be linked to motor imagery. Moreover, connectivity analyzes revealed that the frontal midline was strongly connected with posterior (parietal and occipital) sites (Fz-Oz, Fz-Oz) confirming the involvement of the frontoparietal network.

Event-related changes. Additionally, analyzes showed event-related changes in pre-movement activity. In fact, we observed the well-documented event-related attenuation of alpha power typical of preparation to motor tasks (Babiloni et al., 1999; Cooke et al., 2014; Pfurtscheller & Aranibar, 1979). This effect was was widespread to all electrode sites (cf., Cooke et al., 2014) and characterized all phases (acquisition, retention-pressure). Similarly, prior to movement a progressive event-related isolation (weaker connectivity) of frontal midline (Fz) from other sites was apparent at all phases (acquisition, retention, pressure). Interestingly, after an overnight sleep consolidation this event-related isolation was observed for both left and right temporal sites (T7, T8) too. This latter effect is less well documented for the simple reason that previous studies did not track connectivity changes across different time point but rather averaged connectivity over time or calculated difference scores measures (e.g., Del Percio et al., 2011; Zhu et al., 2011).

Generalized Effects of Practice and Pressure. The performance improvements observed on day-1, were also accompanied by neurophysiological changes in high-alpha power generalized common to both groups. Specifically, these changes suggested a progressive reduction in activity at midline and left-frontal (Fz, F3), midline central and occipital (Cz, Oz), and bilateral temporal (T7, T8) sites. Considering the correlation with performance changes, these results imply a reduction in activity as learners evolve from relatively cognitive to relatively autonomous modes of control, which are compatible with automaticity-based models of motor learning (e.g., Fitts & Posner, 1967). In other words, these alpha-mediated changes might represent a generalized neurophysiological mechanism for smooth execution of sequential movements (i.e., *psychomotor efficiency*, Hatfield & Hillman, 2001). It should be pointed out that in our previous investigation (Bellomo et al., 2018), a similar increase in alpha during sequence acquisition was observed but it was limited to the left-temporal (T7) site. However, since in such investigation only 4 electrodes were employed, the more widespread effects that emerged in the current study may be attributable to greater practice and the wider electrode montage employed in this study.

During the high-pressure block, performance improved, and power and connectivity showed changes that were generalized to both groups. Specifically, compared to retention (R1) and to the low-pressure block (R2), under pressure (T) we observed a generalized increase in activity (power data) which was strongest at frontal and posterior (parietal, occipital) sites; and a relative isolation (connectivity data) of the frontal midline (Fz), and of the right-temporal site from parietal and frontal sites (at T8-Pz and T8-F4). From a functional perspective this suggests that crucial notes of the frontoparietal network (Ashe et al., 2006) were more activated under pressure, although not in synchrony. Taken together, these effects indicate a more cognitively demanding frontoparietal network function under pressure. However, since performance was comparable during the high- and low-pressure block, we believe that these effects might be directly linked to the attentional/emotional effect of increased competitive pressure, rather than representing a change in motor function. Such an interpretation is in line with the attentional-control theory (ACT; Eysenck et al., 2007), which states that performance drops under pressure can be countered by investing, from a limited pool, additional cognitive resources (i.e., effort) into the task. Although speculative, this would imply an interaction between ACT and reinvestment theory, which are traditionally discussed separately to explain the effects of distraction versus. self-focus on performance (see, De Caro et al., 2011). Future studies should clarify this point. Notably, pressure did not induce any left-temporal specific effect, therefore ruling out the possibility that the effects observed in previous studies (Bellomo et al., 2018; Hatfield et al., 2013; Zhu et al., 2011) might have been a direct by-product of psychological pressure.

CHAPTER FOUR

Bellomo, E., Cooke, A., Gallicchio, G., Ring, C., Hardy, J. (in preparation). Effects of skill-relevant vs -irrelevant self-talk on high-alpha left-temporal (T7) power and (T7-Fz) connectivity.

Abstract

Recent evidence discusses two EEG measures, namely left-temporal high-alpha (T7) power and left-frontotemporal (T7-Fz) connectivity, as neurophysiological indices of conscious processing. However, it is not clear whether these measures are actually sensitive to conscious processing, or to other processes linked to skill-relevant verbal processing, more general verbal processing happening during motor performance, or psychological pressure. This study aims at testing the construct validity of these left-temporal EEG measures. Verbal processing during motor performance was manipulated via a self-talk intervention. Thirty-four golf novices practiced a golf-putting task while using either skill-relevant (instructional) or skill-irrelevant (motivational) self-talk preceding each putt. Moreover, they performed the task under low- (block 1, block 2) and high- (block T) psychological pressure conditions. Results failed to show any group- or pressure-dependent difference for either high-alpha T7 power or T7-Fz connectivity, thereby questioning the construct validity of these measures and their predicted relations with verbal processing functional to movement execution, and in turn conscious processing. In conclusion the left-temporal EEG measures traditionally cited as neurophysiological indices of conscious processing may actually reflect the amount of any form of self-talk, rather than serving as distinct markers of movement-specific conscious processing.

Keywords: reinvestment theory; conscious processing hypothesis; psychological pressure; left-temporal activity;

Introduction

The acquisition of complex movements, such as learning to drive a car, play a musical instrument, or perform sports skill, is often characterized at the initial stages by a deliberate top-down effort to control movement execution. According to well established theories of motor learning (e.g., Fitts & Posner, 1967; Hikosaka et al., 1999; Masters, Polman, & Hammond, 1993; Willingham, 1998), such efforts to control movement, often referred to as *conscious processing* (Hardy, Mullen & Jones, 1996; Masters & Maxwell, 2008), mark the so-called explicit route for movement acquisition. In the current experiment, we manipulated, by means of a self-talk intervention, the content of pre-movement verbalizations (skill relevant versus irrelevant) to examine the psychophysiological processes underpinning explicit skill acquisition, and test putative electroencephalographic (EEG) indices of conscious processing.

Conscious processing, EEG, and verbalizations

In motor learning, conscious processing is thought to be characterized by explicit working-memory mediated verbalizations that guide movement execution (Masters & Maxwell, 2008, Zhu, Poolton, Wilson, Maxwell, & Masters, 2011). Evidence that conscious processing is associated with electroencephalographic (EEG) activity in the left hemisphere, which plays a role in working-memory function and language-related processing, has been used to support the hypothesis (Zhu, Yeung et al., 2015; Zhu et al., 2011). In particular, studies measuring EEG activity during self-paced sports skills, such as golf putting or shooting, reported changes in left-temporal (T7) power and left-frontotemporal (T7-Fz) connectivity in the high-alpha frequency band as a function of expertise level and type and amount of practice (Gallicchio, Cooke, & Ring, 2017, 2016; Hatfield et al., 2013; Zhu et al., 2011). For example, left-hemispheric high-alpha power is lower while left-frontotemporal connectivity is greater in novices compared to experts (Gallicchio et al., 2017; 2016).

On the one hand, power in the alpha band is connected to cortical inhibition, whereby more alpha indexes increased inhibition and less alpha indexes decreased inhibition (Klimesch, 2012;

Klimesch, Sauseng & Hanslmayr, 2007). On the other, alpha connectivity reflects long-range cortico-cortical communication, with high synchronicity between sites reflecting increased connectivity and low synchronicity reflecting functional isolation (Lachaux, Rodriguez, Marinerie, & Varela, 1999). Accordingly, studies that distinguish expertise with left-hemispheric EEG (e.g., Gallicchio et al., 2016, 2017; Zhu et al., 2011) interpreted diminished left temporal alpha power alongside elevated left frontotemporal connectivity as indicative of increased verbal activity and active communication between verbal and motor planning brain areas due to conscious processing (Hatfield et al., 2013; Hilmann, Apparies, Janelle, & Hatfield, 2000).

However, studies that also measured self-reported conscious processing noted that subjective reports were disconnected from EEG measures (Bellomo et al., 2018; Gallicchio et al., 2017). For instance, Bellomo and colleagues (2018) found that conscious processing reported by explicit learners while performing a motor skill during acquisition displayed a different pattern than both left-temporal alpha power and left frontotemporal connectivity. This disconnect is surprising since, by definition, individuals who *consciously process* their movements should be aware of and able to accurately report their conscious processing habit. Therefore, Bellomo et al., (2018) raised the possibility that left-temporal high-alpha power and left-frontotemporal connectivity could actually reflect more general verbal processes (e.g., self-motivating statements) rather than specific movement-relevant verbalizations. Our aim is to test this possibility by directly manipulating the semantic content of covert verbalizations emitted in the seconds preceding movement execution and examining the effects on the putative EEG measures of conscious processing.

The vehicle we use to examine this aim is self-talk. In the context of motor skills, the self-talk literature (for a review see Hardy, Comoutos, & Hatzigeorgiadis, 2018) distinguishes two basic functions, namely instructional and motivational, which are respectively more and less relevant to motor execution. Specifically, instructional self-talk consists of verbalizations relevant to movement execution which aim to guide motor execution, while motivational self-talk consists of verbalizations which are more directly related to arousal and confidence (cf., Hardy, 2006).

Therefore, if left-temporal high-alpha power and left-frontotemporal connectivity reflect movement-related verbalizations, we expect them to respond to instructional self-talk but not motivational-self talk.

Conscious Processing and EEG under Pressure

While we assume the instructional self-talk is likely to provoke conscious processing, it has already been established that increases in psychological pressure can increase conscious processing of movements. For example, Vine, Moore, Cooke, Ring and Wilson (2013) found that self-reported conscious processing increased from low-pressure to high-pressure conditions in novice golfers who were following an explicit learning regime. Moreover, according to reinvestment theory (Masters & Maxwell, 2008), pressure-induced increases in conscious processing can provoke impairments to technique and performance. For instance, in concert with their pressure-induced increase in self-reported conscious processing, Vine and colleagues' (2013) novice golfers significantly reduced their putting accuracy from low-pressure to high-pressure conditions. Moreover, Zhu and colleagues (2011) showed that despite no change in performance under pressure, left-frontotemporal connectivity increased in novice golfers that had undergone an explicit training regime. However, it is plausible that subtle performance changes had gone undetected since performance was only measured crudely, in terms of number of holed putts. Hatfield and colleagues (2013), measured performance more precisely via movement kinematics in their study of pistol shooting and found that increased psychological pressure was accompanied by dysfunctional changes to this measure, decreased left-temporal alpha power, and increased left frontotemporal connectivity. Accordingly, if left-temporal activity reflects movement-related verbalizations, we expected that the combination of instructional self-talk and a high psychological pressure would produce particularly strong manifestations of the predicted left-temporal high-alpha power and frontotemporal connectivity patterns.

The Present Study

This study is the first to employ a self-talk intervention[11] to explicitly manipulate the content of pre-movement verbalizations during movement acquisition and performance pressure. Our aims were to clarify the link between the semantic content of pre-movement verbalizations and the putative neurophysiological measures of conscious processing (high-alpha temporal power and frontotemporal connectivity in the left-hemisphere). Based on the conceptual link between instructional self-talk and conscious processing, we hypothesized that if high-alpha temporal power and frontotemporal connectivity in the left-hemisphere are sensitive to movement-related verbalizations only, they should distinguish the instructional self-talk group from the motivational self-talk group. Specifically, we expected the instructional self-talk group to display comparatively less left-temporal high-alpha power, and more left-frontotemporal connectivity than the motivational self-talk group. Since elevated psychological pressure can further provoke conscious processing (Masters & Maxwell, 2008), we expected these group differences in cortical activity to be amplified during a high-pressure condition. We also expected the combination of instructional self-talk and increased pressure would result in elevated self-report conscious processing and degraded technique and performance in the instructional self-talk group. Conversely, if measures of left-temporal activity are more sensitive to general verbal processing not directly connected to the motoric aspects of movement execution, we expected no group differences during low-pressure or high-pressure conditions.

Methods

Participants

Participants were 40, right-handed (Edinburgh Handedness Inventory ≥ +70, Oldfield, 1971) golfing novices ($N_{females}$ = 21; N_{males} = 19), aged ~26 years [instructional M_{age} = 25.95(5.98); motivational M_{age} = 26.00(2.83)]. We used novices and a golf putting task based on meta-analytic

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[11] Please note that chapter 4 and 5 discuss data coming from the same investigation. Chapter 4 focused on a direct test-of the link between pre-movement verbalizations and left-temporal EEG measures. Chapter 5 focused on a larger scale investigation of additional psychophysiological correlates of self-talk type.

evidence showing largest effects sizes for self-talk manipulations for novel tasks with fine-motor requirements (Hatzigeorgiadis et al., 2001) and because EEG can be recorded while putting (e.g., Cooke et al., 2014). Our sample size was powered at .80 to detect up to small interaction effects ($\eta_p^2 = .04$) in a 2 × 3 mixed-model analysis of variance (ANOVA) at the 5% level of significance. All participants had normal/corrected vision, refrained from consuming alcohol, drugs (24 hours before), and caffeine (3 hours before), and reported more than 6 hours of sleep before testing. They provided informed consent and received £10 to compensate for their time. The protocol was approved by the local research ethics committee.

Design

We employed a mixed-model design with Group (instructional self-talk versus motivational self-talk) as a between-participant factor, and Block (block 1, block 2, transfer block) as a within-participant factor. Participants were randomly allocated to an instructional self-talk group or a motivational self-talk group. Participants performed 40 putts under low pressure during block 1 and block 2, and 40 putts under high-pressure during the transfer block.

Putting Task

Participants were asked to putt golf balls (diameter ~ 4.27 cm) on an artificial flat putting surface to a target - adhesive paper marker (diameter = 0.6 cm) - at a distance of 2.46 m, using a blade-style putter (length 90 cm). Participants were instructed to putt at their own pace as accurately as possible in order get each ball “as close as possible to the target”. They were additionally instructed to rehearse an instructional or motivational self-talk cue (see Procedure section and Supplementary Material) immediately before executing the swing. After each putt, the terminal location of the ball was recorded with a photograph taken by a digital camera positioned perpendicularly above the target location (see Neumann & Thomas, 2008). Then the ball was replaced at the start position by the experimenter. This ensured that participants did not need to move between trials, thereby keeping movement artefacts to a minimum while also regulating the inter-trial interval.

Procedure

Participants completed a 2-hour testing session. Following instruction and instrumentation they sat and rested with eyes-closed followed by eyes-open for one minute each while EEG was recorded to adjust frequency bands to the individual alpha peak (IAF, see Bazanova & Vernon, 2014; Corcoran, Alday, Schlesewsky, & Bornkessel-Schlesewsky, 2018. The experiment comprised four phases: (1) 10-putt familiarization task; (2) self-talk training; (3) low-pressure acquisition, (4) high-pressure transfer.

10-putt familiarization task. As participants were novices and unfamiliar with the laboratory setting, they performed 10 putts to familiarize with the experimental conditions.

Self-talk training. Given that Hatzigeorgiadis and colleagues' (2011) meta-data supports the inclusion of a self-talk training phase, our participants practiced the self-talk instructions while performing an aiming motor task. A pre-recorded podcast was used to explain either instructional or motivational self-talk (see Figure 1 and Figure 2 Supplementary Material). Participants then completed 20 trials of a mini basketball free-throw task. In the first 10 trials they were asked to practice the skill without any additional instruction. In the second 10 trials, they rehearsed a self-talk cue corresponding to the group they were assigned to before each attempt. The use of this task ensured that all participants had experience using self-talk during a precision motor task.

Low-pressure acquisition. Next, participants were told that they would begin the main golf putting phase of the experiment (block 1 and block 2). Participants were assigned a group-specific cue for the golf-putting task: instructional cue *"feet still – wrists locked – arms through"*; motivational cue "*come on, I can do this"*. We assigned cues to increase within-group consistency (in terms of content and length) in the use of covert-verbalizations in preparation for each putt. We developed the self-talk cues based on previous protocols (Hardy, 2006; Hardy et al., 2015; Theodorakis et al., 2000), golf-coaching manuals, and pilot testing (see Supplemental Material). We instructed participants to silently say their assigned cue in their mind before every putt. They then completed two blocks of 40 putts, separated by a two-minute break. We reminded participants about their self-talk cue every 5 putts during this phase of the experiment.

High-pressure transfer. Finally, participants completed a last block of 40 putts in a relatively high-pressure condition. To induce pressure, we told participants immediately before this final block that this was the “test-phase”, whereby their performance would be evaluated and compared to other participants. For this purpose, they were induced to believe that a video-camera was set to record their movements. Moreover, they were informed that based on their performance in the previous block, they had earned £10 (same amount for all participants) but whether they would retain that pot of money depended on their performance in this last block. Subsequently, they were informed that before calculating the final performance score, 10 out of the 40 putts would be selected at random and their mean radial error (distance from the target) would be doubled, meaning that each putt was crucial for determining their final score. This last manipulation aimed at preventing a dilution of the pressure effects (i.e., although there were multiple trials, every individual trial was important). The final score would be then compared to other participants’ and, on one side, the top five performers would receive an additional monetary prize (£30, £20, £15, £10, £5), while on the other, the worst five performers would not retain the money, their data would be of no use for the study, and their participation will have been a waste of their and the experimenter’s time. Once again, every five putts we reminded participants about their self-talk cue. On completion of this final block of putts, participants were fully debriefed, thanked and asked not to disclose specific detail about the pressure manipulation to others.

Measures

Manipulation Checks.

State anxiety. To assess the effectiveness of our pressure manipulation we administered the Mental Readiness Form-3 (MRF-3; Krane, 1994) which consists of two statements (i.e., cognitive anxiety: “*my thoughts are…*”; somatic anxiety: “*my body feels…*”) rated on a 11-point Likert scale (range 1-11) respectively anchored *not worried-worried, not tense-tense*. Participants completed this form after instructions but before they began putting in each block.

Self-talk. Self-report frequency of use and relevance of the assigned self-talk cue were measured at the end of each block of 40 putts by asking participants to rate on a 0-100 scale two statements (frequency: "how often have you used the keywords in the previous set of putts"; relevance: "how much do you think that the cue was helpful to your performance") anchored *never-always* and *not relevant at all-totally relevant* (see Theodorakis et al., 2000).

Performance. Participants' performance was evaluated in terms of angle error (degrees), length error (cm) and radial error (cm), which respectively yield measures of directional accuracy, force accuracy, and a combination of direction and force. These measures were computed for each putt using a camera system (Neumann & Thomas, 2008) and averaged (geometric mean) to yield measures for each block.

Movement kinematics. Movement kinematics were recorded using a triaxial accelerometer (LIS3L06AL, ST Microelectronics, Geneva, Switzerland). Acceleration on the X, Y, and Z axes corresponded to lateral, vertical, and back-and-forth movement of the clubhead, and assessed clubhead orientation, clubhead height, and impact velocity, respectively. The signals were conditioned by a bespoke buffer amplifier with a frequency response of DC to 15 Hz. Both accelerometer and amplifier were mounted in a 39 mm × 20 mm × 15 mm plastic housing secured to the rear of the putter head.

To compute kinematic variables, we scored acceleration for each putt from the onset of the downswing phase of the putting stroke until the point of ball contact (e.g., Cooke, Kavussanu, McIntyre, Boardley, & Ring, 2011; Cooke, Kavussanu, McIntyre, & Ring, 2010). Specifically, we calculated average acceleration for the X, Y, and Z axes, and impact velocity for the Z axis as the primary axis involved in the putting stroke.

Conscious processing. We used the task-specific conscious motor processing subscale (see Bellomo et al., 2018; Gallicchio et al., 2017), a version of the movement specific reinvestment scale

(Masters, Eves, & Maxwell, 2005), to measure self-reported conscious processing during acquisition and transfer. This contained five statements (e.g., “I was aware of the way my body was working”) that were rated on a 6-point Likert scale (1 = strongly disagree, 6 = strongly agree). The mean Cronbach’s α coefficient was .59. Participants completed this measure at the end of each block of putts.

Electrophysiological data. EEG activity was recorded from thirty-two (32) active electrodes at Fp1, Fp2, AF3, AF4, F7, F3, Fz, F4, F8, FC5, FC1, FC2, FC6, T7, C3, Cz, C4, T8, CP5, CP1, CP2, CP6, P7, P3, Pz, P4, P8, PO3, PO4, O1, Oz, O2 (10-20 system, Jasper, 1958) [12]. Additionally, active electrodes were positioned on each mastoid, at the outer canthus and below each eye to record vertical and horizontal electrooculogram (EOG). All channels were recorded in monopolar. The signals were sampled at 1024 Hz, with no online filter, using an ActiveTwo amplifier (Biosemi, The Netherlands). Electrode offset was kept below 15 mV. TTL triggers were sent to the BioSemi system to identify swing-onset, identified by the putter head being moved away from and thereby breaking an infrared beam controlled by an optical sensor (S51-PA 2-C10PK, Datasensor, Monte San Pietro, Italy) and a microphone (NT1, Rode, Silverwater, Australia) connected to a mixing desk (Club 2000, Studiomaster, Leighton Buzzard, UK), which detected the putter-to-ball contacts. These signals were recorded using both Actiview (BioSemi) and Spike2 Software (CED-2).

Offline signal processing was performed using EEGLAB (Delorme & Makeig, 2004), ERPLAB (Lopez-Calderon, & Luck, 2014) and bespoke scripts in MATLAB (Mathworks Inc., USA). Signals were offline down-sampled to 250 Hz, re-referenced to the average of all 32 EEG channels, and filtered .01 to 30 Hz (Butterworth, 12dB/40roll-off order2 non-causal). In line with previous research (e.g., Cooke et al., 2014; Hatfield et al., 2013) data were then segmented into epochs from -4000 ms to +1000 ms relative to swing-onset and centered around the average voltages between -200 ms and 0 ms. Epochs were visually inspected and rejected if they contained

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[12] While 32 channels were recorded and used for data pre-processing, we only report the analyses of T7 and the T7-F3 and T7-Fz electrode pairs in this chapter. This is in line with our targeted hypotheses concerning these left frontotemporal sites. For a more exploratory analysis of all the sites please see the next chapter of the thesis.

gross artefacts. The number of epochs retained was for block 1 39.3 (SD = 2.17), for block 2 39.07 (SD = 4.10), and for transfer block 39.47 (SD = 2.18). No bad channels were identified. Independent component analysis (ICA) weights were obtained through the RunICA informax algorithm (Makeig, Bell, Jung, & Sejnowski, 1996) running on these same EEG data (32 channels, yielding the same number of independent components) that, however, were instead high-pass filtered to 1 Hz (FIR [finite impulse response] filter, filter order 826) and concatenated across all trials within each participant. Then ICA weights were applied to the original 0.1-30 Hz filtered signals, and artefactual components (e.g., eye or muscle related) flagged by automated procedures (SASICA plugin; Chaumon, Bishop, Busch, 2015) and then visually inspected were manually rejected.

Time-frequency analysis. Time-frequency analysis was applied by convolving the fast-fourier (FFT) power spectrum of each EEG artefact-free epoch with a family of complex Morlet wavelets, defined as a Gaussian-windowed complex sine wave: $e^{i2\pi tf}e^{-t^2/2\sigma^2}$; where t is time, f is frequency bin, which increased from 4 to 30 Hz in 30 logarithmically steps, and σ defines the width of each frequency band (set to $cycles/2\pi f$, with *cycles* ranging from 3 and 6), and then taking the inverse FFT to obtain the analytic signal z. From the convolution we obtained: (1) estimates of instantaneous power (squared magnitude of the analytic signal); and (2) phase (phase angle of the analytic signal) which was then used to compute connectivity ($\mathrm{ISPC}_{\mathrm{trials}}$).

Individual alpha frequency (IAF). Following the approach advocated by Bazanova and Veron (2014), the frequency bands of interest were adjusted based on the individual alpha peak (IAF, Kilmesh, 1996; 1999, Klimesh et al., 1998). IAF was calculated with the IAF toolbox (Corcoran et al., 2018) based on a 60s segment of eye-closed recording taken before the beginning of the task, which were processed in the same way as task-related data (excluding the epoching). Accordingly, the IAF-adjusted high-alpha frequency band was as IAF to IAF+2. Estimates of IAF were 9.92 ± 1.17 for the instructional and 9.92 ± .83 for the motivational group and were not statistically different.

Power. Changes in instantaneous power were calculated from the complex signal for each frequency bin (f) as the squared magnitude of the result of the convolution defined as Z_t (power time series: $p_t = real(z_t)^2 + imag(z_t)^2$. Crucially, no baseline normalization was employed. Following the approach of Gallicchio and colleagues (Gallicchio, Finkenzeller, Sattlecker, Lindiger, & Hoedlmoser, 2016, Gallicchio et al., 2016, Gallicchio & Ring, 2018) to control for skewness and interindividual differences, trial-averaged absolute alpha power was median-scaled log transformed, whereby values for each participant were scaled by the median of all values (electrode × points × block matrix) per each wavelet (representing a frequency bin) within that participant, and then subjected to a $10 \cdot \log_{10}$ transformation. Power was then averaged across IAF-adjusted frequency bands, and time bins (bin1: -4s to -3s; bin2: -3s to -2s; bin3: -2s to -1s; bin4: -1s to 0s; bin5: 0s to +1s).

Connectivity. Functional connectivity between sites was computed in terms of inter-site phase clustering (ISPC) based on the phase angle time series, $\phi_t = imag(z_t)^2/real(z_t)^2$. This measure was preferred to other (e.g., magnitude squared coherence) as, being based on phase angle differences, it is independent of absolute power variations (Lachaux, Rodriguez, Marinerie, & Varela, 1999). $\text{ISPC}_{\text{trials}}$ measures consistency of phase angle differences at specific time points across trials and is calculated with the following formula: $ISPC_{xy}(f) = \left|n^{-1}\sum_{t=1}^{n} e^{i(\theta_x(tf)-\theta_y(tf))}\right|$; where *n* is the number of trials, *i* is the imaginary operator, θ_x and θ_y are the phase angles of the recorded signal at two different scalp locations, *t* is trial, and *f* is the frequency bin, $e^{i(\theta_x(tf)-\theta_y(tf))}$ is the complex vector with magnitude, $n^{-1}\sum_{t=1}^{n}(.)$ denotes averaging over trials (for $\text{ISPC}_{\text{trials}}$), and $|.|$ is the magnitude of the averaged vector (Cohen, 2014; Lachaux et al., 1999). The resulting ISPC is a real number between 0 (no functional connection) and 1 (perfect functional connection). ISPC values were Z-transformed (i.e., inverse hyperbolic tangent) to ensure normal distribution before statistical analyses were performed (Halliday et al., 1995).

Statistical Analyses

We removed six participants (two motivational, four instructional) due to non-adherence with the self-talk manipulation (i.e., used on < 80% of trials, used additional incompatible verbalizations). Therefore, statistical analyses were conducted on 34 participants.

Self-report and behavioral data were analyzed using 2 Group (instructional, motivational) × 3 Block (block 1, block 2, transfer block) ANOVAs. To test our a priori hypotheses regarding the left-temporal sites (i.e., power at T7, and connectivity at T7-Fz and T7-F3) 2 (Group) × 3 (Block) × 5 (Bin; -4s to -3s, -3s to -2s, -2s to -1s, -1s to 0s, 0s to +1s, where 0s is movement initiation) mixed-model ANOVAs were employed to analyze EEG data. The Bin factor is recommended in studies of self-paced aiming movements in order to account for phasic shifts in power and connectivity during preparation for action (Cooke et al., 2014).

The multivariate method of reporting results was adopted as it minimizes the risk of violating sphericity and compound symmetry assumptions in repeated measures ANOVA (Vasey & Thayer, 1987). Effect size is reported with partial η squared (η_p^2) values of .10, .25, and .40 (for repeated measures ANOVA), and .02, .15, and .35 (for multivariate ANOVA) indicating relatively small, medium, and large effect sizes, respectively (Cohen, 1988).

Results

Pressure manipulation. The Group × Block ANOVAs for cognitive and somatic anxiety revealed main effects of Block, Fs(2, 31) = 9.15 to 16.86, $ps <= .001$, η_p^2s = .37 to .52, and Group, F(1, 32) = 7.32 to 4.13, ps = .011 to .22, $\eta_p^2 < .15$ to .19, Anxiety increased from the second block to transfer under pressure and was higher for the motivational than instructional self-talk group (Table 1). There was no Block × Group interaction, Fs(2, 31) = .24 to .25, ps = .78, η_p^2s = .02.

Self-talk manipulation. The Group × Block mixed-model ANOVA applied to our self-talk measures revealed a main effect of Block for self-talk cue relevance, $F(2, 31) =11.78$, $p < .001$, $\eta_p^2 = .43$, whereby scores increased with practice from block 1 to block 2 (Table 1). No other main effects for either Block, Fs(2, 31) = .56, p = .58, η_p^2s = .03, or Group, Fs(1, 32) = .14 to .53, ps =

.71 to .47, η_p^2s = .00 to .02, nor interaction effects *F*s(2, 31) = .08 to .80, *ps* = .46 to .92, η_p^2s = .00 to .05. These results confirm the success of our self-talk manipulation as the cue was used frequently (>90% of the trials), and with practice it was perceived as progressively more meaningful (Table 1).

Performance. The Group × Block mixed-model ANOVA revealed main effects of Block, *F*s(2, 31) = 3.07 to 18.28, *ps* < .001 to .061, η_p^2s = .16 to .54, for mean radial error, mean angle error and mean length error. Follow-up pairwise comparisons revealed that performance, in terms of accuracy of force and direction, improved across blocks (Table 1). No other main effects of Group, *F*s(1, 32) = 1.54 to 3.56, *ps* = .068 to .223, η_p^2s = .05 to .10, or interactions *F*s(2, 31) = .15 to .56, *ps* = .576 to .863, η_p^2s = .01 to .03, emerged.

Movement kinematics. Group × Block mixed-model ANOVA employed to assess the kinematic variables revealed main effects of Block, *F*s(2, 31) = 3.20 to 3.72, *p*s = .036 to .055, η_p^2s = .17 to .19 and main effects of Group, *F*s(1, 32) = 5.26 to 12.87, *p*s = .001 to .029, η_p^2s = .14 to .29 for lateral (X-axis) and back-and-forth (Z-axis) acceleration. Acceleration on the X and Z axis decreased across blocks and was lower in the instructional group than the motivational group (Table 1). No other main effects of Block, *F*(2, 31) = .46, *p* = .638, η_p^2 = .03, Group, *F*(2, 31) = .00, *p* = .984, η_p^2 = .00, nor interactions, *F*s(2, 31) = .08 to .45, *p*s = .640 to .921, η_p^2s = .00 to .03 emerged.

Conscious processing. The Group × Block mixed-model ANOVA revealed a main effect of Block for conscious motor processing, *F*(2, 31) = 26.36, p < .001, η_p^2 = .63, whereby scores decreased from block 2 to pressure transfer (Table 1). No main effect of Group, *F*(1, 32) = 1.49, *p* = .231, η_p^2 = .04, or interaction, *F*(2, 31) = .86, *p* = .918, η_p^2 = .01,emerged.

Table 1. Mean (SD) of self-report and performance measures in each Block and each Group.

	Block		
Measure (range)	**block 1**	**block 2**	**transfer block**
Pressure Manipulation			
Cognitive Anxiety			
Instructional	2.00 (1.67)	2.50 (1.71)	4.94 (2.98)
Motivational	4.00 (2.45)	4.11 (2.52)	6.67 (2.81)
Somatic Anxiety			
Instructional	2.44 (1.31)	3.25 (2.24)	5.13 (3.07)
Motivational	4.44 (2.72)	4.83 (2.71)	6.39 (2.43)
Self-talk manipulation			
Frequency of use (%)			
Instructional	90.50 (5.83)	95.06 (7.36)	92.88 (9.74)
Motivational	90.67 (14.60)	94.61 (8.30)	94.78 (6.69)
Relevance of the cue (%)			
Instructional	63.06 (18.60)	76.44 (15.37)	79.75 (19.08)
Motivational	60.72 (14.60)	71.89 (18.50)	74.93 (17.15)
Performance			
Radial Error (cm)			
Instructional	30.01 (8.48)	25.49 (5.66)	22.23 (5.20)
Motivational	32.47 (7.90)	27.57 (5.20)	25.82 (5.20)
Angle Error (degrees)			
Instructional	.64 (.25)	.59 (.19)	.55 (.16)
Motivational	.80 (.32)	.72 (.22)	.60 (.29)
Length Error (cm)			
Instructional	26.84 (8.80)	22.63 (5.86)	19.64 (5.30)
Motivational	28.95 (8.55)	24.63 (6.81)	22.79 (5.70)
Movement kinematics			
Lateral (x-axis) acceleration (ms^2)	.30 (.09)	.29 (.11)	.27 (.08)
Instructional	.48 (.20)	.47 (.20)	.45 (.17)
Motivational			
Vertical (y-axis) acceleration (ms^2)			
Instructional	.45 (.14)	.43 (.16)	.42 (.12)
Motivational	.44 (.21)	.44 (.18)	.42 (.15)
Back-and-Forth (z-axis) acceleration (ms^2)			
Instructional	2.19 (.61)	2.13 (.71)	2.04 (.65)
Motivational	3.26 (1.49)	3.24 (2.11)	3.02 (1.71)
Conscious processing			
CMP (1-6)			
Instructional	4.64 (.58)	4.68 (.63)	4.08 (.58)
Motivational	4.42 (.76)	4.41 (.82)	3.78 (.72)

EEG activity

The Group × Block × Bin mixed-model ANOVAs performed on on left-temporal (T7) high-alpha power and on left-frontotemporal connectivity (T7-Fz and T7-F3) revealed an event-related change in T7-F3 connectivity (main effect of Bin, $F(4, 29) = 3.63$, $p = .016$, $\eta_p^2 = .33$), which was best described by a quadratic trend ($p = .008$, $\eta_p^2 = .20$, see Figure 1).

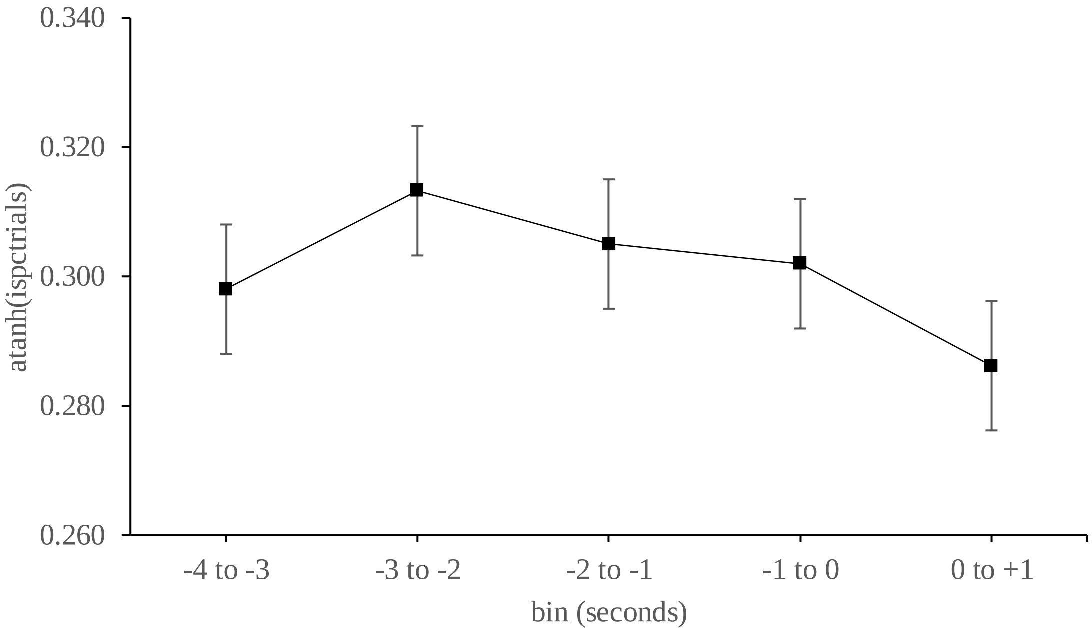

Figure 1. Event-related change (main effect of Bin) for T7-F3 high-alpha connectivity: the initial increase observed at bin 2 (-3 to -2s), was followed by a progressive decrease until the putt was completed (bin 5, 0 to +1s).

