EEG and ERP Biomarkers, Source Localisation and Neurofeedback for Performance Enhancement in Elite Table Tennis Athletes

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Declaration

I certify that:

* The substance of this thesis has not already been submitted for any degree and is not currently being submitted for any other degree or qualification; and,

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And… all the table tennis players from around the world who participated!!!

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Overall Thesis Abstract

It was hypothesised that the EEG of elite table tennis players would differ significantly from the amateur players at cortical source engaged in processing vision of a ‘virtual opponent’ presented in a table tennis video-viewing (VT) task and in ERPs to the two visual-spatial Go-NoGo (vsCPT1/vsCPT4) tasks. Both paradigms were conceptually designed for this research. It was hypothesised that individualized Neurofeedback (NFB) training protocols could be used to train performance in this specific neural circuitry and enhance performance related cognitive skills of elite table tennis athletes.

An original sample of over 200 table tennis players’ EEG was recorded in baseline conditions (eyes open, eyes closed), VT and vsCPT, allowing for a comparison between a group of elite table tennis players to a group of lower level but experienced ‘amateur’ players. Maximal cortical source differences (higher activity in the elite compared to the amateur group) were located by eLORETA at right Brodmann Area (BA) 13 and right BA6 in a narrow frequency band of 10.50 to 11.75 Hz. Source activity was found to be significantly related to superior response speed and perceptual discrimination at the higher processing load (vsCPT4) and reduced response bias at the lower processing load (vsCPT1). Partial least squares analysis showed ERPs during vsCPT accounted for >80% of variance in world rankings of 16 elite athletes.

A NFB protocol was designed using the cortical sources differentiating Elite from Amateur table tennis players. Nineteen nationally ranked players undertook intensive table tennis training, while ten of those players made up the experimental group and also participated in 15 x 30 minute sLoreta-NFB sessions. NFB up-trained EEG source activity at right BA13 and right BA6 within the 10.5-11.5 Hz (upper alpha) band but resulted in a significant decrease in source activity at 11.25Hz in right BA6 post training. Behaviourally, vsCPT results showed improved accuracy to NoGo stimuli.

An adjusted NFB protocol training rightBA40 was then tested. Again, significant post training decreases in source activity resulted, but this time across three conditions (Eyes Open, Eyes Closed and VT). Importantly, pre – post NFB training reduced 9.25 Hz activity during the VT condition and was strongly and significantly correlated with pre – post NFB training increases in NoGo accuracy (vsCPT1). Thus, the changes in cortical activity following this NFB training protocol were directly linked to sport related performance enhancement in this study.

Chapter 1

EEG Biomarkers, Source Localisation and Neurofeedback for Performance Enhancement in Elite Table Tennis Athletes

When the men’s 400m freestyle event was first held in the modern Olympic era in 1908, the difference between gold and silver was a matter of seconds. Henry Taylor, representing Great Britain, came first with a time of 5:36.8, while Frank Beaurepaire, representing Australasia, came second, an entire 7.4 seconds behind (LaMondia, 1999). In the 2008 Olympics, however, the difference between winning and losing was decided by 58 milliseconds (LaMondia, 1999). Because the performance margins between winning and losing are shrinking it is becoming correspondingly more important to exploit every avenue of even the smallest possible gains in performance. For all elite athletes, high performance now involves not just physical preparation but mental preparation as well.

Although mental processes may, at face value, appear secondary to physical condition in athletes, the influence of the brain on the body has substantial empirical support stretching back over 100 years (Mallone, 2009). Recently, converging neuroimaging and clinical findings (Critchley et al., 2003) have clearly demonstrated that the anterior cingulate cortex (ACC) of the human brain modulates bodily arousal states relative to context-driven cognitive and motor tasks. Likewise, Sztajzel (2004) explains the direct relationship between autonomic nervous system functioning – mediated by the ACC – and its impact upon heart rate variability and consequent health risks. Thus, clearly understanding the relationship between thought and physical action will have numerous benefits for both professional athletes and amateurs, and the study of this relationship is now the domain of specialised Sports Psychologists.

In this branch of psychology, particular emphasis is given to assisting athletes to obtain the perfect integration between mind and body; that is, helping athletes to gain control over the physical and technical aspects of their sport that are heavily influenced by emotion and mood. It is this combining of physical aptitude with mental control that is often the difference between a highly skilled athlete winning or losing in their chosen sport. Sport psychology is now commonplace in elite athletes' training schedules (Sime, 2003).

Sport psychology's methods of maintaining and improving elite athletic performance are, for the moment, primarily based on relaxation and arousal regulation, visualization, goal-setting and general attention strategies directly controlled by an athlete at the time of the event taking place (Sime, 2003). The primary goal of this study is to extend the latter of these current methods of mental preparation – specifically, attention to visual stimuli – through a method of behaviour regulation called biofeedback which is based upon one of life's most basic automatic, instinctive learning principles – operant conditioning.

The term 'operant conditioning', first coined by B.F. Skinner (Holland, & Skinner, 1961), is defined as a change of behaviour by the use of reinforcement given after the desired response. Behaviour which is reinforced tends to be repeated, and behaviour which is not reinforced tends to die-out or be extinguished (weakened). Skinner identified three types of reinforcer that can follow behaviour:

1. *Neutral operants*: responses from the environment that neither increase nor decrease the probability of a behaviour being repeated.

2. *Reinforcers*: Responses from the environment that increase the probability of a behaviour being repeated. Reinforcers can be either positive or negative.

3. *Punishers*: Response from the environment that decrease the likelihood of a behaviour being repeated. Punishment weakens behaviour (Skinner, 1938).

Athlete or not, operant conditioning is used every day to learn from mistakes, or increase the efficiency of an action. A particular action produces a desired or undesired result. Athletes use operant conditioning to refine fine motor skills for hours every day, repeating intricate movements of their bodies to produce a desired effect time after time, with or without a mistake, learning by observing the result. An elite table tennis player, for example, spends countless hours practising a particular serve – the movement is produced and the result is observed, evaluated and learned from.

Sport performance enhancement has developed over the last several decades in two main phases. The first phase used operant conditioning principles for the regulation of arousal by placing sensors on peripheral muscles. The resulting measurement of muscle tension and autonomic nervous system activity provided the athlete with biofeedback which was used to control and train various aspects of somatic arousal (Carlstedt, 2007).

However, sport psychology did not remain strictly within its own domain, and the second phase of sport psychology used biofeedback to begin taking advantage of neuropsychological advances in brain therapy – using operant conditioning at a neuronal level. The challenge was to apply operant conditioning (biofeedback) techniques using the electroencephalography (EEG) of the athlete as the measure for control and entrainment. EEG biofeedback, now better known as Neurofeedback (NFB), was born – but its first use did not begin with performance enhancement for athletes.

1.1. History of Neurofeedback

In 1875 British physician Richard Caton observed electrical activity while manipulating the exposed cortices of animals (Masterpasqua, & Healey, 2003). Some 54 years later in 1929, Hans Berger detected electro cortical activity from the surface of the human scalp. EEG activity is detected from the scalp using individual active electrodes placed on conductive gel at pre-defined points, including a reference and ground electrode. The reference electrode produces both a stable and reproducible potential to which the active electrode potential can be compared. The ground electrode is needed for obtaining differential voltage by subtracting the same voltages shown at active and reference points. The signal travels from the electrodes down the electrical wire, is amplified and, nowadays, sent to a computer for manipulation of data (Teplan, 2002).

Berger subsequently termed the detection of these electrical signals from the scalp *electroencephalogram* (EEG). It is now known that EEG *power* reflects changes in postsynaptic membrane potentials, primarily those in cortical pyramidal neurons (Klimesch, Sauseng, & Hanslmayr, 2007). The ions flowing to and from the neuronal dendrites within the extracellular space generate the EEG voltages. EEG detection is not possible for any one neuron in humans using scalp electrodes, but instead is the summation of thousands of neurons with synchronised activity having a similar spatial orientation relative to the scalp (Gruzelier & Egner, 2004). The EEG *waveforms* are generated by oscillatory rhythms of a large number of neurons firing synchronously. From a general point of view, oscillations are present in all physical and biological systems trying to establish equilibrium. Oscillations emerge when the system is controlled by two opposing processes, one that drives the system from equilibrium and one that returns it back. In this respect, EEG oscillations do not differ from oscillations in other biological systems. In the case of any observable EEG rhythm (such as theta, alpha, or beta - see below) there is always a force that drives the neuron or the neuronal network from its equilibrium and a force that returns it back (Kropotov, 2009).

As an example of this the striatum, the anterior component of the basal ganglia, is attributed the role of managing background motor tone and the planning phase of movements. It is a system of fibre connections which form a loop from cerebral cortex and back to cerebral cortex via thalamic relays. The two major components of the striatum include the putamen/globus pallidus complex and the caudate nucleus. The putamen provides an inhibitory input to the globus pallidus. When the putamen is excited by pre-motor and sensorimotor cortex the globus pallidus, which functions to inhibit various thalamic relay nuclei projecting back to motor and pre-motor cortex, is itself inhibited, thus releasing excitatory input to motor and sensorimotor cortex via the thalamic relays. When input to the putamen from the sensorimotor cortex is reduced, the globus pallidus becomes more active, thereby imposing inhibition upon its thalamic relays to motor cortex. This inhibition would alter involuntary motor regulation, reducing muscle tone and the intention to move, giving rise to a well-studied EEG oscillation called the sensori-motor rhythm (Sterman, & Egner, 2006).

Hans Berger then noticed that certain frequencies of these oscillations were associated with different mental states; around 10 cycles per second (10Hz) for subjects sitting quietly with eyes closed, and around 15 Hz for those focused on a mathematics problem with eyes open (Masterpasqua, & Healey, 2003). These discoveries sparked interest around the world for psychologists, neurologists and many other researchers to delve into the new possibilities that lay ahead for the use of EEG in diagnosis and treatment.

Within a few years EEG frequencies were classified into five main bandwidths according to general functional differences: the *delta* wave (~0-4Hz) primarily found in the human EEG during deep sleep; the *theta* wave (~4-8Hz) often associated with drowsiness and early sleep stages; *alpha* wave (~8-12Hz) characteristic of a relaxed waking state; *beta* (~12-30Hz) and *gamma* (above 30Hz) waves, mainly found in more aroused, active cortical processing during mental operations in the alert brain.

More recently (Klimesch, 1999), functional differences have even been found within individual bandwidths. For example, at least three distinct patterns of desynchronization (power decrease) can be observed in the Alpha bandwidth; upper Alpha is identified by desynchronization in the range of about 10–12 Hz, is topographically restricted to the posterior region and develops during the processing of sensory-semantic information; lower Alpha between 6-10Hz, is topographically widespread over the entire scalp and reflects general task demands and attention processes. There is strong evidence (Klimesch, 1999) to suggest that there is even further distinction within the lower Alpha bandwidth. Lower-1 Alpha (6-8Hz) displays desynchronization when a warning signal precedes a target stimulus, followed by synchronisation (power increase) at the time of the stimulus, indicating *alertness* to the coming event; whereas lower-2 Alpha (8-10Hz) displays a steady desynchronization from the time of the warning signal and continues its decrease in power through the time of stimulus and beyond, showing an *expectation* of the coming event. Thus, the Alpha bandwidth can be broken into at least 3 distinct functionally different segments at present.

Further to these incremental functional distinctions within the human EEG, each individual possesses a dominant frequency called Individual Alpha Frequency (IAF). IAF lies in the range of about 9.5–11.5 Hz for young healthy adults and is defined as the point at which, during resting eyes closed baseline EEG, alpha power is at its strongest. There are large inter-individual differences regarding IAF and young adults can show a difference in IAF of more than 2 Hz compared to age and gender matched peers. Functionally, IAF individual differences have been associated with age, processing speed, memory and cognitive performance (Klimesch, 1999).

Bazanova (2012) specifies further important alpha activity phenomena which have recently been identified. Firstly, particularities of a high IAF (10-12Hz) compared to a low IAF (8-10Hz) include, firstly, how easily trainable an individual is through biofeedback; secondly, what Bazanova (2012) describes as the “activation magnitude” which is measured by estimating the amount of alpha amplitude suppression in response to eyes-open relative to individual alpha band width; and thirdly, alpha “auto-rhythmicity” indices: intra-spindle (a burst of oscillatory EEG activity lasting for at least 0.5 of a second) amplitude variability, spindle length, and steepness.

IAF defines the range of each individual’s corresponding bandwidths of Delta, Theta and Beta, and forms the basis around which all EEG analysis and treatment should stem from. These inter-individual differences in EEG and the functional particularities of EEG bandwidths triggered interest in whether any power change in particular frequencies would correspond to behavioural changes, and were one of the main driving forces involved in the development of treatment that could alter this EEG activity in a human subject, which is now termed Neurofeedback (NFB) (Sterman & Egner, 2006).

Neurofeedback began in the late 1950s and early ‘60s through the work of Dr Joe Kamiya at the University of Chicago and Dr Barry Sterman at UCLA. The origins of NFB can be traced to Dr. Kamiya in the 1960s, who, while studying the relationship of changes in EEG activity and consciousness, discovered that by using a simple reward system, people could learn to alter their brain activity (Kamiya, 1969). In the first systematic demonstration of EEG operant conditioning during the 1960s, in the context of sleep research, Sterman and his associates conducted a series of studies investigating learned suppression of a previously rewarded cup-press response for food in cats (Sterman, et al. 1972). During learned suppression of this response, the appearance of a particular EEG rhythm over sensorimotor cortex emerged above non-rhythmic low voltage background activity. This rhythm was characterized by a frequency of 12 – 20 Hz, with a spectral peak around 12 – 14 Hz, and has been referred to as the “sensorimotor rhythm” (SMR). The investigators decided to study this distinct rhythm directly, attempting to apply the operant conditioning method to see if cats could be trained to voluntarily produce SMR, by making a food reward contingent on SMR production. Cats easily accomplished this feat of EEG self-regulation, and the behaviour associated with SMR production was one of corporal immobility, with SMR bursts regularly preceded by a drop in muscle tone (Sterman & Egner, 2006).

Sterman’s laboratory was soon afterwards commissioned to establish dose-response functions of a highly epileptogenic fuel compound. When employing the cats that had previously taken part in SMR conditioning as experimental animals, these cats were found to display significantly elevated epileptic seizure thresholds compared to untrained animals, suggesting that SMR training had somehow inoculated the cats against experiencing seizures. Subsequently, this research was successfully extrapolated to humans, where it was repeatedly documented that seizure incidence could be lowered significantly (or on rare occasions abolished) by SMR feedback training (Sterman & Egner, 2006).

Stemming directly from the experiments conducted in the laboratories of Barry Sterman and his associates just described, NFB is now widely applied as a means of regulating human EEG activity (Vernon et al., 2003). In a typical modern-day NFB set-up, EEG activity is recorded from two scalp electrodes, referenced and grounded to electrodes attached to, for instance, the mastoids (bony prominence on the base of the skull behind the ear). The recorded signal is then filtered in order to extract activity in the bandwidths of interest (Gruzelier & Egner, 2004). The EEG signal is filtered into bandwidths using a mathematical algorithm called the Fast Fourier Transform (Reddy, 1998). The Fourier transform, named after the French mathematician Jean-Baptiste Joseph, Baron de Fourier (1768-1830), converts a time-domain signal into a frequency-domain signal. In other words, it converts the raw EEG signal recorded from the scalp over time, into a distribution of EEG power by frequency. The resulting frequency spectrum forms the platform for the desired NFB protocol to be developed, for example to up-regulate SMR (12-15Hz). Power within the specified frequency bandwidth is presented to the participant in the form of, for example, an audio-visual computer game-style display. The NFB protocol is programmed so that when the individual's EEG signal complies with the desired frequency bandwidth, the participant is rewarded within the computer game and will attempt to reproduce the result. Through a process of trial and error, the participant gradually develops strategies to modify his or her own EEG to maximise reward. This process results in operant conditioning of the clients' EEG (Egner & Sterman, 2006).

More than 35 years of NFB study has shown that changes in EEG are initially short-term, but most people can be trained to make enduring changes over longer training periods (Hammond, 2007). However, for training to be successful, it is vitally important for an assessment to be performed and the training protocol be individualized to the distinctive brainwave patterns and symptoms of each person. Therefore, prior to attempting Neurofeedback training, a quantitative EEG assessment should be performed to objectively and scientifically evaluate a person's brainwave function (Hammond, 2011).

1.2. Using quantitative EEG analysis to guide neurofeedback

Each individual has a unique EEG that is influenced by many factors including genetics, development, learning history and environmental conditions. The quantitative EEG (QEEG) procedure is the current method of choice for assessing a client's EEG prior to NFB. A QEEG usually takes about 45-60 minutes and is administered by placing a snug cap on the head, which contains 19 electrodes placed at defined positions on the scalp using the International 10-20 system for electrode placement (Teplan, 2002). EEG activity is recorded while the client is resting quietly with his or her eyes closed, eyes open, and sometimes during a task. Afterward, a careful process is used to remove as completely as possible artefacts that occurred when the eyes moved or blinked, from body movement, or tension in the jaw, neck, or forehead. The EEG data that were gathered are then statistically compared to a normative database that provides objective information on how the brain should be functioning at the client's age. This assessment procedure allows the professional to then determine in a scientific, objective manner whether a client's brainwave patterns are significantly different from normal, and if so, how and where they differ (Hammond, 2007).

QEEG analysis produces information on the distribution of EEG frequencies over specific electrode locations, the amplitude and topographic (spatial) pattern of the composite frequencies in the EEG, and the symmetry of this data at homologous (left-right mirror image) electrode sites of each hemisphere. When compared to a normative database of eyes open and/or eyes closed resting EEG activity for that person's gender and age-group, the results can be used to support diagnoses for disorders such as autism and attention deficit hyperactivity disorder (ADHD). To illustrate this, the QEEG of ADHD patients is often different to non-clinical samples and research reveals (Masterpasqua & Healey, 2003) that a large percentage of ADHD subjects are differentiated by elevation in the average amplitude of slow brainwave frequencies (4-7Hz or 8-11Hz) and a corresponding decrease in amplitude of higher frequencies (12-15Hz or 15-18Hz), especially over the prefrontal or medial recording sites.

Further to spectral differences, QEEG analysis produces information regarding how various locations of the cortex communicate together – this type of analysis is termed 'functional connectivity'. Functional connectivity is defined as the temporal coherence between the activities of different brain areas (Babiloni et al., 2005). The intricate patterns of cerebral activity associated with our sensory, motor, and cognitive functions are largely defined by neuronal connectivity. The concept of brain connectivity now plays a central role in neuroscience as a way to understand one possible code of the functioning brain, as well as the organized behaviour of cortical regions beyond the simple mapping of their activity (Ilmoniemi, et al. 1997). While local connections between neurons are located within the grey matter, fibres in the white matter bridge functionally related cortical areas over long distances directly or indirectly (Babiloni et al., 2005).

Modern-day NFB practice aims to teach self-regulation of EEG toward more normalized activity patterns on an individual basis, guided by QEEG analysis, in order to normalize the underlying EEG patterns associated with specific symptom patterns. QEEG assessment provides the tool necessary to individualise NFB training protocols by the comparison of spectral and connectivity patterns against a normative database.

To be administered properly, NFB must be conducted or supervised by a specialist with expertise concerning brain function and who is knowledgeable about much more than simply how to operate equipment and software. To emphasise this point, Bazanova and Aftanas (2010) conducted NFB protocols on two outpatients with attention deficit disorder (a schoolboy) and functional pain contraction (a professional musician). The NFB utilizing standard EEG frequency ranges (theta 4-8, alpha 8-12, beta 13-18) was inefficient (average NFB training threshold increase of 0.52% over 10 sessions) and even resulted in aggravation of symptoms in both cases. The individualized NFB that utilized individualised frequency ranges resulted in substantial clinical improvement, for example on parent rating scales of attention and impulsivity, and resulted in a NFB efficiency of 57% threshold increase over 10 sessions.

Additionally, NFB practitioners treating the clinical population may use the so called ‘bulldozer’ principle - if there is an excess of some EEG parameter in a particular patient and in a particular location in the cortex, the aim of NFB is to train this parameter *down*; if there is a lack of an EEG characteristic the corresponding NFB parameter is trained *up*. The method works like a bulldozer filling in the cavities and excavating the bumps. NFB training has now been demonstrated to be an effective treatment for a variety of disorders with a neurological component including ADHD, epilepsy, depression, alcoholism, autism, Asperger’s syndrome, and stress disorders (Kaiser, 2005).

Keeping individualisation of NFB protocols in mind, using NFB with the sporting population, in which deviations from the normal population can also be expected, would place great importance on using QEEG analyses to define individual frequency bandwidths and specify NFB protocols through comparison against a normative database. A similar theoretical framework to that currently used in the clinical population can be used to train athletes appropriately for their given sport. Whereas, in the clinical population patients are trained with the goal being to regulate EEG activity towards the normal population, there would obviously be no benefit in regulating those differing aspects of an athlete’s EEG back towards the norm. In order to train an athlete correctly using NFB, those QEEG aspects in which an elite athlete differs from the normal population in a specific sport must first be identified and then used as a benchmark for others in that sport to be trained towards through NFB. It has been the goal of recent research (cf. Sherlin, Gervais, & Walshe, 2011; Babiloni, & Del Percio, 2008) to identify EEG particularities of elite athletes in order to then be able to set NFB protocols appropriate for performance enhancement in that sport. It is to that recent research focusing upon sporting QEEG differences that we turn to next.

1.3. QEEG differences in athletes

Sherlin and colleagues (2011) compared the resting EEG and visual continuous performance task (CPT) EEG of 10 professional male action sport (extreme surfing) athletes to a control group of 10 male professional athletes in non-contact sports (e.g. baseball, basketball, golf, tennis, etc.). Interestingly, both groups displayed expected frequency maxima distribution with the only exception being the increased presence of focal beta (13-21 Hz) activity in the parietal and occipital cortices. This finding is common in individuals who have increased physiological arousal levels and typically demonstrate thought processes and behaviours consistent with increased cortical activation (Jensen, Hakimian, Sherlin, Fregni, 2008). Further statistical comparisons indicated the predominance of increased alpha frequency band with maximal localization of deviances in the left dorsal lateral prefrontal cortex (DLPFC). Alpha is most associated with disengagement of active processing since alpha synchronises (increases in power) with decreasing task demands – attention and semantic memory demands are powerful factors which lead to a selective suppression of alpha in different 'sub-bands' (Klimesch, 1999). The DLPFC is a cortical area heavily involved in motor planning organization and regulation. The finding of increased alpha during the baseline task suggests that athletes who are performing in life and death situations may have a physiological mechanism that distinguishes them from other professional athletes tested. Sherlin and colleagues (2011) argue that lower baseline cortical arousal in DLPFC allow action sport athletes a greater tolerance for high risk environmental factors.

Deeny, Hillman, Janelle, & Hatfield (2003) further showed QEEG differences in sportsmen when they measured coherence in a 4 second aiming period prior to trigger pull between expert marksmen (n = 10) and skilled shooters (n = 9) over the course of a regulation round of small-bore rifle shooting. Coherence was assessed for three frequency bands (low alpha, 8–10 Hz; high alpha, 10–13 Hz; and low beta, 13–22 Hz). Compared to the skilled group, experts exhibited lower coherence between left temporal (T3) and midline frontal (Fz) regions for low-alpha and low-beta frequencies, lower coherence for high-alpha between all left hemisphere sites and (Fz), and lower coherence between T3 and all midline sites for the low-beta band. The results reveal that, compared to lesser skilled shooters, experts engage in less cortico-cortical communication, particularly between left temporal association and motor control regions, which implies decreased involvement of cognition with motor processes.

In order to assess whether frontal and central cerebral EEG rhythms (measured at Fz, Cz and C4) are implicated in fine motor control and balance, Babiloni and Del Percio (2008) recorded EEG in 12 right-handed expert golfers while playing 100 golf putts. Cortical activity was indexed by the power reduction in spatially enhanced alpha (8–12 Hz) and beta (13–30 Hz) rhythms during movement, referred to as the pre-movement period. High-frequency alpha power (about 10–12 Hz) was smaller in amplitude in the successful than in the unsuccessful putts over the frontal midline and the arm and hand region of the right primary sensorimotor area; the stronger the reduction of the alpha power, the smaller the error of the unsuccessful putts (i.e. distance from the hole). Babiloni and Del Percio (2008) interpreted these results as indicating that high-frequency alpha rhythms (10-12Hz) over associative, premotor and non-dominant primary sensorimotor areas subserve motor control and are predictive of the golfer’s performance. The high-frequency alpha reduction prior to the task over the right primary sensorimotor cortex was maximum during the successful putts, suggesting that a fine cortical control of the left arm and hand movements is crucial for that winning performance. Of note, these results contribute to the debate on the functional significance and hemispheric distribution of alpha rhythms recorded during sporting performance. An inhibitory increase in alpha power (8–12 Hz) in the left hemisphere before the performance of skilled marksmen (Hatfield, Landers, & Ray, 1984) and archers (Salazar et al., 1990; Landers et al., 1994) has already been shown; this would favour visual–spatial processes in the right hemisphere and suppress verbal cognitions in the left hemisphere. Furthermore, a correlation has been reported between the reduction in power of right parietal alpha power and skilled karate performance (Del Percio et al., 2007). Babiloni and Del Percio (2008) also report that successful putts were additionally characterized by high-frequency alpha event-related desynchronization (ERD) over the medial prefrontal, cingulate and/or supplementary motor areas. These cortical areas play a pivotal role in the planning, selection and regulation of learned complex sequences of motor actions. Interestingly for the present study, they suggested that future research might look at understanding which neuronal networks are involved in pre-task attention to visuo-spatial information to better understand which neuro-anatomical areas of the cortex should be trained through NFB.