The hypothesized main effects for group: T7 high-alpha power, $F(1, 32) = .18$, $p = .671$, $\eta_p^2 = .01$, T7-Fz connectivity, $F(1, 32) = 1.83$ $p = .185$, $\eta_p^2 = .05$, T7-F3 connectivity, $F(1, 32) = .22$ $p = .640$, $\eta_p^2 = .01$,were not significant. Most of the hypothesized other interactions Group × Block interactions were non-significant: T7 high-alpha power $F(2,31) = 1.66$, $p = .206$, $\eta_p^2 = .10$, T7-F3 connectivity, $F(2, 31) = 1.79$, $p = .184$, $\eta_p^2 = .10$. Notheworthy, we observed a trend for significance for the hypothesized Group × Block interaction at T7-Fz connectivity, $F(2,31) = 2.77$, $p = .078$, $\eta_p^2 = .15$. Follow-up analyses Group × Bin ANOVAs per each Block revealed trends for significance limited to block 2 for the main effect of Bin, $F(4, 29) = 2.35$, $p = .078$, $\eta_p^2 = .24$; which was best described by a decrease prior to swing execution followed by an increase after swing initiation; and Group, $F(1, 32) = 2.92$, $p = .097$, $\eta_p^2 = .08$, whereby connectivity was stronger for the motivational group (motivational = .243 vs instructional = .202).

Discussion

The present study represents the first study evaluating the impact of a self-talk (instructional versus motivational) manipulation on high-alpha temporal power and frontotemporal connectivity in the left-hemisphere, measures that have been traditionally associated with the construct of *conscious processing* of movement (Masters & Maxwell, 2008). Our aim was to clarify the link between the semantic *content* of pre-movement verbalizations and the putative neurophysiological measures of conscious processing (high-alpha temporal power and frontotemporal connectivity in the left-hemisphere). Manipulation checks confirmed the effectiveness of our self-talk and pressure manipulations. Both groups of participants made frequent and similar use of their respective self-talk cues, thereby standardizing the *amount* of pre-movement verbalizations. Both groups also reported feeling significantly more anxious in the high-pressure than the low-pressure blocks of the experiment. Having satisfied the effectiveness of our experimental manipulations, the results are discussed in relation to each hypothesis.

Effects of Self-talk on proposed left-temporal indices of conscious processing

Based on the conceptual link between instructional self-talk and conscious processing, our first hypothesis was that if high-alpha temporal power and frontotemporal connectivity in the left-hemisphere are sensitive to movement-related verbalizations only, they should distinguish the instructional self-talk group from the motivational self-talk group. Specifically, we expected the instructional self-talk group to display comparatively less left-temporal high-alpha power, and more left-frontotemporal connectivity than the motivational self-talk group. Our results showed that left-temporal power and left-frontotemporal connectivity in the high-alpha band did not differ between instructional versus motivational self-talk groups[13]. Based on theory arguing that elevated

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[13] Although only marginally significant (p = .098), it should be mentioned that results revealed that in block 2, the motivational group was characterized by comparatively stronger left-frontotemporal (T7-Fz) connectivity. This might suggest that motivational self-talk was characterized by more motor-verbal processing compared to the instructional group. This would be possible if motivational self-talk, by motivating to learn, had triggered additional “organic” conscious motor processing. However, in light of the fact that the analysis was performed only on participants who reported to have mentally rehearsed solely the assigned self-talk cue and nothing else, and the fact that no differences in self-reported conscious processing emerged, we deem this interpretation unlikely.

psychological pressure can further provoke conscious processing (Masters & Maxwell, 2008), our second and related hypothesis was that any group differences in cortical activity would be amplified during a high-pressure condition. Since there were no group differences in cortical activity, this prediction was not supported either. These results provide evidence against the popular interpretation of left-temporal EEG measures as representing verbal processing specifically functional to movement execution. One possible explanation is that high-alpha left-temporal power and left-frontotemporal connectivity are sensitive to any verbalizations that casually happen during motor execution, regardless of their semantic content (Bellomo et al., 2018). In support of this contention we observed a consistent and relatively high-level of self-talk usage in both groups across all three blocks. These data provide some tentative support for the idea that, overall, the language-related left-hemisphere was consistently more activated as participants, irrespective of group, rehearsed their assigned cue. However, it is interesting to note that the different semantic content of self-talk (i.e., instructional versus motivational) did not lead to group differences in self-reported conscious processing either. This is somewhat surprising since, if conscious processing consisted principally of movement-related verbalizations (cf., Zhu et al., 2011), individuals using an instructional self-talk cue emphasizing the steps related to the most “correct” execution of a golf putt should report higher conscious processing scores compared to individuals employing a non-movement-relevant motivational self-talk cue. Instead, it seems that conscious processing might encompass processes in addition to movement-relevant verbalizations. In fact, even though they were not supplied with technique-related instructions, members of our motivational self-talk group could have still engaged in conscious processing and scored high on reinvestment scale items such as “*I reflect about my movement a lot”* or *“I am always trying to figure out why my actions failed”* through either verbal or visual analysis of their movement. In other words, it is possible that conscious processing of movements might have happened due to hypothesis-testing and reflection outside the assigned self-talk cue. In light of these considerations, and the fact that previous studies found that self-report conscious processing did not co-vary with either high-alpha left-temporal power or left-frontotemporal connectivity (Bellomo et al., 2018; Gallicchio et al., 2017), we recommend caution when interpreting these neurophysiological measures as uniquely sensitive to conscious processing. We suggest that in future, studies using EEG derived measures to draw conclusions on conscious processing, should employ a more holistic approach looking at the whole pattern of distribution and changes in power and connectivity. This idea is explored in the next chapter of this thesis.

Effects of self-talk on conscious processing, technique and performance during acquisition and pressure

Our final hypothesis was that the combination of instructional self-talk and increased pressure would result in elevated self-report conscious processing and degraded technique and performance in the instructional self-talk group. This hypothesis was not supported. This is unsurprising considering that the two types of self-talk examined in this experiment had no differential effects on self-report conscious processing or left-temporal EEG activity.

Nevertheless, some noteworthy behavioral findings did emerge. Firstly, across blocks both groups showed an improvement in performance. These performance improvements were expected based on the self-talk literature, since both instructional and motivational self-talk have been shown to benefit motor skill practice (Hatzigeorgiadis et al., 2011). However, instructional self-talk showed a relative benefit for this specific skill since movement kinematics data suggested that it led to a comparatively better swinging technique (slower and more stable movement - reduced acceleration on the lateral and back-and-forth axis; Cooke et al., 2014). In other words, this data objectively supports the idea that instructional self-talk benefits fine motor skills (Hatzigeorgiadis et al., 2011) and link this effect to an improvement in technique. Secondly, although based on the conscious processing literature we expected an increase in conscious processing under pressure, in both groups we observed the opposite pattern (i.e., decreased conscious processing under pressure). Since self-reported conscious processing was lowest and performance was best in the final block of putts, our data are partially supportive of Fitts and Posner’s (1967) skill acquisition continuum, which suggests that performance improves and conscious processing decreases with practice (i.e., practice-induced evolution towards automaticity). However, the data are not fully supportive of this model since performance also improved from block one to block two, while conscious motor processing remained stable. Although it is not possible to offer definitive explanations for this effect, one possibility is that the use of self-talk in general (regardless of the type), might have helped participants to limit their conscious processing under pressure by funneling verbal processing onto the assigned self-talk cue.

Limitations and future directions

Our results should be interpreted in light of some methodological limitations. First, we tested novice golfers who would be expected to engage in high-levels of hypothesis testing and conscious processing irrespective of their assigned self-talk cue. Investigating the effects of the implementation of self-talk strategies with more experienced performers (e.g., novices undergoing an intensive training; recreational or expert golfers) could better test whether the use of self-talk induces a decrease in left-temporal high-alpha power and an increase in left-frontotemporal connectivity while also improving our understanding of the effects of self-talk on skills that have already been acquired and consolidated.

Second, since we selected participants that were fully compliant with our self-talk manipulation (> than 90% of trials), we could not assess the effect connected to the frequency of use of self-talk. Future investigations could additionally improve our understanding of the EEG correlates of self-talk, by enabling a more “continuous” characterization of the relationship between cortical activity and self-talk frequency (e.g., in 20% versus in 50% of trials).

Third, we focused our analyses only on the a-priori identified left-temporal sites. Our results can be used to provide rationale for more holistic analytic strategies that go beyond the left-hemisphere to better understand the cortical correlates of conscious processing. This approach is adopted in a second manuscript using additional data from this experiment in the next chapter of this thesis.

Conclusion

The current study was the first attempt to test the hypothesis that high-alpha left-temporal power and left-frontotemporal connectivity are specifically sensitive to movement-relevant verbal processing (i.e., instructional self-talk) or influenced by other types of processing triggered by high-pressure conditions. Our results provide evidence against these ideas and suggest that these EEG measures might be sensitive to more general verbal processing (i.e., generic self-talk) that happen simultaneously to movement planning, and thereby support a broader conceptualization of conscious processing. Our findings have important implications for the sport neuroscience field and caution future research against reliance on self-report and/or left-temporal EEG measures as standalone indices of conscious motor processes. We believe that the successful identification of additional objective neurophysiological measures of conscious processing will strongly benefit the sport and the neurological rehabilitation worlds since they could be employed as measures of efficacy of particular training interventions (e.g., analogy learning, external focus of attention training, self-talk, imagery) and/or be directly modulated via neurofeedback (see Ring et al., 2015) or transcranial direct current stimulation (tDCS; see Zhu et al., 2015).

References

Abdoli, B., Hardy, J., Riyahi, J. F., & Farsi, A. (2018). A closer look at how self-talk influences skilled basketball performance. *The Sport Psychologist*, *32*, 9-15. https://doi.org/10.1123/tsp.2016-0162

Babiloni, C., Del Percio, C., Iacoboni, M., Infarinato, F., Lizio, R., Marzano, N., ... & Eusebi, F. (2008). Golf putt outcomes are predicted by sensorimotor cerebral EEG rhythms. *The Journal of Physiology, 586*, 131-139. https://doi.org/10.1113/jphysiol.2007.141630

Bazanova, O. M., & Vernon, D. (2014). Interpreting EEG alpha activity. *Neuroscience & Biobehavioral Reviews*, *44*, 94-110. https://doi.org/10.1016/j.neubiorev.2013.05.007

Bellomo, E., Cooke, A., & Hardy, J. (2018). Chunking, Conscious Processing, and EEG During

Sequence Acquisition and Performance Pressure: A Comprehensive Test of Reinvestment Theory. *Journal of Sport and Exercise Psychology*, *40*, 135-145. https://doi.org/10.1123/jsep.2017-0308

Cohen, J. (1988). *Statistical power analysis for the behavioral sciences* (2nd ed.). Hillsdale, NJ: Erlbaum. http://doi.org/10.1234/12345678

Cohen, M. X. (2014). *Analyzing neural time series data: Theory and practice.* Cambridge, MA: MIT Press.

Cooke, A., Kavussanu, M., Gallicchio, G., Willoughby, A., Mcintyre, D., & Ring, C. (2014). Preparation for action: Psychophysiological activity preceding a motor skill as a function of expertise, performance outcome, and psychological pressure. *Psychophysiology*, *51*. http://doi.org/10.1111/psyp.12182

Cooke, A., Kavussanu, M., McIntyre, D., Boardley, I. D., & Ring, C. (2011). Effects of competitive pressure on expert performance: Underlying psychological, physiological, and kinematic mechanisms. *Psychophysiology*, 48 1146-1156. https://doi.org/10.1111/j.1469-8986.2011.01175.x

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

Corcoran, A. W., Alday, P. M., Schlesewsky, M., & Bornkessel-Schlesewsky, I. (2018). Toward a reliable, automated method of individual alpha frequency (IAF) quantification. *Psychophysiology*, e13064. https://doi.org/10.1111/psyp.13064

Curran, transfer block., & Keele, S. W. (1993). Attentional and nonattentional forms of sequence learning. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *19*, 189. https://doi.org/10.1037/0278-7393.19.1.189

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

Deeny, S. P., Hillman, C. H., Janelle, C. M., & Hatfield, B. D. (2003). Cortico-cortical communication and superior performance in skilled marksmen: An EEG coherence analysis. *Journal of Sport & Exercise Psychology*, *25*, 188–204. https://doi.org/10.1123/jsep.25.2.188

Del Percio, C., Iacoboni, M., Lizio, R., Marzano, N., Infarinato, F., Vecchio, F., ... & Babiloni, C. (2011). Functional coupling of parietal alpha rhythms is enhanced in athletes before visuomotor performance: a coherence electroencephalographic study. *Neuroscience*, 175, 198-211. https://doi.org/10.1016/j.neuroscience.2010.11.031

Delorme, A., & Makeig, S. (2004). EEGLAB: An open source toolbox for analysis of single-trial EEG dynamics including independent component analysis. *Journal of Neuroscience Methods*, *134*(1), 9–21. http://doi.org/10.1016/j.jneumeth.2003.10.009

Fitts, P. M., & Posner, M. I. (1967). *Human Performance*. Belmont, CA: Brooks/Cole.

Gallicchio, G., Cooke, A., & Ring, C. (2016). Lower left temporal-frontal connectivity characterizes expert and accurate performance: High-alpha t7-fz connectivity as a marker of conscious processing during movement. *Sport, Exercise, and Performance Psychology*, *5,* 14–24. http://doi.org/10.1037/spy0000055

Gallicchio, G., Cooke, A., & Ring, C. (2017). Practice makes efficient: cortical alpha oscillations are associated with improved golf putting performance. *Sport, Exercise, and Performance Psychology, 6,* 89–102. http://doi.org/10.1037/spy0000077

Gallicchio, G., Finkenzeller, transfer block., Sattlecker, G., Lindinger, S., & Hoedlmoser, K. (2018). The influence of physical exercise on the relation between the phase of cardiac cycle and shooting accuracy in biathlon. *European Journal of Sport Science*, 1-9.

https://doi.org/10.1080/17461391.2018.1535626

Gallicchio, G., & Ring, C. (2018). Don’t look, don’t think, just do it! Toward an understanding of alpha gating in a discrete aiming task. *Psychophysiology*, e13298. https://doi.org/10.1111/psyp.13298

Halliday, D. M., Rosenberg, J. R., Amjad, A. M., Breeze, P., Conway, B. A., & Farmer, S. F. (1995). A framework for the analysis of mixed time series/point process data-theory and application to the study of physiological tremor, single motor unit discharges and electromyograms. *Progress in Biophysics and Molecular Biology*, *64*, 237–278. http://doi.org/10.1016/S0079-6107(96)00009-0

Hardy, J. (2006). Speaking clearly: A critical review of the self-talk literature. *Psychology of Sport and Exercise*, *7*, 81–97. http://doi.org/10.1016/j.psychsport.2005.04.002

Hardy, J., Begley, K., & Blanchfield, A. W. (2015). It's good but it's not right: Instructional self-talk and skilled performance. *Journal of Applied Sport Psychology, 27*, 132-139. https://doi.org/10.1080/10413200.2014.959624

Hardy, J., Comoutos, N., & Hatzigeorgiadis, A. (2018). Reflections on the maturing research literature of self-talk in sport: contextualizing the special issue. *The Sport Psychologist, 32*, 1-8. https://doi.org/10.1123/tsp.2017-0141

Hardy, L., Mullen, R., & Jones, G. (1996). Knowledge and conscious control of motor actions under stress. *British Journal of Psychology, 87,* 621-636. https://doi.org/10.1111/j.2044-8295.1996.tb02612.x

Hatfield, B. D., Costanzo, M. E., Goodman, R. N., Lo, L.-C., Oh, H., Rietschel, J. C., … Haufler, A. (2013). The influence of social evaluation on cerebral cortical activity and motor performance: a study of “Real-Life” competition. *International Journal of Psychophysiology*, *90*, 240–9. http://doi.org/10.1016/j.ijpsycho.2013.08.002

Hatzigeorgiadis, A., Theodorakis, Y., & Zourbanos, N. (2004). Self-talk in the swimming pool: The effects of self-talk on thought content and performance on water-polo tasks. *Journal of Applied Sport Psychology, 16*, 138-150. https://doi.org/10.1080/10413200490437886

Hatzigeorgiadis, A., Zourbanos, N., Galanis, E., & Theodorakis, Y. (2011). Self-talk and sports performance: A meta-analysis. *Perspectives on Psychological Science, 6*, 348-356. https://doi.org/10.1177/1745691611413136

Hikosaka, O., Nakahara, H., Rand, M. K., Sakai, K., Lu, X., Nakamura, K., Miyachi, S., & Doya, K. (1999). Parallel neural networks for learning sequential procedures. *Trends in Neurosciences, 22*, 464–471. https://doi.org/10.1016/S0166-2236(99)01439-3

Hillman, C. H., Apparies, R. J., Janelle, C. M., & Hatfield, B. D. (2000). An electrocortical comparison of executed and rejected shots in skilled marksmen. *Biological Psychology, 52*, 71–83. http://doi.org/10.1016/S0301-0511(99)00021-6

Jensen, O., & Mazaheri, A. (2010). Shaping functional architecture by oscillatory alpha activity: gating by inhibition. *Frontiers in Human Neuroscience, 4*, 186. https://doi.org/10.3389/fnhum.2010.00186

Kingston, K. M., & Hardy, L. (1997). Effects of different types of goals on processes that support performance. *The Sport Psychologist, 11*, 277-293. https://doi.org/10.1123/tsp.11.3.277

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

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

Klimesch, W. (1996). Memory processes, brain oscillations and EEG synchronization. *International Journal of Psychophysiology, 24,* 61-100. https://doi.org/10.1016/S0167-8760(96)00057-8

Klimesch, W., Sauseng, P., & Hanslmayr, S. (2007). EEG alpha oscillations: the inhibition–timing hypothesis. *Brain Research Reviews, 53,* 63-88. https://doi.org/10.1016/j.brainresrev.2006.06.003

Klimesch, W., Doppelmayr, M., Russegger, H., Pachinger, transfer block., & Schwaiger, J. (1998). Induced alpha band power changes in the human EEG and attention. *Neuroscience Letters, 244*, 73-76. https://doi.org/10.1016/S0304-3940(98)00122-0

Krane, V. (1994). The Mental Readiness Form as a measure of competitive state anxiety. *The Sport Psychologist*, *8*, 189–202. https://doi.org/10.1123/tsp.8.2.189

Lachaux, J. P., Rodriguez, E., Martinerie, J., & Varela, F. J. (1999). Measuring phase synchrony in brain signals. *Human Brain Mapping*, *8,* 194-208. https://doi.org/10.1002/(SICI)1097-0193(1999)8:4<194::AID-HBM4>3.0.CO;2-C

Landin, D. (1994). The role of verbal cues in skill learning. *Quest*, *46*, 299-313. https://doi.org/10.1080/00336297.1994.10484128

Lopez-Calderon, J., & Luck, S. J. (2014). ERPLAB: an open-source toolbox for the analysis of event-related potentials. *Frontiers in Human Neuroscience*, 8, 213. https://doi.org/10.3389/fnhum.2014.00213

Makeig, S., Bell, A.J., Jung, transfer block.P., Sejnowski, transfer block.J., 1996. *Independent component analysis of electroencephalographic data*. In: Touretzky, D., Mozer, M., Hasselmo, M. (Eds.), Advances in Neural Information Processing Systems Vol. 8. MIT Press, Cambridge, MA.

Masters, R. S. W., & Maxwell, J. (2008). The theory of reinvestment. *International Review of Sport and Exercise Psychology*, *1*, 160–183. http://doi.org/10.1080/17509840802287218

Masters, R. S. W., Polman, R. C., & Hammond, N. V. (1993). ‘Reinvestment’: A dimension of personality implicated in skill breakdown under pressure. *Personality and individual differences, 14,* 655-666. https://doi.org/10.1016/0191-8869(93)90113-H

Masters, R. S. W., Eves, F. F., & Maxwell, J. P. (2005). Development of a movement specific Reinvestment Scale. In & P. transfer block. Morris, P. Terry, S. Gordon, S. Hanrahan, L. Ievleva, G. Kolt & Tremayne (Eds.), *Proceedings of the ISSP 11th World Congress of Sport Psychology*. Sidney, Australia.

Mullen, R., & Hardy, L. (2010). Conscious processing and the process goal paradox. *Journal of Sport and Exercise Psychology*, *32*, 275-297. https://doi.org/10.1123/jsep.32.3.275

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

Oldfield, R. C. (1971). The assessment and analysis of handedness: The Edinburgh Inventory. *Neuropsychologia*, *9*, 71–113. http://dx.doi.org/10.1016/0028-3932(71)90067-4

Sohn, M., Goode, A., Koedinger, K. R., Stenger, V. A., Fissel, K., Carter, C. S., & Anderson, J. R. (2004). Behavioural equivalence, but not neural equivalence – neural evidence of alternative strategies in mathematical thinking. *Nature Neuroscience*, *7*, 1193-1194. https://doi.org/10.1038/nn1337

Theodorakis, Y., Hatzigeorgiadis, A., & Chroni, S. (2008). Self-talk: It works, but how? Development and preliminary validation of the functions of self-talk questionnaire. *Measurement in Physical Education and Exercise Science*, *12*, 10-30. https://doi.org/10.1080/10913670701715158

Theodorakis, Y., Weinberg, R., Natsis, P., Douma, I., & Kazakas, P. (2000). The effects of motivational versus instructional self-talk on improving motor performance. *The Sport Psychologist*, *14*, 253-271. https://doi.org/10.1123/tsp.14.3.253

Tod, D., Hardy, J., & Oliver, E. (2011). Effects of self-talk: A systematic review. *Journal of Sport and Exercise Psychology*, 33, 666-687. https://doi.org/10.1123/jsep.33.5.666

Vasey, M. W., & Thayer, J. F. (1987). The continuing problem of false positives in repeated measures ANOVA in psychophysiology: a multivariate solution. *Psychophysiology, 24,* 479–486. http://doi.org/10.1111/j.1469-8986.1987.tb00324.x

Vine, S. J., Moore, L., & Wilson, M. R. (2011). Quiet eye training facilitates competitive putting performance in elite golfers. *Frontiers in Psychology, 2*, 8. https://doi.org/10.3389/fpsyg.2011.00008

Vine, S. J., & Wilson, M. R. (2010). Quiet eye training: Effects on learning and performance under pressure. Journal *of Applied Sport Psychology, 22*, 361-376. https://doi.org/10.1080/10413200.2010.495106

Willingham, D. B. (1998). A neuropsychological theory of motor skill learning. *Psychological Review, 105,* 558.

Wilson, M. R., Vine, S. J., & Wood, G. (2009). The influence of anxiety on visual attentional control in basketball free throw shooting. *Journal of Sport and Exercise Psychology, 31*, 152-168. https://doi.org/10.1123/jsep.31.6.761

Zhu, F. F., Poolton, J. M., Wilson, M. R., Maxwell, J. P., & Masters, R. S. W. (2011). Neural co-activation as a yardstick of implicit motor learning and the propensity for conscious control of movement. *Biological Psychology*, *87,* 66–73. http://doi.org/10.1016/j.biopsycho.2011.02.004

Zhu, F. F., Yeung, A. Y., Poolton, J. M., Lee, transfer block. M., Leung, G. K., & Masters, R. S. (2015). Cathodal transcranial direct current stimulation over left dorsolateral prefrontal cortex area promotes implicit motor learning in a golf putting task. *Brain stimulation, 8*, 784-786. https://doi.org/10.1016/j.brs.2015.02.005

CHAPTER FIVE

Bellomo, E., Cooke, A., Gallicchio, G., Ring, C., Hardy, J. (submitted to Psychophysiology). Mind and Body: Psychophysiological Profiles of Instructional and Motivational Self-talk.

Abstract

Self-talk is a psychological skill that benefits motor performance by controlling and organizing performers’ thoughts. While the behavioral effects of self-talk are clear, research on the mechanisms underpinning the effects of different modes of self-talk is sparse. To address this issue, we propose and test a psychophysiological model of the effects of self-talk on motor performance. Thirty-four golf novices practiced a golf-putting task while using either instructional or motivational self-talk preceding each putt. We measured performance (radial error), technique (club kinematics and muscle activity), cardiac activity (heart-rate and event-related heart-rate change), as well as electroencephalographic (EEG) alpha power and connectivity in a randomized (group: instructional self-talk, motivational self-talk) experimental design. Instructional self-talk led to better skill execution (performance and technique) and was associated with greater parietal alpha power and weaker frontoparietal connectivity, indicative of increased top-down control of action. These findings suggest an information-processing mechanism underlies the skill execution benefits of instructional self-talk. Motivational self-talk led to increased heart-rate and less event-related heart rate variability, endorsing an effort-based mechanism to explain the benefits of motivational self-talk. Surprisingly, the left-temporal EEG measures usually associated with verbal-analytic conscious processing did not distinguish the groups. Our study represents the most complete multi-measure investigation of self-talk to date. We hope that our psychophysiological model of self-talk will encourage researchers to move beyond the exclusive reliance on behavioral and self-report measures to discover the mechanisms underlying the benefits of self-talk for performance.

Keywords: frontoparietal network; high-alpha; motor performance; verbal processing; conscious processing;

Introduction

Our stream of thoughts can be accompanied by covert verbalisations known as self-talk. Self-talk acts as an accelerator to thinking and understanding (Vygotsky, 1978), and is especially prevalent during the acquisition of motor skills (Hardy, Gammage, & Hall, 2000; Masters, 1993). It is common for performers to recite *instructional self-talk* to guide the steps for successful skill execution (Hardy, Comoutos, & Hatzigeorgiadis, 2018). In addition, to regulate arousal, support confidence, and motivational drive, individuals may also verbalize a series of self-motivating statements (*motivational self-talk*; Hardy et al., 2018). Meta-analytic evidence indicates that both instructional and motivational self-talk benefit performance (Hatzigeorgiadis et al., 2011). However, for motor tasks placing a premium on precision, instructional self-talk seems have a relative advantage over motivational self-talk (Theodorakis, Weinberg, Natsis, Douma, & Kazakas, 2000), as shown by behavioral meta-data revealing larger performance benefits ($d_{instructional} = .83$ vs. $d_{motivational} = .22$; Hatzigeorgiadis et al., 2011) and more consistent movement kinematics (Abdoli, Hardy, Riyahi, & Farsani, 2018).

While the effects of self-talk on motor performance and skill execution are well understood at the behavioral level, the field lacks both data and a guiding model highlighting mechanistic pathways, such as neurophysiological adaptations that explain the processes beyond performance related markers of skill outcome (e.g., missed or holed golf putts). To address this shortcoming, we present and test the first psychophysiological model of self-talk and motor skill execution. This model is grounded on a unique integration of both self-talk and psychophysiological literatures. For instance, we draw from Hardy, Tod, and Oliver's (2009) self-talk framework highlighting broad cognitive (e.g., information processing), motivational (e.g., increased effort), behavioral (e.g., superior technical kinematics/form), and affective (e.g., anxiety control) mechanistic pathways. Precise psychophysiological predictions of our model are based on evidence from investigations of related cognitive constructs, such as conscious motor processing (e.g., Masters & Maxwell, 2008) and motivation (e.g., Harmon-Jones, Gable, Peterson, 2010). Given their different effects on performance, we propose that instructional and motivational self-talk have a different neurophysiological basis and therefore influence motor skill control via different psychophysiological mechanisms.

Instructional self-talk

In guiding the steps for successful skill execution by steering individuals' attention to the correct stimuli at appropriate moments (Theodorakis et al., 2000), instructional self-talk represents a conscious top-down process acting on the motor system (Hardy, 2006). Operationally, this appears comparable to the conscious processing of movement related instructions (Mullen & Hardy, 2010). Indeed, like instructional self-talk, training regimes fostering the conscious processing of movements seem to produce faster skill acquisition and smoother motor performance at the initial stages of motor learning, compared to less explicit forms of training (e.g., Bellomo, Cooke, & Hardy, 2018). Therefore, we hypothesize that compared to motivational self-talk the use of instructional self-talk will, at the initial stages of learning, result in better technique. In the case of golf putting, this could manifest as greater forearm muscle activity at and immediately after the impact to reflect acceleration through the swing, and reduced lateral clubhead acceleration to reflect reduced risk of putts being pushed or pulled wide of the hole (Cooke et al., 2010). These variables distinguish experts from novices (Cooke et al., 2014). Accordingly, we expect instructional self-talk will promote greater forearm muscular activation around impact and reduced lateral club-head acceleration compared to motivational self-talk.

Like conscious motor processing, instructional self-talk may also provoke distinct patterns of neural activity that help explain its behavioral outcomes. Several electroencephalographic (EEG) studies of motor performance have associated EEG alpha activity with conscious motor processing (Hatfield et al., 2013; Masters & Maxwell, 2008; Zhu, Poolton, Wilson, Maxwell, & Masters, 2011). Alpha has an inhibitory function, whereby greater alpha power (i.e., the magnitude of alpha activity) indicates greater inhibition and lower alpha power indicates a greater release from inhibition (Klimesch, Sauseng & Hanslmayr, 2007). Alpha connectivity is another EEG derived index representing cortico-cortical communication, whereby highly-synchronous activity between sites reflects strong connectivity and less-synchronous activity reflects weaker connectivity (Lachaux, Rodriguez, Marinerie, & Varela, 1999). During the final moments of preparation for action, individuals deemed more likely to plan and control movements consciously (e.g., beginners; individuals scoring high in trait movement-related self-consciousness) showed comparatively lower left-temporal (e.g., T7) alpha power and stronger alpha connectivity between left-temporal (e.g., T7) and the frontal (e.g., Fz) channels than their less likely counterparts (Hatfield et al., 2013; Gallicchio, Cooke, Ring, 2017, 2016; Zhu et al., 2011). Taken together, these results associated conscious motor processing with a relative increase in activity (release from inhibition) over the left-temporal region, and an increased communication between left-temporal and frontal regions of the cortex. Considering the conceptual overlap between instructional self-talk and conscious motor processing (Hatfield et al., 2013), we hypothesize that the use of instructional self-talk (compared to motivational self-talk) will be characterized by decreased left-temporal alpha power and increased left-frontotemporal alpha connectivity during movement preparation.

Finally, additional predictions concerning the neural basis of instructional self-talk were made based on neuropsychological models of feedback and feedforward motor control (Ashe et al., 2006; Babiloni et al., 2011; Murata & Ishida, 2007). These models suggest that the top-down (feedforward) control of actions is linked to the activity of the frontoparietal network, a circuit involving frontal and parietal regions. The main function of the frontoparietal network is to integrate frontally generated decisions and action plans with parietally generated multi-modal representations based on an integration of visual and somatosensory information (see Ashe et al., 2006; Murata & Ishida, 2007). When more top-down control is activated, the network is driven more by frontal regions, while when less control is required, execution becomes more sensory-driven and the balance of the network is shifted towards parietal regions (Ashe et al., 2006).

Although this theorizing has yet to be directly tested with EEG data, re-examination of previously published evidence provides a foundation for a series of hypotheses. For example, Cooke and colleagues (2015) revealed that cortical activity over frontal and central regions increased (i.e., less alpha power) in the trials following golf putting movement errors, reflecting increased top-down control to correct the error. Moreover, Gentili and colleagues (2015) reported a progressive isolation of frontal sites (i.e., weaker frontal connectivity), as participants switched from a bottom-up (feedback based) to a top-down (feedforward based) control of movement. Following Ashe and colleagues' frontoparietal network model, we hypothesize that by fostering top-down control, the use of instructional self-talk will be characterized by less frontal and more parietal alpha power, alongside reduced fronto-parietal connectivity. This reflects preferential utilization of conscious instructions (i.e., top down) over more subtle visual and somatosensory (i.e., bottom up) information.

Motivational self-talk

Motivational self-talk is thought to improve performance by nurturing confidence (Hardy, 2006) and creating psychological activation states that can support increased effort and behavioral persistency (cf., Bandura, 1997; Theodorakis et al., 2000). This type of motivational persistency, also known as approach motivation, enables action towards a goal and is linked to the function of the so-called behavioral activation system (Gray, 1994). In contrast, the behavioral inhibition system, which is associated with avoidance-motivation, promotes situational avoidance as well as increased attention toward aversive stimuli (Gray, 1994). To distinguish between approach and avoidance motivation, it is common practice to compute asymmetry scores based on frontal EEG alpha power: relatively greater left-frontal asymmetry characterizes approach motivation, while relatively greater right-frontal activation characterizes avoidance motivation (e.g., Harmon-Jones, Gable & Peterson, 2010). Due to the confidence supportive nature of motivational self-talk (Hardy, 2006), it is likely that the use of motivational self-talk encourages approach rather than avoidance motivation. Thus, we predicted that using motivational self-talk would be characterized by a relative increase in left-frontal cortical activity compared to instructional self-talk.

As motivational self-talk can also influence effort and persistence, it could also be characterized by cardiovascular indices of increased effort. For example, a large body of research has associated increases in effort an increase in heart rate, and reduction in heart rate variability (Obrist, 1976; Mulder, 1992). Accordingly, we predicted that motivational self-talk would elicit greater heart rate and less variability in heart rate during the final seconds of motor preparation (i.e., event-related heart rate; Cooke et al., 2014), when compared to instructional self-talk.

The Present Study

This study[14] investigated a psychophysiological model distinguishing instructional and motivational self-talk and their differential effects on motor skill execution. We instructed novice golfers to putt golf balls under either instructional self-talk or motivational self-talk. On the one hand, we hypothesized that by increasing top-down control of the motor system, instructional self-talk would be characterized by EMG and kinematic indices of better technique, greater left-temporal activation to indicate increased conscious processing, and a frontoparietal network function shifted towards frontal rather than parietal sites to reflect more top-down feedforward control. On the other hand, we hypothesized that by fostering approach motivation, motivational self-talk would be characterized by left-frontal asymmetry indicative of approach motivation, and cardiovascular changes indicative of increased effort.