Loze, Collins and Holmes (2001) found significantly greater EEG alpha power in the left hemisphere during the 3 second pre-shot period over temporal sites, confirming results of other studies in target sports (e.g. Landers et al., 1994; Salazar et al., 1990). Furthermore, the 5 best shots and 5 worst shots for each shooter were selected based on four shot quality indicators. When occipital EEG alpha power during the critical period was compared between best and worst shots, power increased for best shots and decreased for worst shots. Due to this occipital alpha power increase for best shots, the researchers concluded that shooters had greatest success when not having greatest visual focus on where the pistol was aimed, and that suppression of visual focus during the critical period is a necessary prerequisite for automatic shot execution.

NFB practice for sport performance enhancement currently uses research from individual QEEG analysis and QEEG analyses pertaining to the given sport if any has been undertaken. Once QEEG analysis has been performed, current NFB protocols for sport performance enhancement centre on gains in attention and fine motor skill execution using up-regulation of the sensori-motor rhythm due to its role in the regulation of these skills. The sensori-motor rhythm has been a major EEG rhythm used for NFB research and practise in the clinical and performance enhancement populations since its discovery in the 1960s.

1.4. Sensori-Motor Rhythm – Quietening the mind

The precise neural functioning involved in the production of sensori-motor rhythm (SMR) has been well studied and is fairly well understood. Trained SMR responses are associated with changes in both afferent and efferent pathways of the sensorimotor system. These include decreased red nucleus activity, stretch reflex excitability, and muscle tone. These changes produce reduced somatic afferent discharge and lead to thalamic hyperpolarization and reciprocal oscillatory burst activity between the ventrobasal and reticular nuclei of the thalamus. This burst activity is propagated to sensorimotor cortex and initiates corresponding bursts of SMR activity. As SMR is the dominant ‘standby’ frequency of the integrated thalamo-cortical somato-sensory and somato-motor pathways, operant training of SMR is assumed to result in increased thresholds for excitation and improved control of excitation of this system (Sterman, & Egner, 2006).

The functional changes in sensori-motor circuits mediate the onset of SMR activity and are strengthened during NFB training. This results in a lasting decrease in sensorimotor excitability (Sterman, & Egner, 2006). Lubar and Shouse (1976) first successfully used a NFB protocol of SMR enhancement for treatment of ADHD, in acknowledgement of the quietening effect of SMR on the excitability of the sensori-motor system. Put simply, SMR suppresses the competing frequency power around the sensorimotor cortex that impedes the sending of signals from the motor cortex to the muscles. The increase of SMR acts to quieten the mind, and can be most beneficial in the moments preceding a complex motor skill.

1.5. Using SMR NFB for performance enhancement

One of the earliest notable sports performance enhancement studies used slow cortical potential NFB with pre-elite archers (Landers et al., 1994). Slow cortical potentials are slow event-related direct-current shifts of EEG. Slow cortical potential shifts in the electrical negative direction reflect the depolarization of large cortical cell assemblies, reducing their excitation threshold (Strehl, Leins, Goth, Klinger, & Hinterberger, 2006). Athletes (N = 24) were assigned to one of three treatment conditions: 1. ‘Correct’ feedback – the *desired* frequency bandwidth to be up-regulated, in this case, left hemisphere temporal lobe slow cortical potential activity; 2. No feedback control; and 3. ‘Incorrect’ feedback – an *undesired* frequency bandwidth to be up-regulated, in this case, greater right hemisphere slow cortical potential activity, which was included to guard against motivational or expectancy effects of NFB. Although slow cortical potential change was not recorded pre-post testing, the correct feedback group increased left hemisphere alpha and beta frequencies; however, it was not significantly different from the control groups. The correct feedback group significantly increased performance after NFB (post-test shots were 1.66cm closer to the target). While no significant changes were found for the control group, interestingly a significant decrease of performance was found for the incorrect feedback group (post-test shots were 1.87cm farther away from the target). These results provided some initial promising support for the efficacy of NFB to increase performance. Furthermore, the study demonstrated that if the wrong type of feedback was trained, a decrease in performance may result.

Over the past 35 years, beginning with Lubar and Shouse (1976), an increase in SMR using NFB training has been associated with an increase in sustained attention processing and has been used successfully to reduce symptoms in the ADHD population (for example Tinius & Tinius, 2000). More recently, Egner and Gruzelier (2001) found that enhancement of

SMR activity was associated with a reduction in commission errors and improved perceptual sensitivity on the 'Test Of Variables Of Attention' (TOVA), as well as increases in the attention-related P3b event-related potential (cf. Event-related potentials, section 1.9). Neurophysiological research on animals has shown that, during inactive but focused and alert behaviour, the attenuation of somatosensory inputs promotes burst firing in the ventrobasal thalamic nuclei, initiating SMR (Howe and Sterman, 1972). More recently, human research has also shown greater activity in the 11–15 Hz range, localised to the sensory projection area of the cortex, when visually attending to stimuli compared to the completion of a motor task (Mann et al., 1996). This led to the suggestion that motor activity, which would be associated with suppression of SMR activity, may interfere with both perceptual and integrative components of information processing (Sterman, 1996). Consequently, learned voluntary control of SMR activity may facilitate information processing by decreasing such motor interference, whilst at the same time maintaining perceptual and memory functions at the ready. Vernon and colleagues (2003) used NFB to train individuals to selectively increase SMR (12-15Hz) at electrode site Cz (scalp vertex) while simultaneously inhibiting theta (4-7Hz) and beta (18-22Hz) with the aim of increasing sustained attention on a visual continuous performance task in a non-clinical sample. Vernon and colleagues (2003) also trained a second NFB group who were given the aim of increasing theta (4-7Hz) while inhibiting delta (0-4Hz) and alpha (8-12Hz) also at electrode site Cz, to investigate convincing evidence of the direct relationship between theta power increase and working memory performance. This evidence stems from data showing that, during the encoding phase of a recognition task, only words that were later correctly recognised exhibited a significant increase in theta activity (for example, Klimesch, Doppelmayr, Schimke, & Ripper, 1997). Results of this study showed that, after eight sessions of NFB, the SMR-group were able to selectively enhance their SMR activity, as indexed by increased SMR/theta and SMR/beta ratios. In contrast, those trained to selectively enhance theta activity failed to exhibit any changes in their EEG. Furthermore, the SMR-group exhibited a significant and clear improvement in cued recall performance, using a semantic working memory task, and to a lesser extent showed improved accuracy of focused attention processing using a 2-sequence continuous performance task. Vernon and colleagues (2003) interpreted these results by suggesting that normal healthy individuals can learn to increase a specific component of their EEG activity, and that such enhanced activity may facilitate semantic processing in a working memory task and to a lesser extent focused attention. They further explained that the attention CPT used in this study required participants to identify a number of specific target sequences, which may require more than just sustained attention. Thus, it is possible that the different tasks tap distinct aspects of functional attention. Vernon and colleagues (2003) suggest that future research could focus upon the differential influence of SMR training on the distinct networks of attention.

In a recent study, Doppelmayr and Weber (2011) investigated whether healthy individuals are able to learn, within 30 NFB sessions, how to modulate either the SMR (12-15 Hz, n=13) or the Theta/Beta ratio (TBR) (Theta = 4.5-7.5Hz, Beta = 17-21, n=14), and whether such modulation can lead to an enhancement in different cognitive or creative tasks. A control group (n=14) that received NFB with daily changing frequency bands and instructions was included for comparison. Although neither the TBR group nor the control group was able to modulate the EEG in the trained frequency bands, the SMR group was successful in doing so, measured by the amplitude increase of that bandwidth during training over the 30- day training period. In addition, only the SMR group was able to attain significantly better results in simple and choice reaction time tasks and a spatial rotation task after training as compared to the two other groups. No effects of NFB were found for the other attention-related tasks or for creative tasks. The researchers concluded that a series of 30 SMR training sessions can increase the ability to increase SMR amplitudes and therefore may have a future application in settings where the cultivation of fast reactions and good visuospatial abilities are relevant (e.g., in sports).

In the above studies, NFB learning was measured as an increase in the amplitude of the training frequency relative to inhibitory or non-trained frequencies over the training periods. While 8 and 30 sessions of NFB respectively in these studies produced training effects directly after the study, there is no guarantee that there were long-lasting EEG changes outside of the NFB sessions. However, QEEG analyses pre-post NFB training is an accepted measure of NFB training effects and can be used after a certain period of time to measure longer lasting effects (Hammond, 2011).

1.6. Increasing NFB efficacy through QEEG analysis, source localisation and feedback delivery

These above-mentioned NFB protocols have been used with varying degrees of success over the past two decades. It is the aim of the present study to use a different protocol with the aim of increasing NFB effectiveness, but training and regulating particular cortical activity is not as simple as it may seem.

Egner, Zech, and Gruzelier (2004) conducted a two-stage experiment in order to validate QEEG-guided NFB training efficacy. They assessed whether NFB protocols aimed at specific electrode placements, bandwidths, and amplitude directions have a measurable effect on QEEG spectral analysis post NFB training. In Experiment 1, subjects were trained on low beta (12–15 Hz), beta1 (15–18 Hz), and alpha/theta (8–11 Hz/5–8 Hz) protocols, with spectral resting EEG assessed before and after training. It was found that NFB demonstrated measurable dependent variable changes predicted in line with prior research, for example Beta1 increase related to sustained attention improvements (cf. Egner, & Gruzelier, 2001), and Alpha/Theta changes related to improved dance performance (Gruzelier, & Egner, 2004). Whereas spectral topography post training results showed that learning to increase low-beta over the sensori-motor cortex resulted in post-training amplitude decreases in low-beta over pre-frontal- and alpha amplitude decreases over left-frontal cortical locations. Likewise, NFB protocols to raise theta-over-alpha activity over parietal midline sites correlated with post-training beta1 reductions at prefrontal scalp sites.

Based on experiment 1 results, experiment 2 was conducted with the aim of repeating results from experiment 1 where subjects were randomly allocated to independent groups of low beta, beta1, and alpha/theta training. Results showed that only the alpha/theta training group showed the same effect post NFB as in experiment 1, that is, reduction in low-beta in frontal areas. The results document that Neurofeedback training of frequency components does affect spectral EEG topography in healthy subjects, but that these effects do not necessarily correspond to either the frequencies or the scalp locations addressed by the training contingencies. In an fMRI study looking at plastic changes occurring after only one NFB session of alpha down-training, Ros and colleagues (2013) found changes in the functional connectivity in a hub of the salience network (the dorsal anterior cingulate cortex), up to 30 minutes after a single NFB training seesion in which participants were trained to suppress alpha activity recorded at the Pz electrode (parietal midline). These results underline the complexity of the neural dynamics involved in EEG self-regulation and emphasize the need for empirical validation of predictable neurophysiological outcomes of training EEG biofeedback protocols. One possible solution to the problem of identifying the exact NFB effects taking place is the more precise localisation of EEG sources within the three-dimensional cortex during QEEG analysis and NFB.

1.6.1. Source localisation.

Although EEG signals recorded from the surface of the scalp have been studied for nearly 100 years, their origins, exact dynamics, and relationship to brain function has been difficult to assess because signals recorded at the scalp are mixtures of signals from multiple brain generators. There are three disadvantages to classic NFB training using a single electrode site. Firstly, there is a very low spatial specificity (resolution) and therefore the exact cortical location that one desires to train may not fall under one of the electrode placements as defined by the International 10/20 system of electrode placement. Secondly, there is a low signal to noise ratio (SNR), which obviously lowers the quality of the signal being used as feedback. And thirdly, it is difficult to train sites that are typically contaminated by artefact such as FP1/FP2 through eye movement and T3/T4 through muscle tension and jaw movement.

The issue regarding spatial resolution of using a single electrode is not in the positioning of the International 10-20 system, but rather NFB training based on only one single electrode site. A single electrode will reflect mainly oscillatory activity in underlying gyri but with very poor spatial resolution and will, to some extent, also reflect a mix of weaker signals from many other cortical sources. The first steps taken towards the elimination of these problems arose in 1994 with the development of a technique of 3D source localisation that would begin to approach that of functional Magnetic Reasonance Imaging (fMRI) (Mulert et al., 2004).

The ‘inverse’ solution is the computation of three-dimensional images of electric neuronal activity based on extra cranial measurements. There have been five proposed solutions to the so-called ‘inverse problem’ including minimum norm, weighted minimum norm, Backus and Gilbert, weighted resolution optimization (WROP), and low resolution brain electromagnetic tomography (LORETA) (Pascual-Marqui, 1999). Although the debate remains open, of the five inverse solutions tested, only LORETA demonstrates the ability of correct localization in 3D space if the research aim is to localize the neuronal generators of EEG in a 3D brain (Pascual-Marqui, 1999). In 2002, using an improvement of its predecessor, a method called Standardized Low Resolution Electromagnetic Tomography (sLoreta), demonstrated ‘zero error’ for simulated point sources (Pascual-Marqui, 2002; Fuchs, Kastner, Wagner, Hawes, & Ebersole, 2002). The Montreal Neurological Institute (MNI) coordinates (Valer, Daisuke, & Ippeita, 2007) are used by sLoreta to plot estimated EEG sources and increasing the efficiency of NFB by providing training feedback about specific functional oscillations of cortical sources to within several cubic centimetres accuracy (Cannon & Lubar, 2011).

With the use of sLoreta, NFB training can now focus upon any location in the human cortex with specified MNI coordinates rather than the previously designated electrode locations of the International 10/20 system. Rather than training a single channel of EEG on a single electrode point, 19 channels from the International 10/20 system are recorded simultaneously. As an addition to sLoreta source localisation, a mathematical formula called Independent component analysis (ICA) also identifies EEG sources and is typically used as an effective method for removing artefacts and separating sources of the brain signals from EEG recordings (Jung et al., 2004). ICA identifies EEG sources by finding distinctive sources of information from amongst the mixture of signals recorded at each electrode site (for a full review, see Makeig, Debener, Onton, & Delorme, 2004). This form of signal decomposition is used in conjunction with sLoreta to give EEG source localisation on a 3-dimensional plane.

In conventional NFB, EEG activity is recorded at a particular scalp location. The physiological measurements are extrapolated from the signal and converted into auditory stimuli or visual objects that animatedly co-vary with the magnitude of a specified frequency or frequency band-pass region. Similarly, Loreta NFB (LNFB) correlates the physiological signal with a continuous feedback signal; however, the physiological signal is defined as the current density in a specified region of training (ROT). This allows the continuous feedback signal to become a function of the intracranial current density and to covary with it. The advantage over traditional NFB is increased specificity of the training.

In an example of a study using LNFB, Cannon and colleagues (2007) had eight subjects (four male and four female, with a mean age of twenty-two) complete thirty-sessions of LORETA Neurofeedback (LNFB) training of 14–18 Hz activity in the cognitive division of the anterior cingulate gyrus (ACcd) defined as the ROT with Talairach coordinates (-3 31 22) (-3 24 29) (-10 31 29) (-3 31 29) (4 31 29) (-3 38 29) (-3 31 36) and an anatomical label of Brodmann’s Area 32, anterior cingulate gyrus, limbic lobe. Learning (mean current density increase of specified ROT by frequency) occurred in the ACcd at significant levels over sessions and in the anterior regions that receive projections from the AC. Cannon and Lubar (2011) then conducted a follow-up study illustrating the long-term absolute power and coherence (see pg. 10) changes in two of the participants from the original (2007) study. 3-min eyes-closed and eyes-opened baselines were obtained, and analysis of variance procedures showed significant differences between the pre-training baselines and follow-up baselines. Furthermore, there were significant differences between pre- and post-working memory index (WMI) and processing speed index (PSI) scores on the WAIS–III. These objective performance indicators demonstrate efficient long-term effects of LNFB. Similar LNFB procedures are implemented in the present program of studies.

1.6.2 Neurofeedback delivery methods.

It is a parallel aim of this study to assess possible improvements to the delivery of NFB. In the above-mentioned study by Egner and colleagues (2004), amplitude measures in the frequency-bands beta1 (15–18 Hz), low beta (12–15 Hz), theta (4–7 Hz), and ‘high beta’ (22–30 Hz) were represented online as audio-visual feedback displayed via a 16-in. monitor to the trainees. Operant contingencies were such that rewards (‘points’ and auditory ‘beeps’) were gained whenever the trainee enhanced either beta1 (in the beta1 protocol) or low beta (in the low-beta protocol) activity without concurrent rises in theta and high beta activity, relative to a 2-min pre-feedback baseline measure. Common to all NFB protocols, a reward threshold was set for the designated training frequencies using a baseline EEG recording so that, during the natural fluctuation of the client’s EEG, they were rewarded when producing the ‘correct’ or ‘desired’ EEG frequency (generally 50-80% success if using one reward frequency, if using inhibit frequencies distribution would be set at 70% threshold for reward band, 20% for primary inhibit band, and 10% for secondary inhibit band (Demos, 2005). As the client improved control of their EEG and was rewarded more often, the threshold was adjusted in order for the client to be rewarded at an appropriate level.

As feedback for the client, amplitude levels in the desired frequency-bands were transformed into geometrical shapes on the computer screen that continuously change size according to the amplitude in a given frequency-band. It is this feedback delivery aspect of NFB training that may be enhanced in order to increase training effect. By conforming the NFB training delivery modality to the desired skill and to the situations in ‘real-life’ in which the desired state is required, the current study aims to add to develop more efficient modes of NFB delivery.

EEG operant conditioning methods for biofeedback training have diversified as various hardware and software products have emerged and as individuals with differing backgrounds and credentials have entered the field (Sterman, 2010). Although no studies (to the author's knowledge) have compared Neurofeedback delivery modalities on their effectiveness in operant conditioning, it is clear that any feedback of real-time information must be simple, clear, and adhere to the operant conditioning principles. For example, feedback training should be configured to provide for discrete trials, latency between response and reward must be immediate or at least less than a quarter of a second for meaningful learning to occur (Grice, 1948) and trials should provide reward exclusively for the EEG response being reinforced – novel images or sounds accompanying this response may actually overshadow or block the EEG changes sought and divert the reinforcement effect of the reward (Williams, 1999).

'Jammer' Video Mode NFB equipment is a recently developed feedback method for use with biofeedback technology. Rather than classically used geometric shapes or simple computer games, video mode is used as a source of visual presentation of the biofeedback signal. In this mode, the biofeedback parameter controls the level of a 'noise' generated by a separate electronic unit called a 'Jammer' (the unit was designed specifically for this purpose). The amplitude of the noise is maximal if the biofeedback parameter is minimal, and decreases gradually up to zero while the parameter approaches a threshold. The 'noise' is mixed with the video and audio signal of the video-player and is fed to the TV. Thus the client actually controls the quality of the picture and sound on the screen by his/her brainwaves – when the biofeedback parameter is higher than the threshold, the picture on the screen is clear – otherwise the TV picture is blurred by the noise (Kropotov et al., 2005). Thus, using this technology, the subject can watch or listen to a task or event that approaches the physiological state to which training is aimed at enhancing. For example, if an athlete is aiming to decrease anxiety or cortical activation during a match, they would watch a video of one of their matches on the screen while training cortical locations and frequency bandwidths associated with the desired state. While the effects of the Jammer delivery method have not been directly compared to conventional video game methods (to the author's knowledge), the effectiveness of the Jammer (HBIMed) technology NFB training has been demonstrated in industry tests and has since been repeatedly confirmed in clinical applications where it is widely adopted (Sherlin, personal communicaton).

1.7. The Current Program of Studies

Based upon recent developments in cognitive neuroscience, my elite racket sport background and QEEG results of an elite racket sport athlete as pilot data, the aim of the current research program is to take NFB into another phase of development by targeting the specific cognitive skills that make the difference between winning and losing in critical moments of sport. These skills are not limited to muscular control and general sustained attention capacities, but include skills in attending to the opponent, detecting the relevant visual cues (and ignoring non-relevant cues), and selecting the optimal response. Rather than regulating fine motor control and general sustained attention, the targeted skills of visual attention and response selection go beyond the current sport NFB protocols by focusing on reactive and pre-reactive cognitive skills.

1.8. Attention – neural networks

During visual search, objects relevant to behavioural goals must be located in the midst of a cluttered visual environment. Multiple objects presented at the same time compete for active cognitive representation. Does the brain have specialized mechanisms dedicated to efficiently detect search targets? The competition between different objects can be biased by both bottom-up, sensory-driven mechanisms, and top-down influences, such as selective attention (see Figure 1). In effect, attention operates to filter relevant information from nearby distractors (Ungerleider, 2000).

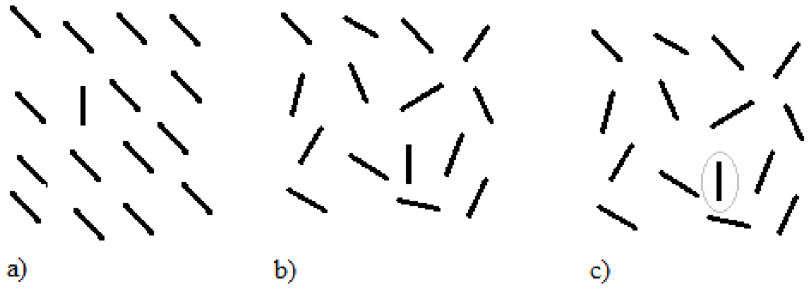

Figure. 1. Cluttered visual scenes. a) Bottom-up salience-driven factor, b) Neutral condition not biased by stimulus salience, and c) top-down process such as spatially directing attention to a particular location.

The sequence of visual attention processing in the brain has been thoroughly investigated by brain imaging experiments. First, the lateral geniculate nucleus modulates incoming signals acting as a gatekeeper to further processing by controlling the neural gain – the sensitivity of the signal relay to the visual cortex. Second, directed attention filters out unwanted information by means of receptive field mechanisms which modulate competitive interations (suppressing distracting stimuli) and operate in visual cortical areas such as V4 and posterior inferior temporal area (cytoarchitectonic area TEO). Third, attention mechanisms operate in the visual system controlled by a distributed network of higher order areas in the frontal and parietal cortex, which generate top-down signals that are transmitted via feedback connections to the visual cortex. And fourth, the pulvinar of the thalamus integrates and feeds forward control signals from the the fronto-parietal network (Kastner, & Pinsk, 2004).

Recent research (e.g. Szczepanski, Konen, & Kastner, 2010; Umarova et al., 2010) has confirmed that there are not only one, but at least three distinct systems of attention regulation, visual perception and response selection. The default mode network (DMN) is related to global attention and speed of response when the location to which a target event will occur is unpredictable (Hahn, Ross, & Stein, 2007); the ventral attention network (VAN) recognises something is important and diverts resources to it to respond appropriately; and, the dorsal attention network (DAN) controls volitional direction of attention to spatial locations and involves the control of one’s eyes, visual focus, as well as picking spatial locations to attend to (Kropotov, 2009).

In terms of an athlete’s performance when attending to an opponent’s movements, the athlete must initiate the correct response to the correct target at the critical moment (selection process), and avoid either the wrong response or the wrong timing (inhibition process). Like many other sports relying on skilled hand-eye coordination, the elite table tennis player demonstrates highly specified skills in attention, visual imagery, perception and visuo-spatial recognition to name just a few. Buckner, Andrews-Hanna and Schacter (2008) have synthesized recent research to show that the DMN is a specific, anatomically defined brain system preferentially activated when the individual is not focused on the external environment. The DMN is activated when individuals are engaged in internally focused tasks including autobiographical memory retrieval, envisioning and planning the future and conceiving the perspectives of others.

Probing the functional anatomy of the DMN reveals the interaction of multiple subsystems. The DMN includes the medial temporal lobes (MTL) and the angular gyrus, in addition to the posterior cingulate cortex (PCC) and the ventromedial prefrontal cortex (VMPFC). The PCC is activated during tasks that involve autobiographical memory and self-referential processes; the VMPFC is associated with social cognitive processes related to self and others; the MTL is engaged in episodic and autobiographical memory, and the angular gyrus is implicated in semantic processing (Buckner et al., 2008).

In an example of recent research in this area, Hahn and colleagues (2007) used fMRI to identify cortical locations involved in the DMN. In their study, participants responded to targets presented randomly in 1 of 4 peripheral locations. By employing a function of reaction time (RT) of individual trials as a linear regressor, brain regions were identified where activation varied with RT on a trial-by-trial basis. Whole brain analysis revealed that the anterior cingulate, posterior cingulate, and left angular/superior temporal gyri were more active in trials with faster RT but only when the target location was unpredictable. No such association was seen in trials where the target location was predicted by a central cue. These results suggest a role for the cingulate and angular gyri in the dynamic regulation of attention to unpredictable events. This is in accordance with the function of the DMN that is active in the absence of top-down-focused attention and is thought to continuously provide resources for broad and spontaneous information gathering (Hahn et al., 2007).

Elite racket sportspeople have the ability to vividly visualise opponents and their game plans both while off the court, and in between points as they prepare themselves tactically for the point to come by shutting themselves off from the present external stimuli to visualise and plan intended future actions. Thus, athletes’ use of the DMN is integral to performance and the cortical locations and neural circuitry involved in the DMN are regions of interest for this study.

Identification of the salient stimuli (novel or unexpected stimuli interpreted as a challenge to homeostasis) involves input from the anterior insula (AI). The ‘saliency network’, the AI switches attention from the DMN and initiates attention allocation. Interaction of the anterior and posterior insula modulates physiological reactivity to salient stimuli and initiates access to the motor system via strong coupling with the anterior cingulate cortex.

In an example of recent research in this area, Caria and colleagues (2007) used real-time fMRI (rtfMRI) to successfully train the right anterior insula, a region of interest (ROI) due to its increased metabolic activity during the perception of emotionally salient stimuli. The right anterior insula is critical for the representation of bodily responses and interoception - sensitivity to stimuli originating inside of the body (Caria et al., 2007). This ROI is particularly important for the racket sportsperson for the control of emotions during critical and highly intense moments in which external information may trigger emotional response.