Methods

Participants

Participants were 40 (19 male, 21 female), right-handed (Edinburgh Handedness Inventory ≥ +70, Oldfield, 1971), golfing novices, aged 26.97 (*SD* = 4.40) years. Participants were randomly allocated to an instructional self-talk or a motivational self-talk group (between-participant factor) and completed 80 trials of a golf-putting task. We used novices and a golf putting task based on meta-analytic evidence showing largest effects sizes for self-talk manipulations involving novel

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[14] Please note that chapter 4 and 5 discuss data coming from the same investigation. Chapter 4 focused on a direct test-of the link between pre-movement verbalizations and left-temporal EEG measures. Chapter 5 focused on a larger scale investigation of additional psychophysiological correlates of self-talk type.

tasks with fine-motor requirements (Hatzigeorgiadis et al., 2011) and because EEG can be recorded while putting (e.g., Cooke et al., 2014). Our sample size was powered at .80 to detect small between-within participant interaction effects ($\eta_p^2 = .16$) in a randomized analysis of variance (ANOVA) at the 5% level of significance. All participants had normal/corrected vision, refrained from consuming alcohol, drugs (24 hours before), and caffeine (3 hours before), and reported more than 6 hours of sleep during the night preceding their participation. Participants provided informed consent before taking part and were paid £10 upon completion. The protocol was approved by the local research ethics committee.

Experimental Task

Participants were asked to putt golf balls (diameter = 4.27 cm) on an artificial flat putting surface to a target - adhesive paper marker (diameter = 6 mm) - at a distance of 2.46 m, using a blade-style putter (length 90 cm). Participants were instructed to putt at their own pace as accurately as possible in order get the final position of each ball “as close as possible to the target”. They were additionally instructed to rehearse an instructional or motivational self-talk cue (see Figure 1 and Figure 2 Supplementary Material) immediately before executing the swing.

Procedures

Participants completed a 2-hour testing session. Following instruction and instrumentation they sat and rested with eyes-closed for one minute followed by eyes-open for one minute while EEG was recorded to later adjust frequency bands to the individual alpha peak (IAF, see Bazanova & Vernon, 2014; Corcoran, Alday, Schlesewsky, & Bornkessel-Schlesewsky, 2018). The experiment then comprised three phases: (1) 10-putt familiarization task; (2) self-talk training; (3) putting task phase.

10-putt familiarization task. As participants were novices and unfamiliar with the laboratory setting, they performed 10 putts to familiarize with the experimental conditions.

Self-talk training. Given that Hatzigeorgiadis and colleagues’ (2011) meta-data supports the inclusion of a self-talk training phase, our participants practiced the self-talk instructions while performing an aiming motor task. A pre-recorded podcast was used to explain either instructional or motivational self-talk (see Figure 1 and Figure 2 Supplementary Material). Participants then completed 20 trials of a mini basketball free-throw task. In the first 10 trials they were asked to practice the skill without any additional instruction. In the second 10 trials, they rehearsed a self-talk cue corresponding to the group they were assigned to before each attempt. The use of this task ensured that all participants had experience using self-talk during a precision motor task that is dissimilar to our experimental task (cf. Hatzigeorgiadis, Zourbanos, Mpoumpaki, & Theodorakis, 2009).

Putting task phase. Next, participants were told that they would begin the main golf putting phase of the experiment. Participants were assigned a group-specific cue for the golf-putting task: instructional cue *"feet still – wrists locked – arms through"*; motivational cue "*come on, I can do this"*. We assigned cues to increase within-group consistency (in terms of content and length) in the use of covert-verbalizations in preparation for each putt. We developed the self-talk cues based on previous protocols (Hardy, 2006; Hardy et al., 2015; Theodorakis et al., 2000), golf-coaching manuals, and pilot testing (see Supplemental Material). We instructed participants to silently say their assigned cue in their mind before every putt. They then completed a total of 80 putts with a two-minute break at the mid-point. We reminded participants about their self-talk cue every 5 putts during this phase of the experiment.

Measures

Self-talk manipulation. Self-report frequency of use and relevance of the assigned self-talk cue were measured at the mid-point and at the end of the 80 putts by asking participants to rate on a 0-100 scale two statements (frequency: "how often have you used the keywords in the previous set of putts"; relevance: "how much do you think that the cue was helpful to your performance") anchored *never-always* and *not relevant at all-totally relevant* (see Theodorakis et al., 2000).

Physiological data

EEG data. EEG was recorded from thirty-two (32) active electrodes at Fp1, Fp2, AF3, AF4, F7, F3, Fz, F4, F8, FC5, FC1, FC2, FC6, T7, C3, Cz, C4, T8, CP5, CP1, CP2, CP6, P7, P3, Pz, P4, P8, PO3, PO4, O1, Oz, O2 (10-20 system, Jasper, 1958). Additionally, active electrodes were positioned on each mastoid, at the outer canthus and below each eye to record vertical and horizontal electrooculogram (EOG). All channels were recorded in monopolar. The signals were sampled at 1024 Hz, with no online filter, using an ActiveTwo amplifier (Biosemi, The Netherlands). Electrode offset was kept below 15 mV. TTL triggers were sent to the BioSemi system to identify swing-onset, identified by the putter head being moved away from and thereby breaking an infrared beam controlled by an optical sensor (S51-PA 2-C10PK, Datasensor, Monte San Pietro, Italy) and a microphone (NT1, Rode, Silverwater, Australia) connected to a mixing desk (Club 2000, Studiomaster, Leighton Buzzard, UK), which detected the putter-to-ball contacts. These signals were recorded using both Actiview (BioSemi) and Spike2 Software (CED-2).

Offline signal processing was performed using EEGLAB (Delorme & Makeig, 2004), ERPLAB (Lopez-Calderon, & Luck, 2014), and bespoke scripts in MATLAB (Mathworks Inc., USA). Data were down-sampled to 250 Hz, re-referenced to the average of all 32 EEG channels (no bad channels were identified), and filtered .01 to 30 Hz (Butterworth, 12dB/40roll-off order2 non-causal). In line with previous research (e.g., Cooke et al., 2014; Hatfield et al., 2013) data were extracted from -4000 ms to +1000 ms relative to swing-onset, and centered around the average voltages between -200 ms and 0 ms. Epochs were visually inspected and rejected if they contained gross artefacts. The number of epochs retained was 78.37 (*SD* = 3.14). No bad channels were identified. Independent component analysis (ICA) weights were obtained through the RunICA informax algorithm (Makeig, Bell, Jung, & Sejnowski, 1996) running on these same EEG data (32 channels, yielding the same number of independent components) that, however, were instead high-pass filtered to 1 Hz (FIR [finite impulse response] filter, filter order 826) and concatenated across all trials within each participant. Then ICA weights were applied to the original 0.1-30 Hz filtered signals, and artefactual components (e.g., eye or muscle related) flagged by automated procedures

(SASICA plugin; Chaumon, Bishop, Busch, 2015) and then visually inspected were manually rejected.

Time-frequency analysis. Time-frequency analysis was applied by convolving the Fast-Fourier Transform (FFT) power spectrum of each EEG artefact-free epoch with a family of complex Morlet wavelets, defined as a Gaussian-windowed complex sine wave: $e^{i2\pi tf}e^{-t^2/2\sigma^2}$; where t is time, f is frequency bin, which increased from 4 to 30 Hz in 30 logarithmically steps, and σ defines the width of each frequency band (set to $cycles/2\pi f$, with *cycles* ranging from 3 and 6), and then taking the inverse FFT to obtain the analytic signal z. From the convolution we obtained: (1) estimates of instantaneous power (squared magnitude of the analytic signal); and (2) phase (phase angle of the analytic signal) which was then used to compute inter-site connectivity.

Individual alpha frequency (IAF). Following the approach advocated by Bazanova and Veron (2014), the individual frequency bands were calculated based on the individual alpha peak (IAF, Kilmesh, 1999). IAF was calculated with the IAF toolbox (Corcoran et al., 2018) based on a 60s segment of eye-closed EEG recording taken before the beginning of the task, which were processed in the same way as task-related data (excluding the epoching). The mean IAF was 9.92 ± 1.17 for the instructional group and 9.92 ± .83 for the motivational group.

Power. Changes in instantaneous power were calculated from the complex signal for each frequency bin (f) as the squared magnitude of the result of the convolution defined as Z_t (power time series: $p_t = real(z_t)^2 + imag(z_t)^2$.

For the analysis of power and connectivity, we focused on the IAF-adjusted high-alpha band (i.e., IAF to IAF + 2 Hz) since it is more sensitive than other frequency bands to task-related changes (Babiloni et al., 2011). Crucially, no baseline normalization was employed. Following the approach of Gallicchio and colleagues (Gallicchio et al., 2016) to control for skewness and interindividual differences, trial-averaged absolute alpha power was median-scaled log transformed, whereby values for each participant were scaled by the median of all values (electrode × points × block matrix) per each wavelet (representing a frequency bin) within that participant, and then subjected to a $10 \cdot \log_{10}$ transformation. Power was then averaged across IAF-adjusted frequency bands, and five 1 s time bins relative to movement initiation (bin1: -4s to -3s; bin2: -3s to -2s; bin3: -2s to -1s; bin4: -1s to 0s; bin5: 0s to +1s).

For the analysis of frontal asymmetry, we focused on the IAF-adjusted low-alpha (i.e., IAF–2Hz to IAF; Davidson, Ekman, Saron, & Senulis, 1990). Asymmetry scores [$\log_e(right) - \log_e(left)$] were computed for each time bin at medial frontal (F3, F4) and lateral frontal (F7, F8) regions (Coan, Allen, & Harmon-Jones, 2001). Raw power values were for the calculation used as normalization and control for skewness is afforded by the natural log transformation and the subtraction (Davidson et al., 1990).

Connectivity. Functional connectivity between sites was computed in terms of inter-site phase clustering (ISPC) based on the phase angle time series, $\phi_t = imag(z_t)^2/real(z_t)^2$. This measure was preferred to others (e.g., magnitude squared coherence) because it is independent of absolute power variations (Cohen, 2014; Lachaux, Rodriguez, Marinerie, & Varela, 1999). $\mathrm{ISPC}_{\mathrm{trials}}$ measures consistency of phase angle differences at specific time points across trials and is calculated with the following formula: $ISPC_{xy}(f) = \left|n^{-1}\sum_{t=1}^{n} e^{i(\theta_x(tf)-\theta_y(tf))}\right|$; where n is the number of trials, i is the imaginary operator, θ_x and θ_y are the phase angles of the recorded signal at two different scalp locations, t is trial, and f is the frequency bin, $e^{i(\theta_x(tf)-\theta_y(tf))}$ is the complex vector with magnitude, $n^{-1}\sum_{t=1}^{n}(.)$ denotes averaging over trials (for $\mathrm{ISPC}_{\mathrm{trials}}$), and $|.|$ is the magnitude of the averaged vector (Cohen, 2014; Lachaux et al., 1999). The resulting ISPC is a real number between 0 (no functional connection) and 1 (perfect functional connection). ISPC values were Z-transformed (i.e., inverse hyperbolic tangent) to ensure normal distribution before statistical analyses were performed (Halliday et al., 1995).

Cardiac activity. Cardiac activity was derived from an electrocardiogram (ECG) obtained using three single-use silver/silver chloride spot electrodes (BlueSensor SP, Ambu, Cambridgeshire, UK) placed on the clavicles and the lowest left rib. The ECG signal was amplified (Bagnoli-4, Delsys, Boston, MA), filtered (1–100 Hz), and digitized at 2500 Hz with 16-bit resolution (CED

Power 1401, Cambridge Electronic Design, Cambridge, UK) using Spike2 software (Cambridge Electronic Design).

The ECG signal was then used to compute the event-related instantaneous heart rate time series. Typically, in golf-putting research, there is a distinct event-related heart rate variability profile characterized by a deceleration in heart rate during the 6 s prior to movement, and an acceleration in heart rate during the 6 s post-movement (e.g., Cooke et al., 2014; Neumann & Thomas, 2009). Event-related heart rate in the final moments pre-movement until the putter-ball-impact (typically around 1 s post movement initiation) are of particular interest because more pronounced heart rate deceleration (i.e., greater event-related heart rate variability) has been associated with increased automaticity and superior performance (e.g., Neumann & Thomas, 2009). Based on previous research (e.g., Cooke et al., 2014) the continuous time series was first segmented into epochs from -6 s to +6 s relative to swing-onset, and then voltages were centered by means of baseline subtraction (mean value of the whole epoch). Instantaneous heart rate was derived from the intervals between successive R-wave peaks (R-R intervals) of the ECG in each epoch. Data were processed as follows: (1) a filter in the frequency domain was applied to remove slow frequencies; (2) an initial set of probable R-wave peaks were identified; (3) segments containing artefacts were identified based on extreme values and were interpolated; (4) the minimum distance between peaks was identified and used to optimize the R-wave peaks identifier; (5) the identified R-wave peaks were manually reviewed and confirmed / adjusted as necessary; (6) the accepted R-wave peaks were used for the calculation of the R-R intervals; and (7) instantaneous heart rate (beats per minute) was calculated as 60000/(R-R interval). Each epoch was then split into thirteen 1s time bins and the nearest instantaneous heart rate value was assigned to each bin. Absolute heart rate was calculated by taking the average heart rate across all bins. Event-related variability in heart rate was calculated by computing a difference score between heart rate in the earliest seconds preceding the swing (bin001: -6; bin002: -5, bin003: -4), where heart rate is typically greatest and the value of the heart rate in the second after the movement intiation (bin007: +1), were maximal bradycardia is normally achieved (Cooke et al., 2014). Accordingly, a greater difference score indicates more event-related heart rate variability (greater rate of change during the event-period) and was expected for the instuctional self-talk group. A smaller difference score indicates less event-related heart rate variability (smaller rate of change during the event-period) and was expected for the motivational self-talk group.

Muscle activity. Muscle activity was derived from an electromyogram (EMG) measured using a differential surface electrode (DE 2.1, Delsys) affixed to the *extensor carpi radialis* and the *flexor carpi ulnaris* of the left arm, and a ground electrode (BlueSensor SP, Ambu, Cambridgeshire, UK) on the left collarbone. These muscles were chosen based on previous research implicating them in the putting stroke of right-handed golfers (e.g., Cooke et al., 2010). The EMG signal was amplified (Bagnoli-4, Delsys), filtered (20–450 Hz), and digitized at 2500 Hz with 16-bit resolution (CED Power 1401) using Spike2 software.

The event-related activity of the flexor and extensor muscles was then calculated via the following steps: (1) the continuous data time series was rectified, (2) continuous data were segmented into epochs from -6 s to +6 s relative to swing-onset; (3) voltages were centered by means of baseline subtraction (mean value of the whole epoch); and (4) each epoch was split into 500ms time bins and the average voltage for each bin was calculated (e.g., muscle activity for 6 seconds before was calculated as the mean activity between 6.25 and 5.75 s prior to movement; see Cooke et al., 2014, 2015).

Behavioral data

Performance outcome. Participants' performance was evaluated in terms of angle error (degrees), length error (cm) and radial error (cm), which respectively yield measures of directional accuracy, force accuracy, and a combination of direction and force. These measures were computed for each putt using a camera system (Neumann & Thomas, 2008) and averaged (geometric mean, Gallicchio et al., 2016) to yield measures for each block.

Movement kinematics. Technique was assessed by means of movement kinematics by using a triaxial accelerometer (LIS3L06AL, ST Microelectronics, Geneva, Switzerland). Acceleration on the X, Y, and Z axes corresponded to lateral, vertical, and back-and-forth movement of the clubhead, and assessed clubhead orientation, clubhead height, and impact velocity, respectively. The signals were conditioned by a bespoke buffer amplifier with a frequency response of DC to 15 Hz. Both accelerometer and amplifier were mounted in a 39 mm × 20 mm × 15 mm plastic housing secured to the rear of the putter head. To compute kinematic variables, we scored acceleration for each putt from the onset of the downswing phase of the putting stroke until the point of ball contact (e.g., Cooke, Kavussanu, McIntyre, Boardley, & Ring, 2011; Cooke, Kavussanu, McIntyre, & Ring, 2010). Specifically, we calculated average acceleration for the X, Y, and Z axes.

Statistical Analyses

We removed ten participants (five motivational, five instructional) due to non-adherence with the self-talk manipulation (i.e., 10 used self-talk on less than 80% of all trials and additionally used additional incompatible verbalizations: motivational statements in the instructional group and vice versa; Hatzigeorgiadis et al., 2009). Therefore, statistical analyses were conducted on 30 participants. Self-report and performance data were analyzed using independent samples *t*-tests to compare the two Groups (instructional, motivational). Instantaneous heart rate and muscle activity were analyzed using Group × Bin (2 × 13; -6, -5, -4, -3, -2, -1, 0, +1, +2, +3, +4, +5, +6) ANOVAs. Power was analyzed by a Group × Site × Bin (bin1: -4s to -3s; bin2: -3s to -2s; bin3: -2s to -1s; bin4: -1s to 0s; bin5: 0s to +1s) ANOVA followed by separate ANOVAs at specific sites based on the effects that emerged. Based on our study aims, the factor Site included the following channel subsets: frontal (Fz, F3, F4, F7, F8), central (Cz, C3, C4), parietal (Pz, P3, P4), occipital (Oz, O1, O2), and temporal (T7, T8).

Connectivity was analyzed with separate Group × Pair × Bin ANOVAs to explore how the frontal-midline (Fz), the parietal-midline (Pz), the left-temporal site (T7) were respectively connected with the other electrodes considered (Fz, C3, C4, Cz, C3, C4, Pz, P3, P4, Oz, O1, O2, T7, T8). Frontal asymmetry scores were analyzed through Group × Block × Bin ANOVAs separately for the medial (F3, F4) and lateral (F7, F8) channel pairs. The Bin factor is recommended in studies of self-paced aiming movements in order to account for phasic shifts in power and connectivity during preparation for action (Cooke et al., 2014)

Significant main effects and interactions were probed by separate ANOVAs for each Group, or Bin, by polynomial trend analyses. The multivariate method of reporting results was adopted as it minimizes the risk of violating sphericity and compound symmetry assumptions in repeated measures ANOVA (Vasey & Thayer, 1987). Effect size is reported with partial eta-squared (η_p^2) values of .10, .25, and .40 indicating relatively small, medium, and large effect sizes, respectively (Cohen, 1988).

Results

Self-talk manipulation.

The independent *t*-tests applied to the self-reported percentages scores of frequency of use and of relevance of the self-talk revealed no group differences. Participants were compliant in using the assigned self-talk cue throughout the study (M frequency = $95.60_{\text{instructional}}$, $95.93_{\text{motivational}}$) and felt it was equally relevant (M relevance = $68.77_{\text{instructional}}$, $68.37_{\text{motivational}}$). These results confirm the success of our self-talk manipulation.

Cortical activity

Power. The Group × Site × Bin mixed-model ANOVA, conducted to obtain a general picture of the power profiles, revealed main effects of Site, $F(15, 14) = 91.36$, $p < .001$, $\eta_p^2 = .99$, Bin, $F(4, 25) = 3.05$, $p = .035$, $\eta_p^2 = .33$, and Group, $F(1, 28) = 3.42$, $p = .075$, $\eta_p^2 = .11$. Event-related changes in power during the preparatory period were evident (main effect of Bin, quadratic trend $p = .009$, $\eta_p^2 = .22$), with a decrease in the two seconds before and in the second after swing-onset. Moreover, we also observed a specific topographic distribution with highest power at occipital (Oz, O1, O2), intermediate at temporal (F7, F8, T7, T8) and then frontal (Fz, F3, F4), reduced at parietal (Pz, P3, P4), and lowest at central sites (Cz, C3, C4) (see Supplementary

Material Figure 3). Of most interest, group differences were characterized by greater power for the instructional compared to the motivational group. No interactions were revealed.

Separate ANOVAs were also performed for each channel: these results are reported in full in the supplementary material (see Supplementary Material Table 3). In brief, these analyses revealed that group differences were localized to the parietal region (Pz, P3, P4), and the main effect of Bin (i.e., event-related pre-swing-onset decrease in power) occurred at Fz, F3, F4, C3 C4, P4, Oz, O1, and O2.

In sum, power analyses show (1) a well-defined topographical distribution of alpha activity (see Supplementary Material Figure 3), with highest power at occipital electrodes, intermediate power at temporal and frontal electrodes, relatively low power at parietal electrodes, and lowest power at central electrodes; (2) a swing-onset related decrease in power strongest at frontal, central, parietal, and occipital sites; (3) group differences with the instructional group showing more power at parietal midline sites (Figure 1A).

Connectivity. We conducted separate analyses to specifically assess the connectivity array with center of mass frontal-midline (Fz), and the parietal-midline (Pz).

Fz connectivity. The Group × Pair × Bin mixed-model ANOVA assessing Fz connectivity revealed a main effect of Pair, $F(9, 20) = 112.25$, $p < .001$, $\eta_p^2 = .98$, with strongest connectivity at frontoccipital (Fz-Oz, Fz-O1, Fz-O2) and frontoparietal pairs (Fz-P4, Fz-P3, Fz-Pz), intermediate at frontocentral pairs (Fz-C3, Fz-C4), and lowest at lateral frontotemporal pairs (Fz-T7, Fz-T8). Moreover, the analysis revealed a main effect of Bin, $F(4, 25) = 6.26$, $p = .001$, $\eta_p^2 = .50$ (cubic trend $p = .002$, $\eta_p^2 = .29$, increase-decrease-increase) characterized by a decrease in connectivity (at bin 4) followed by an increase prior to swing onset (at bin 5). Of most interest, there was also a main effect of Group, $F(1, 28) = 5.39$, $p = .028$, $\eta_p^2 = .16$, whereby connectivity was stronger in the motivational than in the instructional self-talk group. The Group × Bin mixed- ANOVA for left-frontotemporal connectivity (T7-Fz), conducted based on our a priori hypotheses, did not reveal any effect.

Pz connectivity. The Group × Pair × Bin mixed-model ANOVA examining Pz connectivity revealed a main effect of Pair, $F(8, 21) = 90.89$, $p < .001$, $\eta_p^2 = .97$, whereby connectivity was highest at frontoparietal, and parietooccipital pairs (Pz-F3, Fz-Pz, Pz-F4, Pz-O1, Pz-O2), intermediate at parietotemporal pairs (Pz-T7, Pz-T8) and lowest at parietocentral pairs (Pz-C3, Pz-C4). Importantly, it also confirmed the same main effect of Group, $F(1, 28) = 7.03$, $p = .013$, $\eta_p^2 = .20$ (motivational > instructional self-talk) as was observed for Fz connectivity. However, no effect of Bin emerged.

In sum, the connectivity analyses revealed (1) strongest interconnections between frontoccipital and frontoparietal pairs (see Supplementary Material Figure 4); (2) an event-related decrease in Fz connectivity prior to swing-onset; (3) no effect of group on left frontotemporal connectivity; and (4) group differences characterized by stronger connectivity towards the frontal and the parietal midline in the motivational group (Figure 1B).

Frontal Asymmetry. The Group × Bin mixed-model ANOVA failed to reveal any effect for either F3-F4 and F7-F8 asymmetry.

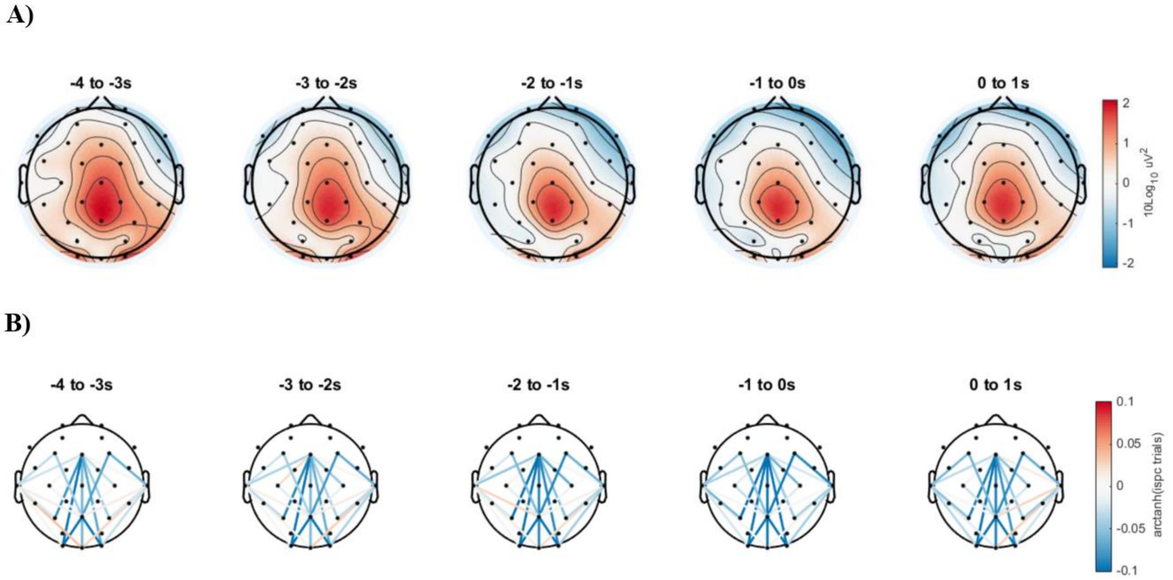

Figure 1. Instructional – motivational group differences: A) topographic distribution of median scaled power; B) topographic connectivity network of atanh($ISPC_{trials}$). Each column represents time bin (-4 to -3, -3 to -2, -2 to -1, -1 to 0, 0 to +1). Red colors indicate higher values for instructional and blue colors indicate higher values for motivational self-talk groups.

Physiological data

Cardiac Activity. The Group × Bin mixed-model ANOVA revealed main effects of Bin, $F(12, 17) = 5.76$, $p = .001$, $\eta_p^2 = .80$, best described by a linear and a cubic trend ($p < .001$, $\eta_p^2 = .69 - .61$), whereby heart rate began decelerating two seconds prior to swing initiation, the strongest bradycardia occurred during movement execution, before heart rate returned progressively to baseline values in the following seconds. The targeted event-related heart rate change analysis was performed by comparing the magnitude of deceleration in the two groups, we calculated difference scores between the average heart rate in the seconds preceding the deceleration (bin001: -6; bin002: -5, bin003: -4) and the value of the heart rate in the second when deceleration was maximal (bin007: +1). These scores were analysed with a two-way randomized ANOVA which revealed a marginal effect of Group, $F(1, 28) = 3.74$, $p = .063$, $\eta_p^2 = .12$, whereby the difference score was larger (i.e., more event-related heart rate variability) in the instructional group ($M = 7.39$ beats) compared to the motivational group ($M = 3.66$ beats). These results are displayed in Figure 2A.

Muscle activity. For the extensor muscle, the Group × Bin mixed-model ANOVA revealed a main effect of Bin, $F(12, 17) = 2.49$, $p = .042$, $\eta_p^2 = .64$, which was best described by a quadratic trend ($p < .001$, $\eta_p^2 = .38$). Muscle activity increased one second before swing-onset, peaked during swing-execution, and returned to baseline thereafter. No main effect of Group or Group × Bin interaction were observed. These results are displayed in Figure 2B.

For the flexor muscle, the same analysis revealed a main effect of Bin, $F(12, 17) = 1.09$, $p = .007$, $\eta_p^2 = .72$, best described by a quadratic trend ($p < .001$, $\eta_p^2 = .32$), and a main effect of Group, $F(1, 28) = 4.33$, $p = .047$, $\eta_p^2 = .13$. Overall, muscle activity increased relative to the swing (i.e., increase in the second preceding swing onset, peak during movement, and return to baseline thereafter) and was higher in the instructional group. These results are displayed in Figure 2C.

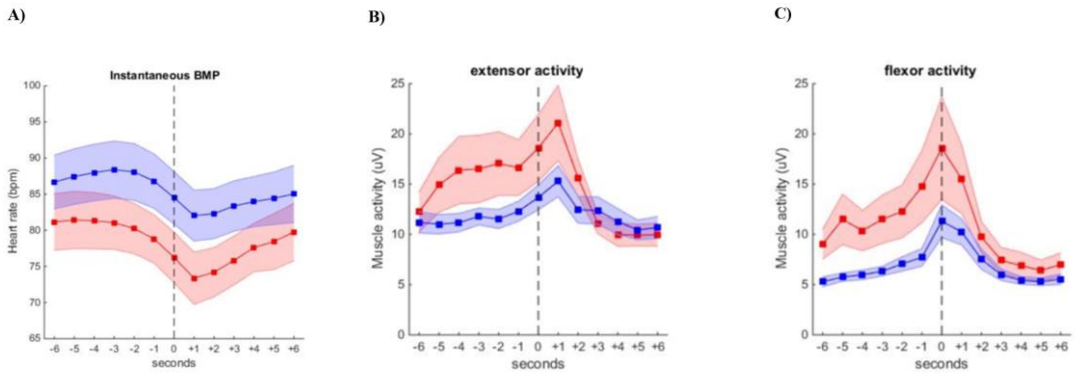

Figure 2. The figures represent the Bin × Group effects for cardiac activity and muscle activity. The x-axis represents seconds around swing-onset (time = 0 s); the y-axis represents (A) instantaneous heart-rate; (B) extensor muscle activation; (C) flexor muscle activation. Red = Instructional self-talk; Blue = Motivational self-talk. Shading indicates standard error of the means.

Behavioral data

Performance Outcome. The independent samples *t*-test revealed a trend for group differences, *t*(28) = -1.99, *p* = .057, for angle error, whereby angle error (degrees) was larger for the motivational (M = .76) than the instructional (M = .62) group. No effect emerged for mean radial error or length error. These results are summarized in Table 1.

Movement kinematics. The independent samples t-test revealed for group differences for X (lateral) axis and Z (back and forth) axis acceleration, *t*s(28) = -3.45 to -2.52, *p*s = .002 to .018, whereby acceleration was smaller for the instructional group. These results are summarized in Table 1.

Table 1. Mean (SD) of performance measures per Group.

Measure (range)	
Radial Error (cm)	
Instructional	27.75 (7.07)
Motivational	30.02 (6.55)
Angle Error (degrees)	
Instructional	0.61 (0.22)
Motivational	0.75 (0.26)
Length Error (cm)	
Instructional	24.73 (7.33)
Motivational	26.79 (7.68)
Lateral (x-axis) Acceleration (ms^{-2})	
Instructional	0.30 (0.1)
Motivational	0.48 (0.20)
Vertical (y-axis) Acceleration (ms^{-2})	
Instructional	.44 (.15)
Motivational	.44 (.20)
Back-and-Forth (z-axis) Acceleration (ms^{-2})	
Instructional	2.15 (.67)
Motivational	3.25 (1.80)

Discussion

The present study is the first to introduce and test a psychophysiological model of self-talk highlighting the distinctive features of instructional and motivational self-talk as it pertains to motor skill execution. The effective integration of multiple data sources (e.g., behavioral, cardiac, muscular, and neural) and contemporarily analyzed (e.g., scalp level time-frequency power and connectivity analysis via wavelet convolution; individual alpha peak adjustment) data afforded us a comprehensive appreciation of how instructional and motivational self-talk might facilitate motor performance. Many predictions of the model were supported while a few were questioned. Each prediction is discussed and suggestions for refinement of our model in light of our findings are considered in the sections below.

Instructional self-talk

We hypothesized that instructional self-talk would benefit motor skill execution via increased top-down control of action (Hardy, 2006). As expected, behavioral and kinematic results supported this prediction. Participants using instructional self-talk tended to perform better, indexed by reduced angular error, and developed better technique, indexed by reduced lateral club-head acceleration, compared to their motivational self-talk counterparts. Participants using instructional self-talk also tended to display greater muscle activity, but since this spanned all epochs rather than being localized to epochs around the moment of impact, it provides only partial support for our muscle activity hypothesis. Rather than reflecting good technique in the form of accelerating through the ball, it is possible that the elevated muscle activity that characterized the instructional self-talk group is simply a further reflection of their top-down control, and their adoption of an internal focus on the mechanics of their swing (e.g., Zachry, Wulf, Mercer & Bezodis, 2005). Accordingly, muscle activity could be reconceptualized in our model as a variable reflecting conscious control, rather than as an index of technique. If considered as an index of conscious control of movements, our muscle activity findings (i.e., greater for instructional than motivational self-talk) are consistent with what our model would predict for a fine-motor skill.

Based on findings from the conscious processing literature (Hatfield et al., 2013; Gallicchio et al., 2016; Zhu et al., 2011), we also expected participants in the instructional group to be characterized by greater left-temporal activity. Our results did not support this hypothesis: no group differences or group-related interactions emerged for either left-temporal power or left-frontotemporal connectivity. This null finding could indicate that instructional self-talk is not associated with conscious motor processing, but since conscious motor processing involves the use of explicit instructions to guide movement, this seems unlikely. An alternative possibility is that the EEG signatures previously interpreted to reflect conscious motor processing may actually reflect self-talk frequency rather than self-talk content. In the current study, while the self-talk content employed by the instructional and motivational groups was clearly different, their self-talk frequency was the same. Previous studies advocating left-temporal activity and left-frontotemporal connectivity as neural indices of conscious motor processing are mainly based on expert versus novice comparisons or comparisons of explicit versus implicit training methods which could elicit different self-talk frequencies. Future studies should further investigate the relative effects of semantic content versus self-talk frequency on left-temporal activity and left-frontotemporal connectivity to shed light on this pressing issue.

Finally, based on neuroscience literature examining feedback and feedforward motor control (Ashe et al., 2006), we hypothesized that participants using instructional self-talk would be characterized by less frontal and more parietal alpha power, alongside reduced frontal and parietal connectivity. This hypothesis was supported. Specifically, the instructional group was characterized by greater parietal alpha power (suggesting diminished sensorimotor processing) and weaker connectivity between frontal and parietal sites (suggesting diminished integration between frontal plans and perceptual information). Together, these findings suggest that instructional self-talk encouraged a reduced relative weight of parietal processing in the frontoparietal network, indicative of more top-down control of action (Ashe et al., 2006). This reduced dependency of sensory feedback (parietal function) can be interpreted as representing a shift to feedforward mechanisms of action control (cf., Gentili et al., 2015). Accordingly, parietal activity and frontoparietal connectivity appear the most promising neurophysiological signatures of instructional self-talk and could explain the performance benefits of this self-talk modality (Hardy, 2006).

Motivational self-talk

We expected motivational-self talk to influence EEG frontal asymmetry and cardiac activity. First, based on theories of approach and avoidance motivation, we hypothesized that motivational self-talk would encourage approach motivation, characterized by a relative increase in left-frontal cortical activity (Harmon-Jones et al., 2010). Results failed to support this hypothesis. There were no group main effects for asymmetry for either electrode pair. It is possible that the lack of group differences were due to instructional self-talk also encouraging approach motivation; future studies measuring frontal asymmetry could compare instructional, motivational and no self-talk groups to test this possibility. It is also possible that any effects of motivational self-talk on frontal asymmetry would manifest more clearly when employed with experts or with gross motor skills, for which this type of self-talk has been demonstrated to be more effective (Hatzigeorgiadis et al., 2011).

Our second hypothesis was that motivational self-talk would elicit greater heart rate and less event-related heart rate variability, when compared to instructional self-talk. This was based on the premise that motivational self-talk would increase effort, and the compelling literature associating increased effort with greater heart rate and reduced heart rate variability (Obrist, 1976; Mulder, 1992). Results partially supported this hypothesis. Members of the motivational self-talk group displayed a trend for higher heart rates, and showed significantly less variability in heart rate during the six seconds preceding putts when compared to their instructional counterparts. While these cardiovascular effects of motivational self-talk did little to aid performance and kinematics during the current fine-motor task, they might be very helpful for gross motor tasks (Hardy, 2006; Hatzigeorgiadis et al., 2011); future research should examine this suggestion.

Limitations and future directions

Our results should be interpreted in light of some methodological limitations. First, the current study did not contain a no-self talk control group. However, there is already a body of literature investigating the psychophysiological profiles of novice golfers who did not receive any self-talk intervention (e.g., Gallicchio et al., 2017); our results can be compared to these extent findings. Second, we did not use an irrelevant self-talk control group. However, we believe that the simple engagement in covert verbal activity, was, to some extent, controlled for by having both groups engage in self-talk. Nonetheless, given the current encouraging findings we see value in a future investigation which would specifically target this question. Third, since we tested novice golfers, and given the short acquisition phase, we believe that a replication of the present investigation with expert golfers could improve our understanding of the effects of self-talk on skills that have already been acquired and consolidated (cf. Tod et al., 2011).

Finally, we concede that the current study tested only a small portion of what is considered the most-comprehensive and up-to-date self-talk taxonomy (Latinjak, Hatzigeorgiadis, Comoutos, & Hardy 2019). In brief, Latinjak and colleagues (2019) distinguish between naturally happening verbalization (organic self-talk) and predetermined verbalizations based on a specific intervention plan (strategic self-talk). Verbalizations are also distinguished based on whether they have been assigned or self-developed and on their timing in relation to the skill (prior, during, after). The instructional or motivational function of self-talk can also be sub-divided (e.g., instructional skill focus, instructional strategy, motivational arousal, motivational mastery, motivational drive). The current study speaks to strategic, assigned, prior-to-skill, instructional skill focus and motivational mastery self-talk in the context of fine motor skills only. Future endeavors should explore the full ramification of this taxonomy and expand the currently presented psychophysiological model of self-talk.

Conclusion

By employing a multi-measure approach, the current study is the first to develop and test a mechanistic psychophysiological model of instructional and motivational self-talk and their effects on motor performance. As predicted by the model, instructional self-talk supported a more top-down control of action via a reduction and a disconnection of sensorimotor parietal processing from frontal processing, which resulted in better technique and performance. This finding supports an information-processing mechanism for the benefits of instructional self-talk, and provides the first evidence for a neurophysiological signature of instructional self-talk. On the other hand, motivational self-talk triggered a cardiovascular response (higher heart rate and reduced event-related heart rate variability) which supports an effort-based mechanism for the benefits of motivational self-talk. In all, the study represents the most thorough self-talk investigation to date, both in detail and range of data collected (e.g., EEG, ECG, EMG, kinematics, and detailed execution parameters). Importantly, had we limited our analysis to the common behavioral measures obtained in the self-talk literature, our key mechanistic findings would have gone undetected. We hope that our development of a psychophysiological model of self-talk alongside the encouraging data to support the model inspires other researchers to follow and move beyond a reliance on behavioral and self-report data collection methods. The identification of objective psychophysiological indices of self-talk could, in a near future become, could become an asset for coaches and performers in the sporting world since such indices could be employed measures of efficacy of interventions as well as be used to improve the likelihood of such interventions if trained via biofeedback.

References

Abdoli, B., Hardy, J., Riyahi, J. F., & Farsi, A. (2018). A closer look at how self-talk influences skilled basketball performance. *The Sport Psychologist, 32*, 9-15. https://doi.org/10.1123/tsp.2016-0162

Babiloni, C., Infarinato, F., Marzano, N., Iacoboni, M., Dassù, F., Soricelli, A., ... & Del Percio, C. (2011). Intra-hemispheric functional coupling of alpha rhythms is related to golfer's performance: A coherence EEG study. *International Journal of Psychophysiology, 82,* 260-268. https://doi.org/10.1016/j.ijpsycho.2011.09.008

Bazanova, O. M., & Vernon, D. (2014). Interpreting EEG alpha activity. *Neuroscience & Biobehavioral Reviews*, *44*, 94-110. https://doi.org/10.1016/j.neubiorev.2013.05.007

Bellomo, E., Cooke, A., & Hardy, J. (2018). Chunking, Conscious Processing, and EEG During Sequence Acquisition and Performance Pressure: A Comprehensive Test of Reinvestment Theory. *Journal of Sport and Exercise Psychology*, *40,* 135-145. https://doi.org/10.1123/jsep.2017-0308

Cacioppo, J. T., Tassinary, L. G., & Berntson, G. G. (2007). Psychophysiological science: Interdisciplinary approaches to classic questions about the mind. *Handbook of Psychophysiology*, *3,* 1-16.

Cohen, J. (1988). *Statistical power analysis for the behavioral sciences* (2nd ed.). Hillsdale, NJ: Erlbaum. http://doi.org/10.1234/12345678

Cohen, M. X. (2014). *Analyzing neural time series data: Theory and practice.* Cambridge, MA: MIT Press.

Cooke, A., Gallicchio, G., Kavussanu, M., Willoughby, A., McIntyre, D., & Ring, C. (2015). Premovement high-alpha power is modulated by previous movement errors: Indirect evidence to endorse high-alpha power as a marker of resource allocation during motor programming. *Psychophysiology*, *52,* 977-981. http://doi.org/ 10.1111/psyp.12414

Cooke, A., Kavussanu, M., Gallicchio, G., Willoughby, A., Mcintyre, D., & Ring, C. (2014). Preparation for action: Psychophysiological activity preceding a motor skill as a function of expertise, performance outcome, and psychological pressure. *Psychophysiology*, *51*. http://doi.org/10.1111/psyp.12182

Cooke, A., Kavussanu, M., McIntyre, D., Boardley, I. D., & Ring, C. (2011). Effects of competitive pressure on expert performance: Underlying psychological, physiological, and kinematic mechanisms. *Psychophysiology*, 48 1146-1156. https://doi.org/10.1111/j.1469-8986.2011.01175.x

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

Corcoran, A. W., Alday, P. M., Schlesewsky, M., & Bornkessel-Schlesewsky, I. (2018). Toward a reliable, automated method of individual alpha frequency (IAF) quantification. *Psychophysiology*, e13064. https://doi.org/10.1111/psyp.13064

Delorme, A., & Makeig, S. (2004). EEGLAB: An open source toolbox for analysis of single-trial EEG dynamics including independent component analysis. *Journal of Neuroscience Methods*, *134*(1), 9–21. http://doi.org/10.1016/j.jneumeth.2003.10.009

Galanis, E., Hatzigeorgiadis, A., Zourbanos, N., & Theodorakis, Y. (2016). *Why self-talk is effective?* Perspectives on self-talk mechanisms in sport. In Sport and Exercise Psychology Research (pp. 181-200). Academic Press. https://doi.org/10.1016/B978-0-12-803634-1.00008-X

Gallicchio, G., Cooke, A., & Ring, C. (2016). Lower left temporal-frontal connectivity characterizes expert and accurate performance: High-alpha t7-fz connectivity as a marker of conscious processing during movement. *Sport, Exercise, and Performance Psychology*, *5*, 14–24. http://doi.org/10.1037/spy0000055

Gallicchio, G., Cooke, A., & Ring, C. (2017). Practice makes efficient: cortical alpha oscillations are associated with improved golf putting performance. *Sport, Exercise, and Performance Psychology, 6*, 89–102. http://doi.org/10.1037/spy0000077

Gentili, R. J., Bradberry, T. J., Oh, H., Costanzo, M. E., Kerick, S. E., Contreras-Vidal, J. L., & Hatfield, B. D. (2015). Evolution of cerebral cortico-cortical communication during visuomotor adaptation to a cognitive-motor executive challenge. *Biological psychology*, *105*, 51-65. https://doi.org/10.1016/j.biopsycho.2014.12.003

Gray, J.A., (1994). *Three fundamental emotion systems*. In: Ekman, P., Davidison, R.J. (Eds.), The Nature of Emotion: Fundamental Questions. Oxford University Press, New York, pp. 243–247.

Halliday, D. M., Rosenberg, J. R., Amjad, A. M., Breeze, P., Conway, B. A., & Farmer, S. F. (1995). A framework for the analysis of mixed time series/point process data-theory and application to the study of physiological tremor, single motor unit discharges and electromyograms. *Progress in Biophysics and Molecular Biology*, *64*, 237–278. http://doi.org/10.1016/S0079-6107(96)00009-0

Hardy, J. (2006). Speaking clearly: A critical review of the self-talk literature. *Psychology of Sport and Exercise*, *7*, 81–97. http://doi.org/10.1016/j.psychsport.2005.04.002

Hardy, J., Begley, K., & Blanchfield, A. W. (2015). It's good but it's not right: Instructional self-talk and skilled performance. *Journal of Applied Sport Psychology*, *27*, 132-139. https://doi.org/10.1080/10413200.2014.959624

Hardy, J., Comoutos, N., & Hatzigeorgiadis, A. (2018). Reflections on the maturing research literature of self-talk in sport: contextualizing the special issue. *The Sport Psychologist*, *32*, 1-8. https://doi.org/10.1123/tsp.2017-0141

Hardy, J., Gammage, K., & Hall, C. (2001). A descriptive study of athlete self-talk. *The Sport Psychologist*, *15*, 306-318. https://doi.org/10.1016/S1469-0292(01)00011-5

Hardy, J., Oliver, E., & Tod, D. (2009). A framework for the study and application of self-talk within sport. In S. Mellalieu and S. Hanton (Eds.), *Advances in Applied Sport Psychology: A review*, 37-74. Routledge.

Hatfield, B. D., Costanzo, M. E., Goodman, R. N., Lo, L.-C., Oh, H., Rietschel, J. C., … Haufler, A. (2013). The influence of social evaluation on cerebral cortical activity and motor performance: a study of "Real-Life" competition. *International Journal of Psychophysiology*, *90*, 240–9. http://doi.org/10.1016/j.ijpsycho.2013.08.002

Hatzigeorgiadis, A., Zourbanos, N., Galanis, E., & Theodorakis, Y. (2011). Self-talk and sports performance: A meta-analysis. *Perspectives on Psychological Science, 6*, 348-356. https://doi.org/10.1177/1745691611413136

Hatzigeorgiadis, A., Zourbanos, N., Mpoumpaki, S., & Theodorakis, Y. (2009) Mechanisms underlying the self-talk–performance relationship: The effects of motivational self-talk on self-confidence and anxiety. *Psychology of Sport and Exercise, 10*, 186–192. doi:10.1016/j.psychsport.2008.07.009

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

Lachaux, J. P., Rodriguez, E., Martinerie, J., & Varela, F. J. (1999). Measuring phase synchrony in brain signals. *Human Brain Mapping*, *8*, 194-208. https://doi.org/10.1002/(SICI)1097-0193(1999)8:4<194::AID-HBM4>3.0.CO;2-C

Latinjak, A. T., Hatzigeorgiadis, A., Comoutos, N., Hardy, J. (2019). Spearking clearly… 10 years on: The case for an integrative perspective of self-talk in sport. *Sport, Exercise, and Performance Psychology*. https://doi.org/10.1037/spy0000160

Lopez-Calderon, J., & Luck, S. J. (2014). ERPLAB: an open-source toolbox for the analysis of event-related potentials. *Frontiers in Human Neuroscience*, 8, 213.

https://doi.org/10.3389/fnhum.2014.00213

Makeig, S., Bell, A.J., Jung, T.P., Sejnowski, T.J., 1996. *Independent component analysis of electroencephalographic data*. In: Touretzky, D., Mozer, M., Hasselmo, M. (Eds.), Advances in Neural Information Processing Systems Vol. 8. MIT Press, Cambridge, MA.

Masters, R. S. W., & Maxwell, J. (2008). The theory of reinvestment. *International Review of Sport and Exercise Psychology*, *1*, 160–183. http://doi.org/10.1080/17509840802287218

Masters, R. S. W., Polman, R. C., & Hammond, N. V. (1993). 'Reinvestment': A dimension of personality implicated in skill breakdown under pressure. *Personality and individual differences, 14*, 655-666. https://doi.org/10.1016/0191-8869(93)90113-H

Mullen, R., & Hardy, L. (2010). Conscious processing and the process goal paradox. *Journal of Sport and Exercise Psychology, 32*, 275-297. https://doi.org/10.1123/jsep.32.3.275

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

Oldfield, R. C. (1971). The assessment and analysis of handedness: The Edinburgh Inventory. *Neuropsychologia*, *9*, 71–113. http://dx.doi.org/10.1016/0028-3932(71)90067-4

Theodorakis, Y., Weinberg, R., Natsis, P., Douma, I., & Kazakas, P. (2000). The effects of motivational versus instructional self-talk on improving motor performance. *The Sport Psychologist*, *14*, 253-271. https://doi.org/10.1123/tsp.14.3.253

Tod, D., Hardy, J., & Oliver, E. (2011). Effects of self-talk: A systematic review. *Journal of Sport and Exercise Psychology*, 33, 666-687. https://doi.org/10.1123/jsep.33.5.666

Vasey, M. W., & Thayer, J. F. (1987). The continuing problem of false positives in repeated measures ANOVA in psychophysiology: a multivariate solution. *Psychophysiology*, *24*, 479–486. http://doi.org/10.1111/j.1469-8986.1987.tb00324.x

Zachry, T., Wulf, G., Mercer, J., & Bezodis, N. (2005). Increased movement accuracy and reduced EMG activity as the result of adopting an external focus of attention. *Brain Research Bulletin*, *67,* 304-309.

Zhu, F. F., Poolton, J. M., Wilson, M. R., Maxwell, J. P., & Masters, R. S. W. (2011). Neural co-activation as a yardstick of implicit motor learning and the propensity for conscious control of movement. *Biological Psychology*, *87,* 66–73. http://doi.org/10.1016/j.biopsycho.2011.02.004

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Supplementary Material

Development of the self-talk cues

Participants in the **instructional self-talk** group were assigned the cue *feet still-wrists locked-arms through* (Appendix 1). We developed the cue based on the following procedure (inspired by research from Gucciardi & Dimmock, 2008). First, a set of general putting set-up rules was devised from a PGA coaching manual. Second, in a pilot session, the most important rules for a novice and their sequential order were identified. Specifically, during the pilot session, a member of the research team (VP), with no previous golfing or mini-golfing experience: 1) read out loud the instructions: 2) performed a putt (distance from target ~3m); 3) ranked the order to which each single rule was used. This procedure was repeated for 30 putts, which represented the moment in which the sequential position of the rules reached a saturation point (see Table 3 for the order of the rules). Third, VP was asked to identify three phonologically-simple keywords that she felt were encompassing the most relevant rules. Once the three words were identified, she performed 10 more putts, but this time she was asked to silently say these words "in her mind" before performing each putt. Then, she reflected on whether she felt that these words were useful, and she was given the chance to change the words if she wanted. This procedure was repeated two times before VP was satisfied. The keywords identified were *feet*, *lock*, and *gentle* and refer to rule 2, 3, and 4 of Table 2 respectively. Fourth, the key-words were evaluated and modified by the rest of the research team (JH, AC, EB) until unanimous consensus was reached on the fact that the cue met the following criteria: 1) compliant to Landin's (1994) recommendations (brief and phonetically simple; logically associated with the referent element of the skill; and conformed to the sequential timing pattern of the task); 2) focus on body parts and skill (rather than strategy focused, cf., Hardy, 2006), or in other words, characterised by an explicit emphasis on relevant motor processes necessary for task. For this reason, a direct reference to body parts was added (i.e., feet, wrists, arms). Moreover, since the third keyword. *gentle*, was considered to be too strategy related as well as too specific to VP, it was substituted with *arms through*. In order to make clear the meaning of each cue words with respect to the task, upon assignment of the cue, participants will be explained how each word connects to the corresponded rule/s (Appendix 1). Participants in the **motivational self-talk** group was assigned the cue *come on-I can do this* (Appendix 2). This cue was derived by previous self-talk research (Hardy, Begley, & Blanchfield, 2015; Linnér & Sandström, 2010; Theodorakis et al., 2000) and was unanimously agreed upon by the research team (JH, AC, EB, VP) for having a focus on mastery (rather than an arousal, see Hardy, 2006) and being comparatively short and phonetically simple as the instructional cue.

Table 1. **Putting rules:**
- Hold the club with your hands close together, the non-dominant hand at the top of the club.
- Stand side-on with your weight even on both feet.
- The club should be vertical to the ball[15].
- Backswing distance is equal to through-swing distance.
- Swing from the arms and shoulders, keeping wrists and elbows locked.
- Lower body and head remain still.
- Stand with your feet close together, the ball in the middle.

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[15] This rule was removed since it has an external focus of attention (cf., Wulf, 2015), and as such, it might trigger a more implicit processing of the movement (for a detailed discussion see: Masters & Maxwell, 2008).

Table 2. **Sequence of rules**[16]**:**

1) Hold the club with your hands close together, the non-dominant hand at the top of the club.
2) Stand side-on with your weight even on both feet.
   Stand with your feet close together, the ball in the middle.
3) Swing from the arms and shoulders, keeping wrists and elbows locked.
   Lower body and head remain still.
4) Backswing distance is equal to through-swing distance.

Appendix 1: self-talk explanation (podcast) instructional

Self-talk is a cognitive strategy that has been shown to improve performance and refers to any verbal cues or phrases we say to ourselves, whether out loud or in our mind, while learning or performing a task.

In the present study we are interested in understanding how self-talk might influence your learning or performance of a golf putting task.

We are particularly interested in a specific type of self-talk that aims to help you to focus on the correct execution of the movements required to perform the task, called instructional self-talk.

Based on previous studies and golfing coaching manuals, the following phrase has been developed:

FEET STILL – WRISTS LOCKED – ARMS THROUGH

The FEET STILL word refers to "standing side-on with your weight even on both feet and the ball in the middle"

The WRISTS LOCKED word refers to "keep wrists and elbows locked and your lower body and head still"

The ARMS THROUGH word refers to "swing through from the arms and shoulders, with backswing distance equal to through-swing distance".

It is important that you say this phrase SILENTLY IN YOUR MIND to yourself before EACH putt.

---

[16] To measure the exact moment during which the swing happened, an infra-red sensor was used to measure when the club was moved away from the starting position. For this reason, participants in both the instructional and motivational self-talk group were asked to "address the ball so that the light of the sensor is orange".

Appendix 2: self-talk explanation (podcast) motivational

Self-talk is a cognitive strategy that has been shown to improve performance and refers to any verbal cues or phrases we say to ourselves, whether out loud or in our mind, while performing a task.

In the present study we are interested in understanding how self-talk might influence your learning and performance of a golf putting task.

We are particularly interested in a specific type of self-talk that aims to increase your self-confidence when performing the task, called motivational self-talk.

Based on previous self-talk research the following phrases have been developed:

COME ON - I CAN DO THIS

These keywords refer to the fact that you have all the skills necessary to perform well in this task.

It is important that you say this phrase SILENTLY IN YOUR MIND to yourself before EACH putt.

***Table 3.* Power analyses single electrodes**

Site	ANOVA	Polynomial trend
Fz	Bin, $F(4, 25) = 4.48$, $p = .007$, $\eta_p^2 = .42$	quadratic $p = .009$, $\eta_p^2 = .22$
F3	Bin $F(4, 25) = 3.58$, $p = .019$, $\eta_p^2 = .36$	quadratic $p = .004$, $\eta_p^2 = .26$
F4	Bin $F(4, 25) = 4.18$, $p = .005$, $\eta_p^2 = .43$	quadratic $p < .001$, $\eta_p^2 = .35$
F7	-	-
F8	-	-
Cz	-	-
C3	Bin $F(4, 25) = 3.85$, $p = .014$, $\eta_p^2 = .38$	cubic $p = .017$, $\eta_p^2 = .19$
C4	Bin $F(4, 25) = 2.74$, $p = .051$, $\eta_p^2 = .31$	linear $p = .007$, $\eta_p^2 = .21$
Pz	Group, $F(1, 32) = 3.44$, $p = .074$, $\eta_p^2 = .11$	instructional > motivational
P3	Bin $F(4, 25) = 2.76$, $p = .050$, $\eta_p^2 = .31$ Bin*Group $F(4, 25) = 2.68$, $p = .055$, $\eta_p^2 = .30$	linear $p = .004$, $\eta_p^2 = .26$
P4	Bin $F(4, 25) = 3.94$ $p = .013$, $\eta_p^2 = .38$ Group, $F(1, 32) = 3.76$, $p = .063$, $\eta_p^2 = .12$	quadratic $p = .003$, $\eta_p^2 = .27$ instrutional > motivational
Oz	Bin $F(4, 25) = 5.88$ $p = .002$, $\eta_p^2 = .48$	quadratic effect $p < .001$, $\eta_p^2 = .32$
O1	Bin $F(4, 25) = 5.12$ $p = .004$, $\eta_p^2 = .45$	quadratic $p < .001$, $\eta_p^2 = .33$
O2	Bin $F(4, 25) = 6.56$, $p = .001$, $\eta_p^2 = .51$	linear $p < .001$, $\eta_p^2 = .40$
T7	-	-
T8	-	-

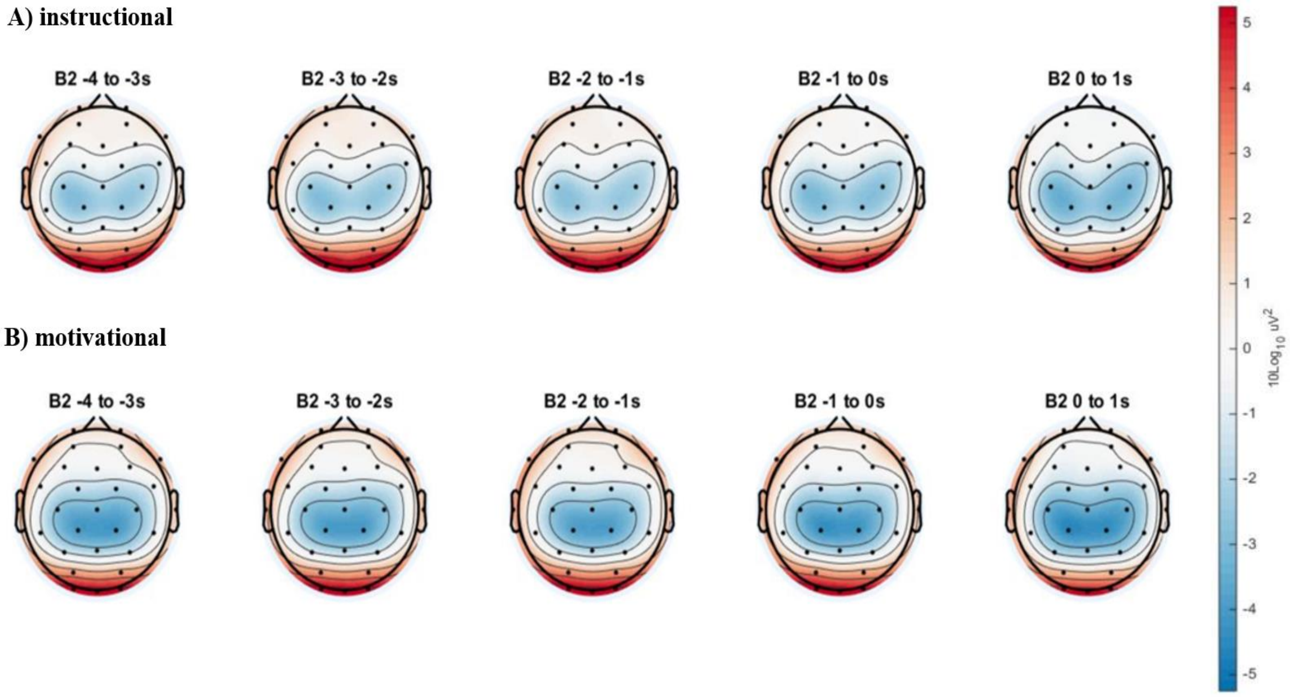

Figure 3. Topographic distribution of median scaled power in the instructional (panel A) and motivational (panel B) group. Each column represents time bin (-4 to -3, -3 to -2, -2 to -1, -1 to 0, 0 to +1 s).

Connectivity

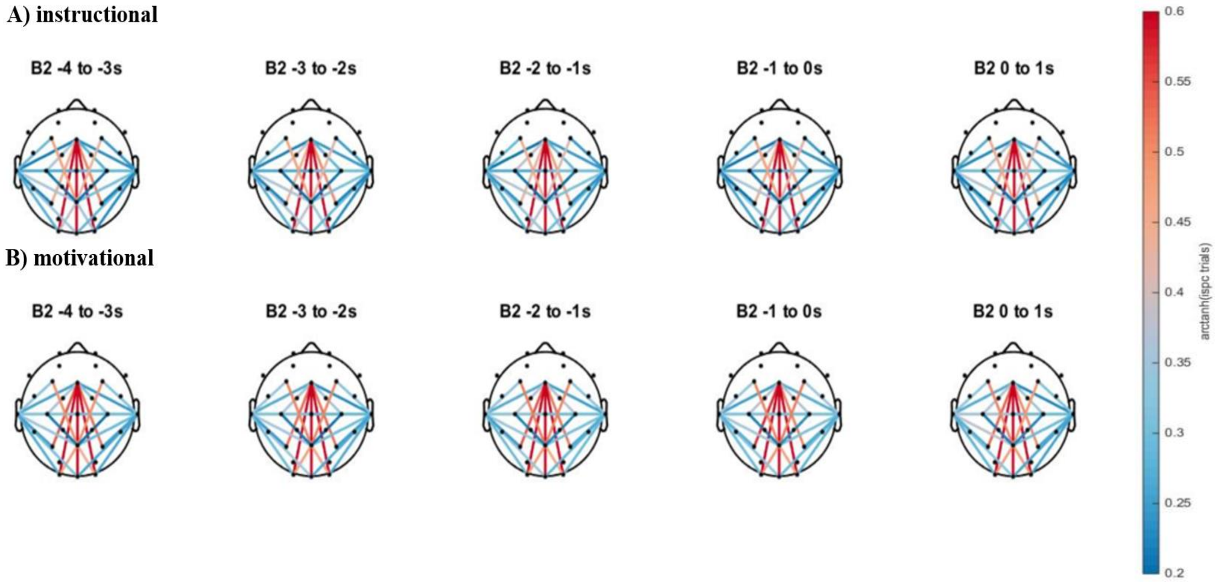

Figure 4. Topographic distribution of atanh(ISPC$_{\text{trials}}$) in the instructional (panel A) and motivational (panel B) group. Each row represents a block (B1, B2), each column represents time bin (-4 to -3, -3 to -2, -2 to -1, -1 to 0, 0 to +1 s)

Control analyses

Following the approach of Nolte and colleagues (2004) reported by the research group of Babiloni (Babiloni et al., 2011; Del Percio et al., 2011), we performed a control analysis to rule out the possibility that our connectivity results were due to volume conduction. As shown in Figure 5, values of the imaginary part of our connectivity measure (ISPC across trials) were non-zero globally for the electrode pairs selected for the analysis. Therefore, it is unlikely that volume conduction affected the connectivity values discussed in the present study.

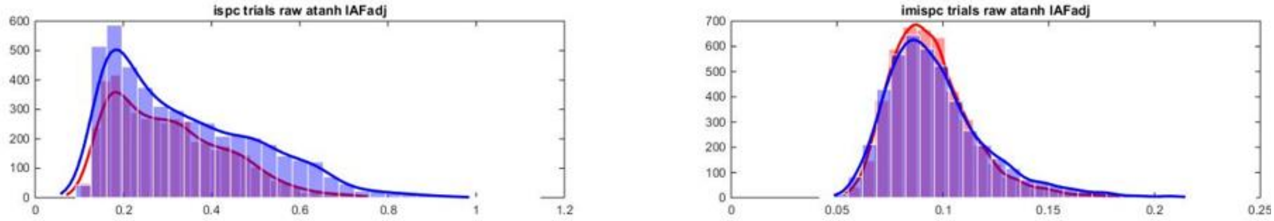

Figure 5. Distribution of connectivity values. Blue: instructional group; Red: motivational group. The left panel shows ISPC across trials, whereas the right panel showsthe imaginary part of ISPC across trials.

CHAPTER SIX

General Discussion

The aim of this thesis was to increase our understanding on the sensitivity of EEG measures, namely left-temporal high-alpha power and left-frontotemporal high-alpha connectivity, which the current literature discusses as EEG measures of conscious processing. This final chapter will provide the reader with a summary of the findings of the experiments conducted, discuss the theoretical implications, and outline a series of avenues which future studies might want to consider in order to advance knowledge in this field.

Summary of chapters

Chapter one introduced the construct of conscious processing of movements and, by means of a discussion of the most relevant behavioural and neuroscientific evidence, highlighted the shortcomings at the roots of the current heuristic interpretation of left-temporal high-alpha power and left-frontotemporal high-alpha connectivity as representative of movement-relevant verbal processing.

Accordingly, as a general framework, the first section of chapter one introduced the concepts of explicit versus implicit motor skill learning and reinvestment theory. This section was followed by a brief review of the behavioural evidence in support of these theorisations and a discussion of methods to limit conscious processing of movements. Finally, after an introduction to the EEG technique, the last section offered a review of the literature on EEG alpha activity and movements, followed by a critique of the evidence at the base of the conceptual link between the left-temporal EEG alpha measures and conscious processing of movements, which acted as a base for the experiments described in the subsequent chapters.

The experiment reported in chapter two (study 1) was designed to provide the most comprehensive test of reinvestment theory, using an innovative multi-measure approach which included an assessment of movement chunking, self-reported conscious processing, and putative

EEG measures of conscious processing. To test reinvestment's theory predictions regarding both learning and performance pressure, a mixed-model design was employed. Participants performed a sequence learning task during an acquisition phase followed by a competitive pressure phase. Crucially, they were assigned to comparatively *high* versus *low* conscious processing (*explicit* versus *implicit*) training groups, which were operationally implemented as *trial-and-error* versus *errorless* practice conditions. In line with previous literature, results confirmed chunking as a general mechanism underpinning both learning routes (e.g., Hikosaka et al., 1999; Song & Cohen, 2014; Willingham, 1998); and supported the idea that this process is, at early stages, benefited by explicit and conscious processes (Curran & Keele, 1993; Hikosaka et al., 1999; Willingham, 1998). Moreover, in additional agreement with the theory, this faster chunking observed in the explicit group was coupled with practice-induced reductions in self-reported conscious processing and cortical activity (especially at the left-temporal site), which was interpreted as increased cortical efficiency (Gallicchio et al., 2017; Landers et al., 1994). However, self-reported conscious processing and left-temporal power were disconnected in the implicit group. Despite the fact that, as expected, in this group chunking happened with low and stable self-reported conscious processing, left-temporal activity was surprisingly high throughout the all phases. Moreover, the pressure-induced effects hypothesised based on reinvestment theory (Masters & Maxwell, 2008) were not confirmed. In fact, although under pressure only explicit group reported increased self-reported conscious processing, no change in performance or power was observed. Moreover, frontotemporal connectivity, which was stable during acquisition, increased under pressure in both groups. As a consequence, the validity of left-temporal alpha power and left-frontotemporal connectivity as pure measures of conscious processing was put in doubt. In particular, the specific sensitivity of these EEG measures to movement-relevant verbal processing was questioned. Moreover, a series of methodological limitations potentially responsible of the absence of reinvestment effects were highlighted.

Building of these findings, the experiment described in chapter three (study 2) was designed to provide a more controlled test of the link between conscious processing and left-temporal alpha power and left-frontotemporal connectivity. In line with chapter two, this experiment employed a sequence learning task and mixed-model design with two training groups, an acquisition phase plus a high-pressure competitive phase. However, rather than trying to affect conscious processing in an indirect way (i.e., by fostering or limiting errors), this study adopted a more direct manipulation of training conditions to induce *high* versus *low* levels of conscious processing. Specifically, two crucial features of the concept of conscious processing, namely, movement-awareness and -verbalizability were manipulated in order to dichotomise the groups into *full* versus *null* levels of movement-relevant verbal declarative knowledge. Moreover, in order to make reinvestment more likely, the design additionally included: an overnight rest after the acquisition phase, in order to introduce a retention phase before the competitive pressure phase, and to foster movement consolidation and create more room for reinvestment to happen; task complexity was increased through the task being performed with the four fingers of the non-dominant hand; EEG was monitored with a higher-density EEG system to obtain a more complete picture of scalp level changes in power and connectivity. Results provided additional evidence against the link left-temporal EEG measures and movement-relevant verbal processing. In fact they showed that left-temporal alpha power and left-frontotemporal alpha connectivity did not differentiate the *full-declarative knowledge* (explicit) from the *null-declarative knowledge* (implicit) group; and did not show a specific change with training or under pressure. Nevertheless, our experimental manipulation affected alpha power and connectivity at other scalp regions. Specifically, the *full-declarative knowledge* group, which showed superior performance at all phases, was characterised by an decreased activation of frontal sites, activation of parietal ones, as well as reduced connectivity between the two regions which was interpreted as indicative of a top-down priming of sensorimotor regions due to the available frontal task relevant information. In other words, these results suggest that *full* versus *null* movement-relevant declarative knowledge trigger a series of electrocortical effects that are not limited to the left-temporal “verbal” region, thereby supporting a broader conceptualisation of conscious processing of movement.

The experiment described in chapter four (study 3) was designed to complement the evidence discussed above by assessing whether left-temporal alpha power and left-frontotemporal connectivity are affected by the semantic content of pre-movement verbalisations. Specifically, since conscious processing is often described as a series of conscious verbal processes relevant for movement execution, this experiment compared participants rehearsing *movement-relevant* versus *movement-irrelevant* verbal content prior to movement execution. This manipulation was implemented with a self-talk intervention whereby participants were dichotomised into instructional (*movement-relevant*) versus motivational (*movement irrelevant*) self-talk groups. Results again questioned the specific sensitivity of these EEG measures to verbal processing functional to movement execution. In fact, they revealed that left-temporal power and left-frontotemporal connectivity did not distinguish the two groups. However, results did not exclude that these measures might be a by-product of general verbal processes happening during movement preparation. Moreover, since these measures were disconnected from self-reported conscious processing, and, similar to chapter three, the manipulation triggered effects at other scalp sites, it was once more argued that conscious processing of movements might encompass a series of cognitive processes happening in modalities other than the verbal one, such as the visual or the kinaesthetic one. In other words, these results provided additional support for a broader conceptualisation of conscious processing.