Once stimuli are perceived and deemed salient, the ventral attention network (VAN) is responsible for the recognition of objects and the dorsal attention network (DAN) is responsible for the recognition of spatial relationships. Within the dorsal and ventral streams of visual information flow distinct representations of the visual world (such as shape, colour, motion, and spatial relationships) are separated from each other by means of segregated streams associated correspondingly with different functions such as recognition of separate objects, differentiation of spatial relations between objects, and defining how these objects can be approached and manipulated. For example, neurons in the ventral stream show response selectivity for stimulus attributes such as shape, colour, and texture. By contrast, neurons in the dorsal stream are not tuned for these attributes; rather, they show response selectivity for the speed and direction of stimulus motion, or to stimuli presented in the attended spatial location. As shown in Figure 2 below, visual information from the retina is projected to a region of the thalamus called the lateral geniculate body (LGB), which subsequently sends this information to the primary visual cortex (BA17 and then 18), where it is then directed to dorsal or ventral streams. If spatial attention is required, information is projected to the dorsal stream sequentially through BA 19, 7, 5 and 3; if recognition attention is required, information is projected to the ventral stream sequentially through BA 37, 21, 20 and 38 (Caria et al., 2007).

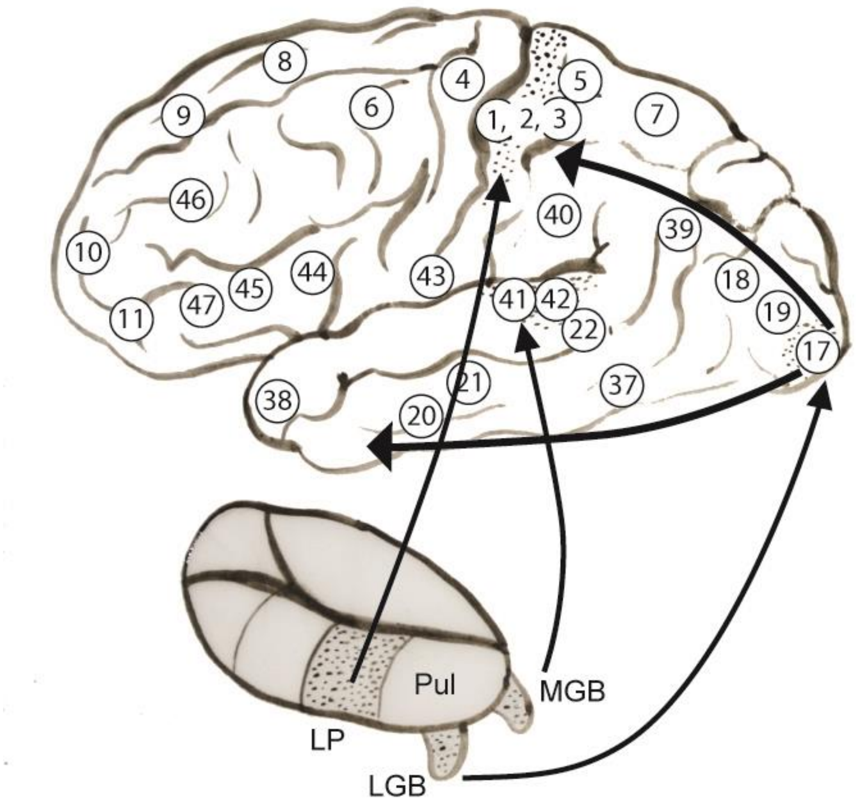

Figure 2. Dorsal and ventral streams of visual attention.

Elite sport performance, being highly dependent upon attention to spatial location, relies heavily on the DAN, also referred to as the fronto-parietal network. Neuroimaging studies, for example, have identified activations within the human intraparietal sulcus (IPS) and frontal eye fields (FEF - An area in the frontal lobe that receives visual inputs and produces movements of the eye) during covert shifts of attention in expectation of a target (e.g., Kastner, & Underleiger., 2000; Corbetta, Kincade, Ollinger, McAvoy, & Shulman, 2000). But unlike earlier visual areas (primary visual cortex) that respond to fixed visual attributes driven by bottom-up sensory processes, these above-mentioned areas of the fronto-parietal network respond to behaviourally-defined target properties – a top-down target detection process of visuo-spatial attention (Guo, Preston, Das, Giesbrecht, & Eckstein, 2012).

Cognitive neuroscience has learnt a great deal about how to measure these attributes, not only behaviourally, but through an individual’s EEG as well. It is the goal of this research to create a continuous performance task that will elicit the neurocognitive processes described above and provide evidence of EEG differences between the elite table tennis player and the normal population. In order to measure these ‘event-specific’ physiological responses, introduction of a method of EEG analysis is required which allows precise temporal resolution of neural functioning – event related potentials.

1.9. Event related potentials

Event related potentials (ERPs) are essential for the investigation of signal processing and information flow in the brain. QEEG and ERPs provide distinct windows on brain functioning: QEEG reflects mechanisms regulating cortical oscillations, whereas ERPs reflect discrete information flow between localized elements of cortical neuronal networks (Kropotov, 2009). ERPs are significant voltage fluctuations resulting from evoked neural activity. They arise from the summation of excitatory and inhibitory post-synaptic potentials within the apical dendrites of pyramidal cells that are arranged in columns within the cerebral cortex (Brunia, Hackley, van Boxtel, Kotani, & Ohgami, 2011). ERPs are initiated by an external or internal stimulus and are a suitable methodology for studying the aspects of both normal and abnormal cognitive processes (assisting diagnosis of neurological or psychiatric disorders) (Teplan, 2002). This method is a particularly useful complement to QEEG analysis since the individual may have a normal self-regulation (resting QEEG analysis) but abnormal information flow (ERP analysis), and vice versa. For example, about 50% of schizophrenic patients show normal EEG spectra but strongly impaired ERPs (Kropotov et al., 2011).

Mental operations, such as those involved in perception, selective attention, language processing, and memory, proceed over time ranges in the order of tens of milliseconds. Whereas Positron Emission Tomography (PET) and functional Magnetic Resonance Imaging (fMRI) can more accurately localize regions of activation during a given mental task, ERPs can help in defining the precise time course of these activations (Teplan, 2002).

Amplitudes of ERP components are often much smaller than spontaneous EEG components, so they are not to be recognised from raw EEG trace. They are extracted from sets of single recordings by digital averaging of epochs (recording periods) of EEG, time-locked to repeated occurrences of sensory, cognitive, or motor events. The spontaneous background EEG fluctuations, which are random relative to the time point when the stimuli occurred (stimuli onset), are averaged out, leaving the ERP as a residual. These electrical signals reflect only that activity which is consistently associated with the stimulus processing in a time-locked way. The ERP thus reflects, with high temporal resolution, the patterns of neuronal activity evoked by a stimulus (Teplan, 2002). Along with QEEG analysis of both spectral and connectivity differences, ERP analysis provides the researcher with another tool to identify aspects of a client EEG that differ from the normal population – indicating abnormal functioning in the clinical population, or exceptional functioning in the case of the elite athlete. Any electrophysiological measure that differentiates one population from another is a useful tool in the classification, diagnosis and treatment/training of the subpopulation.

1.10. EEG 'Biomarkers'

The term 'biological marker' or 'biomarker' is used throughout medical and paramedical fields to describe an anatomical or physiological parameter, biochemical substance or gene that indicates the presence of disease. Once identified, a biomarker can then be used to measure the start of disease, the evolution of disease and to indicate effective treatments for the disease (Sakkalis, 2011).

Neurophysiological biomarkers that are considered to be signals capable of uniquely characterizing a disease or cognitive process include EEG spectral analyses such as the traditionally used Fourier transform (for example, Sherlin et al., 2011); connectivity analysis such as coherence (for example, Deeny et al., 2003) which has the advantage of showing the covariation between two signals in distinct brain regions as a function of frequency; and, ERP components (for example, Mueller 2010) (Sakkalis, 2011).

In psychiatry, the concept of a biomarker has been extended to one of EEG phenotypes or 'endophenotypes'. The endophenotype of a particular disease or disorder consists of any number of EEG biomarkers including, but not limited to, QEEG spectral differences, QEEG connectivity differences and ERP differences from the normal population. ERP biomarkers, for example, on their own provide a method of diagnosis or classification with up to 92% accuracy for classification of adult ADHD (Mueller, et al. 2010).

To become a useful and reliable tool, biomarkers must be rigorously tested using the following 4 step process (Kropotov, 2012):

1. A biological variable is observed to be deviant from healthy controls in a particular patient population.
    1.1. Test-retest reliability is greater than 0.8.
    1.2. Effect size must be greater than 0.8.
    1.3. Must be replicable by independent groups.
2. Clinical usefulness of the finding must be demonstrated – for example, identification of the clinical group within a subpopulation typically given a differential diagnosis.
3. Identification of a clinical pattern of the patient group is measured by the biomarker – for example, illness duration, severity, effects of medication, etc. This step will likely be a combination of several biomarkers.
4. Operationalization of biomarker.
    4.1. Standardisation of the tests.
    4.2. Developing the normative and patient databases.
    4.3. Developing standard discrimination procedures.
    4.4. Large multi-centre trials

Once biomarkers have been identified within the elite table tennis population, it is the goal of this study to use these electrophysiological measures to train the precise neural circuitry using sLoreta NFB. If the biomarkers found in the resting EEG of elite tennis players include spectral differences or connectivity differences, classic QEEG-guided NFB will be appropriate. However, if the continuous performance task aimed at the specific attention systems provides significant differences, training of these time-locked events will require a form of NFB that is still in the experimental stages of development, and only a few attempts at ERP-based NFB have been made (e.g. Mnatsakanian & Dorokhov, 1995; Kropotov, Pronina, Ponomarev, & Murashev, 2011).

Kropotov and colleagues (2011) recently produced some encouraging results when they attempted to overcome these difficulties using the P3b ERP component as the NFB parameter (a positive evoked wave occurring approximately 300 milliseconds after stimulus located in the centro-parietal cortex in response to the engagement of an executive system operation). The referencing method of ERP component localisation was replaced by the recently designed and previously described Independent Component Analysis (ICA). The low signal to noise ratio of a single independent component of the ERP was significantly amplified in order to distinguish each single trial from raw EEG.

To generate a P3b component, a Go-NoGo task was used to engage executive functioning response. A Go-NoGo task is one in which the objective (in most computer-based tasks) is to press a mouse button in response to a pre-determined ‘correct’ stimuli, and withhold from pressing the button in response to an ‘incorrect’ stimuli. The visual paired Go-NoGo paradigm used in this study measures ERP components of the Ventral Attention Network and comprised three categories of visual stimuli: (a) 20 different images of animals, referred to as ‘A’; (b) 20 different images of plants, referred to as ‘P’; (c) 20 different images of people of different professions, and this was presented together with an artificial ‘novel’ sound, referred to as ‘H+Sound.’ All visual stimuli were selected to have similar size and luminosity. The randomly varying novel sounds consisted of five 20-ms fragments filled with tones of different frequencies (500, 1000, 1500, 2000, and 2500 Hz). Stimulus intensity was about 70 dB SPL (sound-pressure level), measured at the patient’s head. The trials consisted of presentations of paired stimuli with inter-stimulus intervals of 1 second. Duration of stimuli was 100ms. Four categories of trials were used: A-A, A-P, P-P, and P-(H+Sound). The trials were grouped into four blocks with 100 trials each. In each block a unique set of five A, five P, and five H+ stimuli were selected. Each block consisted of a pseudo-random presentation of 100 pairs of stimuli with equal probability for each stimulus category and for each trial category. Participants practiced the task for 30 seconds before the recording started. Subjects rested for a few minutes after 200 of the 400 trials. Subjects sat upright in an easy chair looking at a computer screen. The task was to press a button with the right hand to all A-A pairs as fast as possible and to withhold from button pressing to other pairs. Pressing the button correctly to this pair incites the P3b ERP component over the parietal cortex in the normal individual.

The goal of the ERP NFB was to generate higher amplitude of the P3b component generated over the parietal cortex compared to a previously calculated baseline average recorded from that individual. If the generated ERP was higher than baseline, a ‘+’ sign was immediately presented on the screen to the individual, if not, a '-' sign was presented. A sham control group underwent the same process in which a different individual's ERP recording was used to provide false feedback. The effect of one 20-minute session of ERP NFB did not result in significantly higher amplitude of the P3b component for either the experimental or control group. However, 2 of the 10 subjects were able to discriminate between the sham and real feedback conditions and managed to significantly increase their P3b component. Furthermore, both sham and real feedback groups significantly decreased the amplitude of another component called the Slow Positive Wave (SPW) generated in the parahippocampal gyrus. Results of this study showed that it is quite difficult to learn to control the P3b component in one session. Results also show that 2 subjects were able to achieve increase of the P3b component, and that the effort made by both real and sham groups of trying to control their ERPs resulted in significant increase in amplitude of the SPW component.

1.11. Research Hypotheses

General hypothesis: It is hypothesized that QEEG guided sLORETA NFB training will significantly increase operational efficiency in specifically targeted neural systems leading to measurable performance outcomes in ERPs and behaviours related to match play in participating elite table tennis players.

Hypothesis 1: The EEG of elite table tennis players will differ significantly from the amateur population in EEG source analysis to the specific table tennis video task and in ERPs to the visual-spatial Go-NoGo task paradigm designed for this study (see Method section). These differences are likely to include cortical locations of the parietal and pre-motor cortex and connectivity between regions associated with the dorsal and ventral attention networks, allowing for the future identification of biomarkers for the elite racket sport athletes as a group.

Hypothesis 2: Once differences outlined in hypothesis 1 are identified in elite table tennis players, it is hypothesised that individualized NFB training protocols can be used to train performance in this specific neural circuitry and increase the cognitive performance of elite table tennis athletes during match play and, in particular, during critical match moments.

This will aid in the support for these areas as biomarkers by showing that change in these regions alters associated elements of behavioural performance.

1.12 Research Plan

Data collection. EEG data (Resting eyes open, eyes closed and during a table tennis video task) and ERP data (using a visual-spatial Continuous Performance Task - vsCPT – Go-NoGo paradigm) will be recorded from elite table tennis athletes, together with amateur players throughout the world. Analysis of source EEG using sLORETA and ERP data will then guide the development and provision of specific sLoreta NFB training protocols designed to increase sport specific cognitive and motor performance. Repeated measures analysis of performance related source EEG, ERP and behavioural measures will assess the success of the novel NFB protocol.

Data Analysis

Phase 1. Resting EEG (Eyes Open and Eyes Closed), active EEG (table tennis viewing task) and ERP (vsCPT) data will be analysed and compared to a group of amateur table tennis players. sLoreta will be used to determine the source of the EEG signal, and the corresponding neural circuitry and cortical functioning involved in the production of the EEG signal.

Phase 2. The data from phase 1 will be used to set the sLoreta NFB protocols of participating athletes. The athlete's QEEG/ERP data will be recorded as a pre-post training measure giving results as to the changes taking place throughout NFB training.

Subjects

Recording of QEEG and ERP data from elite table tennis athletes (together with club players and controls). Groups will be properly matched for age, gender, and handedness. The 'elite' group will be defined on the following criteria (flexible):

1. Number of hours of training per week (>15hrs)
2. Skill level (determined by ranking/competition performance within age group, e.g. Top 10 State ranking, or Top 30 National Ranking)

3. Minimum number of years playing table tennis at elite level (>3yrs fulfilling the above 2 criteria)

The 'amateur' group will play table tennis regularly at club level, but will have fulfilled none of the above ('elite') criteria within their sporting lives.

Dependent Variables

1. Like most other racket sports, the serve and service return in table tennis are some of, if not the most important aspects of the game, and if executed well, can win the point outright or set up the point to the advantage of that player. Racket sport specialists consulted on this issue (Australian, French, and English International players and coaches) frequently note that under high pressure or emotional situations, the serve and service return are the skills that suffer the most and consequently have the largest negative effect on results.

In order to measure the performance enhancement effect of NFB training, a closed skill task (vsCPT) based upon the cognitive demands of service return and anticipation of opponent’s shot has been devised and will be utilized as both independent and dependent variable.

2. QEEG/ERP/sLoreta Analysis – pre-post NFB (EEG measured as resting eyes closed, resting eyes open, active table tennis viewing task and Go-NoGo visual-spatial continuous performance task.

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Statement of Originality:

We, the PhD candidate and the candidate's Principal Supervisor, certify that the following text, figures and diagrams are the candidate's original work.

Type of work	Page number/s
Figure 1	21
Figure 2	25

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Trevor Brown	90%
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Chapter 2

Quantitative Electroencephalogram and eLoreta Source Localisation Identify EEG Biomarkers of Visuo-Spatial Processing and Motor-Preparation in Elite Table Tennis Players

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Abstract

Background: Electroencephalography (EEG) biomarkers have been identified in clinical populations with cognitive and behavioural deficits and are employed to guide treatment of these deficits. Similarly, identification of EEG indicators of superior performance in elite athletes may be used to guide performance enhancement psychophysiological training interventions. The aim of this study was to identify EEG indicators of performance differences between elite and amateur table tennis players related to visuo-spatial guided response selection.

Method: 206 table tennis athletes' EEG was recorded from elite and amateur table tennis athletes representing elite and non-elite but experienced performance from across the International Table Tennis Federation. EEG was obtained during eyes closed (EC) and eyes open rest (EO) and a 4-minute video task (VT). The VT was filmed from the player's perspective so as to simulate actual match-play against a top 100 world ranked player. The participant was instructed to imagine playing against the on-screen player. Players also completed a visuo-spatially cued version of the continuous performance (Go-NoGo) task (vsCPT). eLORETA compared EEG source activity between an age and gender matched sample of 16 elite and 16 amateur players. Activity at maximal source differences was then correlated with behavioural vsCPT performance measures.

Results: EEG source differences between elite and amateur players reached a maximum between 10.50 and 11.75 Hz (upper alpha) in the VT condition with loci in right BA6 (supplementary motor area, sensory selection for motor control) and right BA13 (insula cortex, salience detection) regions. eLORETA estimates of this source activity correlated significantly with superior processing speed and perceptual sensitivity under increased processing demands on the vsCPT.

Conclusion: Upper alpha synchronisation in right BA6 and right BA13 when actively processing an opponents' match specific motion is greater in elite than amateur players and indicates superior visuo-spatial guided response selection. Findings suggest table tennis engages an inhibition-timing mechanism for detection and selection of response salient motion for guidance of motor control.

Keywords: EEG biomarkers, alpha, mu, visual attention, spatial attention, motor control, performance enhancement, table tennis.

Introduction

The human brain regulates performance through neuro-plastic change. Applied electroencephalography (EEG) research in both the clinical (Sakkalis, 2011), and performance enhancement (Cannon et al., 2007) fields aims to assist the development of techniques to re-train the brain and enhance neuro-plasticity. The purpose of this paper is to add to the field of performance enhancement by identifying key EEG differences in the operation neural circuitry related to the performance of elite table tennis players versus amateur players. Ultimately, these results will inform the creation of protocols for neuro-modulation techniques, including Neurofeedback and transcranial magnetic and electric stimulation, to further increase performance for athletes participating in sports requiring similar cognitive skills.

EEG as a biomarker

The term ‘biological marker’ or ‘biomarker’ is used throughout medical and paramedical fields to describe an anatomical or physiological parameter, biochemical substance or gene that indicates the presence of disease. Once identified, a biomarker can then be used to measure the start of disease, the evolution of disease and to indicate effective treatments for the disease (Sakkalis, 2011).

In neuropsychiatry, the concept of a biomarker has been extended to include EEG phenotypes or ‘endophenotypes’. A particular disease or disorder may be linked with any number of EEG biomarkers including, but not limited to, Quantitative EEG (QEEG; the average EEG over a time period) differences-, or Event-Related Potential (ERP) differences from the normal population. ERP biomarkers, for example, on their own provide a method of diagnosis or classification with up to 92% accuracy for classification of adult ADHD. To be considered for use as a ‘biomarker’, an EEG signature must be validated by multiple independent criteria (Mueller, Candrian, Kropotov, Ponomarev & Baschera, 2010).

Guided by QEEG analysis and EEG biomarkers, individualised neuro-modulation techniques such as Neurofeedback (self-regulation of EEG via operant conditioning toward more normalized activity patterns) are used within clinical practice. Normalization of the underlying EEG patterns associated with specific symptom patterns relies on comparison to an age and gender matched normative sample. In the case of peak performance, related EEG markers may serve as reference points for performance enhancement training. However, these will differ depending on the cognitive skill set required in each performance domain (sport, business, etc). In these applications a 'normative sample' of performance-related EEG data is required to act as a reference point for peak performance neuro-modulation training. The present study seeks to achieve this in relation to elite table tennis performance. Previously research on EEG parameters related to elite performance across a range of sports has identified alpha EEG (8-12Hz) as the most salient frequency range in delineating performance levels (Babiloni & Del Percio, 2008; Sherlin, Gervais, & Walshe, 2011). Furthermore, alpha's functional role in neural mechanisms involving motor planning, motor execution and visual imagery is well established (Pineda, 2005).

Alpha Bandwidth in the Human Electroencephalography

Alpha (8-12Hz) activity is typically strongest when recorded at posterior cortical locations. Because alpha is most pronounced in an eyes closed, relaxed state of wakefulness and suppressed when the eyes are opened, it was traditionally considered an "idling" rhythm generated while the brain was at rest (Klimesch, 2012; Klimesch, Sauseng, & Hanslmayr, 2007; Schürmann & Başar, 2001). Similarly, increases in a second alpha rhythm, 'tau', detectable only from magnetoencephalography (MEG) recordings over the auditory cortex in the temporal lobe, correlate with deactivation in the auditory cortex after reduced acoustic stimuli. Thirdly, independently from other alpha rhythms, 'Mu' is detected by EEG recordings over the motor cortex and increases in power with the reduction in motor related task demands (Klimesch, 1999).

Klimesch (1999) determined that the dominant alpha frequency (peak alpha) varies greatly between individuals. Low peak alpha is seen in aged populations and can be as low as 7Hz (Klimesch, 1999). High peak alpha (10-12Hz) is often seen in highly intelligent individuals and elite athletes (Capotosto et al., 2009; Klimesch, 2012). Alpha rhythms are also associated with the control of attention and alertness (Klimesch, 2012). Two sub-bands of alpha oscillations have been identified, each with their own mechanism for controlling and enhancing attention (Babiloni et al., 2008; Klimesch, 2012). Lower alpha (4Hz below peak alpha) is responsible for general attention and arousal while upper alpha (2Hz above peak alpha) directs task-related attention (Klimesch, 1999; Klimesch et al., 2007). Upper alpha has consistently been found to be related to intelligence (Babiloni et al., 2008; Klimesch, 2012), and faster response times (Klimesch et al, 1999). Furthermore, alpha is now known to have a dynamic functional role with relation to information processing (Foxe & Snyder, 2011; Hanslmayr et al., 2005; Klimesch, 1999, 2012; Pfurtscheller, 1999).

As described by Pfurtscheller (1999) sensory, cognitive and motor processing can result in changes of the ongoing EEG in the form of an event-related desynchronization (ERD) or event-related synchronization (ERS). Both phenomena are time-locked to the event and they are highly frequency-band specific. The alpha ERD is interpreted as a correlate of an activated cortical area with increased excitability and the ERS in the alpha band can be interpreted, at least under certain circumstances, as a correlate of a deactivated cortical area. Spatial mapping of ERD/ERS can also be used to study the dynamics of cortical activation patterns. For example, Klimesch (1999) found that when participants were monitoring for auditory stimuli, alpha synchronised over the occipital and parietal lobes, thus inhibiting processing of potentially distracting visual and/or motor information.

While large rhythmic activity recorded by EEG reflects widespread populations of synchronously firing neurons typically within the lower (8-10Hz) alpha range, ERD when found in the upper alpha range (10-12Hz) reflects higher order cognitive demands. For example, ERD has been shown to occur prior to stimulus presentation and as such suggests an anticipatory function of alpha that prepares a task relevant area to process incoming stimuli (Min & Herrmann, 2007; Schürmann & Başar, 2001). The anticipatory function of pre-stimulus alpha was demonstrated by Min and Herrmann (2007) who found that greater pre-stimulus ERD was associated with enhanced cognitive processing and reduced reaction time.

Foxe & Snyder’s (2011) study supported the idea of functionally dynamic ERS. They found that subjects asked to attend to stimuli in their right field of vision experienced a corresponding increase in alpha activity over the ipsilateral visual hemisphere and a decrease in contralateral alpha activity. Babiloni et al. (2009) and Klimesch et al. (2007) have found that high ERS and the magnitude of ERD are directly related to how effectively cognitive and visual information is processed and how intelligent or skilled a subject is. While Babiloni et al. (2009) argued that less ERD is associated with optimal cognitive performance (supporting their “neural efficiency” hypothesis), Klimesch (1999) and Klimesch et al. (2007) found that greater ERD was predictive of superior performance. The difference in findings was resolved when it was found that the type of task was also a relevant factor in alpha activity (Capotosto et al., 2009). Capotosto et al. (2009) found semantic memory encoding and retrieval were associated with greater ERD in the occipital-parietal lobes and that visuo-spatial tasks were associated with less ERD but only in the frontal regions of the cortex (Capotosto et al., 2009).

The in-depth study of alpha has also revealed that it is essential for visual and motor processing and is strongly associated with optimal performance (Capotosto et al., 2009; Llanos, Rodriguez, Rodriguez-Sabate, Morales, & Sabate, 2013; Pineda, 2005; Schürmann & Başar, 2001). Alpha enhances cognitive functioning by inhibiting task-irrelevant areas of the brain while simultaneously desynchronising in task-relevant areas to facilitate active processing (Klimesch, 1999; Min & Herrmann, 2007; Schürmann & Başar, 2001).