Theoretical implications

As discussed above, the experimental findings hereby discussed provide tentative evidence against the popular idea connecting the construct of conscious processing, operationalised in terms of movement-relevant verbal processes, and two EEG measures, namely left-temporal alpha power and left-frontotemporal alpha connectivity (Gallicchio et al., 2016; Hatfield et al., 2013; Zhu et al., 2011). Specifically, these measures were shown to be insensitive to the levels of movement-relevant declarative knowledge (chapter three) and to the skill-relevance of the semantic content of pre-movement verbalisations (chapter four). That is these measures failed to distinguish groups dichotomised by manipulating verbal processes (chance for declarative knowledge and sematic content) happening prior to movement execution. Moreover, these EEG measures were consistently disconnected from self-reported conscious processing. In this regard, it should be pointed out that in chapter two, when conscious processing was manipulated through high versus low chances for error, self-reported conscious processing changed as expected based on reinvestment theory. On the contrary, when the manipulation focused more on verbal processes (chapter four) this did not happen. However, since these "verbal" manipulations were connected with changes in alpha power and connectivity changes at other sites, it was suggested that conscious processing might be more broadly characterised.

The idea behind this suggestion stems from a reflection on the nature of conscious and unconscious memory. Explicit, conscious, declarative processes can, by definition, be verbally reported; whereas implicit, unconscious, procedural processes cannot (cf., Squire & Dede, 2015). However, the possibility for a thought to be verbally described, does not imply that the thought itself happened exclusively in verbal format or in cortical areas deputed to verbal processing (i.e., left-temporal lobe). In fact, consciously imagining a complex movement encompasses in all likelihood a series visual, auditory, and kinaesthetic details which can be verbally reported post-hoc (Roberts, Callow, Hardy, Markland, & Bringer, 2008). This idea represents the foundation of a series of approaches which, in essence, propose that thinking or doing largely share a common neural base (e.g., *embodiment approach*, Shapiro 2010; *ideomotor approach,* Greenwald, 1970; *functional equivalence hypothesis*, Jeannerod, 1994). Support for this idea comes from a series of imaging and neuropsychological studies on the phenomenon of motor imagery, which partially overlaps with the one of conscious motor processing.

Motor imagery is a conscious and active process whereby performance of movements is imagined without any overt physical production (Jeannerod, 1994). Neuroscientific investigations of this cognitive process commonly report that akin to motor execution, motor imagery activates (although to a lesser extent) the so-called frontoparietal network, a neural circuit including pre-motor, sensorimotor, and parietal regions as well as basal ganglia (Formaggio, Storti, Cerini, Fiaschi, & Manganotti, 2010; Meister, Krings, Foltys, Boroojerdi, Muller, Topper, & Thron, 2004; Pfurtscheller & Neuper, 1997; Szameitat, Shen, & Sterr, 2007; Yuan, Liu, Szarkowski, Rios, Ashe, & He, 2010). For example, functional magnetic resonance imaging (fMRI) studies (e.g., Meister et al., 2004; Szameitat et al., 2007), report that this pattern of activation includes the medial and lateral regions of both frontal cortex (dorsolateral prefrontal cortex, pre-supplementary motor area, supplementary motor area), parietal cortex (precuneus, inferior and superior parietal lobule), and the basal ganglia. Notably, while frontal activation seems to be bilateral, parietal activation seem to have a left-hemisphere lateralisation (Meister et al., 2004; Szameitat et al., 2007), we will come back to this point later on. Moreover, in EEG-fMRI co-registrations studies (Formaggio et al., 2010; Yuan et al., 2010) the somatotopic (i.e., contralateral to the limb used) activation of the sensorimotor cortex observed with the fMRI (increased blood oxygenation level dependent signal; BOLD) corresponded to a decrease in alpha power (at C3, Cz, C4; see also Pfurtscheller & Neuper, 1997).

The frontoparietal network seems to be crucial for goal-directed actions (e.g., grasping, reaching), for corporeal awareness and body consciousness, as well as for the sense of agency and ownership of one’s actions (for an extended discussion see Murata & Ishida, 2007). In this model, frontal regions would be deputed to conscious action selection and generation of a model of how the movement should feel (efferent model). Whereas, parietal regions would be deputed to sensorimotor integration of multi-modal sensory inputs (especially visual, somatic, and proprioceptive) to generate a model of the surrounding space and of movement sensations which is then interfaced with the frontally generated efferent model.

Crucially, this neuropsychological evidence (see also Curran & Keele, 1993; Willingham, 1998) suggests that conscious, working-memory mediated, control of motor acts, whether it is actually performed or just imagined, is associated with activity of the frontoparietal network (Babiloni et al., 2004b; Baddeley 1998; Colette et al., 1999; Colette & Van der Liden, 2002; Kondo et al., 2004; Li et al., 2004; Osaka et al., 2004), especially with frontal regions. In fact, these regions (especially the prefrontal cortex) are involved in conscious awareness and executive working memory functions such as inhibition and updating (Miyake, Friedman, Emerson, Witzki, & Howerter, 2000; Shimamura, 2000), which enable executive planning and hypothesis testing, arguably two crucial characteristics of conscious processing (cf., Masters & Maxwell, 2008). These strategic functions would be especially important to explore potential motor plans and select the optimal action to satisfy task's demands (Ashe et al., 2006; Murata & Ishida, 2007). Moreover, suppression of conscious control in cognitive tasks is associated with a dampening of activity in these regions (Baddeley, 2012; Logie, 2012). In other words, within the frontoparietal network activity in the frontal regions might be mainly responsible for conscious processing of movements (cf., Moran, 2012).

In further agreement with this position, it is worth discussing evidence from neuroscientific investigations of sequence learning, which, as mentioned in the experimental chapter, offer a mirror on the basics behind the acquisition of any complex movement (cf., Ashe et al., 2006). Crucially, as discussed by Ashe and colleagues (2006), frontoparietal network activity changes based on whether the learning environment fosters a more explicit or implicit movement processing. In short, movements performed with awareness and explicit, top-down, efforts (i.e., conscious processing) would mainly involve activity in the medial-temporal lobe (i.e., hippocampus), important for storing information from long term memory, and the prefrontal cortex to consciously select the motor acts (possibly via working memory). Then, based on this information and on the multi-modal representation of the surrounding space generated in the posterior parietal cortex, the supplementary motor area (SMA) would temporally sequence the movements in the appropriate ordinal position (i.e., chunking). Finally, movements would be implemented by the motor cortex. On the contrary, movements performed in an implicit way, would rely on a less conscious, more perceptual, bottom-up mechanism. In this case, the first node would be the posterior parietal cortex, which represents the perceptual (mainly visual) information that guides movement implementation in the motor cortex, and only later would involve the SMA. Crucially, the medial-temporal lobe would not be involved (this will be discussed in the next paragraph). Moreover, with extensive practice and automatization, cortical representation of movements would progressively leave the stage to subcortical structures such as the basal ganglia. However, this would happen only for actions that are then execute in a truly reflexive manner. In simple terms, explicit execution would be more frontally driven; implicit execution would be more parietally driven; while truly automatic and almost reflexive execution would be subcortical (cf., Ashe et al., 2006).

On a closer look, this neuropsychological evidence is in agreement with the experimental the effects observed in the experimental chapters of this thesis. In fact, in both chapter three and five, power and connectivity data other than showing a clear involvement of the frontoparietal network, as suggested by the focused (power data) and collaborative (connectivity) activation of frontal, central, and parietal sites, highlighted group differences that are in line with the neuropsychological model discussed by Ashe and colleagues (2006).

In chapter three, the explicit (full-movement relevant declarative knowledge) training group was characterised by more intense and independent activity at parietal sites compared to the implicit group (null-movement relevant declarative knowledge). At the same time, in the explicit group during acquisition, a phase in which more conscious processing is necessary (cognitive stage of learning), frontal and parietal sites were less connected than in the implicit group, which suggests that thanks to the availability of movement-relevant declarative knowledge, frontal regions could exert top-down control on actions with less need to rely on parietal sensorimotor information. In other words, the explicit, high-conscious processing group was characterised by a more active and possibly frontally driven frontoparietal network. Moreover, since connectivity group differences weakened at retention, it is possible that with consolidation the network progressed to a more implicit mode (cf., Ashe, 2006).

Similarly, in chapter five, the use of an instructional self-talk cue, which consisted of movement-relevant verbal information, was connected to: less activity at parietal sites (power), which suggests that behaviour was less guided by sensorimotor processes (cf., Ashe, 2006); and weaker connectivity between frontal and parietal sites, which, akin to chapter three, suggests reduced need for the frontal regions to rely on sensorimotor information. In other words, the availability of explicit movement-relevant declarative knowledge affected the frontoparietal nework by triggering a reduced involvement (less activity and less connectivity with frontal sites) of the parietal sensorimotor regions. This suggests that instructional self-talk helped exerting a more top-down control of the action, possibly by helping action selection or offering an explicit chunking strategy (Hardy, 2006).

In conclusion, the present evidence supports a broader conceptualisation of conscious processing in terms of a more complex and multidimensional explicit cognitive process. Moreover, it suggests that activity of the frontoparietal network, which is crucial for movement execution as well as movement imagery, should be considered by future studies interested in extending the literature on conscious processing.

Left-temporal activity, verbal processing, and explicit learning.

This thesis was based on evidence connecting EEG alpha activity measured at left-temporal sites, conscious verbal processing of movements, and explicit learning. However, the results obtained did not support this interpretation, suggesting that these left-temporal measures are not connected to movement-specific verbal processing. For this reason, this paragraph will briefly outline a series of considerations on the role the temporal lobe and then offer an alternative interpretation of the left-temporal effects reported by the literature.

As mentioned above, the medial temporal lobe seems to be crucial for explicit, declarative memory (Ashe et al., 2006). Crucial brain structures for this function are the hippocampus and surrounding cortex, which have the function of storing information in long-term memory (Nadel & Moscovitch, 1997). Lesions of these structures mainly result in anterograde declarative memory deficits but do not impair previously consolidated information[17]. On the contrary, damage to the lateral temporal neocortex, which is assumed to be the storage of consolidated declarative memories, results in retrograde semantic and episodic memory deficits (see Ward, 2010 for a discussion). However, although these structures are important for explicit learning, the information they process is not limited to verbal material. For example, in their now seminal fMRI study, Maguire and colleagues (2000) showed that the volume of the posterior hippocampal region was larger in licensed London's cab drivers compared to regular drivers. Crucially, since cab drivers are specialised with visuospatial information, the authors suggested a role of this structure in spatial navigation. In other words, explicit visuospatial knowledge requires hippocampal processing as much as verbal information does. Moreover, although the medial temporal lobe is involved in explicit learning, the conceptual link between left-temporal activity and explicit learning through verbal processing is more based on a heuristic rather than actual evidence.

If the left-temporal cortex is not associated to movement-relevant verbal processing, how can be the left-temporal effects reported by the EEG literature be explained? I suggest an alternative explanation which is based on a series of evidence coming from the functional imaging and the neuropsychological literature. First, functional imaging literature suggests that the left-hemisphere might be important for object-based actions (see Ward, 2010 for a discussion). In fact, damage to the left-hemisphere is associated with ideomotor apraxia, a deficit in production of appropriate actions based on objects or explicit commands (Gonzalez Rothi, Ochipa, & Heilman, 1991). Second, the so-called Broca region (left-inferior frontal gyrus), which is traditionally associated to verbal processing, seems to play a more general role for motor control by integrating external sensorimotor input about biological motion internal representations of hand, arms, and mouth (Binkofski & Buccino, 2004). Third, motor imagery studies (Meister et al., 2004; Szameitat et al., 2007) suggested the left-portion of the posterior parietal cortex might be where motor images are

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[17] If information was not completely consolidated the deficit can be, to a certain extent, retrograde too (Ward, 2010).

stored and recalled during imagery (Sirigu et al., 1996, 1995). Fourth, these two regions (left-inferior frontal gyrus and left-inferior parietal lobe) seem to collaborate for use of tools as part of the frontoparietal network (Chao & Martin, 2000; Rumiati et al., 2004).

Now, considering that that these regions lie extremely close to the left-temporal cortex and that the EEG methodology has in spatial resolution its weakness, it cannot be excluded that the left-temporal effects observed by previous EEG studies might depend on activity happening in regions surrounding the left-temporal cortex. If this was the case, the expertise related differences observed would be linked to object manipulation and conscious recall of motor images rather than verbal processing of movements. Although the experimental work of this thesis provides some tentative support for this idea, future studies aiming to clarify this point should employ methodologies, such as near-infrared spectroscopy (NIRS) which, compared to EEG, are characterised by superior spatial resolution.

Limitations of the Research

Although the experimental work reported in this thesis was designed to address the gaps of previous research by employing a more comprehensive approach, it was not free from limitations. This paragraph will discuss a series of limitations in addition to those discussed in each experimental chapter.

The main limitation is the absence of pressure-induced drops in performance as predicted by reinvestment theory. This might be linked to (1) side-effects of our pressure manipulation; and/or (2) to the complexity of the movements required.

First, our pressure manipulation consisted of a competitive environment build around a mixture of evaluation and rewards/punishments. Although our manipulation-check data suggest that participants were cognitively anxious, it might be possible that such a manipulation might have caused enjoyment. As suggested by the broaden-and-build theory (Friedrickson, 2004), this positive affect might have helped maintaining performance under pressure and prevented reinvestment. For this reason, future studies employing a pressure manipulation should consider measuring enjoyment in addition to anxiety scores.

Second, reinvestment effects are more likely with complex movements that have been automated with practice, as they offer more room for regressing to a less efficient form of movement control. In other words, the movements required by the sequence learning tasks in chapter two and chapter three might have been too simple. In fact, rather than generating a totally new pattern of muscle coordination, they required the sequencing of a series of highly automated movements via eye-hand coordination. As such the motor requirements might have been subjected to a floor effect. However, when we employed a task such as golf putting, which did required a new movement, results did not change.

Directions for Future Research

In addition to the suggestions for future investigations presented in each experimental chapter and in the preceding discussion, it is worth discussing additional key research themes.

Given the complexity of the construct of conscious processing, future research should build experimental manipulation that directly tap on the operation definition of conscious processing implemented by in the Movement Specific Reinvestment Scale (Masters, Eves, Maxwell, 2005) in an attempt to identify the cortical correlates of each subcomponent. Given the explorative stance of this investigation and the magnitude of information that can be measured by the EEG, research could make use of pattern recognition and machine learning techniques, to identify pattern of power and connectivity pathways which reliably distinguish individuals with high versus low levels of conscious processing. These high versus low levels of conscious processing could be induced through a training phase extended over several weeks (e.g., Landers et al., 1994) or by having expert performers to execute their highly automated skills in normal versus unusual motoric conditions in order to de-automate them (e.g., Beilock & Carr, 2011). Such modified conditions could involve funny-shaped putter in the case of golfers or for more general motor skills, practice conditions in which visuomotor mapping is modified, for example by means of a mirror.

Applied Implications

The successful identification of the neurophysiological correlates of conscious processing and of its sub components would have important applied implications for the sporting and rehabilitative work. In fact, it would provide objective measures which could be directly or indirectly targeted by interventions aiming at improving motor control function. For example, a coach or a rehabilitation practitioner could verify the success of an intervention deemed to limit conscious processing (e.g., analogy learning; training conditions that force external focus of attention) by assessing how these neurophysiological measures changed from pre- to post-intervention. Moreover, practitioners wanting to act directly on neurophysiological processes linked to conscious processing with the goal of affecting performance, could apply neuromodulation techniques such as neurofeedback training (see Ring et al., 2015) or tDCS (Zhu et al., 2015). Considering the fast-technological advancements such as wireless data stream and cloud computing, such neurophysiological tools could be soon integrated into handheld devices such as smart phones and provide a real time monitoring of conscious processing, becoming a powerful ally of motor control stake-holders.

Conclusion

Despite the experimental work produced in the last decade, little was known about the neurophysiological mechanisms underpinning the construct of *conscious processing* of movements. Accordingly, this thesis aimed to advance our knowledge of such mechanisms by combining several performance, self-report, and physiological measures. Results scaled down the importance of the left-temporal measures of brain activity as indexes of conscious processing and shifted the focus to frontal and parietal regions, which appeared to be more directly sensitive to changes along the continuum between top-down and bottom-up control of movements. As a whole, this thesis provides the base for the re-discussion of the conscious processing and new neurophysiological measures worthy of attention.

References

Ashe, J., Lungu, O. V., Basford, A. T., & Lu, X. (2006). Cortical control of motor sequences. *Current Opinion in Neurobiology*, *16*, 213-221. https://doi.org/10.1016/j.conb.2006.03.008

Baddeley, A. (2012). Working memory: theories, models, and controversies. *Annual Review of Psychology, 63,* 1-29. https://doi.org/10.1146/annurev-psych-120710-100422

Beilock, S. L., & Carr, T. H. (2001). On the fragility of skilled performance: What governs choking under pressure? *Journal of Experimental Psychology: General*, 130, 701–725.

Binkofski, F., & Buccino, G. (2004). Motor functions of the Broca's region. *Brain and Language, 89,* 362-369. https://doi.org/10.1016/S0093-934X(03)00358-4

Chao, L. L., & Martin, A. (2000). Representation of manipulable man-made objects in the dorsal stream. *Neuroimage, 12*, 478-484. https://doi.org/10.1006/nimg.2000.0635

Curran, T., & Keele, S. W. (1993). Attentional and nonattentional forms of sequence learning. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *19*, 189. https://doi.org/10.1037/0278-7393.19.1.189

Formaggio, E., Storti, S. F., Cerini, R., Fiaschi, A., & Manganotti, P. (2010). Brain oscillatory activity during motor imagery in EEG-fMRI coregistration. *Magnetic Resonance Imaging, 28,* 1403-1412. http://doi.org/10.1016/j.mri.2010.06.030

Gallicchio, G., Cooke, A., & Ring, C. (2016). Lower left temporal-frontal connectivity characterizes expert and accurate performance: High-alpha t7-fz connectivity as a marker of conscious processing during movement. *Sport, Exercise, and Performance Psychology, 5,* 14–24. http://doi.org/10.1037/spy0000055

Gallicchio, G., Cooke, A., & Ring, C. (2017). Practice makes efficient: cortical alpha oscillations are associated with improved golf putting performance. *Sport, Exercise, and Performance Psychology, 6,* 89–102. http://doi.org/10.1037/spy0000077

Greenwald, A. G. (1970). Sensory feedback mechanisms in performance control: with special reference to the ideo-motor mechanism. *Psychological Review, 77*, 73. http://dx.doi.org/10.1037/h0046798

Hardy, J. (2006). Speaking clearly: A critical review of the self-talk literature. *Psychology of Sport and Exercise*, *7*, 81–97. http://doi.org/10.1016/j.psychsport.2005.04.002

Hatfield, B. D., Costanzo, M. E., Goodman, R. N., Lo, L.-C., Oh, H., Rietschel, J. C., … Haufler, A. (2013). The influence of social evaluation on cerebral cortical activity and motor performance: a study of "Real-Life" competition. *International Journal of Psychophysiology*, *90*, 240–9. http://doi.org/10.1016/j.ijpsycho.2013.08.002

Hikosaka, O., Nakahara, H., Rand, M. K., Sakai, K., Lu, X., Nakamura, K., Miyachi, S., & Doya, K. (1999). Parallel neural networks for learning sequential procedures. *Trends in Neurosciences*, *22*, 464–471. https://doi.org/10.1016/S0166-2236(99)01439-3

Jeannerod, M. (1994). The representing brain: Neural correlates of motor intention and imagery. *Behavioral and Brain sciences*, *17*(2), 187-202. http://doi.org/10.1017/S0140525X00034026

Landers, D. M. Han, M., Salazar, W., & Petruzzello, S. J. (1994). Effects of learning on encephalographic and electrocardiographic patterns in novice archers. *International Journal of Sport Psychology, 25*, 313-330.

Logie, R. H. (2012). The functional organization and capacity limits of working memory. *Current Directions in Psychological Science, 20*, 240–245. https://doi.org/10.1177/0963721411415340

Masters, R. S. W., & Maxwell, J. (2008). The theory of reinvestment. *International Review of Sport and Exercise Psychology*, *1*, 160–183. http://doi.org/10.1080/17509840802287218

Masters, R. S. W., Eves, F. F., & Maxwell, J. P. (2005). Development of a movement specific Reinvestment Scale. In & P. T. Morris, P. Terry, S. Gordon, S. Hanrahan, L. Ievleva, G. Kolt

& Tremayne (Eds.), *Proceedings of the ISSP 11th World Congress of Sport Psychology*. Sidney, Australia.

Meister, I. G., Krings, T., Foltys, H., Boroojerdi, B., Müller, M., Töpper, R., & Thron, A. (2004). Playing piano in the mind—an fMRI study on music imagery and performance in pianists. *Cognitive Brain Research, 19*, 219-228. http://doi.org/10.1016/j.cogbrainres.2003.12.005

Miyake, A., Friedman, N. P., Emerson, M. J., Witzki, A. H., Howerter, A., & Wager, T. D. (2000). The unity and diversity of executive functions and their contributions to complex "frontal lobe" tasks: A latent variable analysis. *Cognitive Psychology, 41*, 49-100. https://doi.org/10.1006/cogp.1999.0734

Moran, A. (2012). Thinking in action: Some insights from cognitive sport psychology. *Thinking Skills and Creativity, 7*, 85-92. https://doi.org/10.1016/j.tsc.2012.03.005

Murata A., Ishida H. (2007). *Representation of Bodily Self in the Multimodal Parieto-Premotor Network*. In: Funahashi S. (eds) Representation and Brain. Springer, Tokyo. https://doi.org/10.1007/978-4-431-73021-7_6

Nadel, L., & Moscovitch, M. (1997). Memory consolidation, retrograde amnesia and the hippocampal complex. *Current Opinion in Neurobiology, 7*, 217-227. https://doi.org/10.1016/S0959-4388(97)80010-4

Pfurtscheller, G., & Neuper, C. (1997). Motor imagery activates primary sensorimotor area in humans. *Neuroscience Letters, 239*, 65-68. https://doi.org/10.1016/S0304-3940(97)00889-6

Roberts, R., Callow, N., Hardy, L., Markland, D., & Bringer, J. (2008). Movement imagery ability: development and assessment of a revised version of the vividness of movement imagery questionnaire. *Journal of Sport and Exercise Psychology, 30*, 200-221. https://doi.org/10.1123/jsep.30.2.200

Rothi, L. G., Ochipa, C., & Heilman, K. M. (1997). A cognitive neuropsychological model of limb praxis and apraxia. Apraxia: *The Neuropsychology of Action, 29-49*. https://doi.org/10.1080/026432991082533 82

Rumiati, R. I., Weiss, P. H., Shallice, T., Ottoboni, G., Noth, J., Zilles, K., & Fink, G. R. (2004). Neural basis of pantomiming the use of visually presented objects. *Neuroimage, 21*, 1224-1231. https://doi.org/10.1162/089892904970753

Shapiro, L. (2010). Embodied cognition. Routledge. http://doi.org/10.5840/philtopics201139117

Shimamura, A. P. (2000). The role of the prefrontal cortex in dynamic filtering. *Psychobiology, 28,* 207-218. http://doi.org/10.3758/BF03331979

Sirigu, A., Cohen, L., Duhamel, J. R., Pillon, B., Dubois, B., Agid, Y., & Pierrot-Deseilligny, C. (1995). Congruent unilateral impairments for real and imagined hand movements. *Neuroreport, 6*, 997-1001. http://doi.org/10.1097/00001756-199505090-00012

Sirigu, A., Duhamel, J. R., Cohen, L., Pillon, B., Dubois, B., & Agid, Y. (1996). The mental representation of hand movements after parietal cortex damage. *Science, 273*, 1564-1568. http://doi.org/10.1126/science.273.5281.1564

Song, S., & Cohen, L. (2014). Impact of conscious intent on chunking during motor learning. *Learning & Memory, 21*, 449–51. http://doi.org/10.1101/lm.035824.114

Squire, L. R., & Dede, A. J. (2015). Conscious and unconscious memory systems. *Cold Spring Harbor Perspectives in Biology*, 7, a021667. http://doi.org/10.1101/cshperspect.a021667

Szameitat, A. J., Shen, S., & Sterr, A. (2007). Motor imagery of complex everyday movements. An fMRI study. *Neuroimage, 34*, 702-713. https://doi.org/10.1016/j.neuroimage.2006.09.033

Ward, J. (2015). *The student's Guide to Cognitive Neuroscience*. Psychology Press. https://doi.org/10.4324/9781315742397

Willingham, D. B. (1998). A neuropsychological theory of motor skill learning. *Psychological Review, 105,* 558. http://dx.doi.org/10.1037/0033-295X.105.3.558

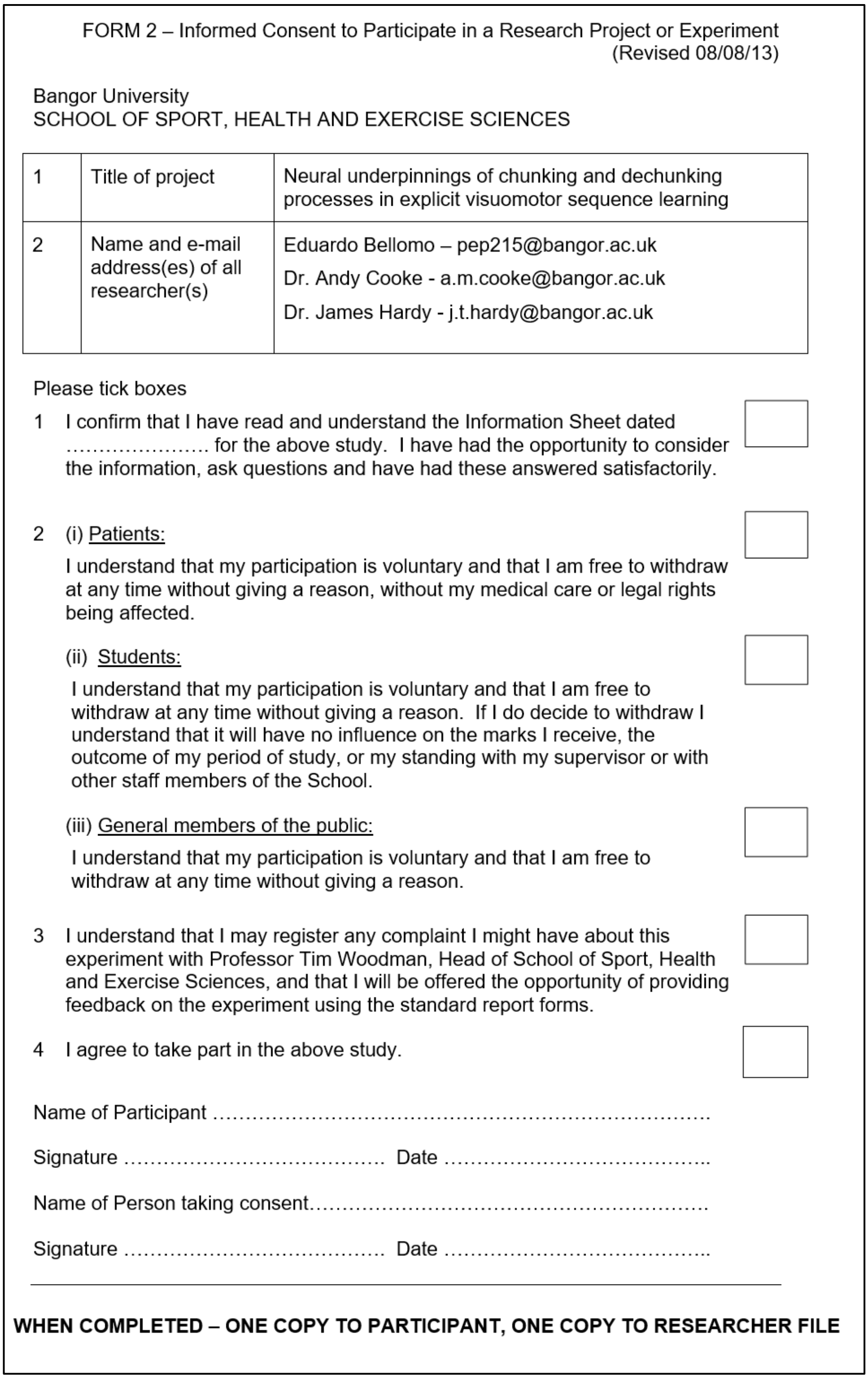
Yuan, H., Liu, T., Szarkowski, R., Rios, C., Ashe, J., & He, B. (2010). Negative covariation between task-related responses in alpha/beta-band activity and BOLD in human sensorimotor cortex: an EEG and fMRI study of motor imagery and movements. *Neuroimage, 49*, 2596-2606. https://doi.org/10.1016/j.neuroimage.2009.10.028

Zhu, F. F., Poolton, J. M., Wilson, M. R., Maxwell, J. P., & Masters, R. S. W. (2011). Neural co-activation as a yardstick of implicit motor learning and the propensity for conscious control of movement. *Biological Psychology*, *87*, 66–73. http://doi.org/10.1016/j.biopsycho.2011.02.004

APPENDICES

A. CHAPTER 2

A.1 Informed consent



FORM 2 – Informed Consent to Participate in a Research Project or Experiment
(Revised 08/08/13)

Bangor University
SCHOOL OF SPORT, HEALTH AND EXERCISE SCIENCES

1	Title of project	Neural underpinnings of chunking and dechunking processes in explicit visuomotor sequence learning
2	Name and e-mail address(es) of all researcher(s)	Eduardo Bellomo – pep215@bangor.ac.uk Dr. Andy Cooke - a.m.cooke@bangor.ac.uk Dr. James Hardy - j.t.hardy@bangor.ac.uk

Please tick boxes

1 I confirm that I have read and understand the Information Sheet dated …………………. for the above study. I have had the opportunity to consider the information, ask questions and have had these answered satisfactorily. ☐

2 (i) Patients: ☐

I understand that my participation is voluntary and that I am free to withdraw at any time without giving a reason, without my medical care or legal rights being affected.

(ii) Students: ☐

I understand that my participation is voluntary and that I am free to withdraw at any time without giving a reason. If I do decide to withdraw I understand that it will have no influence on the marks I receive, the outcome of my period of study, or my standing with my supervisor or with other staff members of the School.

(iii) General members of the public: ☐

I understand that my participation is voluntary and that I am free to withdraw at any time without giving a reason.

3 I understand that I may register any complaint I might have about this experiment with Professor Tim Woodman, Head of School of Sport, Health and Exercise Sciences, and that I will be offered the opportunity of providing feedback on the experiment using the standard report forms. ☐

4 I agree to take part in the above study. ☐

Name of Participant ………………………………………………………………….

Signature …………………………………. Date …………………………………..

Name of Person taking consent…………………………………………………….

Signature …………………………………. Date …………………………………..

WHEN COMPLETED – ONE COPY TO PARTICIPANT, ONE COPY TO RESEARCHER FILE

A.2 Participant information sheet

Participant Information Sheet

PRIFYSGOL
BANGOR
UNIVERSITY

Investigation: Neuroscience of Skill Acquisition

Dear Participant,
We would like to invite you to participate in this research project conducted by researchers at the School of Sport Health and Exercise Sciences, Bangor University. You should only participate if you want to; choosing not to take part will not disadvantage you in any way. Before you decide whether you want to take part, it is important for you to understand why the research is being done and what your participation will involve. Please take time to read the following information carefully and discuss it with others if you wish. Ask us if there is anything that is not clear or if you would like more information.

Research Aims

We are interested in better understanding: a) how brain activity changes when we learn and memorise movements during training; and b) how the brain reacts when our movements are evaluated.

Who Must We Exclude?

The only exclusion criteria for this study is not having a strong enough degree of right handedness. In the screening phase you will be asked to complete the Edinburgh Inventory (Oldfield, 1971) which measures your degree of handedness from -100 (fully left-handed) to +100 (fully right handed). In line with previous research you will be considered to have a strong enough degree of right handedness to take part if you score +75 or higher.

Where Will the Study Take Place?

The study will take place at the School of Sport, Health and Exercise Sciences, Bangor University (see the map at the end of this form).

How Long Will the Study Last?

The experiment consists of one session, which will take about 2 hours to complete.

What Will You Be Asked to Do?

Essentially, you will be asked to press 20 buttons that will illuminate in pairs on a 4x4 matrix. In the eventuality of an error, the whole matrix will illuminate in red, and you will be asked to start again from the first pair of the sequence. For each session, your objective is to press the buttons correctly 20 times. The study is composed by 5 sessions, so in total you will have to press the buttons 100 times.

During this task your brain activity will be measured through you wearing a special cap that includes sensors that will rest on your scalp. You will also wear a heart-rate monitor. Finally, at the beginning of each session you will be asked to complete some demographic and personality questionnaires.

Why Are We Measuring my Brain Activity?

It is important to measure brain activity as doing so will allow us to objectively demonstrate how the brain changes during learning and when faced with evaluative conditions. This is important as it could allow us to develop more effective training methods, such as "brain training" protocols, which could help us to speed up learning and to achieve personal best performances when it matters most (e.g., a golfer faced with a putt to win a major golf championship; a surgeon faced with a complex laparoscopic procedure).

Will You Compensate Me for My Time?

Yes. You will gain lab experience for your JXH-2020 Motor Control & Learning module which is required for your lab practical worksheet summative assessment.

Are There Any Risks Involved in Participating?

The risks involved in participating are minimal. The surface electrodes used to monitor your brain activity can cause short-lasting minor skin irritation to participants with sensitive skin. However, this eventuality is unlikely.

Are There Any Benefits Involved in Participating?

The results of the study will give us important information about mechanisms related to motor skill acquisition.

What If I Have Questions about the Project?

If you have any question regarding this research please feel free to contact us. Thank you in advance for your participation, it is greatly appreciated.
It is up to you to decide whether to take part or not. If you decide to take part you are still free to withdraw at any time and without giving a reason. If you do decide to take part you will be given this information sheet to keep and be asked to sign a consent form.

Yours Sincerely,

Eduardo Bellomo, pep215@bangor.ac.uk
Samuel James Harn, peu2a6@bangor.ac.uk
Dr Andrew Cooke, a.m.cooke@bangor.ac.uk
Dr James Hardy, j.t.hardy@bangor.ac.uk

Participants should arrive on time at the decided time. The experiment will take place in the Padarn, situated on point number 4 on the map below. A researcher will meet you at the Bistro Cafè, (number 6 on the map).