The role of alpha and motor control. Alpha oscillations recorded over the motor and motor control cortex with dominant frequencies anywhere between 8-13Hz are referred to as ‘mu’ (Gastaut, 1952). In healthy populations these oscillations are limited to brief periods of 0.5 to two seconds duration and are generally recorded in the absence of movement. Mu desynchronises in response to activation in the motor cortex and is therefore spatially differentiated from occipital alpha. Mu can further be functionally differentiated from posterior alpha since, in general, mu rhythms reflect sensorimotor processing in fronto-parietal networks, while posterior alpha reflects primarily visual processing in occipital networks (Shaw, 2003, p. 17).

Recordings in normal human adults show that mu ERD starts two seconds before movement onset and that the size and magnitude of the ERD effect reflect the size of the neural network involved in the performance of the task. This is supported by the observation that increasing task complexity increases ERD presumably because a larger group of cells is involved (Van Winsun, Sergeant & Geuze, 1984). In general, the two main factors that have been reported to affect the occurrence or maintenance of mu rhythms are motor inactivity and the level and quality of attention. The induction of actual movement is a reliable blocking mechanism of pre-existing mu rhythms (Pfurtscheller, Neuper & Krausz, 2000), but attention alone (most likely to the motor imagery itself) is also able to provoke the same mu ERD (Pfurtscheller, Brunner, Schlögl & Da Silva, 2006).

Mu has further been shown to be implicated in the processing of visuo-motor information and the translating of visual information into action (Llanos et al., 2013; Sabate, Llanos, Enriquez, & Rodriguez, 2012). Sabate et al. (2012) demonstrated that mu enhances vision to action processing by presenting subjects with a visual stimulus that indicated direction of a movement. In the active condition, subjects were asked to perform the movement and in the control condition subjects observed the presentation with no response required (Sabate et al., 2012). Sabate et al. (2012) found that mu was much stronger in the active condition and was followed by a significant and widespread desynchronisation that the authors posit is necessary to prevent further processing of potentially distracting information.

Llanos et al. (2013) also found that mu increases when motor planning is required in response to visual stimuli compared to when the stimuli are to be observed with no response. Both Sabate et al.'s (2012) and Llanos et al.'s (2013) research support Pineda's (2005) description of mu as cortical activity that is instrumental in linking visual stimuli to action response. Pineda (2005) also showed that mu is essential for stimulus detection and that an intermediate level of mu facilitates optimal detection rates. Furthermore, and with great importance to performance enhancement EEG training, Pineda (2005) determined that mu is particularly responsive to operant conditioning and that volitional control of mu can be learnt within a brief period of time.

Previous research (Babiloni et al., 2008; Del Percio et al., 2009; Cannon et al., 2014) has demonstrated that mu has an 'expertise-effect' by which the more one is practiced in a particular motor skill, the greater ERD occurs when both watching and undertaking the activity. In their study, Cannon et al. (2014) found that observing tool use after experience with tools modulated mu more than observation of tool-use without the previous experience. The so-called Mu ERD 'expertise-effect' has further been demonstrated to not only delineate 'experts' from 'novice' (Del Percio et al., 2009), but also 'good' from 'bad' performance (Babiloni et al., 2008) in the athlete population.

Alpha in athletes

From golfers to gymnasts and pistol shooters, researchers have demonstrated that the alpha activity in elite athletes differs significantly from amateur and non-athletes and can predict and differentiate between best versus worst performance (Babiloni et al., 2009; Baumeister, Reinecke, Liesen, & Weiss, 2008; Del Percio et al., 2007; Loze, Collins & Holmes, 2001). Babiloni et al. (2008) measured the EEG activity of 12 expert golfers and found no difference between successful and unsuccessful putts in lower alpha (8-10Hz) indicating that successful performance is not related to general arousal or attention. They did find significant differences in upper alpha Mu (10-12Hz), particularly in the right primary sensory-motor cortex (visuo-spatial processing) with greater ERD associated with successful putts (Babiloni et al., 2008). This finding suggests that the role of alpha in motor control goes beyond simply the execution of the motor act to the visual spatial processing and selection processes which guide the motor action. Further, as a control measure Babiloni et al. (2008) also compared the ERD of the unsuccessful putts. The results found that the putts that were closer to the hole (least error) compared to those that were further away (most error) were associated with greater ERD lending further support to the idea that alpha activity is related to optimal performance (Babiloni et al., 2008). These findings support Babiloni et al.'s (2009) neural efficiency hypothesis, and findings by Klimesch (1999, 2012) that greater ERD is indicative of better performance.

Loze et al. (2001) investigated the alpha activity of six expert pistol shooters immediately prior to shooting. They discovered the difference between the five best and five worst shots, based on target accuracy, was a large ERS over the occipital lobe in addition to ERS over the left anterior temporal sites for the successful shots (Loze et al. 2001). The findings reflect increased inhibition of visual and verbal (self-talk) processing (Loze et al., 2001). They posit that experts attain a high level of motor expertise and require less cognitive resources to process relevant external information and instead rely more heavily on internal, well-practiced, motor representations. In contrast to experts, Loze et al. (2001) suggest that novices display less inhibition and require a much larger degree of conscious decision making and visual processing while they learn *what* external information is *relevant* to make the shot (Loze et al., 2001). While this seems a reasonable conclusion, the study would have been better served if there was a sample of novices included in the research to lend support to that particular theory. The current study seeks to address this problem by using a novice (in this case 'non-elite but experienced') comparison group.

In another Babiloni et al. (2009) study, alpha activity in elite and non-athletes was compared during the judgment of performance of observed sporting actions. Fifteen rhythmic gymnasts and 10 non-athletes watched a series of videos of elite gymnasts performing routines and were asked to judge the artistic/athletic performance of each video. During the viewing of the videos, EEG readings indicated less ERD in the right visuo-spatial cortical areas of the elite athlete group suggesting that judgment of observed sporting performance requires less cortical activation in athletes than it does in non-athletes (Babiloni et al., 2009). These findings further supported Babiloni et al.'s (1999) neural efficiency hypothesis however they concede that not all areas of the visuo-motor system respond with lower ERD and that neural efficiency may account for only a portion of the difference in alpha requirements of optimal performance.

Whilst the neural efficiency hypothesis may explain performance-related ERD over motor cortex during (or just preceding) motor execution, it may not explain alpha modulation relating to the wider network of visual spatial processing guiding sensory selection and planning of motor responses accessed in high level sport. Referred to as the dorsal attention network (DAN), regions in dorsal frontal and parietal cortex, including bilateral medial intraparietal sulcus, superior parietal lobule, precuneus, supplementary eye field and frontal eye field respond to symbolic cues to shift attention voluntarily to a location (Corbetta, & Shulman, 2011). The DAN will be activated in response to cues to shift attention voluntarily to a location as is the case in many high level sports.

The exact role alpha activity plays in the modulation of this extended fronto-parietal network remains unknown. However, transcranial magnetic stimulation (TMS)–EEG studies extend research on the alpha rhythm by indicating that local alpha amplitude carry information about the momentary (excitability) state of neurons within the dorsal processing stream. The findings show that up- and down-regulation of alpha, possibly involving top-down control, is likely to condition the cortex for forthcoming perception or action. This has added to a mounting body of information on the role of alpha oscillations in top-down attention selection (Thut, & Miniussi, 2009; Jensen, Gips, Bergmann, & Bonnefond, 2014).

Aims of the study

The aim of this investigation was to find the EEG signature for specific cognitive processes required by a particular (in this case table tennis) elite sport performance. Access was gained to a large group of professional table tennis athletes. Throughout the 2013 European competition season this study had the possibility to test over 200 players that were competing in several championships all over Europe. This gave rise to the possibility of testing elite players as well as lower ranked players, resulting in a data base of table tennis players across a wide range of competitive skill and experience levels.

We sought firstly to identify and measure those aspects of EEG activity which are most characteristic of the differences in brain activity between ‘elite’ table tennis players and lower ranked but experienced players (henceforth referred to as ‘amateur’). A comparison of the elite players to age and gender matched amateur players was undertaken to find functional differences in the activity of cortical sources at specific frequencies in eyes open resting and eyes closed resting states and when actively watching an opposing player and imagining playing against them in a continuous table tennis match.

Secondly we sought to demonstrate that these differences in the EEG are due to differences in activity within neural networks which implement cognitive processing specific to skilled table tennis performance. The cognitive processing demands of (successfully) responding to the actions of an opposing table tennis player must include motor decisions (Go versus NoGo) triggered by the detection of salient changes at specific locations in the visual field. We adopted a unique version to the Go-NoGo task cued by rapid changes at precise visual locations to objectively measure performance on these core cognitive skills (the vsCPT, described in the Method section). These behavioural measures were used to assess the external validity of the EEG source differences identified in our first aim above.

Hypotheses

Building upon the recent understanding of the functional role of upper alpha in the timing and control of cognitive processing (Klimesch et al., 2007; Jensen, & Mazaheri, 2010) and specifically in visual-spatial performance (Cooper, Croft, Dominey, Burgess & Gruzelier, 2003; Vernon et al., 2003), it was hypothesised that elite table tennis athletes, whose skilled performance depends upon the precise timing and control of visuo-spatial information processing, would display increased Mu (10-12Hz) power in the underlying neural networks compared to the amateur group. It was hypothesised firstly that EEG sources of increased Mu in elite versus amateur players would be found in the fronto-parietal nodes of the dorsal attention network during the active Table Tennis Video viewing condition, which elicits similar cognitive processing requirements to actual play. Secondly it was hypothesised that the magnitude of this Mu activity at the locations of maximum elite-amateur source differences would be directly related to superior performance on the vsCPT an objective measure of core visuo-spatial attention skills employed in the game of table tennis.

Method

Participants

206 table tennis players were recruited representing elite and non-elite but experienced (amateur) performance from across the International Table Tennis Federation (ITTF). From this group, a sample of ‘elite’ players was selected with a World ranking (WR) ranging from 20 – 261 (*M* = 134, *SD* = 81.6) and were compared against an age and gender matched ‘Amateur’ group of lower level (WR>1000) but experienced players (who had played at least 5 years at >10 hours per week). The average age of the elite group was 28.6 (ranged from 18-47 years, *SD* = 8.5), this group consisted of 6 female and 10 male players. The average age of the amateur group was 27.5 (ranged from 18-51 years, *SD* = 10.0), this group consisted of 5 female and 11 male players.

All participants were screened for any medications currently being taken or history of epilepsy in the family, and gave biographical data including age, gender, ranking, years played at greater than 10 hours per week, current level of education and email contact details. All data were treated with confidentiality and the experiment was approved by the Human Research Ethics Committee of the University of New England.

Measures

Eyes Open and Eyes Closed. The study used resting EEG recorded in both Eyes Open (looking at a fixation cross in the centre of a computer monitor) and Eyes Closed states to assess intrinsic network activity at rest (absence of external information processing) in standard baseline conditions.

Table Tennis Video Task (VT). The study employed a novel measure to engage and assess the neurocognitive networks specific to table tennis performance. Due to the practical limitations of recording the EEG of a moving player it was determined to use visual imagery to elicit the cognitive processes and neural networks of a table tennis player through mirror neuron activation of those regions. To do so, a four-minute video was prepared by placing a video camera on a tripod 30cm above a table tennis table (central position) directly behind the baseline. Australia’s current number one ranked player (WR86) was requested to play a variety of shots of elite calibre against an opposing player who returned the ball from behind the camera, resulting in a ‘player’s perspective’ video (Figure 1).

Figure 1. Still image of the four-minute table tennis video task. Participants watched this video for four minutes and were instructed to “imagine playing against this player”.

Visual Spatial Continuous Performance (Go-NoGo) Task (vsCPT). The vsCPT was specifically developed as a behavioural task in order to assess the aspects of visual attention, decision making and motor control directly required by the cognitive processing demands (but not the motor programming and execution skills) of correctly responding to the motion of an opposing player. This task requires distinguishing salient from non-salient events at different spatial locations and selecting the former to guide motor responses while inhibiting motor responses to the latter, that is, the interaction of the dorsal and ventral attention networks with frontal networks of motor control (Szczepanski, Konen, & Kastner, 2010; Umarova et al., 2010; Vossel, Geng, & Fink, 2014).

The vsCPT is a unique adaptation of the widely used continuous performance task (a Go-NoGo -task using images of different types of object) to the visual-spatial attention demands of response decisions required in table tennis which are triggered by visual events at specific spatial locations. In this task participants respond (Go) or withhold response (NoGo) to rapidly occurring visual stimuli depending on the spatial location of each stimulus.

Each of the two Go-NoGo continuous performance tasks included 192 trials – 96 ‘Go’ and 96 ‘NoGo’. After an initial delay of 300ms the participant was exposed to stimulus 1 for 100ms. Stimulus 1 consisted of a target area (represented by either 1 grey coloured circle outline in the ‘1 circle’ task (vsCPT1) or 4 circles in the ‘4 circle’ task (vsCPT4)). The difference between the two tasks was the level of visual working memory demanded between the instruction cue offset and stimulus onset. A jittered delay of 1100, 1300, 1500 or 1700ms proceeded stimulus 2, also with an exposure of 100ms, consisting of a small black dot somewhere either slightly inside or slightly outside where the stimulus 1 circle had previously appeared. The participant was instructed to click the left mouse button for ‘inside’ the circle (‘Go’ response) and not to click if ‘outside’ the circle (‘NoGo’ response) “as quickly and as accurately as possible” (Figure 2 below).

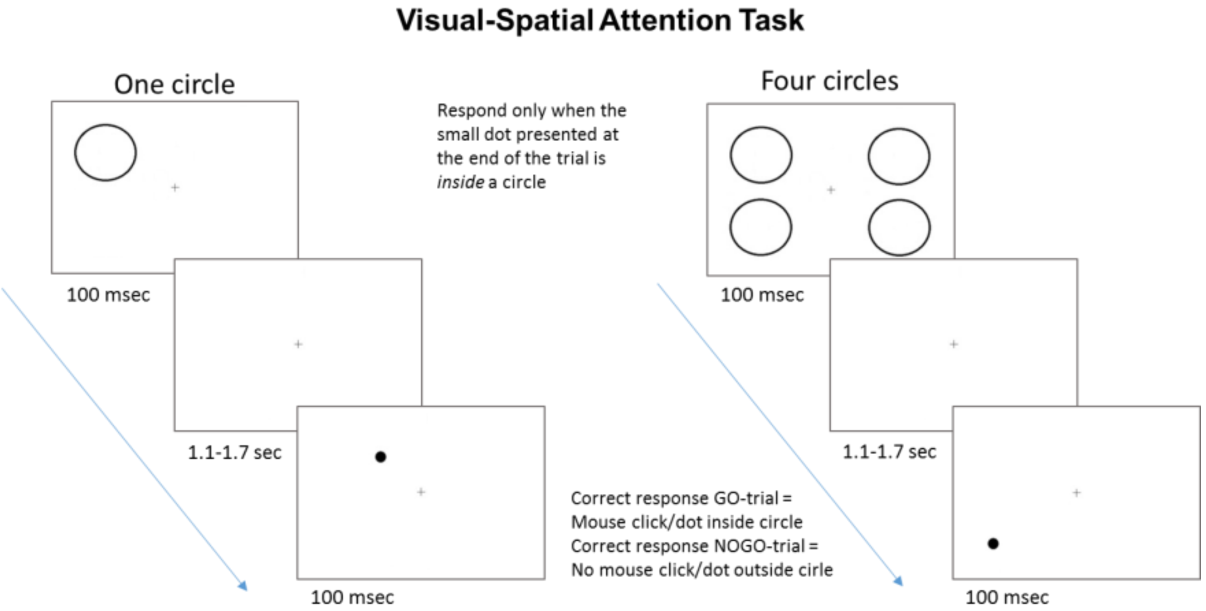

Figure 2. Example of a 'Go' response trial in the vsCPT tasks. Each circle had 8 possible 'Go' responses and 8 possible 'NoGo' responses. Of the 192 trials, there were 96 'Go' and 96 'NoGo' responses. Quasi-randomisation ensured that there were never more than four 'Go'or four 'NoGo' responses in succession. ISI: Inter-stimulus-interval.

EEG recordings and Materials

The EEG was recorded using a stretchable electro cap (Electro-Cap Inc., USA), Quikcells (Compumedics Neuroscan) were inserted into each of the silver-chloride electrodes and foam discs placed at FP1/FP2 were added for participant comfort. Impedance was established using Quikcell electrolyte solution (Compumedics Neuroscan) and maintained under 10kOhms. EEG was recorded continuously from a Mitsar 201 21-channel system (Mitsar, Russia) over 19 scalp locations according to the international 10-20 system (FP1, FP2, F7, F8, Fz, F3, F4, Cz, C3, C4, Pz, P3, P4, T3, T4, T5, T6, O1, O2) and a mid-forehead placement of the ground electrode (Pivik et al. 1993).

Referential ear-clip electrodes were attached to the participant using Ten20 electrode paste and inserted directly into the Mitsar 201 amplifier. EEG data was sampled at 250Hz and recorded onto hard disk for off-line analysis. A Toshiba Satellite Pro Notebook computer (Intel Core 2 DUO CPU) acquired data through WinEEG software (version 2.91.54).

Procedure

The study was conducted at multiple locations around Europe beginning at the World Table Tennis Championships, Paris, 2013. A high level of consistency between location settings was achieved, controlling for sound interference, participant comfort while seated and dulled lighting. During preparation with the size-appropriate electro cap (ElectroCap Inc., USA), participants were explained the importance of maintaining a relaxed forehead, jaw and low bodily movement during recording, and any further questions were answered. Participants' EEG was recorded in the following order:

1. vsCPT1 or 4 (10 mins)
2. Four minutes in a relaxed Eyes Closed
3. Four minutes in a relaxed Eyes Open
4. Four-minute table tennis video task
5. vsCPT1 or 4 (10 mins)

vsCPT1 and vsCPT4 order was counter-balanced across subjects. Following recording completion, Electro cap and ear clips were removed and residue gel from participants' ears was cleaned.

Research Design and Analyses

Design. The experiment was a mixed measures design (between groups independent variables: Elite and Amateur). The dependent variable for the EEG recordings (EC, EO, VT) was the distributed density of current neural source activity (explained further below). The dependent variables for vsCPT1 and vsCPT4 were reaction time on correct go trials (processing speed), and the signal detection measures of discriminability (*d'* an index of perceptual processing accuracy) and response criterion (*c* an index of the bias towards selecting a go response).

EEG data preparation and Analyses. WinEEG software was used to prepare each EEG file. A common average reference was selected (the average of all other channels at each point forms the reference for each channel at the corresponding point) and a 0.5 to 30Hz band-pass filter was applied. Artefacts from physiological (eye movements/blinks, skin potentials) and non-physiological (electromagnetic interference, electrode popping) sources were removed with independent components analysis (ICA). ICA decomposes the data into maximal information independent components (which extends beyond the simple linear independence of principal components analysis) based on selected parameters (Stone, 2002).

Automatic artefact detection thresholds were set for the recording at the following bandpass settings: 0-30Hz +/- 70µmV, 0-1Hz +/- 50µV, 20-30Hz +/- 35µV. Time segments of +/- 300ms were marked in the recording around these artefacts and excluded from further analysis. EEG was then visually inspected for any remaining artefacts, and contaminated EEG was manually removed. Each 4-minute recording segment was then divided into artefact free epochs of 4000 ms. For the resulting epochs power spectra from 0.5 to 30 Hz with a frequency resolution of 0.25 Hz were calculated in Win EEG by Fast Fourier Transform. These were then averaged for each participant in each condition.

Spectral averages for the VT, EO and EC conditions for each individual in the Elite and Amateur groups were entered into exact Low Resolution Electromagnetic Tomography (eLORETA) software to estimate cortical source activity at each frequency bin (Pascual-Marqui, 2007). A three-dimensional realistic head model represents cortical sources with 6239 5mm voxels (Fuchs, Kastner, Wagner, Hawes, & Ebersole, 2002). Three-dimensional source space is restricted to cortical grey matter as determined by the Talairach Atlas (Lancaster et al., 2000). Discrete measurements of the strength and direction of activity in each voxel determine the distributed density of current source activity (Pascual-Marqui, Michel, & Lehmann, 1994). A linear computation smooths the values of neighbouring voxels. eLORETA has the property of exact localisation of point sources in simulated data, although with low resolution (Pascual-Marqui, 2007). The significance of source activity differences between groups or conditions is determined in eLORETA with a nonparametric randomisation test which estimates the distribution of a test statistic under the null hypothesis (effects of experimental conditions are random) by repeatedly randomising (permutating) estimated voxel activations across all frequency bins (or time points in an ERP analysis) between experimental conditions. This allows the calculation of the exact probability of the obtained test statistic for the difference between conditions at each voxel corrected for testing at multiple voxels (Canuet et al., 2011; Nichols & Holmes, 2002).

Common Average Reference and Global Field Power Measures.

All forms of LORETA employ a Common Average Reference (CAR) where EEG data is re-referenced to the common average of all channels at each time point of the recording. This creates a virtual reference so eliminating the topographic distortion introduced into the EEG recording by activity related to the specific spatial location of a physical/actual reference electrode, a key step in calculating unbiased current source estimates (Pasqual-Marqui & Lehmann, 1993). This is particularly important for frequency domain cortical source estimates (Murray, Brunet, & Michel, 2008).

Common Average Reference (CAR) Formula

Where n is the number of electrodes in the montage[1]

$\overline{U_i}$ is the measured value of the ith electrode for a given condition at time point t

$\bar{u}$ is the mean value of all U_i's (for a given condition at time point t)

$$\bar{u} = \frac{1}{n} \cdot \sum_{i=1}^{n} U_i$$

Where u_i is the average-referenced potential of the ith electrode (or LORETA voxel estimate) for a given condition, at time point t

$$u_i = U_i - \bar{u}$$

LORETA voxel current source density estimates are a measure of local spatial variance of the elctical field potential relative to the CAR. LORETA Global Field Power (GFP) then is the standard deviation of all voxel CSD estimates at each timepoint (Lehmann & Skrandies, 1984).

Global Field Power (GFP)

$$GFP_u = \sqrt{\frac{1}{n} \cdot \sum_{i=1}^{n} u_i^2}$$

$$= \sigma_u$$

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[1] Note: WINEEG output format precludes the inclusion of ground and linked ear reference electrodes in this calculation.

Results

Elite versus amateur player EEG source differences

The spectral averages calculated above for EC, EO and VT conditions were entered into eLoreta to compare source activity differences between elite and amateur groups. For EC, EO and VT, the eLORETA Global Field Power (GFP calculated across voxel estimates) was plotted as the Y axis against each frequency bin as the X axis (see Figure 3 below). The GFP peak indicates maximum spatial heterogeneity in the voxel CSD differences between elite and amateur groups providing an independent criterion for selecting frequency bins for statistical analysis (Pascual-Marqui et al., 2011). Across EC, EO and VT the GFP maxima were very close and lay, as hypothesised, in the narrow upper alpha band.

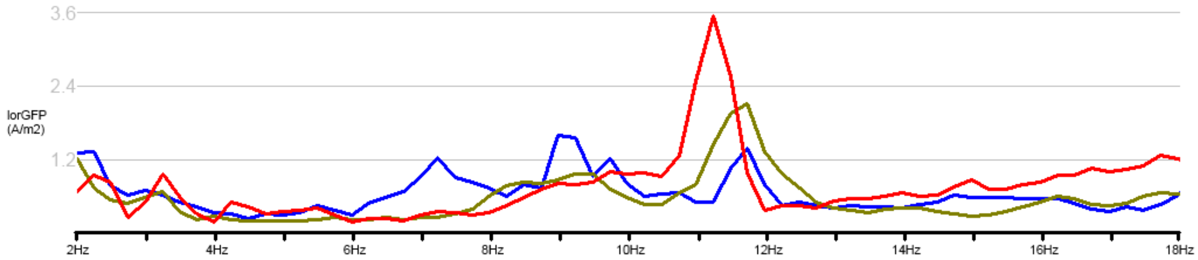

Figure 3. Global Field Power for difference between Elite and Amateur groups during EC Blue), EO (Green) and VT (Red) condition plotted from 2Hz to 18Hz. GFP units are expressed as Amperes per square meter.

The GFP maximum was observed as a sharp GFP peak in the alpha band rising from 10.50 Hz to a maximum at 11.25 Hz before dropping sharply to 11.75 Hz (see the top panel of Figure 4 below). The GFP maximum indicates the frequency bins (or time points depending on the domain of the analysis) of greatest topographic variability between conditions (Lehmann & Skrandies, 1980) and is therefore widely used in conjunction with eLORETA to select the specific frequency bins employed for statistical analysis. The maximal cortical voxel statistic (here the log of the F ratio or likelihood of a group difference) is plotted against frequency bin in the lower panel of Figure 4 (below). As seen below, the peak statistical difference between elite and amateur groups in VT coincides exactly with the GFP peak in the alpha band with a sharp maximum at 11.25 Hz. A p-value of .05 was used for all statistical tests.

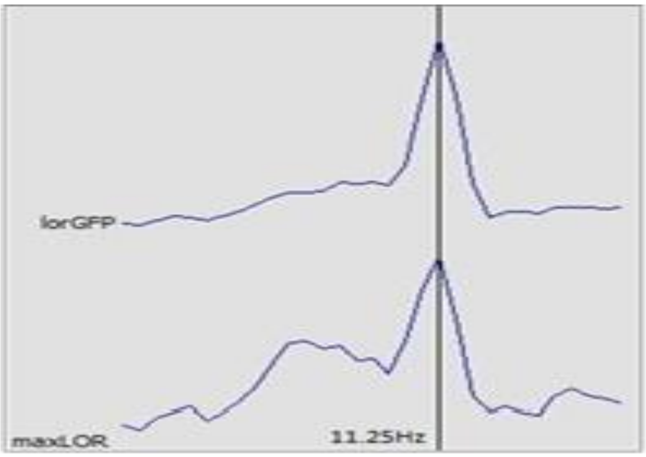

Figure 4. Maximum Global Field Power difference between Elite and Amateur groups during VT condition at 11.25Hz.

The maximum voxel activity at 11.25 Hz is greater in the elite than the amateur group (log F = 5.96, p = .38). This difference was not statistically significant as determined by the random permutation test however our aim here was not to perform a statistical test but rather to identify those structures within EEG source frequency space most related to elite versus amateur group differences. This was the maximum voxel difference statistic for the comparison of elite and amateurs of any frequency bin in the VT recording. By comparison the corresponding maximum voxel statistic from the EC and EO recordings returned a p value for the null hypothesis approaching 1 (see Figure 5 below). The latent structure of the EEG (frequency bands and cortical sources) and the condition (VT) which maximally differentiates the elite and amateur groups has been identified through GFP and maximum voxel statistic comparisons. However, in the absence of significant statistical differences the validity of these cortical sources, as functional nodes in the specific cognitive processing required by table tennis, will be assessed through their capacity to predict individual differences in independent behavioural performance measures.

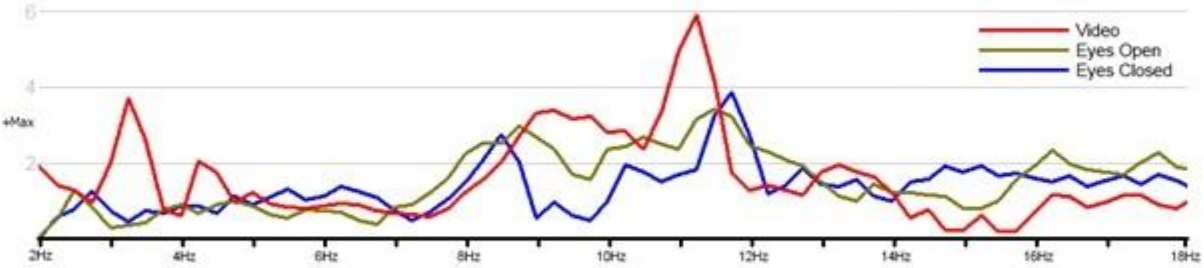

Figure 5. Maximum voxel statistic for Elite > Amateur comparison in EC, EO and VT plotted from 2Hz to 18Hz.

An eLORETA analysis was then conducted to identify the maximum (most likely) cortical sources differences in VT guided by the GFP results described above. A comparison was conducted in eLORETA between the elite and amateur groups during the VT condition constrained to the narrow frequency band of 10.50 to 11.75 Hz. Voxels were listed in order of descending order of the log F ratio. Two anatomical clusters of enhanced cortical activity in elite versus amateur within this frequency band clearly emerged within the top 100 voxels. These were anatomically distinct and lay within the right insula (BA13) and the right precentral gyrus (BA6) respectively (Figure 6). The voxel with the highest log F value within right BA13 was at MNI coordinates (35 -15 20) and for right BA6 at MNI (40 -10 35).

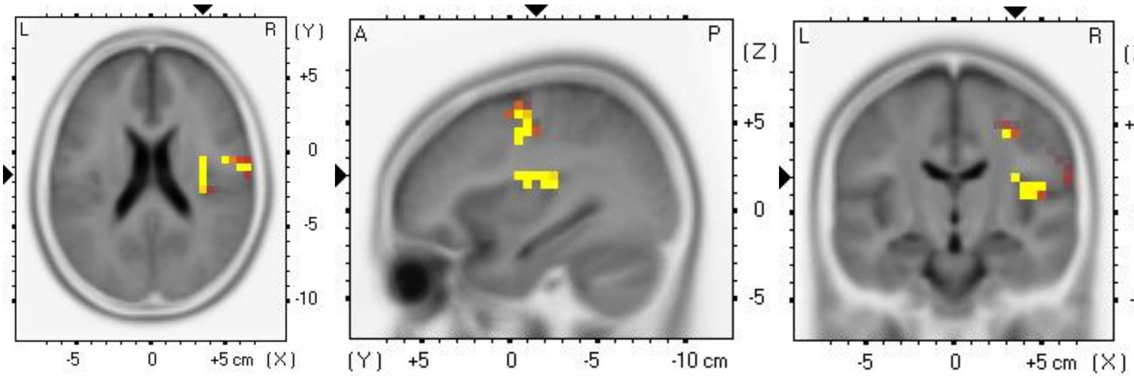

Figure 6. eLORETA images of transverse, sagittal and coronal slices showing top 100 voxel log F ratio for differences between elite and amateur groups from 10.50Hz – 11.75Hz. All voxels lie within right BA13 and BA6 Black arrows on the axes mark the eLORETA maximum voxel difference at MNI (35 -15 20).

For each individual eLORETA estimates of current source density from 10.50Hz – 11.75Hz during VT were retrieved for the maximal voxel statistic coordinates identified above in right BA13 and right BA6 respectively. If these variables within the structure of the EEG in VT are valid indicators of cognitive processes critical to elite table tennis performance then it was expected that they would be significantly related to objective performance on the visuo-spatial Go-NoGo paradigm separately designed to index cognitive skills employed in elite table tennis performance (Brown, Jamieson, Evans, Tordoir, & Cooper, submitted).

Elite versus amateur player behavioural relationship to EEG sources

Performance on the vsCPT is summarised here by 3 behavioural measures; reaction time on correct go trials (processing speed) (Thorpe, Fize, & Marlot, 1996) and the signal detection measures of discriminability (*d'* an index of perceptual processing accuracy) and response criterion (*c* an index of the bias towards selecting a go response) (Stanislaw & Todorov, 1999). For each participant in the VT condition, eLORETA estimates of EEG current source density in the 10.50Hz – 11.75Hz frequency band were obtained for the voxels with maximal log F ratios (see coordinates above) in right BA13 and right BA6 respectively. These values were then correlated with the reaction time, discriminability index and response criterions for each level of processing demand (1 circle and 4 circles) on the vsCPT. It was expected that EEG source activity during VT that is functionally related to real world player performance would also be associated with superior performance on each of the 3 objective vsCPT measures above.

These correlations are presented in Table 1 below. In order to ensure a normal distribution, current source density was first converted from power to amplitude by square root transform and reaction times were log base 10 transformed (Whelan, 2010).

Table 1

Correlation of Group Sensitive eLoreta Current Source Density during VT with vsCPT Performance.

		vsCPT_1 RT	vsCPT_4 RT	vsCPT_1 d'	vsCPT_4 d'	vsCPT_1 C	vsCPT_4 C
Right BA13 (MNI: 35, -15, 20)	r	-.263	-.332*	.077	.288*	-.288*	.012
	p	.066	.026	.332	.046	.049	.473
	n	34	35	34	35	34	35
Right BA6 (MNI: 40, -10, 35)	r	-.265	-.328*	.073	.286*	-.278	.017
	p	.065	.027	.340	.048	.056	.461
	n	34	35	34	35	34	35

Note. *p < .05

Lower reaction time (superior processing speed) was related to eLORETA current source density estimates during the VT (mental play) condition in the narrow upper alpha frequency band of 10.50Hz – 11.75Hz in each of the target voxels from right BA13 and right BA6 respectively. These correlations were significant (with medium effect size) for the 4 circle cue (higher processing demands) and at the margin of significance (low to medium effect size) for the 1 circle cue. The same eLORETA VT current sources were consistently related with superior signal processing performance, higher perceptual discrimination (*d'*) and lower response bias (*c*). However, these relationships were closely tied to the processing demands imposed by the 1 and 4 circle cues. The relationship with superior (lower) response bias was observed only for the 1 circle cue (vsCPT1) while the relationship with superior perceptual discrimination was found only for the 4 circle cue (vsCPT1).

Common Average Reference (CAR) Channel Comparisons: elite versus club players

Because eLORETA seeks to identify spatial variance in signal source (voxel) activity it employs the CAR which subtracts the average value of the electrical field for each observation in each individual. However theoretically meaningful differences between groups or conditions in mean field strength values cannot be ruled out. Therefore, field strength in the common average reference channel was computed for the same epochs and in the same manner as reported above for eLORETA GFP and eLORETA CSD voxel estimates.

Mean amplitude in the frequency range 10.5 – 11.5 Hz was calculated for the CAR channel and compared between elite and club players for each of the eyes closed, eyes open and table tennis video baseline conditions. In each case the comparison did not approach significance and effect sizes were negligible. For EC F(1,32) = .338, p =.565; for EO F(1,32) = 1.279, p =.266; and for VT F(1,32) = .270, p =.607.

As a more fine-grained test of the relationship of mean (CAR) band amplitude in each of the baseline conditions and table tennis performance we calculated the correlation with world ranking (n=21): for EO r=.137, p=.555; for EC r=-.051, p=.825; for VT r=-.171, p=.460. We also calculated correlations of mean band amplitude during VT with participant’s vsCPT performance measures and found no significant relationships. Therefore, no relationship was found between the mean (CAR) band amplitude, excluded by eLORETA, and table tennis or vsCPT performance in this study.

Discussion

We sought to identify intrinsic cortical network activity linked to elite performance in table tennis. Exact Low Resolution Electromagnetic Tomography (Pascual-Marqui, 2007) compared EEG source activity in 16 elite world ranked table tennis players with 16 age- and gender-matched amateur players during 3 conditions: EO, EC and actively watching a table tennis video (VT) of an opposing player. In each condition Global Field Power plots showed a sharp maximum in a narrow band in the upper alpha range (see Figure 4 above) consistent with our initial expectations. Maximum voxel statistics comparing elite and amateur players closely followed these same GFP peaks (see Figure 3 and Figure 5 above). Maximum voxel statistics did not reach significance at these peaks however this is not required in the current context. Rather the aim of this comparison was to identify candidate structural features of the EEG (underlying sources and frequencies) separating these groups and then to examine whether these ‘deep-structures’ (Burgess, 2007) are related to cognitive functions demanded by successful player responses.

GFP plots directed EEG source analysis to focus on the VT condition in the narrow frequency band of 10.50 to 11.75 Hz. Maximal cortical source differences (higher activity in the elite than amateur group) in this frequency band were located by eLORETA at right Brodmann Area (BA) 13 and right BA6.

These then were the variables selected for external validation. Source activity in the identified frequency band, at the location of maximal group difference in each of these clusters (right BA13 and right BA6), while engaging in the mental activity of simulated table tennis play (the VT condition) was found to be significantly related to superior response speed and perceptual discrimination at the higher processing load (vsCPT4) and reduced response bias at the lower processing load (vsCPT1) of a separate visuo-spatial (Go-NoGo) continuous performance task. Analyses of mean (CAR) band amplitude (10.5 – 11.5 Hz) showed negligible non-significant differences between elite and club level groups over the three conditions (EO, EC, VT). Correlations of CAR band amplitude during VT with world ranking or with vsCPT performance were similarly non-signifcant and negligible, supporting the conclusion that mean bandpower differences in this frequency band are not contributing to differences in player performance.

Frontal lobe upper alpha during motor imagery

The VT condition was carefully designed to elicit the specific cognitive processing required for monitoring and planning a response to an opponent's ongoing actions during table tennis match play but without the physical action (therefore controlling for EMG and movement artefacts). The video simulated the flowing state of a table tennis player in which attention and focus are high in order to respond correctly to the opponent, allowing EEG recording to capture the specific topographies of EEG activity in specific functional frequency bands related to table tennis performance. When comparing the EEG of elite to amateur table tennis players during active video viewing of (mentally playing against) an opposing table tennis player, the maximal group difference was found within the upper alpha band in the regions of right Brodmann Area 13 and 6.

BA13 corresponds to the insula cortex, which is the core node of a network of brain regions (ventral attention network) which detects and signals the salience of ongoing events and acts to trigger the dorsal attention network to focus processing resources on the newly salient stimulus (Menon & Uddin, 2010). Importantly, BA13 plays a role in the split-second detection of salient stimuli, stimuli to which attention should be directed and dedicated to occupying the main resources for the motor planning systems that are selecting the responses. BA6 is located within the premotor cortex and plays a functional role in deciding which sources of visual information will guide the selection of motor responses (Chouinard & Paus, 2010). The functional significance of these latent variables within the EEG were externally validated by their observed relationship with objective performance on the vsCPT which was most pronounced at the highest level of visuo-spatial information processing demands (vsCPT4). The magnitude of group differences in the eLORETA comparison is likely to be constrained by the similarity of the mental skills of the comparison group to the elite group. Therefore, it will be useful to include an additional group of novice table tennis players in a future study.

Dorsal and ventral attention networks

In order to execute a motor response a player must first select salient events from the available visual information. The ventral and dorsal attention systems respond to visual processing outputs of the 'what' and 'where' pathways of visual information processing. Salient stimuli must be detected in the environment (ventral attention system) and those sources of visual information must then be utilized to guide and select successful goal-directed behaviour (dorsal attention system) (Eckert et al., 2009). In the case of a table tennis player, a salient stimulus is not only ball direction but also the opponent's bodily movement and the *meaning* of that movement. Thus, elite players actively watching the table tennis video seem to have evoked these processes in the ventral and dorsal attention network. This theoretical analysis presumes that the ventral attention system and the dorsal attention system work together, acting to guide the selection and generation of an appropriate motor response.

Intriguingly, the brain regions found in response to the VT condition are indeed engaged in these attention networks. The precentral gyrus (right BA6), part of the dorsal attention network, is involved in cognitive processes such as spatial working memory and spatial attention (Tanaka, Honda, & Sadato, 2005). This brain region selects between sources of sensory input to be utilized in the control of motor responses (Chouinard & Paus, 2010). In turn, the insula (BA13) supports the switching of processing resources to respond to new salient stimuli detected in the environment. The insula is known to be a central hub in the ventral attention network, supporting coordination and evaluation of task performance and playing a crucial role in judging the significance of a stimulus. Moreover, previous research has demonstrated that the ventral and dorsal stream interact during behavioural tasks and that this interaction is regulated by the insula (Eckert et al., 2009; Menon & Uddin, 2010). These findings support the interpretation of EEG differences between groups in the VT task in the current study as indexing elements of sport specific cognitive processing that are crucial for making a (correct) response to the opponent's motion. Furthermore, these findings support the theoretical analysis proposing an interaction between the ventral (perhaps greater than expected given our results) and dorsal attention networks which provided the rationale for the design of the video task.

Alpha, inhibition-timing and elite motor control

The frequency range (10.50 – 11.75 Hz) in which group differences were localised in this study falls within the upper-alpha band, that was previously found to be related to the accuracy of fine motor skills in a variety of sports (Babiloni et al., 2009; Baumeister et al., 2008; Del Percio et al., 2007; Loze et al., 2001). BA6 is located in the precentral gyrus, which is part of the premotor cortex in the frontal lobe (Tanaka et al., 2005); hence we can be confident in our classification of this frequency as a mu rhythm. Our finding of increased mu in the VT task condition supports Llanos et al.'s (2013) research finding that mu is activated when motor planning is required in response to visual stimuli compared to when the stimuli are to be observed with no response.

Mu plays a functional role in processing visuo-motor information and in particular the translation of visual information into action (Llanos et al., 2013; Sabate et al., 2012). In contrast to the current study, Cannon et al. (2014) found that mu is related to expertise in a skilled movement so that the more one is practiced in a particular motor skill, the greater the desynchronization that occurs when either watching or performing the skilled activity. The current study found that mu was greater in the elite group than amateur skill levels when participants engaged in the task of watching the table tennis video while actively imagining playing against the player. The VT condition in our study, however, is distinct from both the active movement and passive observation conditions in which Cannon et al. (2014) observed mu desynchronization. Therefore, the increased mu in elite players observed in the current study is most likely related to the high level of cognitive processing required by participants in order to process the relevant aspects of the visual stimuli in preparation for movement responses, rather than the direct motor control of that movement.

Alpha is known to have an inverse relationship to metabolic rate, as shown by MRI studies showing the negative relationship between alpha and the blood oxygen level-dependent (BOLD) response (Lipp et al., 2012). Therefore, the increase in Mu found over BA6 and BA13 in this study points, initially, to a deactivation of these regions and seems to support the neural efficiency hypothesis. However, the finely tuned *timing* of motor control required in table tennis, requiring split-second sensory processing, suggests that the inhibitory role of alpha seems to be related, not so much to neural efficiency, but to the *timing* of oscillations playing the pivotal role in sensory processing or inhibition.

Regarding the functional role of alpha in the timing, selection of relevant information and the inhibition of irrelevant sensory information, Mathewson et al. (2011) introduced a ‘pulsed inhibition’ hypothesis. They proposed that alpha oscillations ‘phase-lock’ to irrelevant visual stimuli and influence subsequent visual awareness. The authors provided evidence of counter-phase alpha oscillations between detected and undetected stimuli; that is, an alpha oscillation was high (positive voltage) when stimuli were detected, whereas it was low (negative voltage) when stimuli were undetected. In this way, the authors posited that brief visual events occurring in a particular phase of ongoing oscillations do not reach awareness, while those in the opposite phase do.

According to Mathewson et al.'s (2011) 'pulsed-inhibition' hypothesis, top-down signals from fronto-parietal areas control alpha oscillations when inhibition of some part of visual space, some part of time, or some visual feature is needed, fluctuating as a function of current level of task engagement. In addition, cortical excitability will determine whether alpha phase reaches a level of significant sensory inhibition – as cortical excitement is high, all sensory information will pass the detection threshold and be processed. However, if cortical excitability is low, alpha oscillations are high in voltage and certain aspects of visual stimuli linked to alpha negative phase will not be processed. Thus, 'pulsed-inhibition' is an inhibition-timing mechanism guided by top-down processes that will inhibit irrelevant aspects of the visual sensory environment phase-locked to the frequency of incoming sensory information (Mathewson et al., 2011).

In the current study, it is suggested that the high amplitude mu generated by elite table tennis players in right BA13 and BA6 during the VT condition may represent an example of pulsed-inhibition. The bombardment of visual information hitting the elite table tennis player demands that there be a selection of what *not* to allow into awareness. The timing mechanism of alpha phase allows for top-down control of visual processing synchronised to the speed of a table tennis game.

As demonstrated in several studies alpha plays a key role in the preparatory period preceding an action in sports requiring high levels of accuracy and there is a strong positive correlation between sport performance and alpha power (Babiloni et al., 2008; Crews & Landers, 1993; Loze et al., 2001). In the current study, analysis was conducted in the frequency domain by means of the Fourier transform which has no time domain resolution. Frequency analysis was derived from the EEG recording during the VT condition over the whole recording time period. Unfortunately, it is therefore not possible to specify the timing of the alpha power increases over the course of watching the video or to time lock them with specific events in that video. The next logical step to develop a deeper understanding of alpha oscillations in these conditions would be to analyse EEG source activity employing time-frequency domain methods, making it possible to track frequency changes in cortical source activity across time. In this way, future research would allow us to assess whether pulsed-inhibition best explains the role of alpha shown within elite table tennis athletes.

Conclusion and Future Directions

Elite table tennis players were found to differ from lower-level but experienced ‘amateur’ players by showing greater Mu in right BA13 and BA6 during mental operations similar to those of actual play and this same activity was shown to be related to superior performance on the vsCPT which objectively measures key cognitive skills demanded by table tennis. These EEG measures may, in the future, be used as benchmarks in the development of training protocols for high performance visual-spatial decision making in table tennis and related skill domains.

For example, in addition to linking visual stimuli to action responses, mu is highly responsive to operant conditioning (Pineda, 2005) and enables voluntary control of mu to be learnt within a brief period of time. Consequently, mu is particularly suitable as the target for Neurofeedback training. By using the findings of this study as targets for a Neurofeedback protocol, we may influence a higher level of motor control – not by influencing the motor system directly but by targeting the underlying attention and decision making system.

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Statement of Originality:

We, the PhD candidate and the candidate's Principal Supervisor, certify that the following text, figures and diagrams are the candidate's original work.

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Chapter 3

Event-Related Potential Biomarker of Visuo-Spatial Attention Predicts World Rankings of Elite Table Tennis Athletes

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Event-related potential biomarker of visuo-spatial attention predicts world rankings of elite table tennis athletes

Abstract

Background: Electroencephalography (EEG) biomarkers have been identified in clinical populations with cognitive and behavioural deficits and are employed to guide diagnoses and treatment recommendations of these deficits. Similarly, identification of EEG indicators of superior performance in elite athletes may be used to assess performance enhancement psychophysiological training interventions and identify talented individuals with high future potential. The aim of this study was to identify EEG indicators of visuo-spatial processing and motor-preparation present in elite table tennis players using world ranking as a performance measure.

Method: EEG was recorded from 16 elite table tennis athletes from across the International Table Tennis Federation. Event-related potential (ERP) data and behavioural results were recorded during a novel visuo-spatial (Go-NoGo) continuous performance tasks (vsCPT) designed to elicit processing in the ventral and dorsal attention networks under two difficulty levels, ‘1 circle’ (vsCPT1) and ‘4 circles’ (vsCPT4). ERP data from each condition was analysed using partial least squares to identify neural processing components related to world ranking.

Results: Partial least squares analysis of 16 elite players using world ranking as a regressor identified components with highly significant correlations with world ranking, and large effect sizes, in all conditions of the vsCPT. Correlations of these components with each other and with world rankings, and inspection of spatial-temporal electrode weights revealed all 4 components to be highly similar networks.

Conclusion: This study has demonstrated the validity of the vsCPT as an ERP measure of cognitive processing in neural networks which contribute to the world ranking of elite table tennis athletes. Neurocognitive processing is an important factor in elite table tennis performance. Neuromodulation training of these networks may contribute to future athletic success.

Keywords: Event related potential, visuo-spatial attention, Go-NoGo, partial least squares, performance enhancement, table tennis.

Introduction

Humans have the ability to increase performance through neuro-plastic change. As a result, Electroencephalography (EEG) research has been growing in both the clinical (Sakkalis, 2011) and performance enhancement fields (Cannon et al., 2007) in order to assist the development of techniques to re-train the brain. The purpose of this study is to add to the field of performance enhancement literature by demonstrating the contributions of a new task, the visuo-spatial Continuous Performance Task (vsCPT; Brown, Jamieson, Tordoir, Evans & Cooper, submitted), to identify neural components in the EEG of cognitive processes that directly contribute to success in elite table tennis competition. Ultimately, these results may assist in the development of protocols for neuro-modulation training, such as Neurofeedback, to assist talented young athletes to become elite players.

Event Related Potentials as cognitive markers

Mental operations, such as those involved in perception, selective attention, language processing, and memory, proceed over time ranges in the order of tens of milliseconds. Event Related Potentials (ERPs), averages of fixed segments of EEG time locked to a common processing event can provide a sensitive measure of the time sequence of the neural processing events unfolding in the brain during specific cognitive operations (Rugg, & Coles, 1995).

ERPs related to peak sporting performance will differ depending on the elite cognitive skill elicited in specific sports and may vary considerably between elite fields (various sports, professional careers, etc). No ‘normative sample’ of performance related ERPs is currently available in any sport to be used as a reference marker to guide neuro-modulation training for peak performance. As such, extended research is needed to identify the neural circuitry involved within specific peak performance fields and their corresponding specialised cognitive demands.

ERPs and table tennis

Table tennis players must process a significant amount of visuo-spatial information within a constrained time window in order to identify and select salient information, inhibiting irrelevant information, plan a motoric response and finally execute actions appropriately and quickly. As such, table tennis athletes represent an ideal population to study superior development of visuo-spatial attention to guide the selection (or inhibition) of trained motor responses.

It is the ventral and dorsal attention systems which respond to visual processing outputs of the 'what' and 'where' pathways of visual information processing respectively (Corbetta, & Shulman, 2011). Salient stimuli must be detected in the environment (ventral attention system) and those sources of visual information must then be utilized to guide and select successful goal-directed behaviour (dorsal attention system) (Eckert et al., 2009). The visuo-spatial Go-NoGo task (visuo-spatial continuous performance task; vsCPT) adopted here is explicitly designed to evoke time locked neural processing throughout these interacting neural networks. This novel Go-NoGo task requires no sport-specific knowledge and can be employed to test the efficiency of underlying networks/cognitive skills employing ERP/behavioural measures in individuals with different levels of sport specific motor skills.

The visuo-spatial Go-NoGo paradigm

Typically, a 'Go-NoGo paradigm requires subjects to generate an overt or covert response (e.g. press a key or count) to one stimulus event type (Go) and to withhold the response to another type of stimulus event (NoGo) (Pfefferbaum, Ford, Weller, & Kopell, 1985). For example, in the Continuous Performance Task (CPT; Rosvold, Mirsky, Sarason, Bransome Jr, & Beck, 1956) widely used in clinical neuropsychological assessments a series of visual stimuli are presented in the centre of the visual field and participants make or withhold a response depending on what kind of stimulus appears.

Two features of the ERP waveform have been reliably associated with the Go-NoGo manipulation: (i) an enhanced positive peak at anterior electrodes in NoGo relative to Go ERPs in the 300–500 ms range post stimulus onset, referred to as P3 (Roberts, Rau, Lutzenberger, & Birbaumer, 1994) and (ii) a larger negative shift (N2) relative to Go stimuli, with a central-anterior scalp distribution (e.g. Jodo & Kayama, 1992; Eimer, 1993). Traditionally, N2 and P3 amplitude differences have been assumed to reflect the inhibition of the prepotent response in NoGo trials (N2 and P3 latency effects have also been found, (Lavric, Pizzagalli, & Forstmeier, 2004).

ERP research using a conventional form of the Go-NoGo task has been conducted on basketball players (Nakamoto & Mori, 2008a); baseball players (Kida, Oda & Matsumura, 2005; Nakamoto & Mori, 2008b); and fencers (Chan, Wong, Liu, Yu & Yan, 2011; Di Russo, Taddei, Apnile & Spinelli, 2006). Results show faster responses and fewer errors in athletes when compared to non-athletes in Go-NoGo tasks where subjects are required to refrain from responding to the NoGo signals. Di Russo et al. (2006; as cited in Wang, et al., 2013) found that fencers responded faster with respect to non-athletes selectively in the mixed go no-go stimulus condition rather than in the simple response stimulus condition, suggesting that sport training may result in enhanced control of response selection/inhibition. Most sport related (visual) ERP research (e.g. Hung, Spalding, Maria, & Hatfield, 2004; Hack, Rupp, & Memmert, 2009), have required participants to focus visual attention on the centre of their visual field. However, the use of salient information from the peripheral visual field is an additional cognitive feature present in many athletic events requiring the rapid selection of a response to the actions of an opponent.