● Mynedfeydd
Entrances
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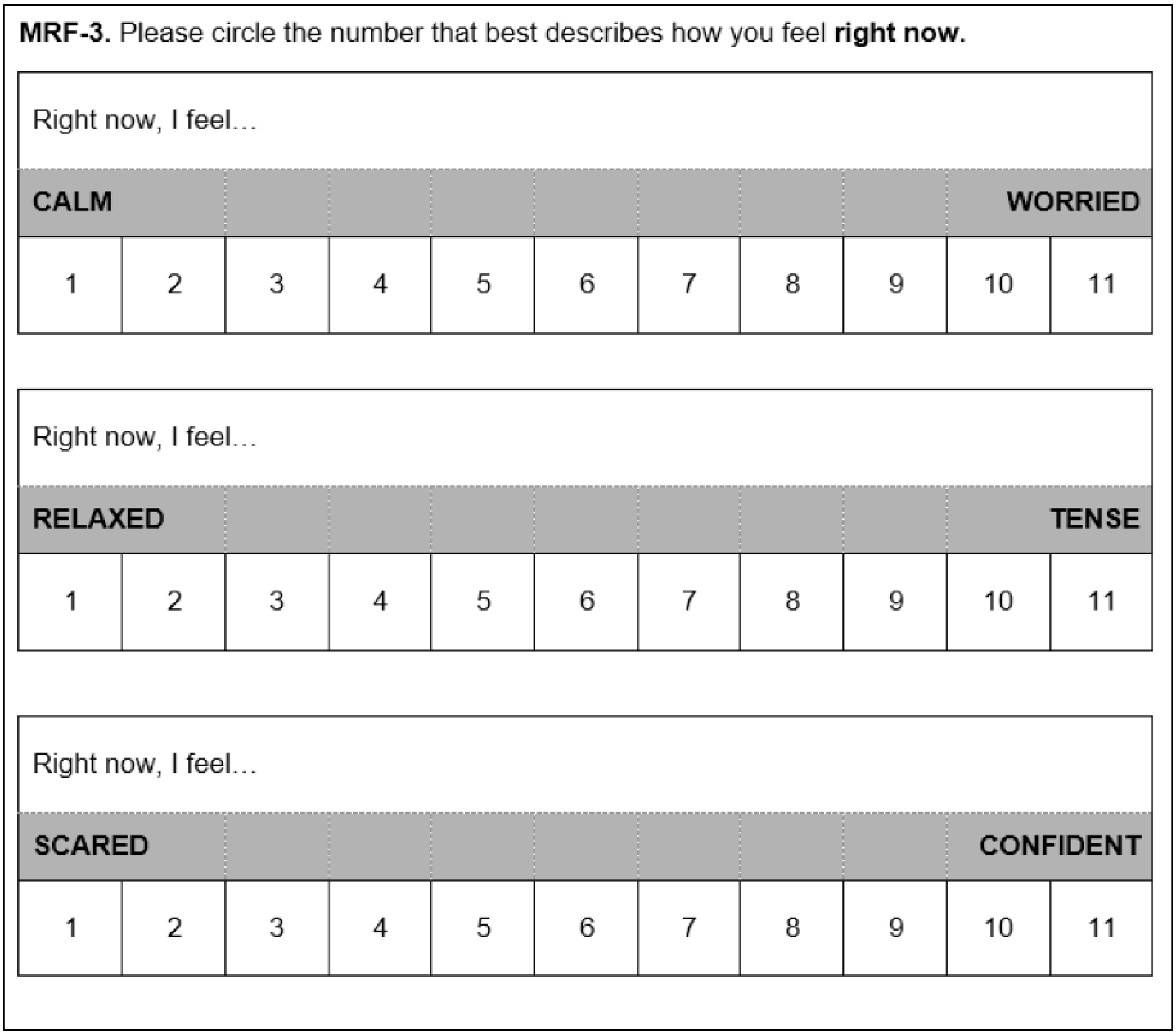
A.3 Mental Readiness Form (MFR-3)



MRF-3. Please circle the number that best describes how you feel **right now.**

Right now, I feel…

CALM									**WORRIED**	
1	2	3	4	5	6	7	8	9	10	11

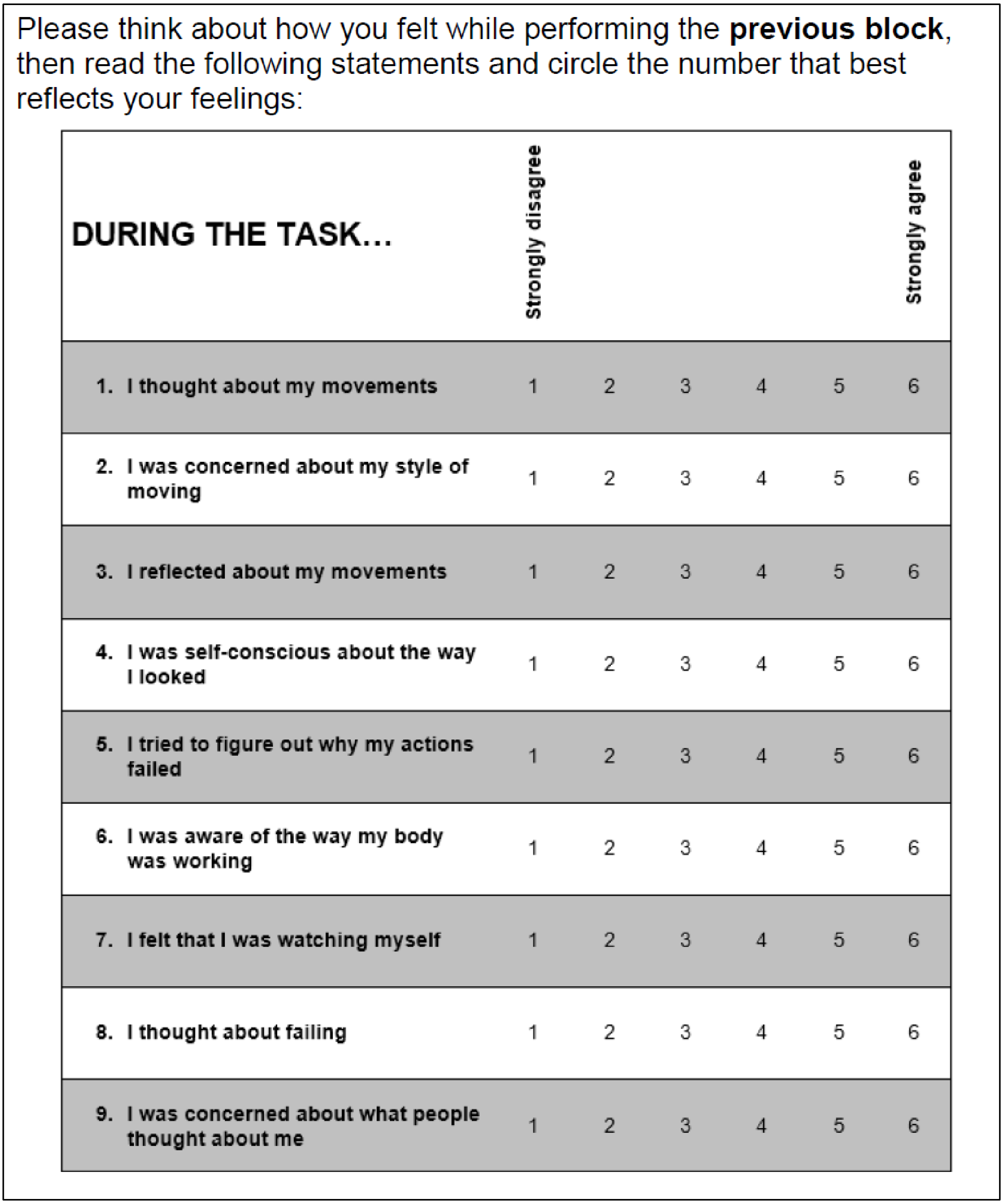
Right now, I feel…

RELAXED									**TENSE**	
1	2	3	4	5	6	7	8	9	10	11

Right now, I feel…

SCARED									**CONFIDENT**	
1	2	3	4	5	6	7	8	9	10	11

A.4 Movement Specific Reinvestment Scale

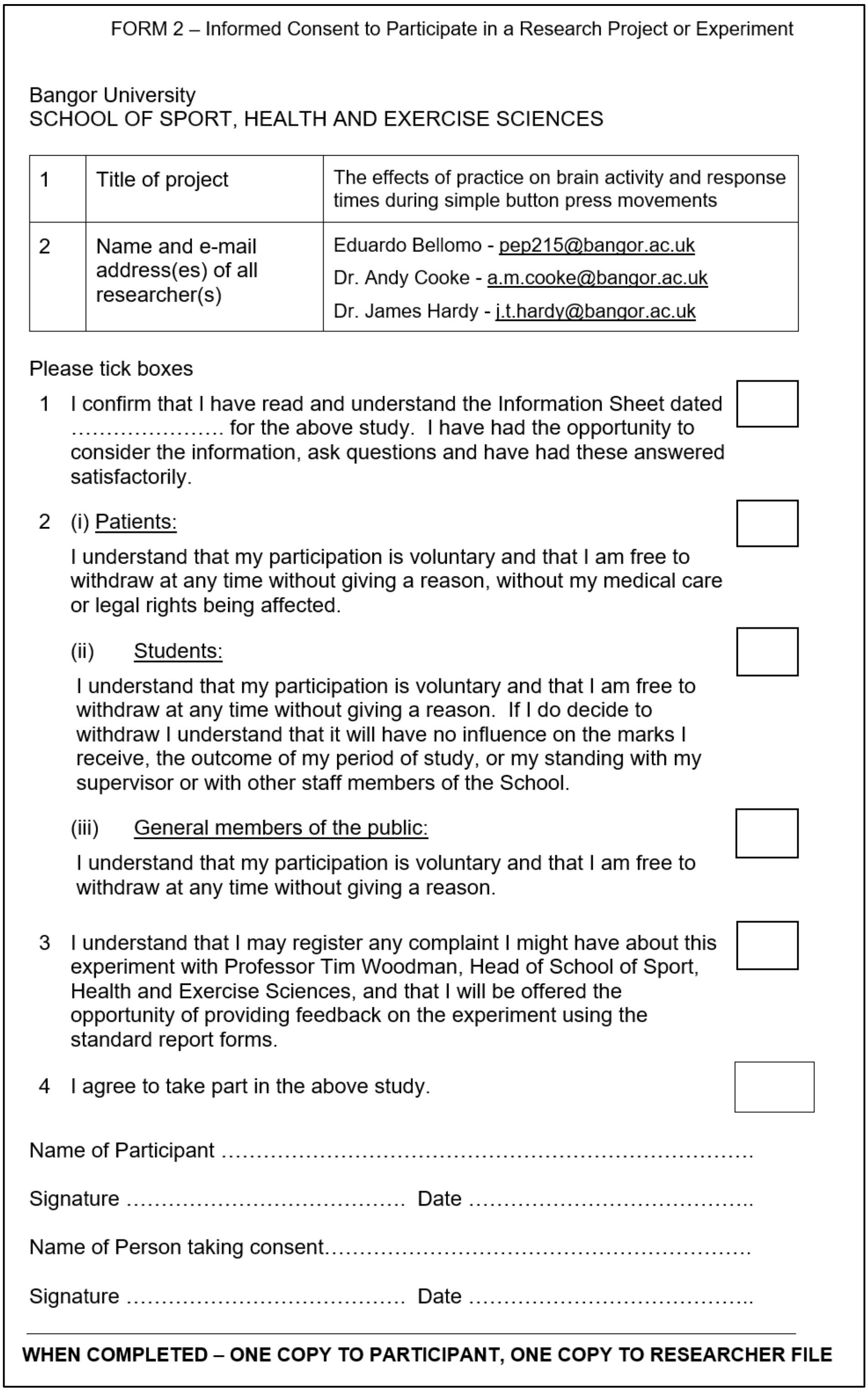


Please think about how you felt while performing the **previous block**, then read the following statements and circle the number that best reflects your feelings:

DURING THE TASK…	**Strongly disagree**					**Strongly agree**
1. I thought about my movements	1	2	3	4	5	6
2. I was concerned about my style of moving	1	2	3	4	5	6
3. I reflected about my movements	1	2	3	4	5	6
4. I was self-conscious about the way I looked	1	2	3	4	5	6
5. I tried to figure out why my actions failed	1	2	3	4	5	6
6. I was aware of the way my body was working	1	2	3	4	5	6
7. I felt that I was watching myself	1	2	3	4	5	6
8. I thought about failing	1	2	3	4	5	6
9. I was concerned about what people thought about me	1	2	3	4	5	6

B. CHAPTER 3

B.1 Informed consent



FORM 2 – Informed Consent to Participate in a Research Project or Experiment

Bangor University
SCHOOL OF SPORT, HEALTH AND EXERCISE SCIENCES

1	Title of project	The effects of practice on brain activity and response times during simple button press movements
2	Name and e-mail address(es) of all researcher(s)	Eduardo Bellomo - pep215@bangor.ac.uk Dr. Andy Cooke - a.m.cooke@bangor.ac.uk Dr. James Hardy - j.t.hardy@bangor.ac.uk

Please tick boxes

1 I confirm that I have read and understand the Information Sheet dated …………………. for the above study. I have had the opportunity to consider the information, ask questions and have had these answered satisfactorily. ☐

2 (i) Patients: ☐

I understand that my participation is voluntary and that I am free to withdraw at any time without giving a reason, without my medical care or legal rights being affected.

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I understand that my participation is voluntary and that I am free to withdraw at any time without giving a reason. If I do decide to withdraw I understand that it will have no influence on the marks I receive, the outcome of my period of study, or my standing with my supervisor or with other staff members of the School.

(iii) General members of the public: ☐

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4 I agree to take part in the above study. ☐

Name of Participant ……………………………………………………………………

Signature …………………………………. Date …………………………………..

Name of Person taking consent……………………………………………………

Signature …………………………………. Date …………………………………..

WHEN COMPLETED – ONE COPY TO PARTICIPANT, ONE COPY TO RESEARCHER FILE

B.2 Participant information sheet

PRIFYSGOL BANGOR UNIVERSITY

Participant Information Sheet

PRIFYSGOL BANGOR UNIVERSITY

Study title: The effects of practice on brain activity and response times during simple button press movements

Project Primary Investigator:	**Research supervisors:**
Eduardo Bellomo, pep215@bangor.ac.uk	Dr James Hardy, j.t.hardy@bangor.ac.uk Dr Andrew Cooke, a.m.cooke@bangor.ac.uk

Invitation

We would like to invite you to participate in this research project conducted by researchers at the School of Sport Health and Exercise Sciences, Bangor University. You should only participate if you want to; choosing not to take part will not disadvantage you in any way. Before you decide whether you want to take part, it is important for you to understand why the research is being done and what your participation will involve. Please take time to read the following information carefully and discuss it with others if you wish. Ask us if there is anything that is not clear or if you would like more information.

Background to the study

We are interested in better understanding how brain activity and response times change as we practice executing elementary movements such as button presses. In fact, shedding light on these brain mechanisms could inform the development of new methods for enhancing motor execution in a range of domains including sport and neurological rehabilitation.

Who Must We Exclude?

Due to the nature of the study, we must exclude individuals who are:

- **left-handed**
- **colour-blind** (individuals that cannot distinguish between the colour red, green, and blue)

Your handedness will be assessed via an online questionnaire that has been sent to you along with this information pack after you have expressed interest in participating in the study. The questionnaire is an electronic version of the Edinburgh Inventory (Oldfield, 1971), which measures your degree of handedness from -100 (fully left-handed) to +100 (fully right handed). In line with previous research you will be considered to have a strong enough degree of right handedness to take part if you score +75 or higher.

What will the study involve?

The study will take place at the psychophysiology laboratory of the School of Sport, Health and Exercise sciences (see map at the bottom of the page). It consists of **2 visits** (ideally on two consecutive days) of the duration of **2 hours each**. Therefore, **in total** you will be asked to spend **4 hours** in the laboratory split over 2 separate visits.

Essentially, you will be asked to perform a computer task that involves pressing buttons on a keyboard corresponding to stimuli appearing on a screen. During this task your brain activity will be measured through you wearing a special cap that includes sensors that will rest on your scalp. You will be also asked to complete some general information, personality, and cognitive questionnaires. In addition, we will have video-cameras set in the lab that we may use to record your movements, assess how your response-times change while practicing the task, and have an expert in motor-control to evaluate them.

What are the possible advantages and disadvantages of taking part?

Advantages include:

- **Chance to win £30: on completion of the second lab visit you will be paid £10 to compensate for your time**;
- gaining **5xp points for the Bangor Employability Award** (Activity V722 - Research Support Participant)
- contributing to a branch of research that has the potential of benefitting the general and clinical (e.g., neurological) population.

Disadvantages include:

- restrictions on your habits **during the days preceding and between the lab visits. We must ask participants to**:
    - refrain from consuming alcohol or drugs in the 24 hours before each lab visit
    - refrain from consuming caffeine in the 6 hours before each lab visit
    - sleep more than 6 hours during the night that precedes each visit
- We'll need to apply a small amount of gel on your scalp to allow our sensors to record your brain activity. It feels like hair styling gel, and can be easily washed away with a normal shampoo after your participation);
- participants with very sensitive skin may experience minor skin irritation associated with having sensors on your scalp, but this risk is considered very minor and unlikely (our products are from approved medical suppliers and are routinely used every day in research and healthcare settings). If you do experience discomfort the sensors can be removed and the sites washed with warm water, and the irritation will normally cease within an hour.
- As mentioned above, we may record your movements using video cameras and have an expert in motor control to evaluate how your response-times change while practicing the task in the later stages of the experiment. This footage may be shown to other researchers after the study is complete in order to demonstrate the study results.

Of course, you are free to stop each of these tasks when you wish in the unlikely event that you should encounter any excessive discomfort. The total time for taking part in this study will be 4 hours plus travel time.

Can I stop taking part in the study at any time?

Yes, you have the right to withdraw from the study at any time without disclosing why.

What If I Have Questions about the Project?

If you have any question regarding this research, please feel free to contact us.
If you wish to participate then please contact **Eduardo Bellomo** on the contact information disclosed at the top of the form for more information.

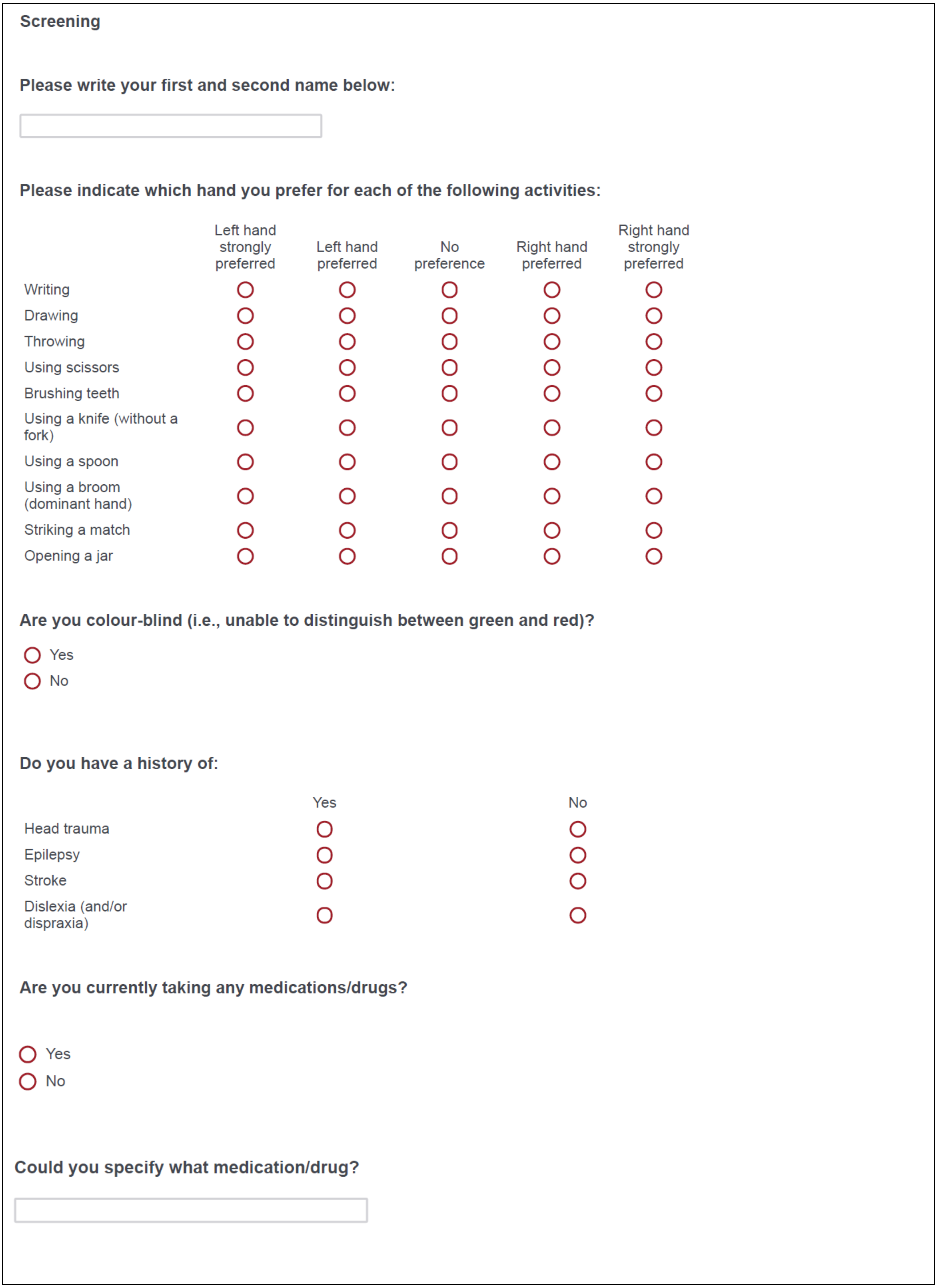
Psychophysiology Laboratory, School of Health, Sports and Exercise Sciences, Normal Site:

Participants should arrive on time at the decided time.

The experiment will take place in the **Padarn Building** (**nr. 4** on the map).

A researcher will **meet you at the Bistro Cafè**, (**nr. 6** on the map).

B.3 Screening



Screening

Please write your first and second name below:

☐

Please indicate which hand you prefer for each of the following activities:

	Left hand strongly preferred	Left hand preferred	No preference	Right hand preferred	Right hand strongly preferred
Writing	○	○	○	○	○
Drawing	○	○	○	○	○
Throwing	○	○	○	○	○
Using scissors	○	○	○	○	○
Brushing teeth	○	○	○	○	○
Using a knife (without a fork)	○	○	○	○	○
Using a spoon	○	○	○	○	○
Using a broom (dominant hand)	○	○	○	○	○
Striking a match	○	○	○	○	○
Opening a jar	○	○	○	○	○

Are you colour-blind (i.e., unable to distinguish between green and red)?

○ Yes
○ No

Do you have a history of:

	Yes	No
Head trauma	○	○
Epilepsy	○	○
Stroke	○	○
Dislexia (and/or dispraxia)	○	○

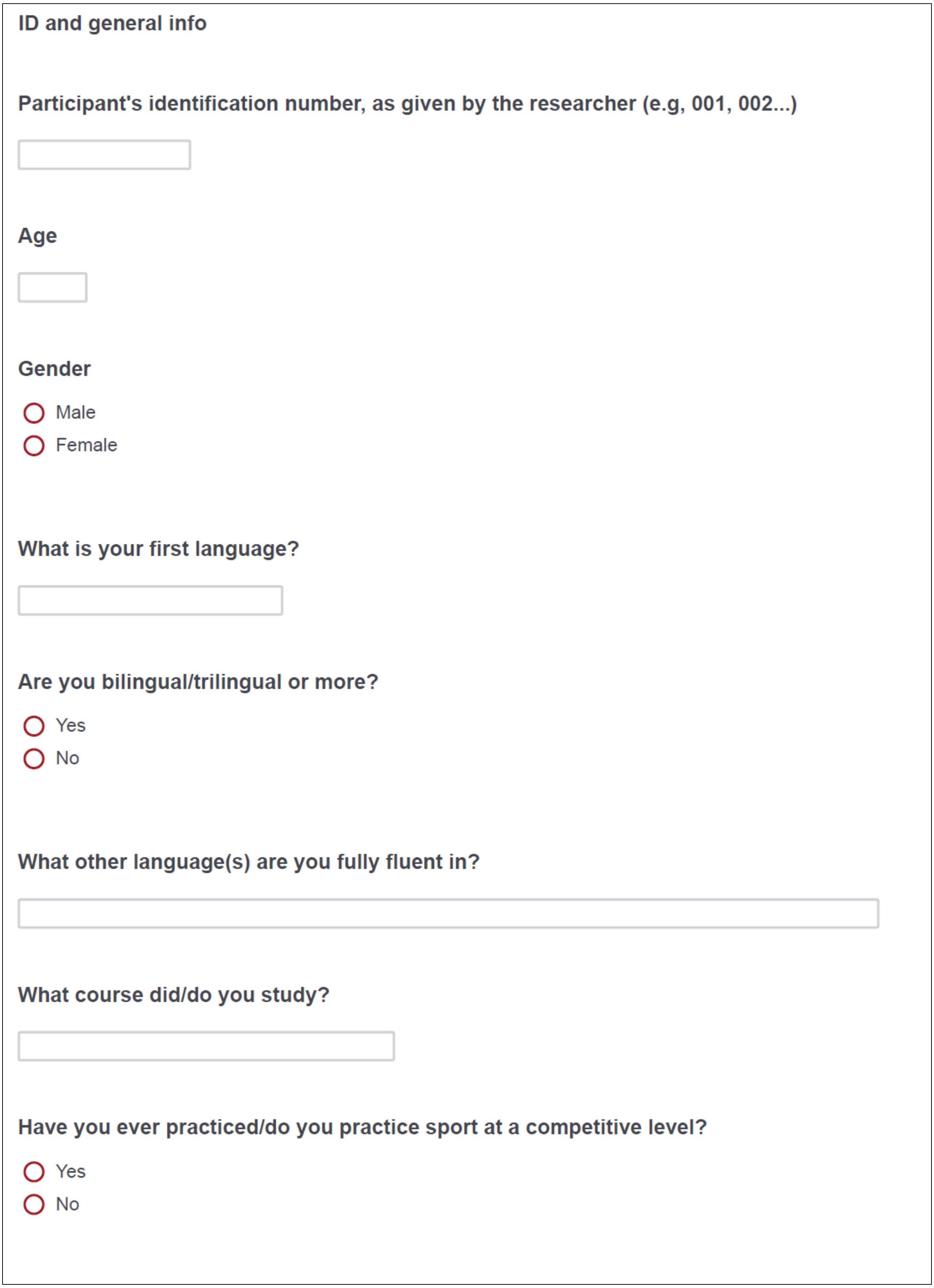
Are you currently taking any medications/drugs?

○ Yes
○ No

Could you specify what medication/drug?

☐

B.4 Demographics



ID and general info

Participant's identification number, as given by the researcher (e.g, 001, 002...)

Age

Gender

○ Male
○ Female

What is your first language?

Are you bilingual/trilingual or more?

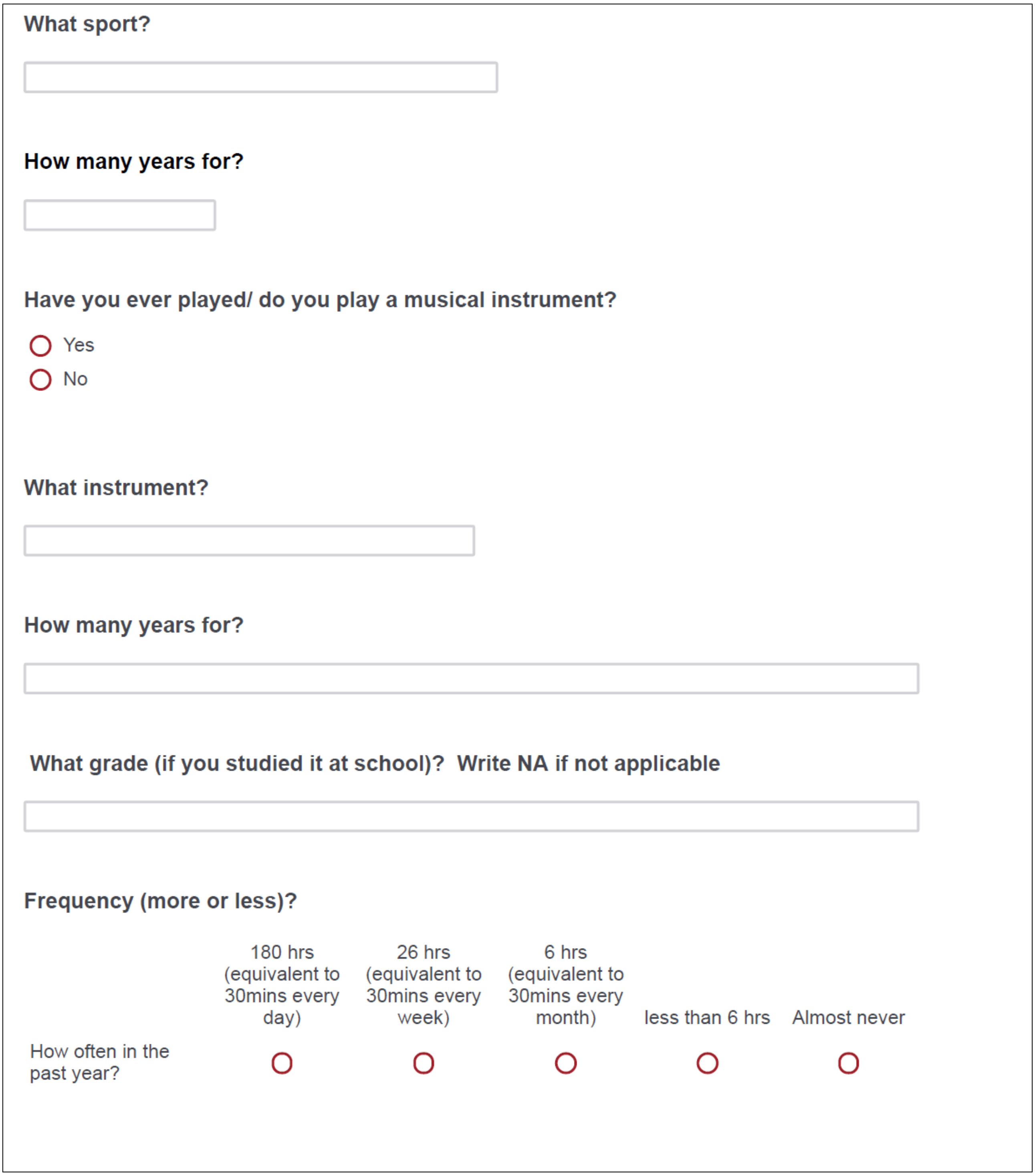
○ Yes
○ No

What other language(s) are you fully fluent in?

What course did/do you study?

Have you ever practiced/do you practice sport at a competitive level?

○ Yes
○ No



What sport?

How many years for?

Have you ever played/ do you play a musical instrument?

○ Yes
○ No

What instrument?

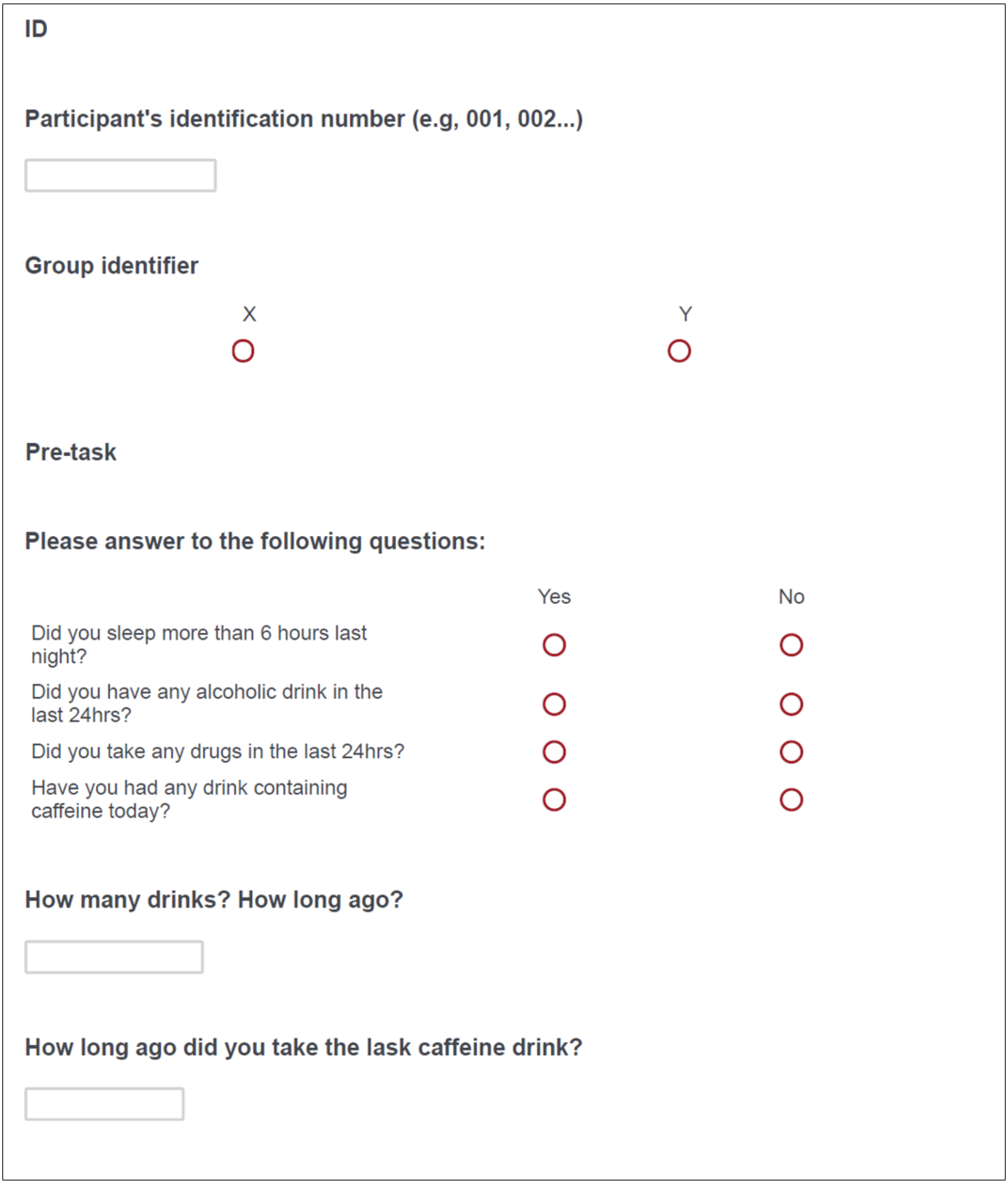
How many years for?

What grade (if you studied it at school)? Write NA if not applicable

Frequency (more or less)?

	180 hrs (equivalent to 30mins every day)	26 hrs (equivalent to 30mins every week)	6 hrs (equivalent to 30mins every month)	less than 6 hrs	Almost never
How often in the past year?	○	○	○	○	○

B.5 Pre-task questionnaire



ID

Participant's identification number (e.g, 001, 002...)