The Current Study

It has been proposed that the vsCPT elicits specific cognitive processes, as distinct from actual motor skills, which contribute to elite performance in table tennis and functionally related sports. If this is correct then it is expected that the neural network activity expressed in the ERPs of the vsCPT stimulus conditions will directly predict the world rankings of elite table tennis players.

Access was gained to a group of professional table tennis athletes throughout the 2013 European competition season. This study was able to test players that were competing in several championships all over Europe. We measured EEG in these players as they undertook the vsCPT. Averaged ERPs were then calculated for stimuli at each level of each condition in this task to identify the neural counterpart of cognitive processing required by this purpose built task. World ranking was then employed as the regressor in a behavioural partial least squares analysis of the ERPs (PLS; McIntosh, & Lobaugh, 2004) to identify components of the vsCPT (functional neural networks) related to elite table tennis performance.

The aim of the current study is to evaluate the claim that functional neural network activity implementing the cognitive processing demands of the vsCPT, a task which requires attention to rapidly changing visual spatial cues in order to correctly select (or inhibit) required motor responses, predicts the level of sport performance (current world rankings) in elite table tennis players. The vsCPT was designed to reproduce key cognitive processing requirements for successful responses to the fast-paced visual stimuli found in table tennis, particularly in elite competition. It specifically focuses on the chain of cognitive processing which detects changes in the visual field, discriminates salient and non-salient events and makes this information available for the guidance of motor decision making. That is, the processing steps which must be implemented in the brain prior to the initiation of highly trained motor skills. It is expected that these neuro-cognitive processes play a critical role in the effective utilisation of physical attributes and trained motor skills by table tennis athletes in a competitive situation.

In this study the method of partial least squares (Krishnan, Williams, McIntosh, & Abdi, 2011) is employed to identify components in the ERPs elicited by the vsCPT that contribute to world rankings in a group of elite players participating in the 2013 World Table Tennis Championships, Paris. It is predicted that significant relationships with world ranking will be found for PLS components of the ERP in each condition of the vsCPT. However different task conditions are expected to make different processing demands (Go versus NoGo trials and high versus low visuo-spatial working memory load). Therefore, it is also expected that distinct neural networks (hence different ERP components) will be related to world rankings in each vsCPT condition.

Method

Participants

206 table tennis players were recruited representing elite and non-elite but experienced (amateur) performance from across the International Table Tennis Federation (ITTF). From this group, a sample of ‘elite’ players was selected with a World ranking (WR) ranging from 20 – 261 (*M* = 134, *SD* = 81.6). The average age of this elite group was 28.6 (range from 18-47 years, *SD* = 8.5), this group consisted of 6 female and 10 male players. Participants were screened for current psychoactive medications, history of epilepsy in the family, and gave biographical data: age, gender, ranking, years played at greater than 10 hours per week, current level of education and email contact details. All data were treated with

confidentiality and the experiment was approved by the Human Research Ethics Committee of the University of New England.

Measures

Visual Spatial Continuous Performance (Go-NoGo) Task (vsCPT). The vsCPT was specifically developed as a behavioural task in order to assess the aspects of visual attention, decision making and motor control directly required by the cognitive processing demands (but not the motor programming and execution skills) of correctly responding to the motion of an opposing player. This task requires distinguishing salient from non-salient events at different spatial locations and selecting the former to guide motor responses while inhibiting motor responses to the latter, that is, the interaction of the dorsal and ventral attention networks with frontal networks of motor control (Szczepanski, Konen, & Kastner, 2010; Umarova et al., 2010; Vossel, Geng, & Fink, 2014).

The vsCPT is a unique adaptation of the widely used continuous performance task (a Go-NoGo task using images of different types of object) to the visual-spatial attention demands of response decisions required in table tennis which are triggered by visual events at specific spatial locations. In this task participants respond (Go) or withhold response (NoGo) to rapidly occurring visual stimuli depending on the spatial location of each stimulus.

Each of the two go-nogo continuous performance tasks included 192 trials – 96 ‘Go’ and 96 ‘NoGo’. After an initial delay of 300ms the participant was exposed to stimulus 1 for 100ms. Stimulus 1 consisted of a target area (represented by either 1 grey coloured circle outline in the ‘1 circle’ task (vsCPT1) or 4 circles in the ‘4 circle’ task (vsCPT4)). The difference between the two tasks was the level of visual working memory demanded between the instruction cue offset and stimulus onset. A jittered delay of 1100, 1300, 1500 or 1700ms proceeded stimulus 2, also with an exposure of 100ms, consisting of a small black dot somewhere either slightly inside or slightly outside where the stimulus 1 circle had previously appeared. The participant was instructed to click the left mouse button for ‘inside’ the circle (‘Go’ response) and not to click if ‘outside’ the circle (‘NoGo’ response) “as quickly and as accurately as possible” (Figure. 1).

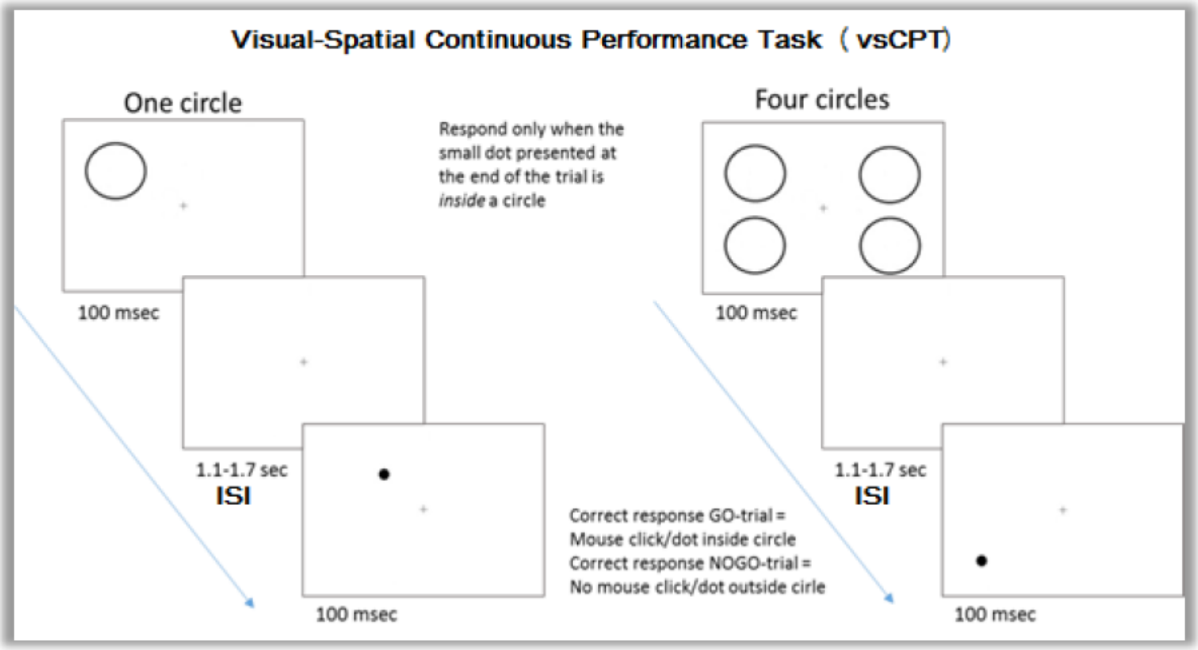


Figure 1. Example of a 'Go' response trial in the two vsCPT tasks. Each circle had 8 possible 'Go' responses and 8 possible 'NoGo' responses. Of the 192 trials, there were 96 'Go' and 96 'NoGo' responses. Quasi-randomisation ensured that there were never more than four 'Go' or four 'NoGo' responses in succession. ISI: Inter-stimulus-interval.

EEG recordings and Materials

The EEG was recorded using a stretchable electro cap (Electro-Cap Inc., USA), Quikcells (Compumedics Neuroscan) were inserted into each of the silver-chloride electrodes and foam discs placed at FP1/FP2 were added for participant comfort. Impedance was established using Quikcell electrolyte solution (Compumedics Neuroscan) and maintained under 15kOhms. EEG was recorded continuously from a Mitsar 201 21-channel system (Mitsar, Russia) over 19 scalp locations according to the international 10-20 system (FP1, FP2, F7, F8, Fz, F3, F4, Cz, C3, C4, Pz, P3, P4, T3, T4, T5, T6, O1, O2) and a mid-forehead placement of the ground electrode (Pivik et al., 1993).

Reference ear-clip electrodes were attached to the participant using Ten20 electrode paste and inserted directly into the Mitsar 201 amplifier. EEG data was sampled at 250Hz and recorded onto hard disk for off-line analysis. A Toshiba Satellite Pro Notebook computer (Intel Core 2 DUO CPU) acquired data through WinEEG software (version 2.91.54). A 'slave' laptop computer (Dell Latitude D630, Intel Core 2 DUO CPU) was connected via Comports to synchronise both Go-NoGo tasks, created and displayed with

Psytask software. The ‘slave’ computer screen (30cm x 20cm) was angled perpendicular to line of sight and placed 60cm from the participant.

Procedure

The study was conducted at multiple locations around Europe beginning at the World Table Tennis Championships, Paris, 2013. A high level of consistency between location settings was achieved, controlling for sound interference, participant comfort while seated and dulled lighting. During preparation with the size-appropriate electro cap (ElectroCap Inc., USA), participants read the instructions for the two vsCPT Go-NoGo tasks of 10-minutes each and the 3 continuous EEG recording conditions (EC, EO, VT) which are not reported here. Participants were explained the importance of maintaining a relaxed forehead, jaw and low bodily movement during recording, and any further questions were answered. Participants’ EEG was recorded in the following order:

1. First of the 10-minute Go-NoGo Task (1 circle for odd numbered IDs, 4 circle for even numbered IDs)
2. Break 1-2 minutes
3. Four minutes in a relaxed Eyes Closed state
4. Four minutes in a relaxed Eyes Open state looking at a fixation cross in the centre of a computer monitor
5. Four-minute table tennis video task (see Brown et al., submitted)
6. Break 1-2 minutes
7. Second of the 10-minute Go-NoGo Tasks

Following recording completion, Electro cap and ear clips were removed and residue gel from participants’ ears was cleaned.

ERP data preparation

WinEEG software was used to prepare each EEG file. A common average reference was selected (the average of all other channels at each point forms the reference for each channel at the corresponding point) and a 0.5 to 30Hz band-pass filter was applied. Artefacts from physiological (eye movements/blinks, skin potentials) and non-physiological (electromagnetic interference, electrode popping) sources were removed with independent components analysis (ICA). ICA decomposes the data into maximal information independent components (which extends beyond the simple linear independence of principal components analysis) based on selected parameters (Stone, 2002). Parameters were selected to identify and remove artefact from 0-30Hz > 70mV, 0-1Hz > 50mV, 20-30Hz > 35mV. Automatic artefact detection thresholds were set for the recording at the following bandpass settings: 0-30Hz +/- 70µV, 0-1Hz +/- 50µV, 20-30Hz +/- 35µV. Time segments of +/- 300 ms were marked in the recording around these artefacts and excluded from further analysis. EEG was then divided into epochs from 300 ms pre stimulus until 700 ms post stimulus for each vsCPT stimulus presented. Epochs were baseline corrected over the pre stimulus interval and then visually inspected for any remaining artefacts; contaminated epochs were manually removed. For each participant averaged ERPs were calculated separately for correctly responded stimuli in: go trials 1 circle cue condition, NoGo trials 1 circle cue condition, Go trials 4 circle cue condition, and NoGo trials 4 circle cue condition.

Behavioural Partial Least Squares Analysis

ERPs were analysed using a statistical method known as Partial Least Squares (PLS) analysis (Lobaugh, West, & McIntosh, 2001; McIntosh, Bookstein, Haxby, & Grady, 1996; McIntosh & Lobaugh, 2004) in order to identify the ERP signature of neural networks active in the vsCPT that are related to the differences in world ranking between the players. PLS is a method for determining whether the values of a multivariate dataset are systematically affected by the experimental manipulation. The PLS analysis was performed in MatLab using a software package available from http://www.rotman-baycrest.on.ca/.

PLS analysis assesses the linear relationships between a set of independent measures (in this case the vector of world rankings) and a set of dependent measures (in this case, the total ERP data matrix composed of electrodes x time points x participants). PLS computes the optimal least-squares fit to the cross-block correlation between the independent and dependent measures (Lobaugh et al., 2001), thus enabling the examination of the relationship between neural activity and the independent variable/s (Lobaugh et al., 2001; McIntosh et al., 1996). The analysis identifies the set of latent variables (LV‘s) defined by maximal linear relationships between the set of vectors coding the independent variable/s and the total ERP data matrix. These resultant LV‘s are similar in principle to the factors isolated through factor analysis methods.

Behavioural PLS employs singular value decomposition of the cross-product of the vector/s of independent behavioural observations (in this case there is only 1 independent variable, the players’ world ranking) and the (ERP) data matrix to extract LVs that maximally differentiate covariances in the data. The significance of the LV, the extent to which it is differentiated from random noise in the data set, was determined by permutation testing with

1000 random resamples of the data (Good, 2000; McIntosh & Lobaugh, 2004). Only LVs with p < .05 were retained for interpretation.

PLS also produces 'saliences' which indicate the extent to which each element of the multivariate dataset contributes to each LV. Electrode saliencies are the set of weights at each electrode at each time point in the ERP that define the activity of the LV as a whole. In the case of behavioural PLS the permutation test, indicates whether each of the LVs is statistically significant, and the saliences indicate how the relationship of the LV with world ranking is expressed at each time point of each electrode channels. Bootstrap estimation (Efron & Tibshirani, 1986) was employed to estimate the reliability of the electrode saliencies. Standard errors of the electrode saliencies were calculated by bootstrap resampling with replacement for 500 iterations. Time points where the salience is greater than twice the standard error (and thus reliable) are indicated on the output files with a blue circle above the electrode salience plots.

Results

Behavioural Data

Descriptive behavioural data (accuracy, reaction time and reaction time variability) for Go and NoGo trials of the vsCPT for the 1 circle and 4 circle cue conditions are presented in Table 1 below. Although performance for each behavioural measure is lower in the 4 circle than the 1 circle cue condition (consistent with higher working memory demands) these differences were not significant.

Table 1

Visuo-spatial Continuous Performance Task Behavioural Data.

	vsCPT_1	**vsCPT_4**
‘Go’ Hit	79.4 (11.2)	74.6 (9.3)
‘Go’ RT	390.5 (58.7)	450.9 (63.0)
‘Go’ RTV	12.2 (3.3)	13.7 (4.1)
‘NoGo’ Hit	86.5 (11.7)	78.4 (7.7)

Note. RT = Reaction Time in milliseconds, Hit = percentage accuracy, RTV = Reaction Time Variability. Mean; standard deviation in brackets.

PLS Analysis

The behavioural PLS analysis extracted four latent variables (LV‘s), one for the relationship of world ranking with the ERP in each of the 4 vsCPT conditions: 1 circle Go, 1 circle NoGo, 4 circle Go and 4 circle NoGo. In each case permutation testing showed the LV was highly significant see Table 2 below.

Table 2

Behavioural PLS Latent Variables: Significance by vsCPT condition.

Latent Variable (vsCPTcondition)	Exact probability
vsCPT_1 ‘Go’	.009
vsCPT_1 ‘NoGo’	.007
vsCPT_4 ‘Go’	.007
vsCPT_4 ‘NoGo’	.013

Note. Exact probability determined by permutation testing with 1000 iterations.

The scatterplots and bivariate correlations of each participant‘s world ranking with their total scores for the LV from each vsCPT condition are presented in Figure 2 below. Total LV scores were highly significant and very strongly correlated with world ranking in each vsCPT condition. Effect sizes were large ranging from r^2 = .624 (4 circle NoGo) to r^2 = .826 (1 circle NoGo). Correlations were consistently negative for both 1 and 4 circle go conditions, as total LV increased world ranking was superior (hence numerically lower). Positive correlations were found for the respective LVs in the 1 circle and 4 circle go conditions, as total LV increased world ranking was inferior (hence numerically greater).

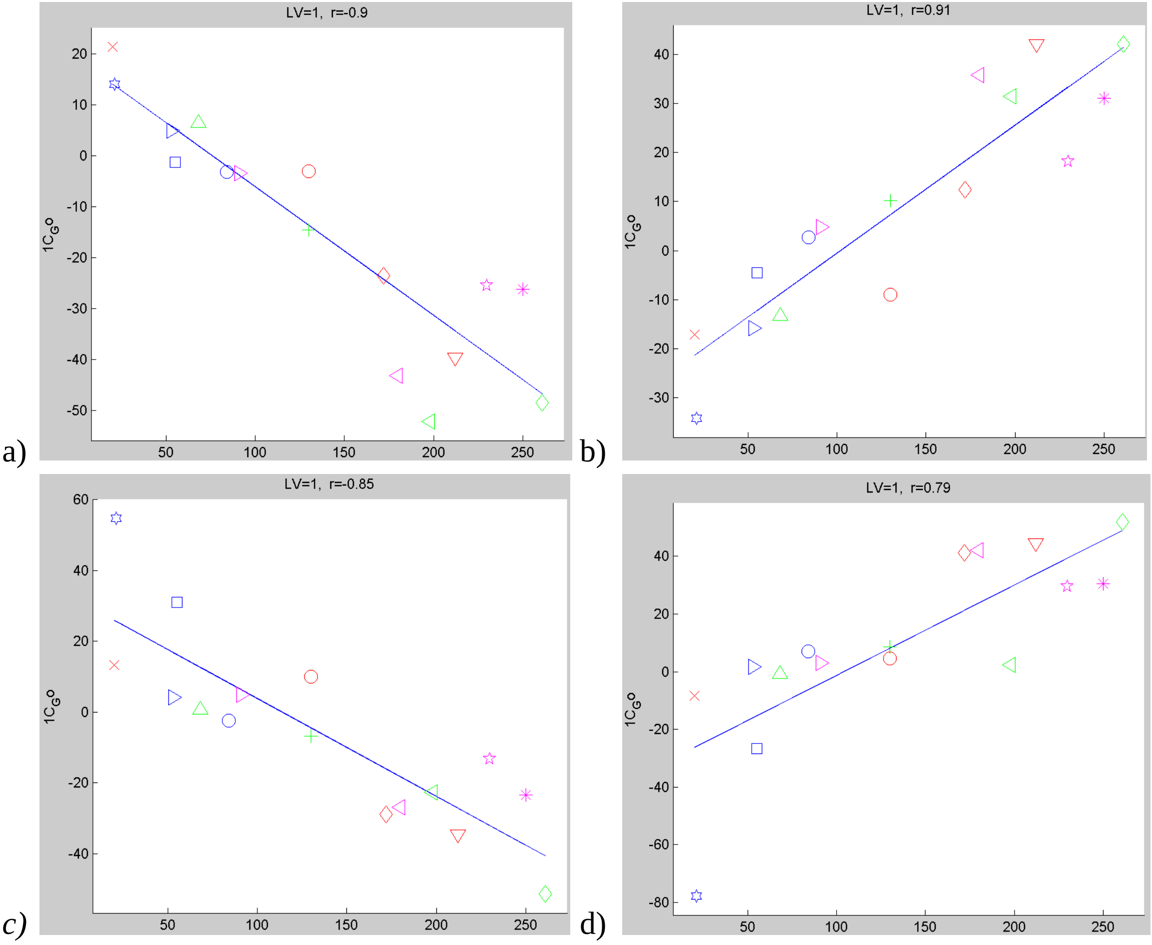
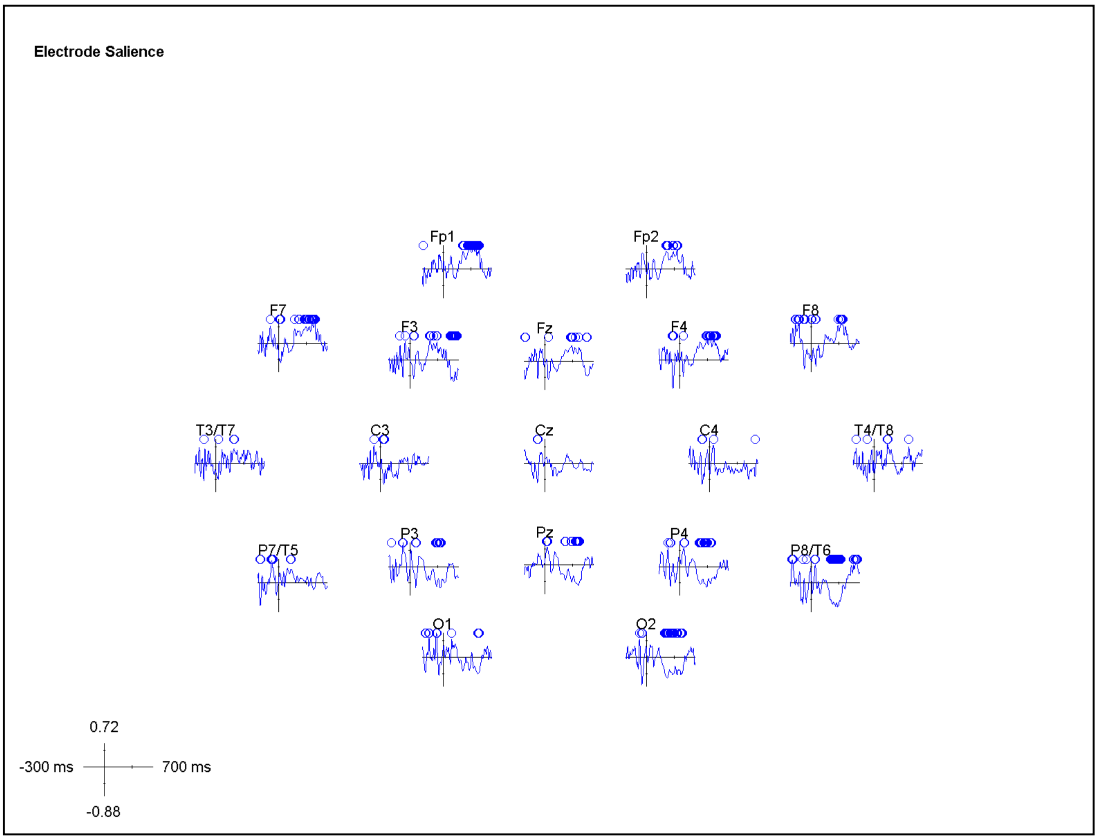


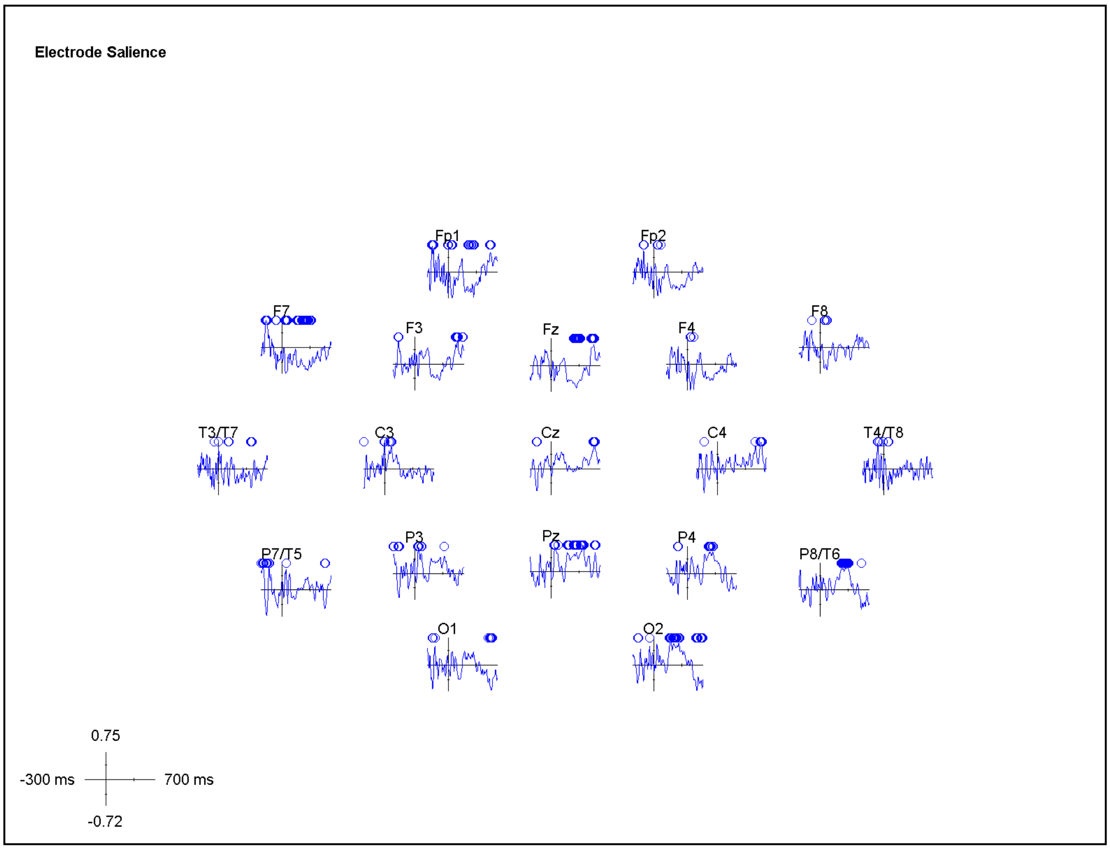
Figure 2. Scatterplots and bivariate correlations of each participant‘s world ranking with their total scores for the LV from each vsCPT condition.