Group identifier

X	Y
○	○

Pre-task

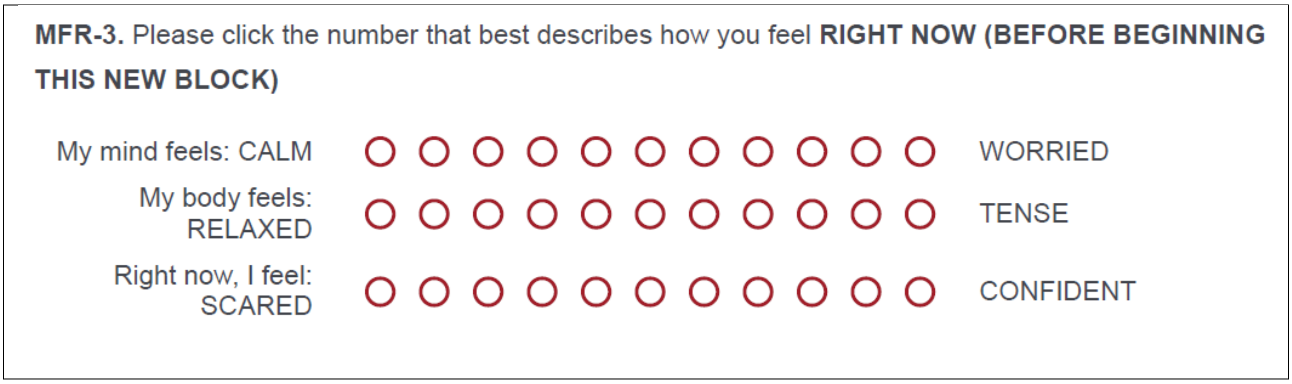
Please answer to the following questions:

	Yes	No
Did you sleep more than 6 hours last night?	○	○
Did you have any alcoholic drink in the last 24hrs?	○	○
Did you take any drugs in the last 24hrs?	○	○
Have you had any drink containing caffeine today?	○	○

How many drinks? How long ago?

How long ago did you take the lask caffeine drink?

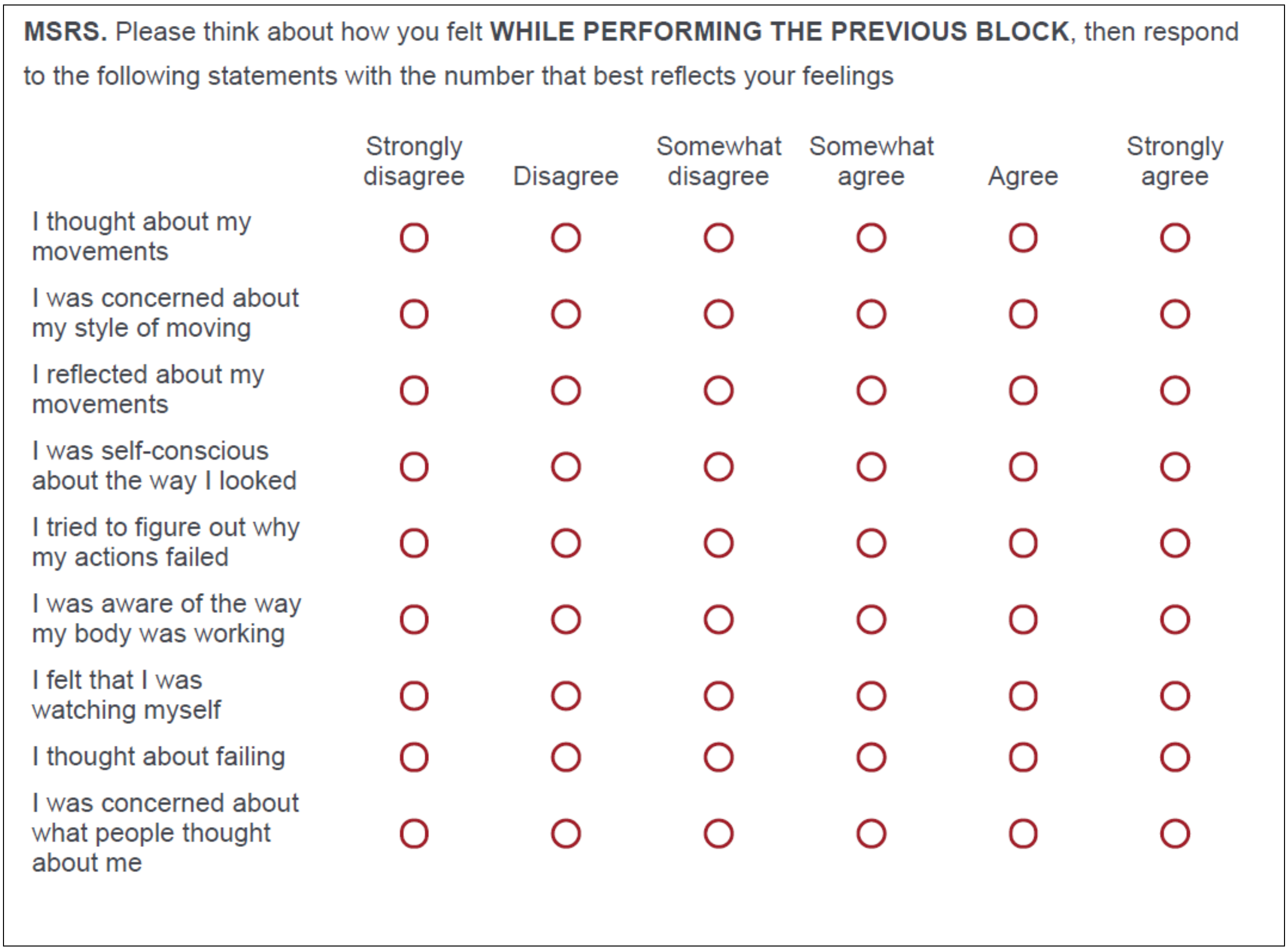
B.6 Mental Readiness Form (MFR-3)



MFR-3. Please click the number that best describes how you feel **RIGHT NOW (BEFORE BEGINNING THIS NEW BLOCK)**

My mind feels: CALM	○	○	○	○	○	○	○	○	○	○	○	WORRIED
My body feels: RELAXED	○	○	○	○	○	○	○	○	○	○	○	TENSE
Right now, I feel: SCARED	○	○	○	○	○	○	○	○	○	○	○	CONFIDENT

B.7 Movement Specific Reinvestment Scale – state version (MSRS-S)

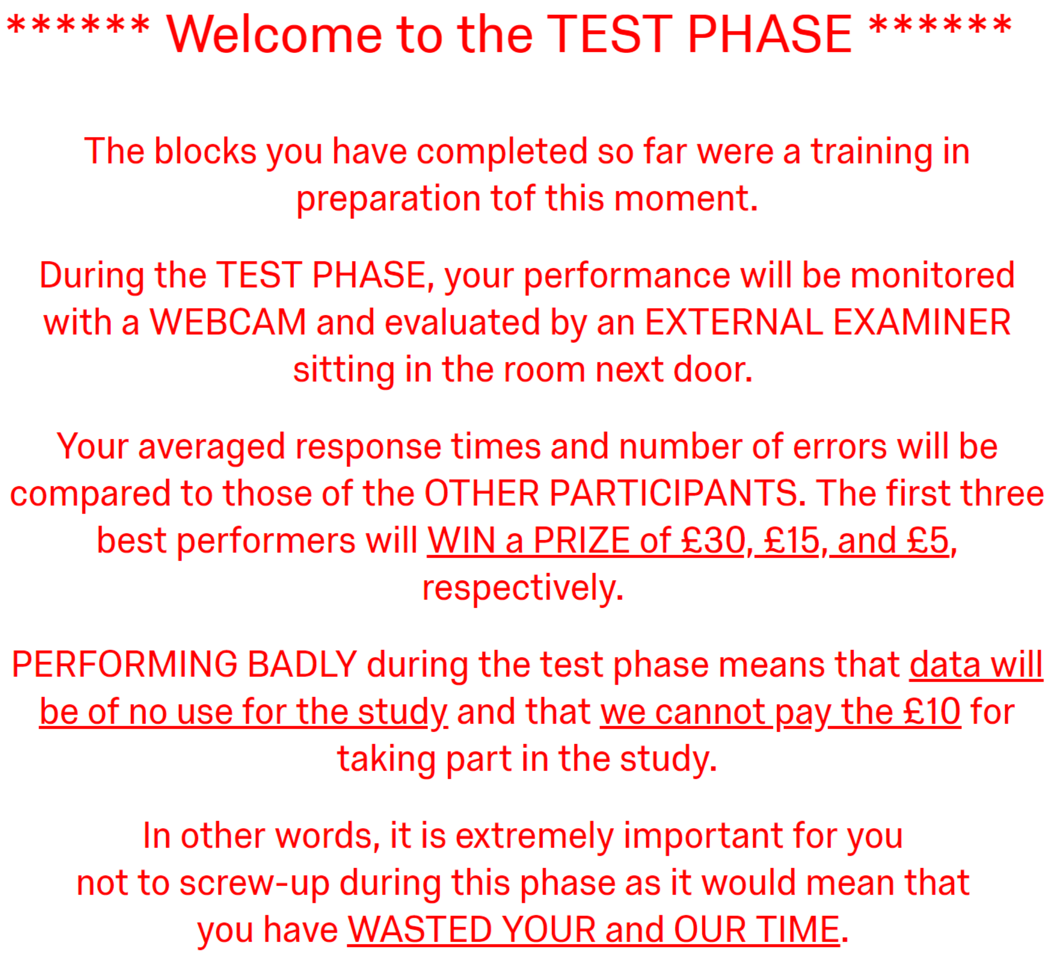


MSRS. Please think about how you felt **WHILE PERFORMING THE PREVIOUS BLOCK**, then respond to the following statements with the number that best reflects your feelings

	Strongly disagree	Disagree	Somewhat disagree	Somewhat agree	Agree	Strongly agree
I thought about my movements	○	○	○	○	○	○
I was concerned about my style of moving	○	○	○	○	○	○
I reflected about my movements	○	○	○	○	○	○
I was self-conscious about the way I looked	○	○	○	○	○	○
I tried to figure out why my actions failed	○	○	○	○	○	○
I was aware of the way my body was working	○	○	○	○	○	○
I felt that I was watching myself	○	○	○	○	○	○
I thought about failing	○	○	○	○	○	○
I was concerned about what people thought about me	○	○	○	○	○	○

B.8 Pressure Manipulation Script

A) Introduction



****** Welcome to the TEST PHASE ******

The blocks you have completed so far were a training in preparation tof this moment.

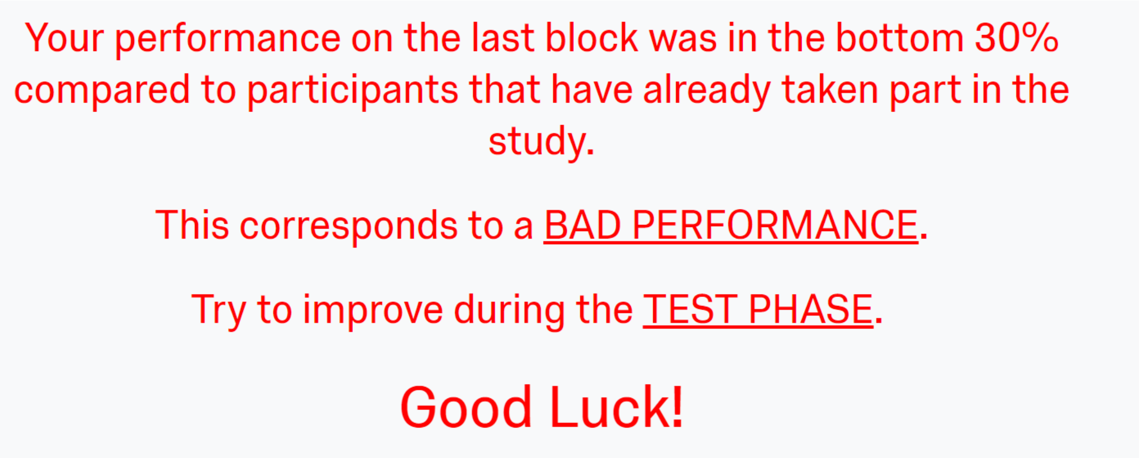
During the TEST PHASE, your performance will be monitored with a WEBCAM and evaluated by an EXTERNAL EXAMINER sitting in the room next door.

Your averaged response times and number of errors will be compared to those of the OTHER PARTICIPANTS. The first three best performers will WIN a PRIZE of £30, £15, and £5, respectively.

PERFORMING BADLY during the test phase means that data will be of no use for the study and that we cannot pay the £10 for taking part in the study.

In other words, it is extremely important for you not to screw-up during this phase as it would mean that you have WASTED YOUR and OUR TIME.

B) Non-contingent feedback



Your performance on the last block was in the bottom 30% compared to participants that have already taken part in the study.

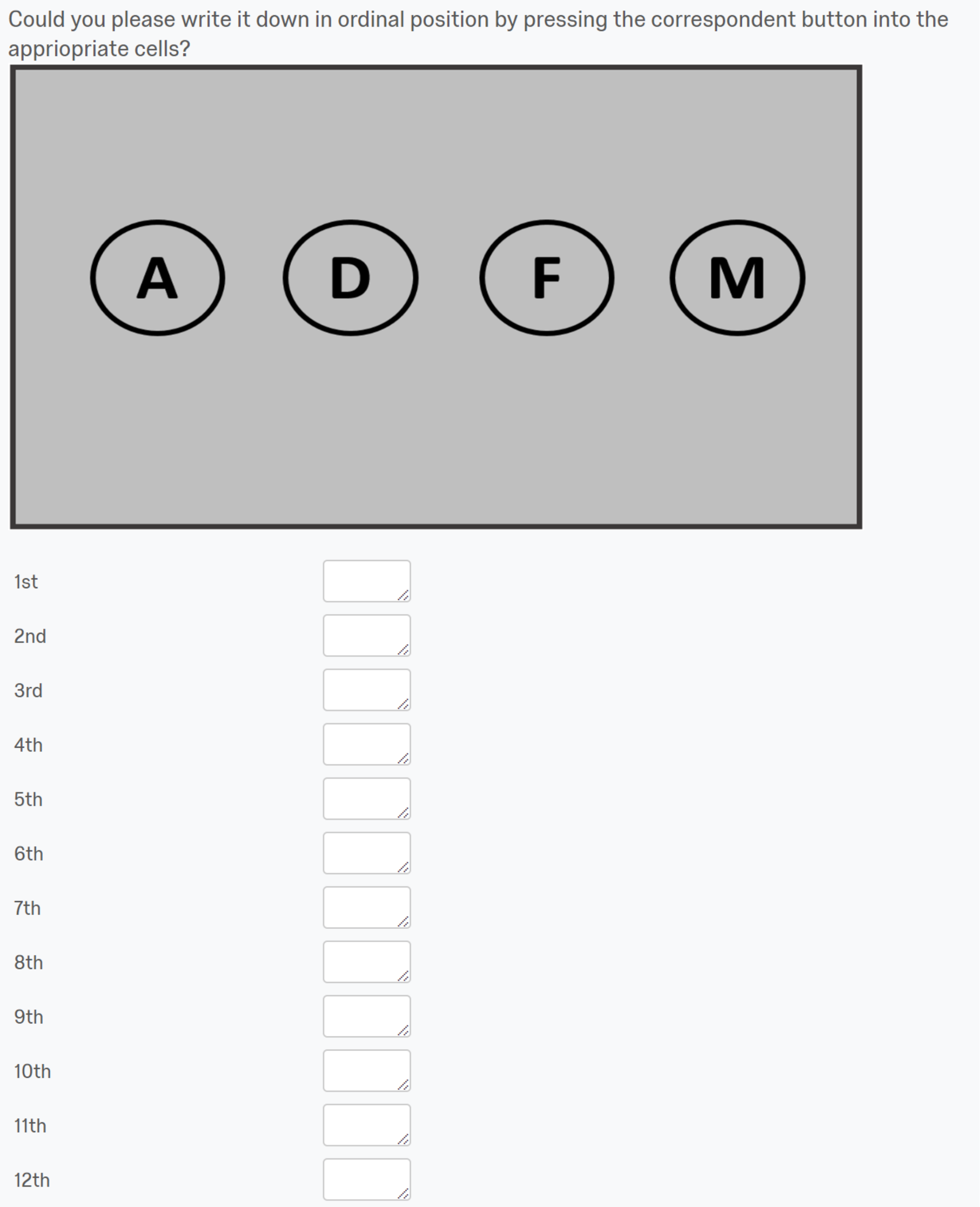
This corresponds to a BAD PERFORMANCE.

Try to improve during the TEST PHASE.

Good Luck!

B.9 Sequence awareness and knowledge assessment

A) Explicit group



Could you please write it down in ordinal position by pressing the correspondent button into the appriopriate cells?

1st

2nd

3rd

4th

5th

6th

7th

8th

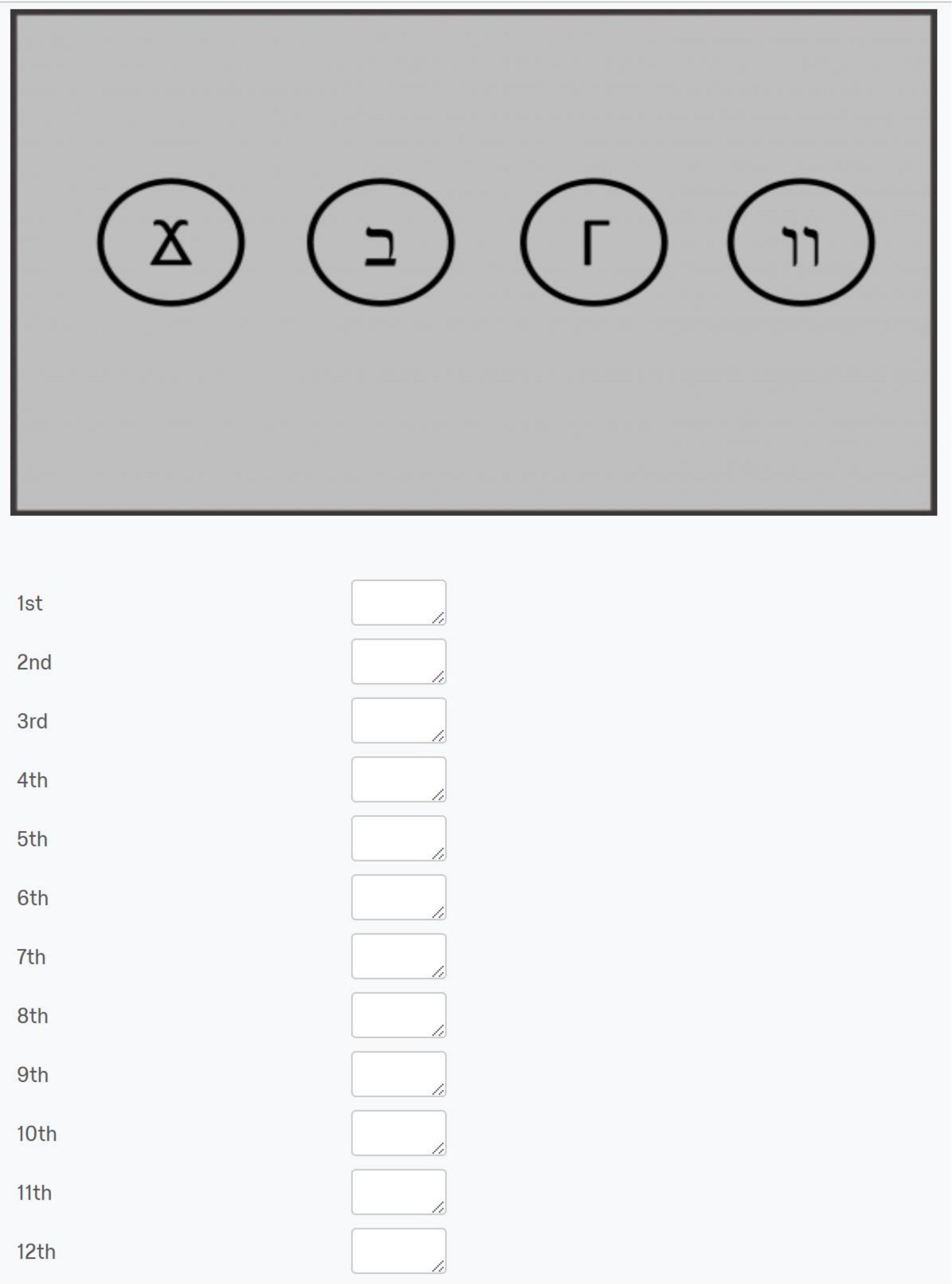
9th

10th

11th

12th

B) Implicit group



1st

2nd

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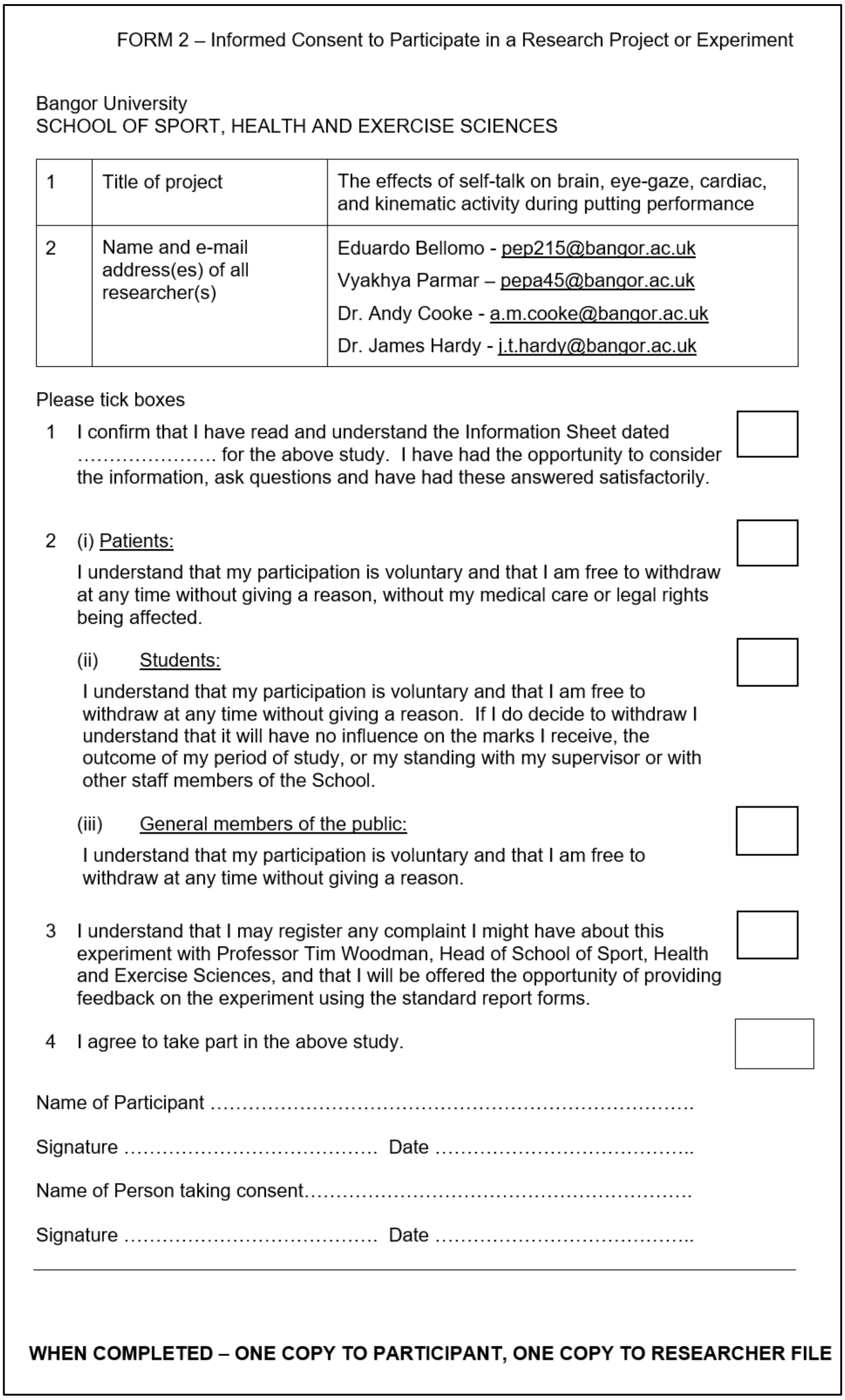
10th

11th

12th

C. CHAPTER 4-5

C.1 Informed consent



FORM 2 – Informed Consent to Participate in a Research Project or Experiment

Bangor University
SCHOOL OF SPORT, HEALTH AND EXERCISE SCIENCES

1	Title of project	The effects of self-talk on brain, eye-gaze, cardiac, and kinematic activity during putting performance
2	Name and e-mail address(es) of all researcher(s)	Eduardo Bellomo - pep215@bangor.ac.uk Vyakhya Parmar – pepa45@bangor.ac.uk Dr. Andy Cooke - a.m.cooke@bangor.ac.uk Dr. James Hardy - j.t.hardy@bangor.ac.uk

Please tick boxes

1 I confirm that I have read and understand the Information Sheet dated …………………. for the above study. I have had the opportunity to consider the information, ask questions and have had these answered satisfactorily. ☐

2 (i) Patients: ☐

I understand that my participation is voluntary and that I am free to withdraw at any time without giving a reason, without my medical care or legal rights being affected.

(ii) Students: ☐

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3 I understand that I may register any complaint I might have about this experiment with Professor Tim Woodman, Head of School of Sport, Health and Exercise Sciences, and that I will be offered the opportunity of providing feedback on the experiment using the standard report forms. ☐

4 I agree to take part in the above study. ☐

Name of Participant ………………………………………………………………….

Signature ………………………………… Date …………………………………..

Name of Person taking consent…………………………………………………….

Signature ………………………………… Date …………………………………..

WHEN COMPLETED – ONE COPY TO PARTICIPANT, ONE COPY TO RESEARCHER FILE

C.2 Participant information sheet

Welcome to the study!!!

Participant Information Sheet

Study title: The effects of self-talk on brain, eye-gaze, cardiac, and kinematic activity during putting performance.

Project Primary Investigators:	**Research supervisors:**
Eduardo Bellomo, pep215@bangor.ac.uk	Dr James Hardy, j.t.hardy@bangor.ac.uk
Vyakhya Parmar, pepa45@bangor.ac.uk	Dr Andrew Cooke, a.m.cooke@bangor.ac.uk

Invitation

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Background to the study

We are interested in better understanding how putting performance, as well as brain, eye-gaze, cardiac, and kinematic activity change when individuals use different types of self-talk strategies. This is the first study attempting to do so and, as such, it can potentially improve our understanding of the psychophysiological and biomechanical mechanisms behind the effects of self-talk.

Who Must We Exclude?

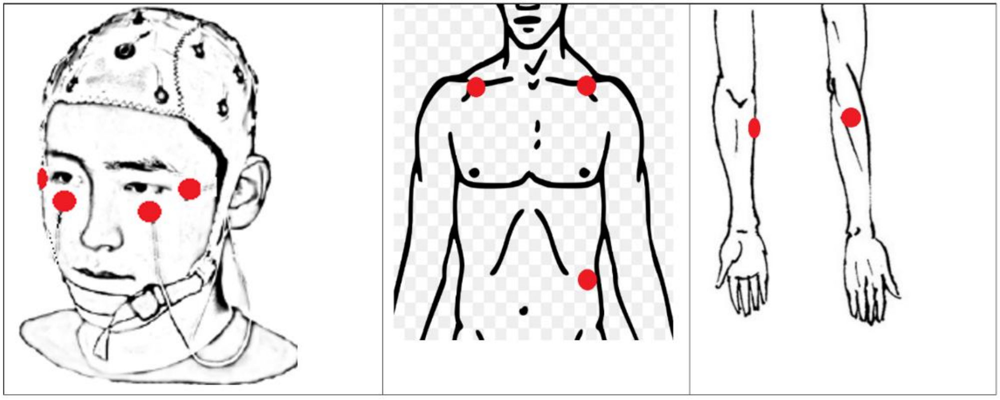
Due to the nature of the study, we must exclude individuals who are **left-handed**.
Your handedness will be assessed via an online questionnaire that has been sent to you along with this information pack after you have expressed interest in participating in the study. The questionnaire is an electronic version of the Edinburgh Inventory (Oldfield, 1971), which measures your degree of handedness from -100 (fully left-handed) to +100 (fully right handed). In line with previous research, you will be considered to have a strong enough degree of right-handedness to take part if you score +75 or higher. Moreover, to control for confounding factors, we need to exclude invividuals that consumed alcohol or drugs in the 24 hours before the visit; individuals that consumed caffeine in the 6 hours before the visit; and individuals that slept less than 6 hours during the night that precedes the visit. This information will be collected via a questionnaire that you will be asked to complete before the beginning of the experiment.

What will the study involve?

The study will take place in the research laboratories in the **Padarn Building**, School of Sport, Health and Exercise Sciences, Normal Site (follow the link for the map https://goo.gl/maps/RW7qWYaqkyk).
It consists of **1 visit** for the duration of **~3 hours** (including set up psychophysiological equipment set-up, task, and questionnaires).

Essentially, you will be asked to perform a golf putting task while wearing a series of surface sensors that measure your brain, eye, cardiac, and muscular activity (EEG, EOG, ECG, EMG respectively).

The EEG sensors (total of 32) will rest on your scalp and be applied via a special lycra cap (akin to a water polo one). The EOG sensors (total of 4) will be applied on your left and right cheekbones, and close to your left and right temples. The ECG sensors (total of 3) will be applied to your collarbones and at the level of your last left rib bone. The EMG sensors (total of 2) will be applied to your forearm. For a visual representation of the electrode locations, please check the red dots in the diagram.



Crucially, before commencing the task, you will receive a **self-talk intervention** and you will be assigned a self-talk cue to be used during the putting task.
You will be also asked to complete some general information, personality, and cognitive questionnaires. In addition, we will have video-cameras set in the lab to monitor your putting performance.

What are the possible advantages and disadvantages of taking part?

Advantages include:

On completion of the experiment you will be paid £10 to compensate for your time;
Additional chance win up to £30;
5xp points for the Bangor Employability Award (Activity V722 - Research Support Participant)
Gaining insight into the application of self-talk strategies.
Contributing to a cutting-edge branch of research.
Helping a PhD and an MSc to complete their project ☺

Disadvantages include:

Restrictions on your habits during the days preceding and between the lab visit. We must ask participants to:
refrain from consuming alcohol or drugs in the 24 hours before;
refrain from consuming caffeine in the 6 hours before;
sleep more than 6 hours during the night that precedes the visit;
We'll need to apply a small amount of gel on your scalp and on the other body locations described above to allow our sensors to record your physiological activity. It feels like hair styling gel and can be easily washed away with a normal shampoo after your participation; participants with very sensitive skin may experience minor skin irritation associated with having sensors on your scalp, but this risk is considered very minor and unlikely (our products are from approved medical suppliers and are routinely used every day in research

and healthcare settings). If you do experience discomfort the sensors can be removed and the sites washed with warm water, and the irritation will normally cease within an hour.
As mentioned above, we will record and monitor your performance using video cameras.
Of course, you are free to stop each of these tasks when you wish in the unlikely event that you should encounter any excessive discomfort. The total time for taking part in this study will be 3 hours plus travel time.

Can I stop taking part in the study at any time?

Yes, you have the right to withdraw from the study at any time without disclosing why.

How is my privacy guaranteed?

To ensure data confidentiality, all records will be identified by participant identification numbers and not by name in accordance with the General Data Protection Act, 2018. All raw data collected will be kept in locked offices and on password projected computers and will only be accessed by members of the research team.
Similarly, names and email addresses that will be collected during the screening phase will be stored separately from collected data on password protected computer accessible only by members of the research team and will be used only to contact participants who are eligible to take part in the study.

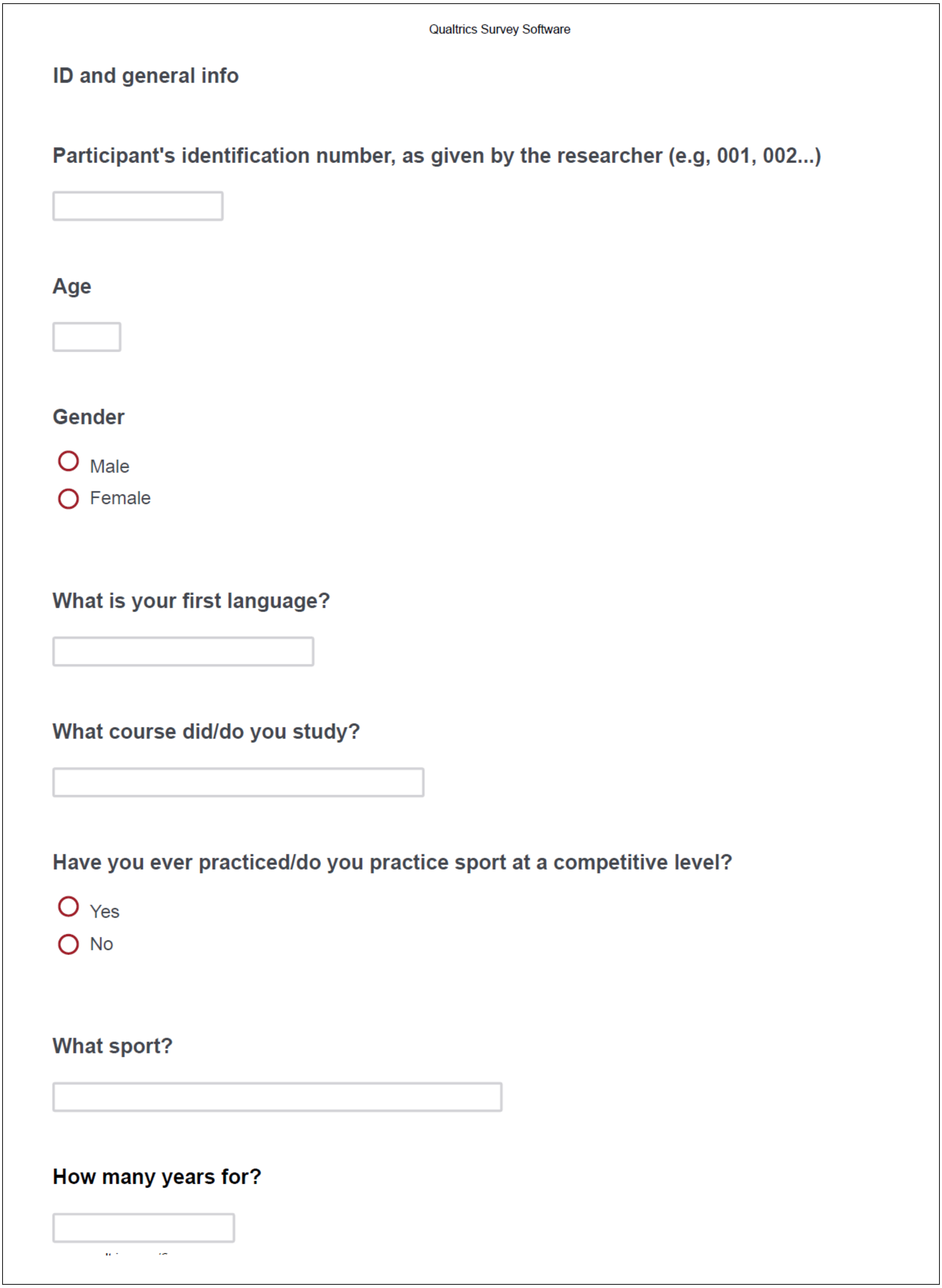
What If I Have Questions about the Project?

If you have any question regarding this research, please feel free to contact us.
If you wish to participate then proceed to the next set of questions. If eligible, you will be contacted by one of the experimenters (using the email address provided at the beginning of this document) at the email address that you will be asked to input.

Confirmation

I have read and understood what the study will involve:

C.3 Demographics



Qualtrics Survey Software

ID and general info

Participant's identification number, as given by the researcher (e.g, 001, 002...)

Age

Gender

- ○ Male
- ○ Female

What is your first language?

What course did/do you study?

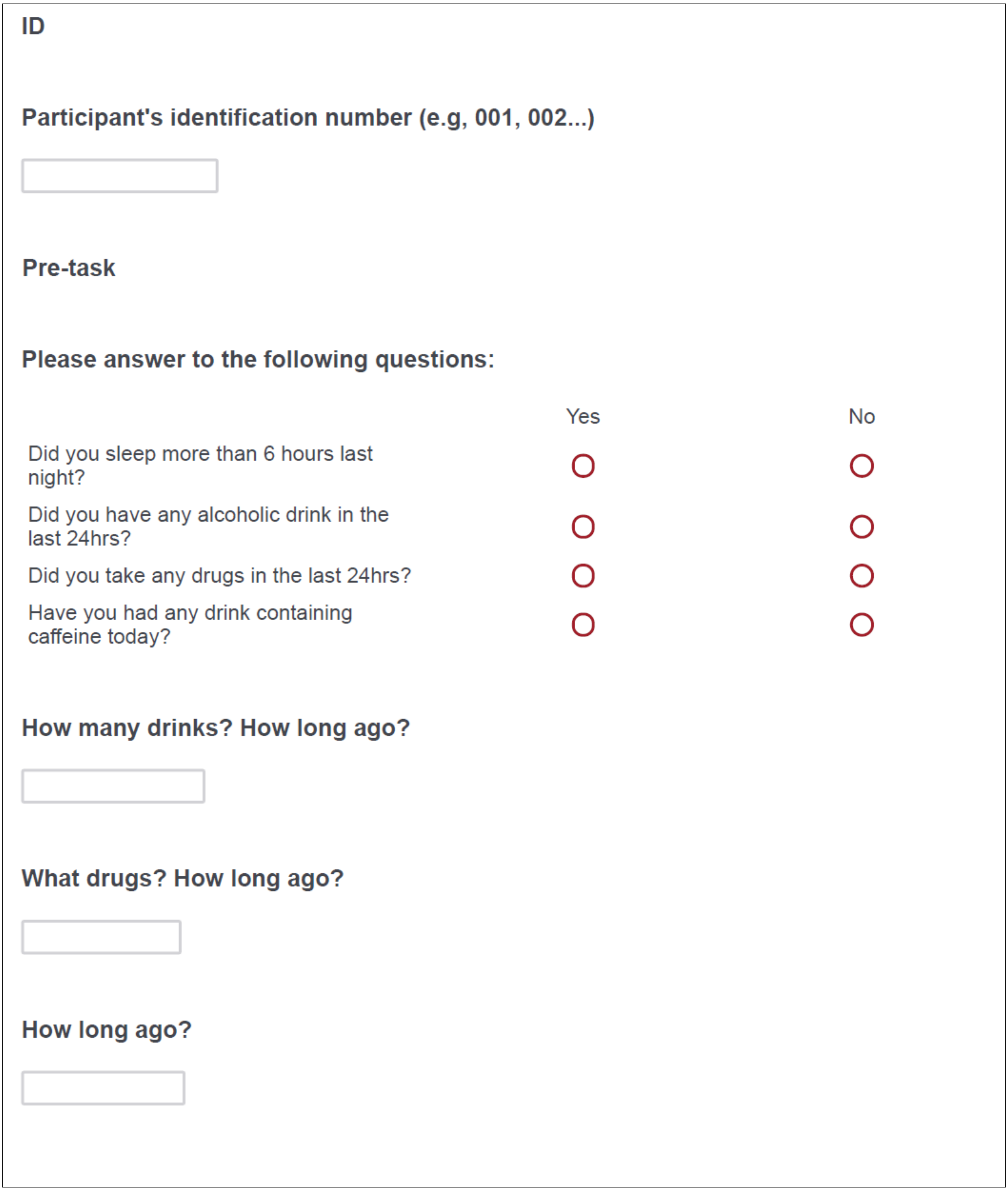
Have you ever practiced/do you practice sport at a competitive level?

- ○ Yes
- ○ No

What sport?

How many years for?

C.4 Pre-task questionnaire



ID

Participant's identification number (e.g, 001, 002...)

Pre-task

Please answer to the following questions:

	Yes	No
Did you sleep more than 6 hours last night?	○	○
Did you have any alcoholic drink in the last 24hrs?	○	○
Did you take any drugs in the last 24hrs?	○	○
Have you had any drink containing caffeine today?	○	○

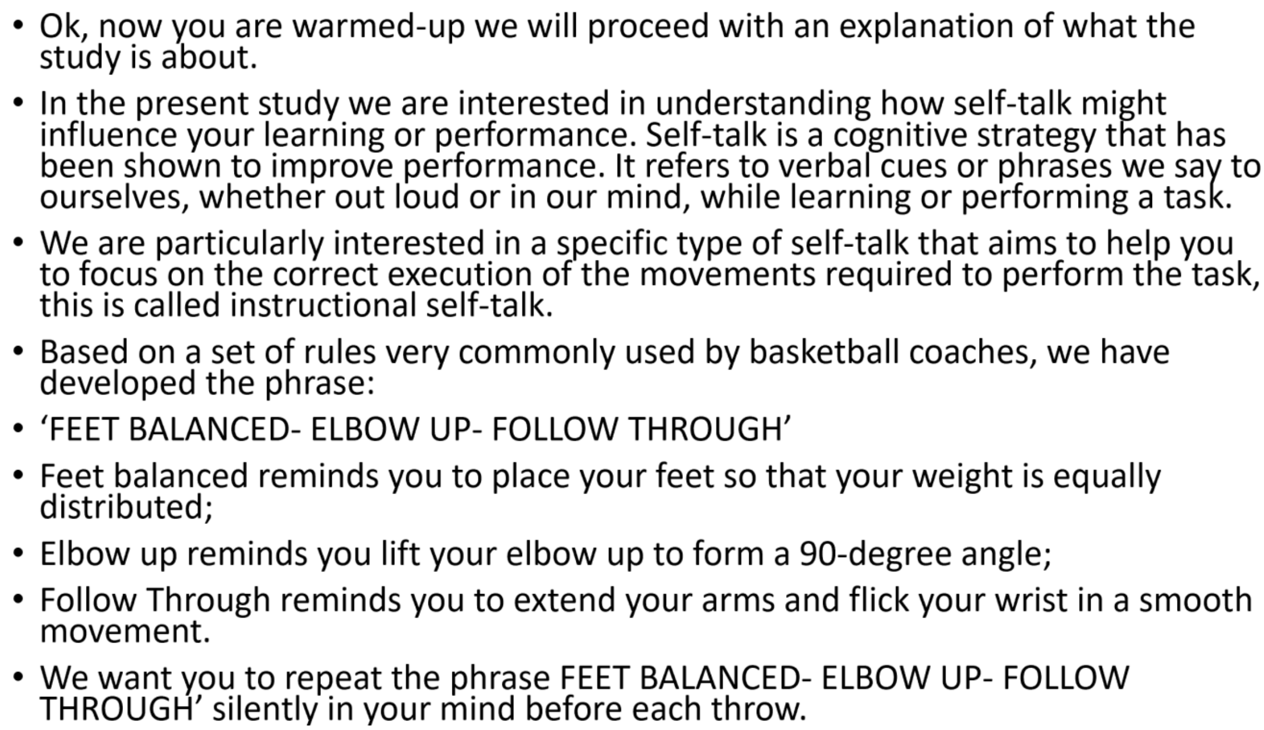
How many drinks? How long ago?

What drugs? How long ago?

How long ago?

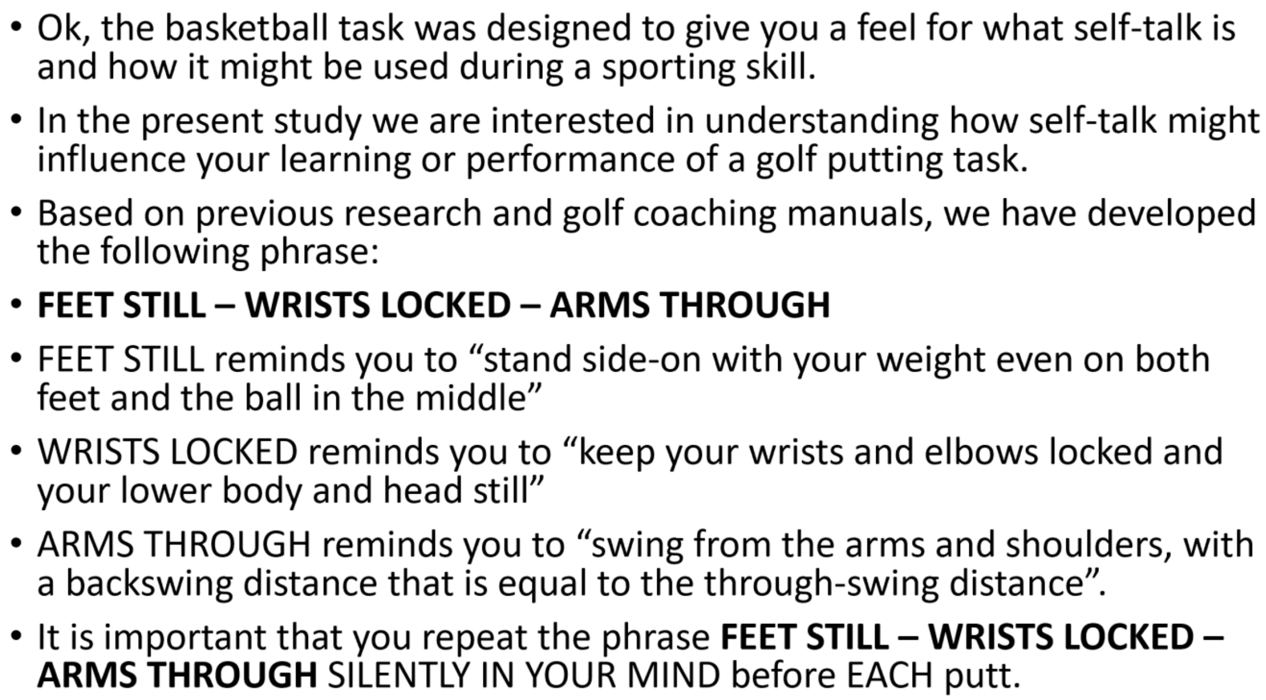
C5. Self-talk intervention (played as an audio file)

A) Instructional, basketball task



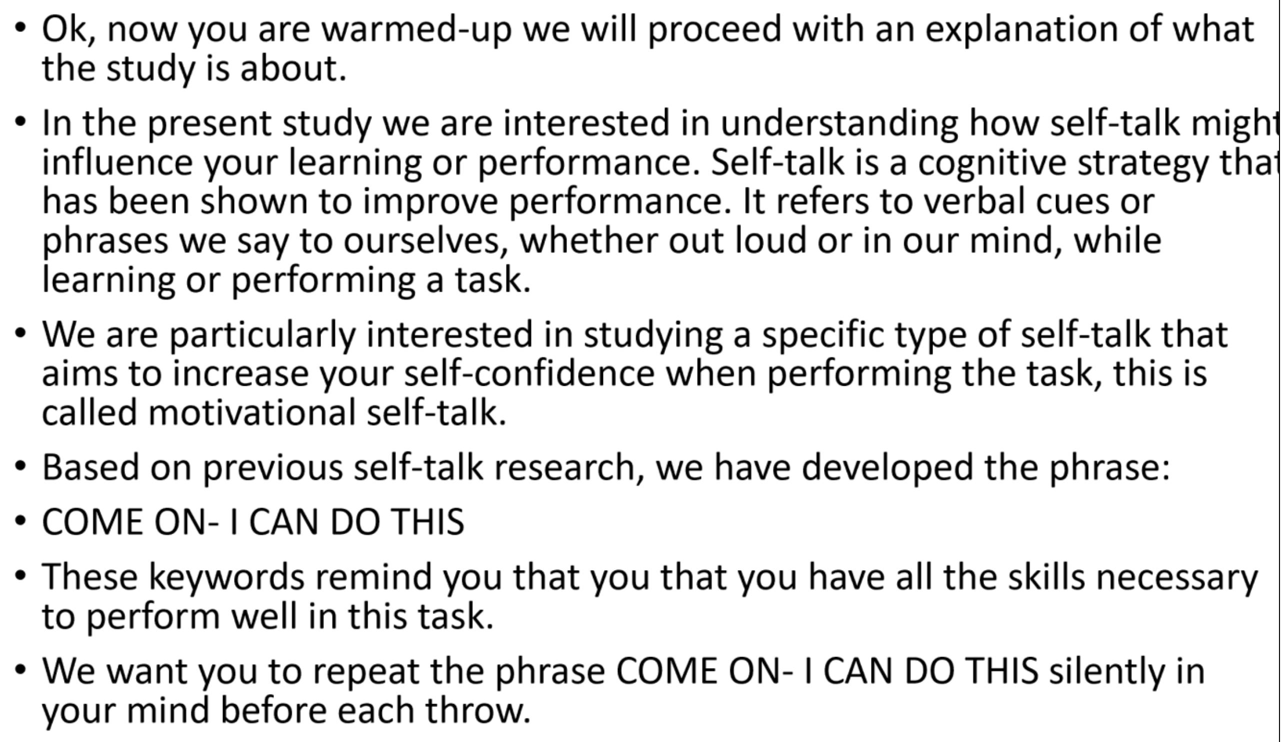
- Ok, now you are warmed-up we will proceed with an explanation of what the study is about.
- In the present study we are interested in understanding how self-talk might influence your learning or performance. Self-talk is a cognitive strategy that has been shown to improve performance. It refers to verbal cues or phrases we say to ourselves, whether out loud or in our mind, while learning or performing a task.
- We are particularly interested in a specific type of self-talk that aims to help you to focus on the correct execution of the movements required to perform the task, this is called instructional self-talk.
- Based on a set of rules very commonly used by basketball coaches, we have developed the phrase:
- 'FEET BALANCED- ELBOW UP- FOLLOW THROUGH'
- Feet balanced reminds you to place your feet so that your weight is equally distributed;
- Elbow up reminds you lift your elbow up to form a 90-degree angle;
- Follow Through reminds you to extend your arms and flick your wrist in a smooth movement.
- We want you to repeat the phrase FEET BALANCED- ELBOW UP- FOLLOW THROUGH' silently in your mind before each throw.

B) Instructional, golf task



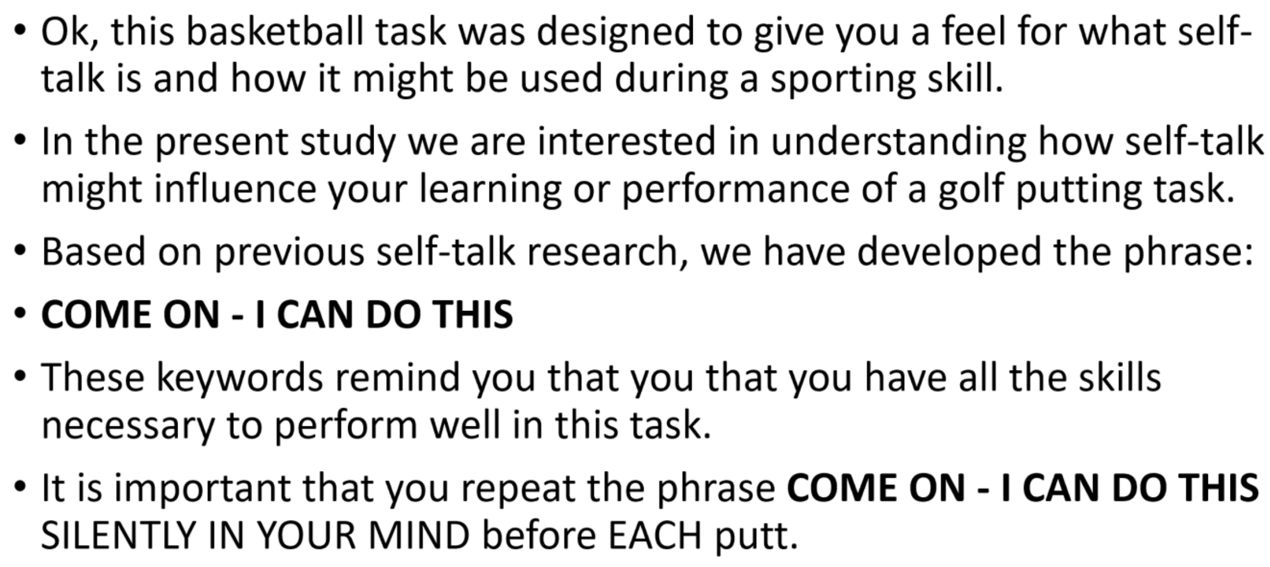
- Ok, the basketball task was designed to give you a feel for what self-talk is and how it might be used during a sporting skill.
- In the present study we are interested in understanding how self-talk might influence your learning or performance of a golf putting task.
- Based on previous research and golf coaching manuals, we have developed the following phrase:
- **FEET STILL – WRISTS LOCKED – ARMS THROUGH**
- FEET STILL reminds you to "stand side-on with your weight even on both feet and the ball in the middle"
- WRISTS LOCKED reminds you to "keep your wrists and elbows locked and your lower body and head still"
- ARMS THROUGH reminds you to "swing from the arms and shoulders, with a backswing distance that is equal to the through-swing distance".
- It is important that you repeat the phrase **FEET STILL – WRISTS LOCKED – ARMS THROUGH** SILENTLY IN YOUR MIND before EACH putt.

C) Motivational, basketball task



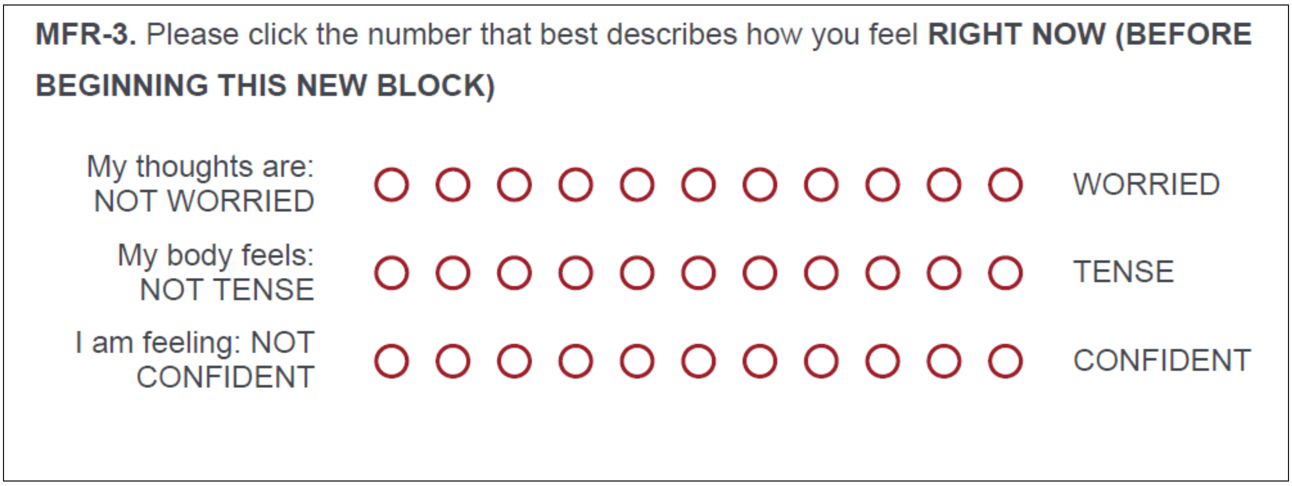
- Ok, now you are warmed-up we will proceed with an explanation of what the study is about.
- In the present study we are interested in understanding how self-talk might influence your learning or performance. Self-talk is a cognitive strategy that has been shown to improve performance. It refers to verbal cues or phrases we say to ourselves, whether out loud or in our mind, while learning or performing a task.
- We are particularly interested in studying a specific type of self-talk that aims to increase your self-confidence when performing the task, this is called motivational self-talk.
- Based on previous self-talk research, we have developed the phrase:
- COME ON- I CAN DO THIS
- These keywords remind you that you that you have all the skills necessary to perform well in this task.
- We want you to repeat the phrase COME ON- I CAN DO THIS silently in your mind before each throw.

D) Motivational, golf taks



- Ok, this basketball task was designed to give you a feel for what self-talk is and how it might be used during a sporting skill.
- In the present study we are interested in understanding how self-talk might influence your learning or performance of a golf putting task.
- Based on previous self-talk research, we have developed the phrase:
- **COME ON - I CAN DO THIS**
- These keywords remind you that you that you have all the skills necessary to perform well in this task.
- It is important that you repeat the phrase **COME ON - I CAN DO THIS** SILENTLY IN YOUR MIND before EACH putt.

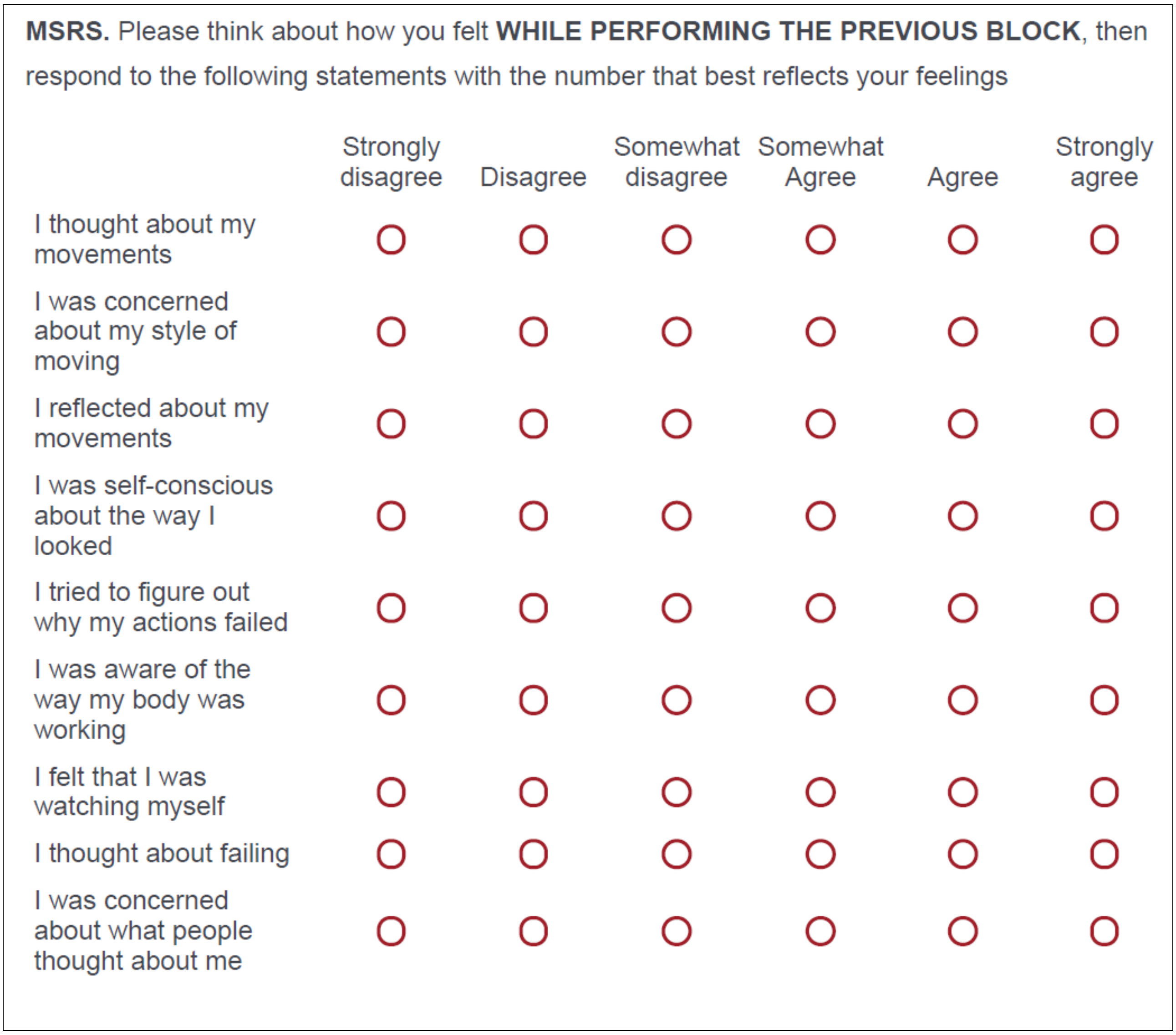
C.6 Mental Readiness Form (MRF-3)



MFR-3. Please click the number that best describes how you feel **RIGHT NOW (BEFORE BEGINNING THIS NEW BLOCK)**

My thoughts are: NOT WORRIED	○	○	○	○	○	○	○	○	○	○	○	WORRIED
My body feels: NOT TENSE	○	○	○	○	○	○	○	○	○	○	○	TENSE
I am feeling: NOT CONFIDENT	○	○	○	○	○	○	○	○	○	○	○	CONFIDENT

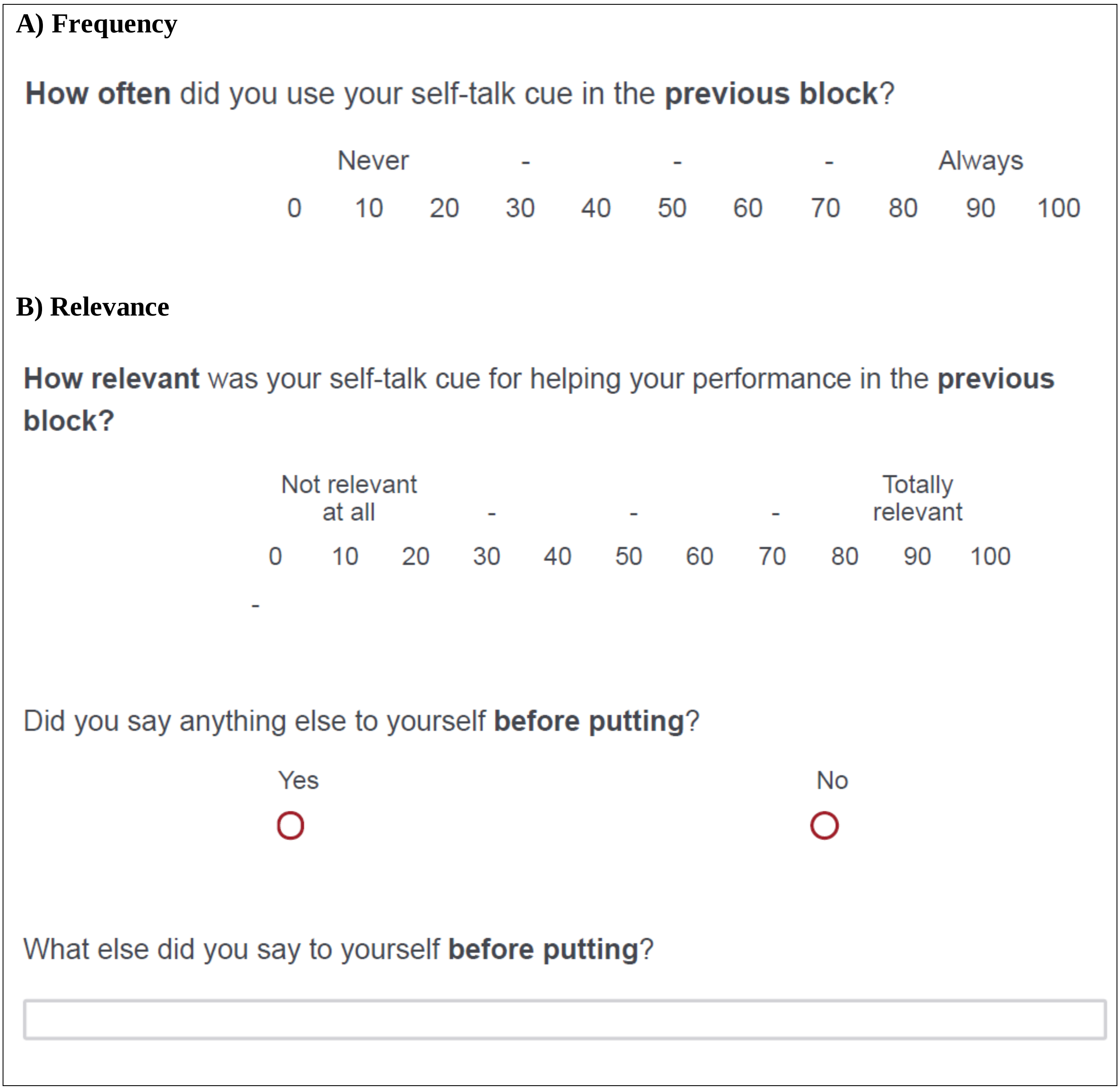
C.7 Movement Specific Reinvestment Scale – state version (MSRS-S)



MSRS. Please think about how you felt **WHILE PERFORMING THE PREVIOUS BLOCK**, then respond to the following statements with the number that best reflects your feelings

	Strongly disagree	Disagree	Somewhat disagree	Somewhat Agree	Agree	Strongly agree
I thought about my movements	○	○	○	○	○	○
I was concerned about my style of moving	○	○	○	○	○	○
I reflected about my movements	○	○	○	○	○	○
I was self-conscious about the way I looked	○	○	○	○	○	○
I tried to figure out why my actions failed	○	○	○	○	○	○
I was aware of the way my body was working	○	○	○	○	○	○
I felt that I was watching myself	○	○	○	○	○	○
I thought about failing	○	○	○	○	○	○
I was concerned about what people thought about me	○	○	○	○	○	○

C8. Self-talk frequency and relevance



A) Frequency

How often did you use your self-talk cue in the **previous block**?

	Never		-		-		-		Always	
0	10	20	30	40	50	60	70	80	90	100

B) Relevance

How relevant was your self-talk cue for helping your performance in the **previous block?**

	Not relevant at all		-		-		-		Totally relevant	
0	10	20	30	40	50	60	70	80	90	100

-

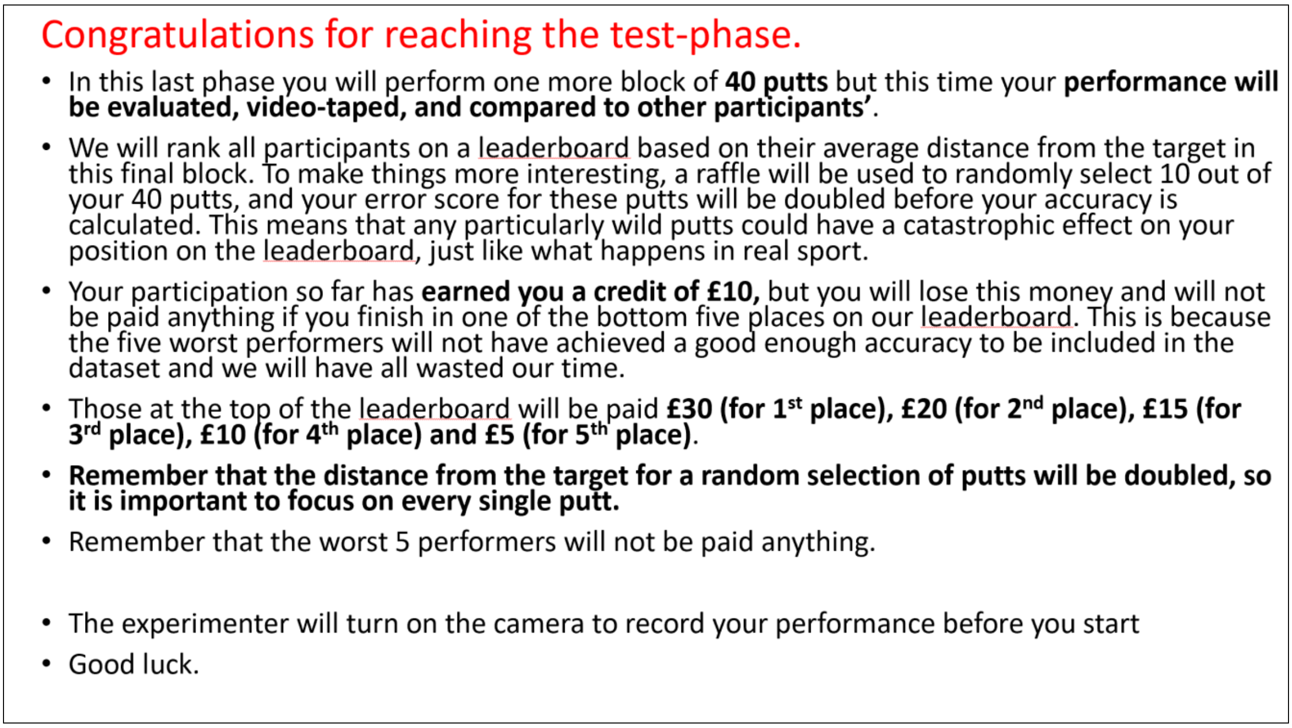
Did you say anything else to yourself **before putting**?

Yes ○

No ○

What else did you say to yourself **before putting**?

C9. Pressure manipulation



Congratulations for reaching the test-phase.

- In this last phase you will perform one more block of **40 putts** but this time your **performance will be evaluated, video-taped, and compared to other participants'**.
- We will rank all participants on a leaderboard based on their average distance from the target in this final block. To make things more interesting, a raffle will be used to randomly select 10 out of your 40 putts, and your error score for these putts will be doubled before your accuracy is calculated. This means that any particularly wild putts could have a catastrophic effect on your position on the leaderboard, just like what happens in real sport.
- Your participation so far has **earned you a credit of £10,** but you will lose this money and will not be paid anything if you finish in one of the bottom five places on our leaderboard. This is because the five worst performers will not have achieved a good enough accuracy to be included in the dataset and we will have all wasted our time.
- Those at the top of the leaderboard will be paid **£30 (for 1st place), £20 (for 2nd place), £15 (for 3rd place), £10 (for 4th place) and £5 (for 5th place)**.
- **Remember that the distance from the target for a random selection of putts will be doubled, so it is important to focus on every single putt.**
- Remember that the worst 5 performers will not be paid anything.

- The experimenter will turn on the camera to record your performance before you start
- Good luck.