Note. A) vsCPT1 ‘Go’, b) vsCPT1 ‘NoGo’, c) vsCPT4 ‘Go’ and, d) vsCPT4 ‘NoGo’.

The electrode saliencies of each LV are shown above the electrode labels in Figure 3 below. Visual inspection shows the topography and timing of reliable saliencies to be similar across all LVs. However where and when saliencies are negative for 1 and 4 circle Go trials, they tend to be positive for 1 and 4 circle NoGo trials and vice versa.


Electrode Salience
Fp1
Fp2
F7
F3
Fz
F4
F8
T3/T7
C3
Cz
C4
T4/T8
P7/T5
P3
Pz
P4
P8/T6
O1
O2
0.72
-300 ms
700 ms
-0.88

a)


Electrode Salience
Fp1
Fp2
F7
F3
Fz
F4
F8
T3/T7
C3
Cz
C4
T4/T8
P7/T5
P3
Pz
P4
P8/T6
O1
O2
0.75
-300 ms
700 ms
-0.72

b)

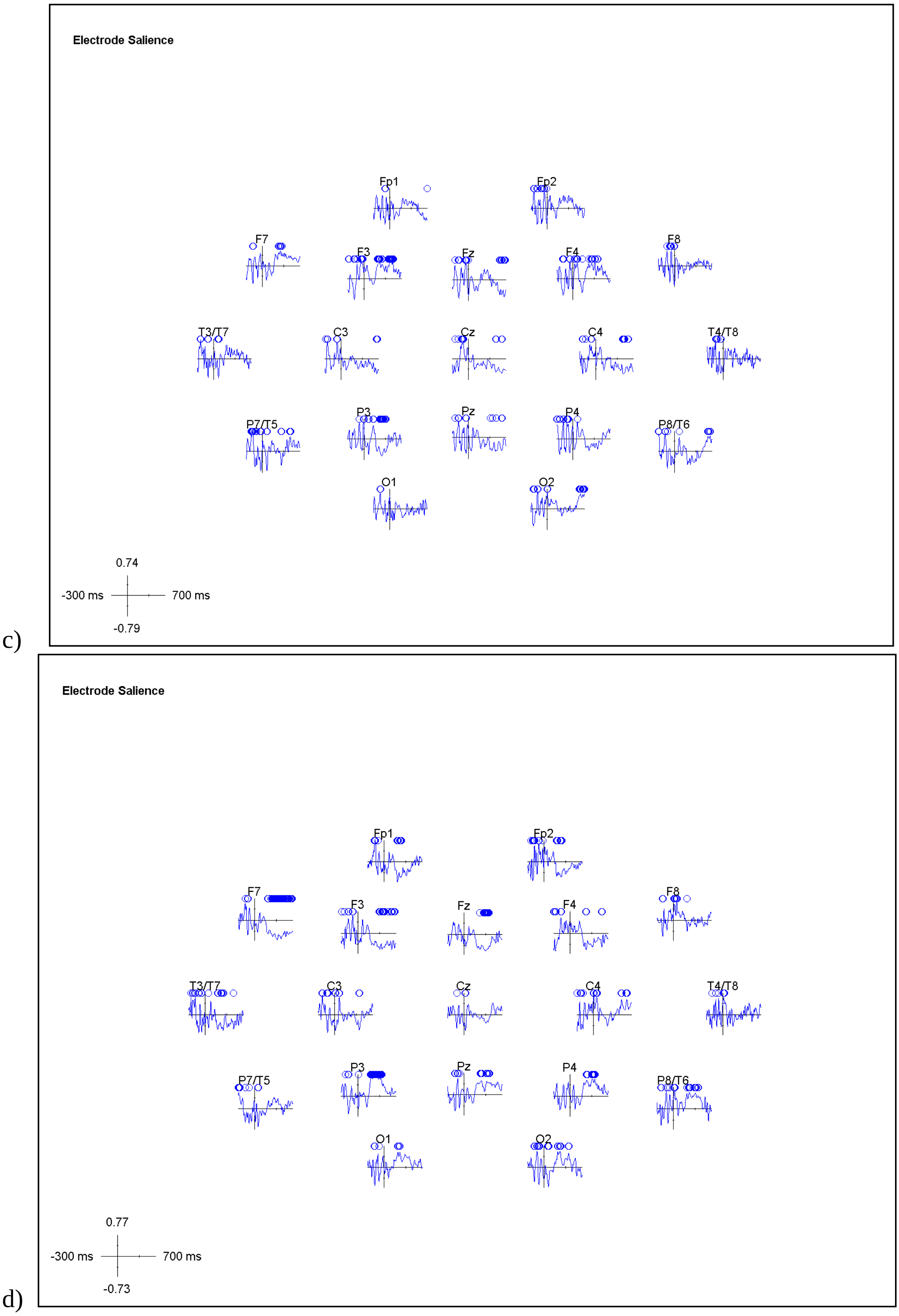


Figure 3. Electrode saliencies of each LV.

Note. Topography and timing of reliable saliencies, determined by boot-strap test, are indicated with blue circles. A) vsCPT1 ‘Go’, b) vsCPT1 ‘NoGo’, c) vsCPT4 ‘Go’ and, d) vsCPT4 ‘NoGo’.

This impression is confirmed by the correlations between total LV scores for each of these LVs, presented together with their world ranking correlation in Table 3 below. Despite being derived from vsCPT conditions with distinct and specific cognitive demands the total LVs were highly intercorrelated; 1 and 4 circle Go trial LVs were highly positively correlated as were 1 and 4 circle NoGo trial LVs however in each case LVs for Go and NoGo trials were highly negatively correlated.

Table 3

Correlations Between World Ranking and Latent Variable Scores for Each vsCPT Condition

Measure	**GO Task – One Circle**	**NOGO Task – One Circle**	**GO Task – Four Circles**	**NOGO Task – Four Circles**
World Ranking	-.900**	.908**	-.854**	.794**
GO Task – One Circle		-.945**	.838**	-.715*
NOGO Task - One Circle			-.895**	.826**
GO Task - Four Circles				-.945**

Note: N = 16. *p < .01 , **p < .001

It appears that each of the LVs (across all conditions) index essentially the same sequence of neural processing steps. Electrode saliences are analogous to factor coefficients, providing weights for the computation of LV scores from the raw data. Just as the sign of factor coefficients is arbitrary (so long as consistent) so too are PLS electrode saliencies. Thus the negative correlation of Go LVs with world ranking and the positive correlation of the NoGo LVs with world ranking appear to reflect the same relationship between neural processing responses in the vsCPT and competitive success in this elite group of table tennis athletes.

Discussion

A visuo-spatial (Go-NoGo) continuous performance task (vsCPT) was devised to index cognitive processing in the pathway leading from a changing visual stimulus to the control and selection of skilled motor responses in table tennis athletes (Brown et al., submitted). The design of this task was informed by recent cognitive neuroscience developments in the understanding of dorsal (executive) and ventral (salience) networks. Conceptually the task was expected to elicit neural processing in (and between) these extended networks that directly overlapped similar processing required to control motor responses to an opponent's play in an actual match situation. This functional neural network activity was assessed by means of ERP. It was predicted that components of the vsCPT ERPs would directly contribute to superior performance as indicated by the ultimate performance indicator, a players' current world ranking.

This prediction was directly supported in each of 4 performance conditions (comprised by Go or NoGo trials with either low or higher visuo-spatial working-memory demands) of the vsCPT. PLS, a particularly useful analysis tool for assessing the relationship of brain activity with experimental manipulations and behavioural measures, identified highly significant components of the ERP with strong relationships to world ranking in each of these conditions. The significance of each component (LV) was assessed by random permutation testing and indicates that it is not spurious noise optimally fitted by the PLS analysis (see Table 2 above). The magnitude of the relationship with world ranking is given through the simple correlation of the LV (see Table 3 above). These correlations were highly significant even in this relatively small sample and each accounted for between 62 and 83 percent of the variance in world ranking. The magnitude of these relationships demonstrates that, amongst elite table tennis athletes, the cognitive processing response of neural networks plays a major role in competitive success. This finding is extremely important for athletes and coaches as it suggests the possibility of developing training protocols, such as neurofeedback, to directly target the efficiency of neural processing in these networks.

It was further expected that distinct components, corresponding to functional network differences, would be related to world ranking in different conditions of the vsCPT, in particular differences were expected between Go and NoGo trials and between 1 circle and 4 circle cue conditions. This did not emerge. ERPs from each of these conditions were analysed separately in the behavioural PLS however the magnitude of the correlations between these LVs (Table 3 above) and the temporal-spatial pattern of the saliences which define each LV (see Figure 3) indicate that these LVs are indexing essentially the same neural processing response in each of these conditions.

This study has demonstrated the validity of the vsCPT as an ERP measure of cognitive processing in neural networks which largely contribute to the world ranking of elite table tennis athletes. This processing is prior to the selection and execution (or non-execution) of actual motor responses. It is likely that these networks provide the inputs required for the efficient and effective control of motor performance however this study stops short of identifying those cortical sources. It is expected that these networks will play a role in the competitive performance of athletes in sports with functionally similar cognitive processing demands (e.g. tennis). These are issues which await resolution in future studies. The importance of neurocognitive processing as a factor in elite table tennis (and similar) performance strongly suggests the development of methods to directly train these networks (neuromodulation) in addition to training targeting motor skills and physical attributes to maximise athletic success.

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Statement of Originality:

We, the PhD candidate and the candidate's Principal Supervisor, certify that the following text, figures and diagrams are the candidate's original work.

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Event-related potential biomarker of visuo-spatial attention predicts world rankings of elite table tennis athletes

Statement of Contribution by Others:

Trevor Brown	70%
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Dr Nicholas Cooper	5%
Ian Evans	5%
Quirine Tordoir	5%

Chapter 4

sLORETA Neurofeedback Enhances Neural Efficiency of Upper-Alpha Inhibition-Timing Control during Visuo-Spatial Processing in Elite Table Tennis Players

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Abstract

Background: Electroencephalography (EEG) biomarkers have been identified in clinical populations with cognitive and behavioural deficits and are employed to guide treatment of these deficits. Similarly, identification of EEG biomarkers of superior performance in elite athletes may be used to guide performance enhancement psychophysiological training interventions. The aim of this study was to use a previously identified EEG indicator of visuo-spatial processing of opponents' motion in elite table tennis players as the basis for a peak performance sLORETA Neurofeedback (sLNFB) protocol used with a group of nationally ranked table tennis players.

Method: 19 nationally ranked European players participated in a table tennis training camp for 12 days. All 19 players undertook intensive table tennis training (5 hours per day), while an experimental group of 10 players also participated in 15 x 30 minute sLNFB sessions training right BA6 (supplementary motor cortex, MNI coordinates 40 -10 35) and right BA13 (insula, MNI coordinates 35 -15 20) to increase amplitude in the frequency band 10.5 – 11.5 Hz. Pre-post sLNFB testing consisted of QEEG recording in Eyes Open, Eyes closed, an active video-viewing task (VT), two visual-spatial attention tasks (vsCPT1 and vsCPT4) and responded to the Dimensions of Attention Questionnaire (DAQ) after sLNFB session 1, 5, 10 and 15.

Results: Source localisation revealed a significant decrease in Mu 11Hz activity pre-post training camp during the VT task in both the experimental and control groups in right BA 6 and right BA 40 respectively. Behavioural results showed vsCPT 1/vsCPT4 NoGo accuracy improvements, but slower go reaction times post-NFB. DAQ Flexibility rating significantly improved throughout the camp for the NFB group and was significantly correlated to a post training increase in lower alpha at 8.2Hz.

Conclusion: Changes in source EEG pre-post table tennis training plus Mu (11Hz) sLNFB provide elite players with a method of increasing neural efficiency in inhibition-timing control of visual spatial processing of an opposing player's motion.

Keywords: sLORETA Neurofeedback, alpha, upper-alpha, inhibition-timing, visuo-spatial attention, performance enhancement, table tennis.

Introduction

Interest in the field of Neurofeedback (NFB) training has been steadily growing from its original use as a clinical application to treat epilepsy to its potential to enhance performance in healthy populations in the fields of cognition, sports, and the creative arts (Babiloni et al., 2009; Gruzelier & Egner, 2005; Niv, 2013; Sterman, 1996). To appreciate how NFB training enhances performance and to set efficient NFB protocols it is vitally important to understand the neural mechanisms of optimal performance and the role of specific cortical activity in making this possible. With that intention, Brown, Jamieson, Tordoir, Evans, & Cooper (submitted) compared elite table tennis athletes to an amateur group while watching an elite player from an opponent's perspective and imagining oneself playing against him. Maximal source differences were found in right Brodmann Area (BA) 6, supplementary motor cortex, and right BA13, insula, at 11.25Hz (Mu rhythm). The authors suggested that the role of the Mu rhythm in the supplementary motor cortex and insula involve the interaction of the dorsal attention network (visual-spatial sensory selection) and ventral attention network (sensory salience detection). Furthermore, they hypothesise the functional role of alpha in elite visual-spatial performance is to phase-lock cortical processing with incoming stimuli and to inhibit processing of irrelevant sensory information through an inhibition-timing mechanism termed 'pulsed-inhibition' (Mathewson et al., 2011).

The purpose of this study is to further the work commenced by Brown et al. (submitted) by using the identified EEG indicator of elite performance (Mu in right BA6 and BA13) to increase visual-spatial attention flexibility in developing table tennis players. We aim to train self-regulation of Mu like activity in the right BA6 and right BA13 through NFB training. Table tennis players will train their EEG with contingent reward for up regulating (synchronising) upper alpha activity at 11.25Hz at both the above sources while viewing table tennis video stimuli. We hypothesise that amplitude of Mu related activity will increase at these sources post-NFB training particularly when processing vision of a 'virtual opponent'.

NFB and performance enhancement in sports

Elite athletes have been found to differ from amateur and non-athletes in terms of alpha (8-12Hz) cortical activity (Babiloni et al., 2008; Del Percio et al., 2007a; Del Percio et al., 2007b). Not only is this difference clear between elite, amateur, and non-athletes but also within athletes (Loze, Collins, & Holmes, 2001). With patterns of alpha able to differentiate between elite and amateur athletes as well as good versus bad performance, the study of alpha patterns and how they can be modulated with NFB to enhance sporting performance has blossomed (Babiloni et al., 2008; Babiloni et al., 2009; Del Percio et al., 2007b; Loze et al., 2001).

Despite the relationships observed between patterns of oscillatory activity and enhanced sport performance (for an extensive review see Cooke, 2013), investigations of the usefulness of NFB in facilitating optimal sport performance are extremely limited. In the last decade very few studies have been published investigating the use of NFB in the development of expertise and excellence in sport (Arns, Kleinnijenhuis, Fallahpour, & Breteler, 2008; Ring, Cooke, Kavussanu, McIntyre, & Masters, 2014; Rostami, Sadeghi, Karami, Abadi, & Salamati, 2012) and although results are not conclusive, they are certainly promising. Rostami and colleagues (2012) examined the effect of NFB on the improvement of rifle shooters' performance. The aim of the NFB protocol was to increase the power of the sensory motor rhythm (13 – 15 Hz) over central motor areas. A significant improvement in shooting accuracy was found for the NFB group when comparing pre- to post-test results, whereas no improvements were found in the control group who were not given NFB training. Unfortunately it was not possible to evaluate whether these marksman were able to regulate their brain activity outside of NFB training because there were no measures of EEG activity obtained during the pre and post NFB training (Rostami et al., 2012). Therefore, it remains unclear whether improvement can be attributed to the learning targeted by this NFB training.

In 2008, Arns and colleagues established a NFB protocol in which the training parameters were based on personalized event-locked EEG profiles of amateur golf players. These EEG profiles were created by recording EEG during golf-putting sessions in which successful putts and unsuccessful putts were compared for each person individually, resulting in a personalized and customized NFB protocol for each player. A personal event-locked EEG frequency profile was determined for successful versus unsuccessful putts and used to derive personalized target frequencies for the NFB training protocol. Furthermore, NFB training was given in a real-life golf setting. During a session, participants received feedback on their brain pattern through a go/no-go tone which was terminated when their EEG signal was above or below the target thresholds determined by their personalized profile for successful versus unsuccessful putts. Participants were required to putt within 1.5 seconds of the termination of the go/no-go tone. The percentage of successful putts were significantly larger (on average 25% larger) for sessions where the participants received this NFB compared to the sessions without NFB training (Arns et al., 2008). This study encourages the further investigation of NFB training as a means for enhancing sport specific skill performance.

In a recent study, Ring and colleagues (2014), investigated whether golfers could learn to regulate their EEG activity when undergoing NFB training. The NFB group was trained to reduce their upper alpha (10 – 12Hz) power over motor and premotor areas prior to putting. In line with the study by Arns et al. (2008) a tone informed the participant whether they were above or below the threshold. The control group received the same procedure, except the occurrence of the tone was not influenced by their EEG activity. Golfers participating in the NFB group were able to control their pattern of cortical activation, but the NFB training failed to enhance performance. Improvement increased equally for both groups, despite successful modification in frontal high alpha power in the NFB group (Ring et al., 2014). The researchers argue that this could be due to a lack of understanding about the cortical correlates of expertise. They suggest that future studies should gain more insight into the neurophysiological mechanisms of sport specific excellence so as to refine NFB protocols.

Different sports, or even different performance components within one sport, can be expected to make different demands on the brain. NFB training has been shown to be able to improve specific aspects of performance at certain electrode locations, but when training occurs at different electrode locations performance can even decrease (Landers et al., 1991). Moreover training a specific frequency band does not always result in the desired modulation of amplitude of that frequency and/or enhancement in cognitive performance (Ring et al., 2014; Vernon et al., 2003). Furthermore it proves to be challenging to empirically and/or theoretically underpin and define a relevant target for a NFB protocol (Arns et al., 2008; Ring et al., 2014; Rostami et al., 2012). Thus, it is essential to determine the specific spatial pattern of cortical activity that is related to expertise and its underlying cognitive processes in order to train the brain for effective performance enhancement through NFB.

In order to determine the cortical network activity supporting table tennis players' superior mental processing of salient visuospatial cues for the guidance of response selection, Brown et al. (submitted) recorded EEG from over 200 table tennis players while watching a video of an elite player from an opposing player's perspective and imagining oneself playing against him. Elite table tennis players were found to be maximally differentiated from lower-level but experienced ‘amateur’ players by high Mu power in right BA6 and BA13 which may, in the future, be used as an indicator of high visual-spatial performance. Source activity in this frequency band at those voxels showing peak differences between elite and club players, and which was recorded during the execution of sport specific mental skills was significantlty related to objective visuospatial GoNoGo task performance. However, mean bandpower in the CAR, which reflects global cortical activity rather than topographically specific activity at localised sources was found to be unrelated to those performance measures.

The performance of an elite table tennis player is so acutely tuned to the identification and the timing of an opponent’s visual cues. Brown et al. propose that this process visual selection for action is coordinated through top-down modulation of phase-locked pulses (see Mathewson et al., 2011) of high amplitude alpha oscillations in right BA6 and BA13. They suggest that the *timing* function of alpha oscillations is intrinsic to its role in the mental processes critical to success in the sport of table tennis. Furthermore, it was suggested that the high amplitude Mu (11.25Hz) found in the elite population may be trained via NFB to increase performance of visual-spatial attention as players regulate the timing aspect of their Mu oscillations.

Hypotheses

Based on the Mu rhythm (11.25Hz) indicator of play related cognitive processing in elite table tennis players and its’ association with objective performance on visuo-spatial guided motor control (Brown et al., submitted), a NFB protocol was developed using the MNI coordinates from that study corresponding to the max voxel statistic locations within right BA6 and right BA13 respectively. Furthermore, the NFB training modality employed a video jammer device in order to develop players’ control of upper alpha EEG oscillations while they are viewing table tennis match play presented on the video.

A developing group of table tennis athletes underwent NFB training to assess NFB learning during the experimental protocol and to assess the preliminary neurocognitive effects of training this NFB protocol. It was hypothesized firstly (H1) that players would be able to modulate the target frequency at the brain region of interest during administration of the training protocol. This is operationalised as the NFB learning index of percentage of training time for which a reward is received, calculated across successive 5-minute time periods from the beginning to end of each training session (Dempster & Vernon, 2009).

It was also expected (H2) that training in the NFB protocol would increase upper alpha EEG activity in the active VT context at the sources trained following completion of NFB training when compared to the pre NFB training baseline (as assessed by pre- post NFB eLoreta analyses).

In order to assess the effects of NFB training on neurocognitive processes related to conscious attention the Dimensions of Attention Questionnaire (DAQ) was administered at regular intervals throughout the NFB training intervention. It was hypothesised that salient attributes of attentional experience, as measured by the DAQ, would be progressively enhanced during NFB training across the time course of the training sessions (H3).

The pre – post effects of the training protocol were evaluated on objective (behavioural) performance of a Go-NoGo sustained attention task requiring response selection/inhibition to visual-spatial stimulus attributes. It was hypothesized that, following NFB training, performance would be enhanced on objective measures of this attention task which is closely related to table tennis skill (H4).

It was hypothesized that, for any cognitive process enhanced by the neuromodulation effects of NFB training, improved performance on these measures would be directly related to the changes in the EEG observed following NFB training (H5).

Method

Participants

19 table tennis players were recruited during an international table tennis training camp in Denmark. From this group, an experimental group of 10 players (8 male and 2 female: age 16-28, *M* = 20, *SD* = 3.56) were compared against an age and gender matched control group of nine players (7 male and 2 female: age 15-28, *M* = 18.67, *SD* = 4.27) of similar table tennis ability and experience.

All participants, were screened for current psychoactive medications, family history of epilepsy, age, gender, competitive ranking, years played at greater than 10 hours per week, current level of education and email contact details. The experiment was approved by the Human Research Ethics Committee of the University of New England and all participants provided written informed consent.

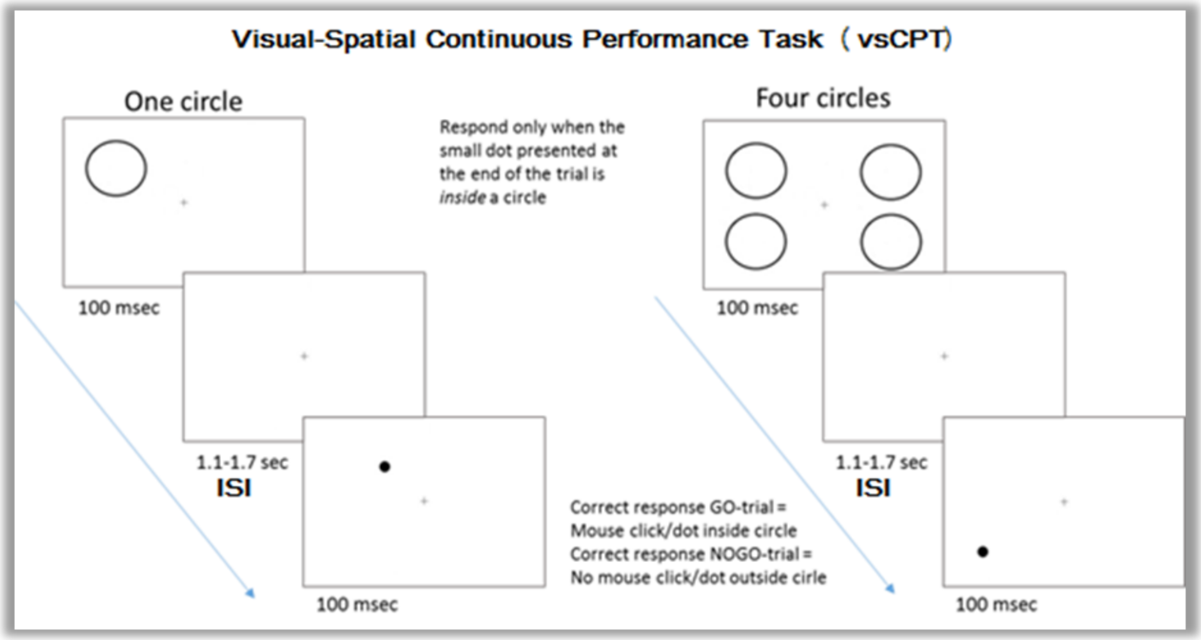
Measures

Pre-Post QEEG Table Tennis Video Task (VT). A four-minute video was prepared by placing a video camera on a tripod 30 cm above a table tennis table (central position) directly behind the baseline. Australia's current number one ranked player (World Ranking 86) was requested to play a variety of shots of elite calibre against an opposing player who returned the ball from behind the camera - a 'player's perspective' video resulted (Figure 1).

Figure 1. Still image of the four-minute table tennis video task (VT). Participants watched this video for four minutes and were instructed to "imagine playing against this player".

Pre-Post visual-spatial Continuous Performance 'Go-NoGo' Tasks (vsCPT). Each of the two Go-NoGo continuous performance tasks included 192 trials – 96 'Go' and 96 'NoGo'. After an initial delay of 300ms the participant was exposed to stimulus 1 for 100 ms. Stimulus 1 consisted of a target area (represented by either 1 grey coloured circle outline in the '1 circle' task or 4 circles in the '4 circle' task). A jittered delay of 1100, 1300, 1500 or

1700 ms proceeded stimulus 2, also with an exposure of 100ms, consisting of a small black dot somewhere either just inside or just outside where a stimulus 1 circle had previously appeared. The participant was instructed to click the left mouse button for ‘inside’ and not to click if ‘outside’ the circle “as quickly and as accurately as possible” (Figure 2).



Visual-Spatial Continuous Performance Task（vsCPT)

Respond only when the small dot presented at the end of the trial is *inside* a circle

Correct response GO-trial = Mouse click/dot inside circle
Correct response NOGO-trial = No mouse click/dot outside cirle

Figure 2. Example of a ‘Go’ response trial in the two vsCPT tasks. Each circle had 8 possible ‘Go’ responses and 8 possible ‘NoGo’ responses. Of the 192 trials, there were 96 ‘Go’ and 96 ‘NoGo’ responses. Quasi-randomisation ensured that there were never more than four ‘Go’ or four ‘NoGo’ responses in succession. ISI: Inter-stimulus-interval.

Dimensions of Attention Questionnaire (DAQ). The DAQ (Pekala, 1991) has been used successfully as a measure of subjective experience of attention in NFB training (Downham, Macnamara, & Jamieson, 2012). The DAQ is a 40-item self-report inventory measuring experience of attention in a specific reference period, in this case the sLoreta NFB (sLNFB) training session. Pekala (1991) demonstrated the reliability of the DAQ when used up to 30 minutes after the state being rated, with groups who rated their attention in preceding states of rest and of hypnosis. Each item in the DAQ is expressed on a 7-point Likert scale with a maximum score of 6 and a minimum of 0. Items are anchored by bipolar statements at each pole. For example, an item from the Flexibility dimension reads, “I felt it very difficult to move and focus my attention; my mind kept returning to certain impressions” *versus* “I was easily able to move, control and focus my attention on whatever impressions came into my mind”.

The DAQ has 12 categories by which to measure dimensions of attention: Simultaneity (SI), Density (DN), Locus (LO), Perspicacity (PE), Attentional Control (CO), Vigilance (VI), Absorption (AB), Direction of Attention (DI), One-Pointedness (OP), Equanimity (EQ), Flexibility (FL) and Detachment (DE). Since the subjective ratings evaluate attention during the preceding 30-minute time period, the questionnaire was completed immediately following allocated sLNFB training sessions (1, 5, 10 and 15).

EEG recordings and Materials

QEEG testing and sLNFB session cap preparation. The EEG was recorded using a stretchable electro cap (Electro-Cap Inc., USA), Quikcells (Compumedics Neuroscan) were inserted into each of the silver-chloride electrodes and foam discs placed at FP1/FP2 were added for participant comfort. Impedance was established using Quikcell electrolyte solution (Compumedics Neuroscan) and maintained under 15kOhms. EEG was recorded continuously from a Mitsar 201 21-channel system (Mitsar, Russia) over 19 scalp locations according to the international 10-20 system (FP1, FP2, F7, F8, Fz, F3, F4, Cz, C3, C4, Pz, P3, P4, T3, T4, T5, T6, O1, O2) and a mid-forehead placement of the ground electrode (Pivik et al. 1993). Linked left and right ear lobes were used as the recording reference and the ground electrode was located at FCz. EEG data was sampled at 250Hz and recorded onto hard disk for off-line analysis. A Toshiba Satellite Pro Notebook computer (Intel Core 2 DUO CPU) acquired data through WinEEG software. A ‘slave’ laptop computer (Dell Latitude D630, Intel Core 2 DUO CPU) displayed the table tennis video task and was connected via Comports to synchronise both Go-NoGo tasks created and displayed with Psytask software. The 'slave' computer screen (30cm x 20cm) was angled perpendicular to line of sight and placed 60cm from the participant.

sLNFB training. The NFB training signal was presented visually using a special purpose electronic unit called a Jammer (HBIMed). In video mode, the biofeedback parameter controls the level of noise generated by the unit which degrades the quality of visual images during video playback. The amplitude of the noise was maximal if the biofeedback parameter was minimal and decreased gradually up to zero (maximum image clarity) as the parameter approached the training threshold. The noise was mixed with the video-signal of the DVD player and was fed to the TV monitor (Figure 3). Thus, the participant controlled the quality of the picture on the screen by his/her EEG: when the biofeedback parameter was higher than threshold, the picture on the screen was clear, otherwise the TV picture was blurred by the noise. In all sLNFB sessions participants watched DVDs of elite table tennis match play. Sound from the DVD was muted.

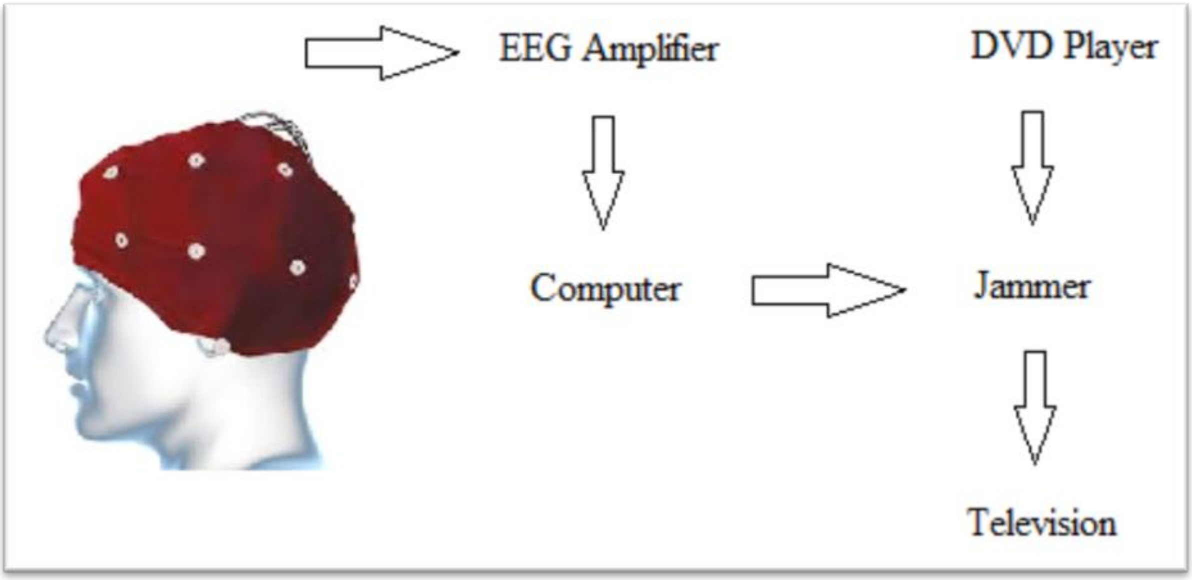


Figure 3. Schematic representation of EEG Amplifier, Computer, Jammer and DVD player interaction. The EEG amplifier receives input from the participant, sending it to a computer which uses BrainTuner software to assess real-time EEG relative to sLNFB protocol parameters. The Jammer receives input from the computer instructing it to 'Jam' the signal flowing from the DVD player to the Television screen when the participant's EEG does not exceed threshold.

Procedure

Pre-Post Camp QEEG testing. During preparation of their head-size matched electro cap (ElectroCap Inc., USA), participants were instructed on the importance of maintaining a relaxed forehead, jaw and low bodily movement during recording and any further questions were answered. Participants read instructions for two 10-minute Go-NoGo tasks (see Measures) and the 3 continuous EEG recording tasks (see Measures). Their EEG was recorded in the order outlined in Figure 4.

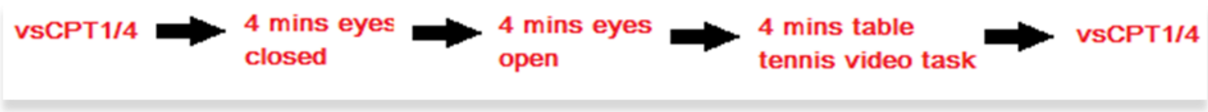


Figure 4. Procedure for EEG recording pre-post NFB sessions.

Participants had a 1-2 minute break after the first 10-minute vsCPT task and before the second 10-minute Go-NoGo task – half the participants commenced with vsCPT1 while the other half commenced with vsCPT4.

sLNFB training. Brown et al. (submitted) reported intrinsic network differences between elite and amateur table tennis players were maximal at two regions of interest (ROI), right BA6 and right BA13, at a frequency of 11 Hz in the VT condition. This activity was in turn found to be significantly related to the processing speed and perceptual sensitivity of these players employing the vsCPT. The ROI and frequency band of sLNFB training in the present study were based on these findings. The sLNFB training frequency bandwidth was set to 10.5 – 11.5 Hz; sLORETA estimated the voxel signal for the coordinates reported in Brown et al. (submitted) to have the greatest statistical difference between elite and amateur groups in - for right BA6 (MNI coordinates 40 -10 35) and right BA13 (MNI coordinates 35 -15 20) respectively.

The participant was informed about the rationale of sLNFB training, as well as about the dependence of the biofeedback signal on their brain activity and attention. Before sLNFB training, participants were encouraged to relax, decrease muscular tension and maintain regular diaphragmatic breath. Participants undertook 15 x 30minute sLNFB sessions over 10 days (either one or two times per day) with one-day break after Day 5. Session times were changed daily and were equally spread between participants. Each session consisted of 5 x 5-minute training periods with 1-minute relaxation after each period.

BrainTuner software was used to control the Jammer module, to set sLNFB parameters and to record the percentage time during training that participants' EEG exceeded threshold in each period. The training frequency bandwidth and the ROI in which the signal was trained were constant throughout the 15 sLNFB sessions, however the EEG power threshold for training rewards were determined at the start of each session. The threshold for reward was set at 90% of average power in the target frequency band in the ROI throughout an initial 2-minute period of viewing a table tennis match at the start of each NFB training session. This threshold level is expected to be that required to deliver reward feedback for about 55% of the time during the baseline period. If the observed signal exceeded that threshold at any data point during each consecutive 0.5 second time segment during any of the training periods in that session a reward point was awarded (and counted towards percentage time spent above threshold) and the television signal was clear. As the training parameter decreased below threshold noise was progressively added to the visual display. For each training period the participant's percentage of time above threshold was calculated to serve as an index of learning performance.

Research Design and Analyses

Design. The experiment was a mixed model ANOVA design with a between groups factor of sLNFB training (experimental group) versus no-sLNFB training (control group), and the repeated EEG and behavioural measures recorded pre and post training camp. Dependent EEG variables were estimated current densities during EC, EO, and VT. The dependent behavioural variables from the vsCPT1 and vsCPT4 were reaction time (RT), reaction time variability (RTV), correct 'Go' responses, incorrect 'Go' responses, correct 'NoGo' responses and incorrect 'NoGo' responses. The DAQ provided a set of repeated measures dependent variables for the experimental group (sLNFB training) only. Participants from both groups played approximately 5 hours per day of table tennis during the 10-day camp.

Behavioural Data Analyses. Reaction time and accuracy data from the vsCPT tasks was analysed in SPSS (Version 20) using a 2x2x2 mixed model ANOVA with factors: group (NFB training/no NFB-training) x time (pre-/post-training) x cue level (1-circle/4-circles).

DAQ dimensions are a set of repeated self-report dependent variables available for the NFB training group only. A polynomial trend analysis was conducted to test for a linear trend for these repeated measures across the 4 consecutive repeated measures with a Bonferroni correction for multiple testing set for the number of dimensions in the DAQ.

Pre-Post Camp QEEG Data Preparation and Analyses. WinEEG software (version 2.91.54) was used to prepare each EEG file. A common average reference was selected (the average of all other channels at each point forms the reference for each channel at the corresponding point) and a 0.5 to 30Hz band-pass filter was applied. Artefacts from physiological (eye movements/blinks, skin potentials) and non-physiological (electromagnetic interference, electrode popping) sources were removed with independent components analysis (ICA). ICA decomposes the data into maximal information independent components (which extends beyond the simple linear independence of principal components analysis) based on selected parameters (Stone, 2002). Automatic artefact detection thresholds were set for the recording at the following bandpass settings: 0 – 30Hz +/- 70µV, 0 – 1Hz +/- 50µV, 20 – 30Hz +/- 35µV. Time segments of +/- 300ms were marked in the recording around these artefacts and excluded from further analysis. EEG was then visually inspected for any remaining artefacts, and contaminated EEG was manually removed. Each 4-minute recording segment was then divided into artefact free epochs of 4000 ms. For the resulting epochs power spectra from 0.5 to 30 Hz with a frequency resolution of 0.25 Hz were calculated in Win EEG by Fast Fourier Transform. These were then averaged for each participant in each condition.

Spectral averages for the VT, EO and EC conditions for each individual in the Elite and Amateur groups were entered into exact Low Resolution Electromagnetic Tomography (eLORETA) software to estimate cortical source activity at each frequency bin (Pascual-Marqui, 2007). A three-dimensional realistic head model represents cortical sources with 6239 5mm voxels (Fuchs, Kastner, Wagner, Hawes, & Ebersole, 2002). Three-dimensional source space is restricted to cortical grey matter as determined by the Talairach Atlas (Lancaster et al., 2000). Discrete measurements of the strength and direction of activity in each voxel determine the distributed density of current source activity (Pascual-Marqui, Michel, & Lehmann, 1994). A linear computation smooths the values of neighbouring voxels. eLORETA has the property of exact localisation of point sources in simulated data, although with low resolution (Pascual-Marqui, 2007). The significance of source activity differences between groups or conditions is determined in eLORETA with a nonparametric randomisation test which estimates the distribution of a test statistic under the null hypothesis (effects of experimental conditions are random) by repeated random permutations of estimated voxel activations across all frequency bins between experimental conditions. This allows the calculation of the exact probability of the obtained test statistic for the difference between conditions at each voxel corrected for testing at multiple voxels (Canuet et al., 2011; Nichols & Holmes, 2002).

Results

Neurofeedback learning index

The percentage of time that the NFB training signal was above the target threshold (set at the beginning of each session) was utilised to assess learning performance during the NFB task. For each participant the mean learning index was calculated for each of the five consecutive periods which comprise each session averaged across all 15 NFB training sessions (Figure 5). One way in which NFB learning has been assessed is by the increase in the learning index across consecutive training periods (Dempster, & Vernon, 2009). Following the analysis methods of Dempster and Vernon (2009) a polynomial contrast analysis was conducted on this mean learning index based on the expectation of a linear trend for improving performance (learning) from the beginning to end of each NFB training session. In this case the result was clearly non-significant, $F(1, 8) = 0.028$, $p = .871$. However, inspection of Figure 5 shows that this was due to an unexpected drop in learning performance in the second training period which then appears to recover linearly over the remainder of the training session.

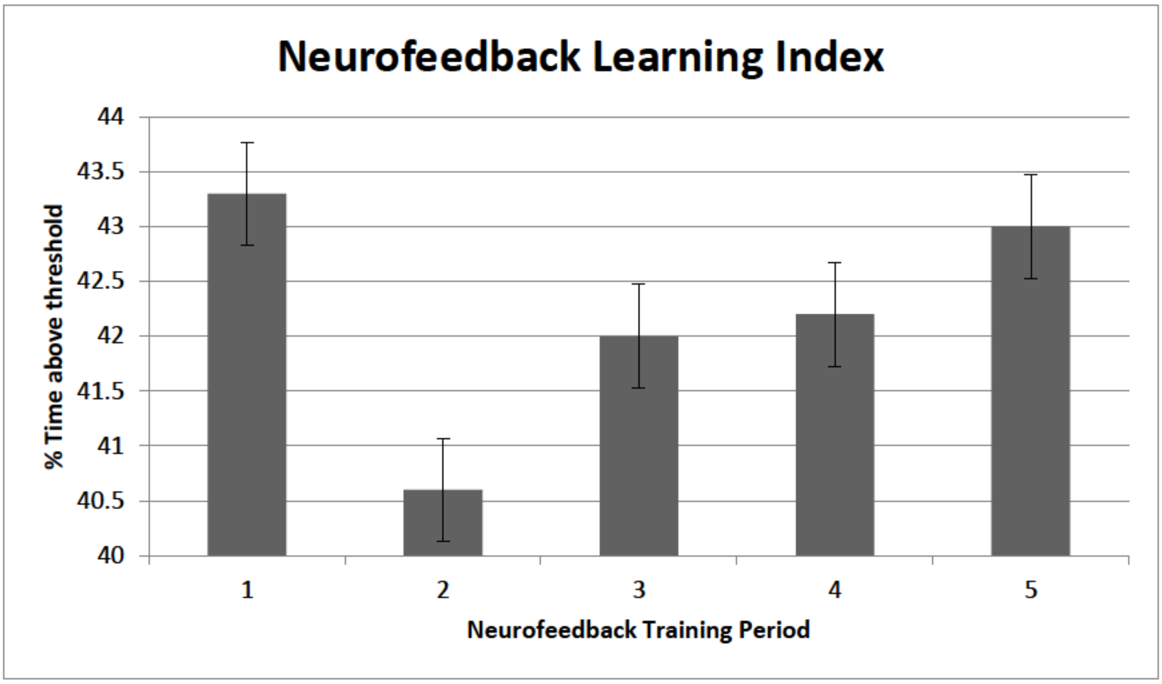


Figure 5. Percentage time participants' sLNFB parameters were above threshold. All 10 participants averaged for each of the 5-minute training periods over each of the 15 training sessions.

Table Tennis Video Task

It was hypothesized that the experimental group would show an increase in trained alpha band power generated by right BA6 and BA13 during active viewing of the VT task after NFB training and that this change would not be observed in the control group who did not receive NFB training. eLORETA analysis was conducted to determine the cortical sources of pre- versus post-NFB training period, VT changes in frequency band trained by NFB for the experimental and control groups respectively.

For the control group a compact cluster of 9 voxels, all located in right inferior parietal lobule (right BA40) were found to have significantly decreased 11 Hz activity during active viewing of the VT task at the end of the testing period. The maximum voxel statistic was located at MNI coordinates (35, -50, 40) with $p < .02$ (Figure 6).

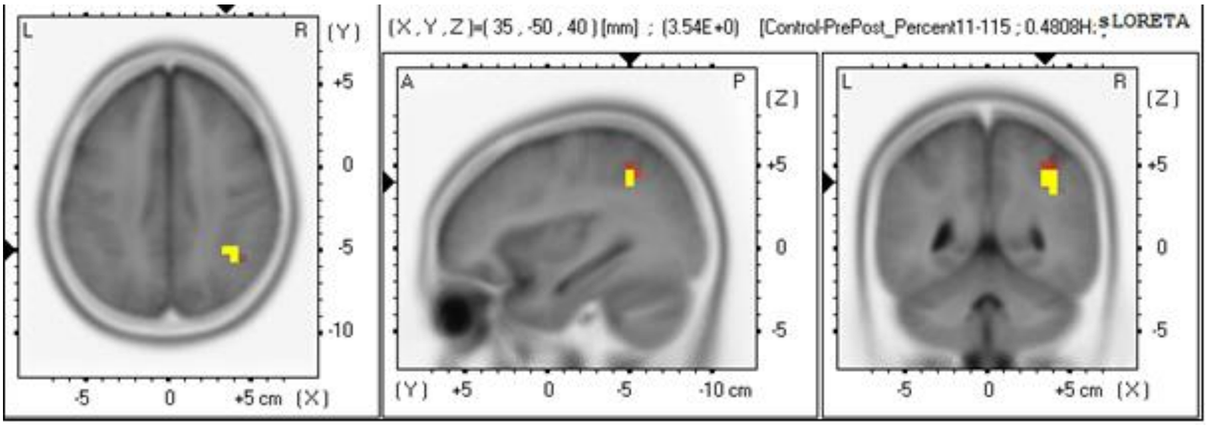


Figure 6. Control group eLORETA images of transverse, sagittal and coronal slices showing a significant decrease in the upper alpha rhythm (at 11Hz) from pre- to post table tennis training camp in right BA40.

For the experimental (NFB training) group a larger cluster comprised of 25 voxels, located across right medial gyrus and superior frontal gyrus (right BA 6) was found to have significantly decreased 11 Hz activity during active VT at the end of the training period. The maximum voxel statistic was located at MNI coordinates (10, -10, 70) with *p* < .03 (Figure 7).

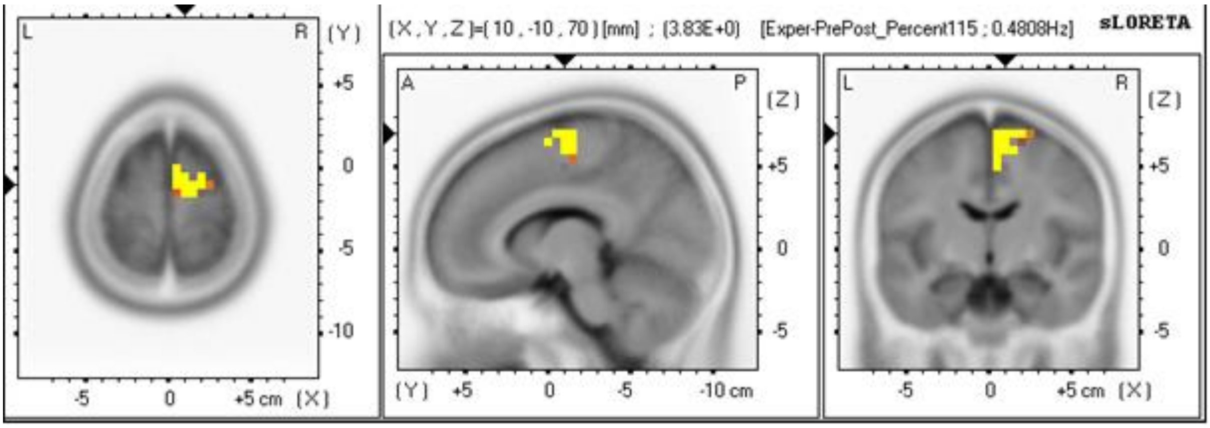


Figure 7. Elite group eLORETA images of transverse, sagittal and coronal slices showing a significant decrease in upper alpha (at 11Hz) in right BA6 from pre- to post sLNFB training (plus participation in table tennis training camp).

Significant source activity decreases were found pre – post training at 11 Hz for both groups but in different areas for the experimental and control group respectively. In the experimental group this was observed in right BA6, one of the regions trained by the NFB protocol and also within the frequency band (10.5-11.5 Hz) that was trained by the NFB protocol. No significant change was observed in the right BA13 training location. In the control group the significant change occurred in right BA40. Contrary to expectations, in both groups 11Hz source activity while watching the table tennis video was significantly lower after the intensive training period than at the beginning.

Common Average Reference (CAR) Channel Band Amplitude Comparisons

Mean amplitude in the frequency range 10.5 – 11.5 Hz was calculated for the CAR channel for the same cleaned epochs in Eyes Closed (EC), Eyes Open (EO) and Table Tennis Video (VT) conditions, pre and post training, in the experimental (NFB training) and controls groups described in the above Method section.

We then conducted a mixed model 3-way ANOVA consisting of 2 repeated measures and 1 between groups factor. The first repeated measure factor was Baseline which has 3 levels: Eyes Closed (EC), Eyes Open (EO) and Table Tennis Video (VT). The other repeated measures factor Time had 2 levels; pre training and post training. The between groups factor consisted of 2 groups, NFB training versus no NFB training. There was a significant effect for Baseline condition, F (2, 34) = 13.199, p=.001, η_p^2 = .437. Consistent with the most robust findings in the alpha band literature the mean band amplitude falls from EC (M = .675, SE = .077) to EO (M = .535, SE = .061) and slightly less so to VT (M = .484, SE = .050).

There was a significant main effect for Time F (1, 17) = 6.827, p=.018, η_p^2 = .287 with mean band amplitude higher post training (M = .592, SE = .059) than pre training (M = .537, SE = .062). There were no other significant main effects or interaction effects (including the NFB group). That is the increase in the average amplitude of the frequency band trained was unrelated to NFB training.

Visuospatial Continuous Performance Task (Go/NoGo) Behavioural Analyses

Accuracy and Reaction Time. In order to test the prediction that experimental group participants would perform better than the control group on the vsCPT tasks post-sLNFB training, reaction time, correct and incorrect responses were compared and analysed for GO-trials. The overall ANOVA was conducted for Group (Control versus Experimental) X Time (pre- versus post-sLNFB training) X task cue (1-circle versus 4-circles). No significant difference was found in performance between the control and the experimental group. There was no significant interaction effect between group and any other factor.

GO-trials: Experimental and Control groups combined. Reaction time was significantly higher at the end of the experiment (436.72ms) than at the beginning for vsCPT1 and vsCPT4 combined (414.38ms); $F(1,15) = 18.089$, $p<.001$, $\eta_p^2 = .547$.

A significant reaction time main effect was also found for task cue (1-circle versus 4-circles). Overall the mean reaction time for participants of both groups was significantly slower in the 4-circles task cue (474.13ms) as opposed to the 1-circle task (376.97ms); $F(1,15)=18.043$, $p=.003$. Reaction time variability was significantly higher in the 4-circle cue task (15.41ms) than the 1-circle cue task (14.03ms); $F(1,15) = 4.942$, $p= .042$, $\eta_p^2 = .248$.

NoGo-trials: Experimental and Control groups combined. Accuracy rates for the NoGo-trials were higher in the 1-circle task (92.29%) than the 4-circles task (84.52%); $F(1,15) = 11.155$, $p = .004$. These findings, taken together with the longer reaction time for GO-trials above, imply that the 4-circles task was more cognitively demanding.

Participants responded to NoGo-trials with significantly greater accuracy after training than before training ($F(1,15) = 9.467$, $p = .008$, $\eta_p^2 = .387$). Accuracy rates for the NoGo-trials were higher post-sLNFB (92.16%) than pre-sLNFB (84.66%). If this were due to a simple practice effect both Go- and NoGo-trials would increase in accuracy but for Go-trials after sLNFB training accuracy was lower (74.07%) than before training (83.10%). Therefore, in this case a practice effect can be eliminated as an explanation.

Participants were significantly less accurate on Go-trials following the intensive training period ($F(1,15) = 6.69$, $p = .021$, $\eta_p^2 = .308$) suggesting that there has been an increased hesitation to respond impulsively on both Go and NoGo-trials alike for all participants across the training period (Figure 8). This is consistent with the significant slowing of Go-responses (longer reaction time) on the vsCPT from pre- to post training testing observed above.

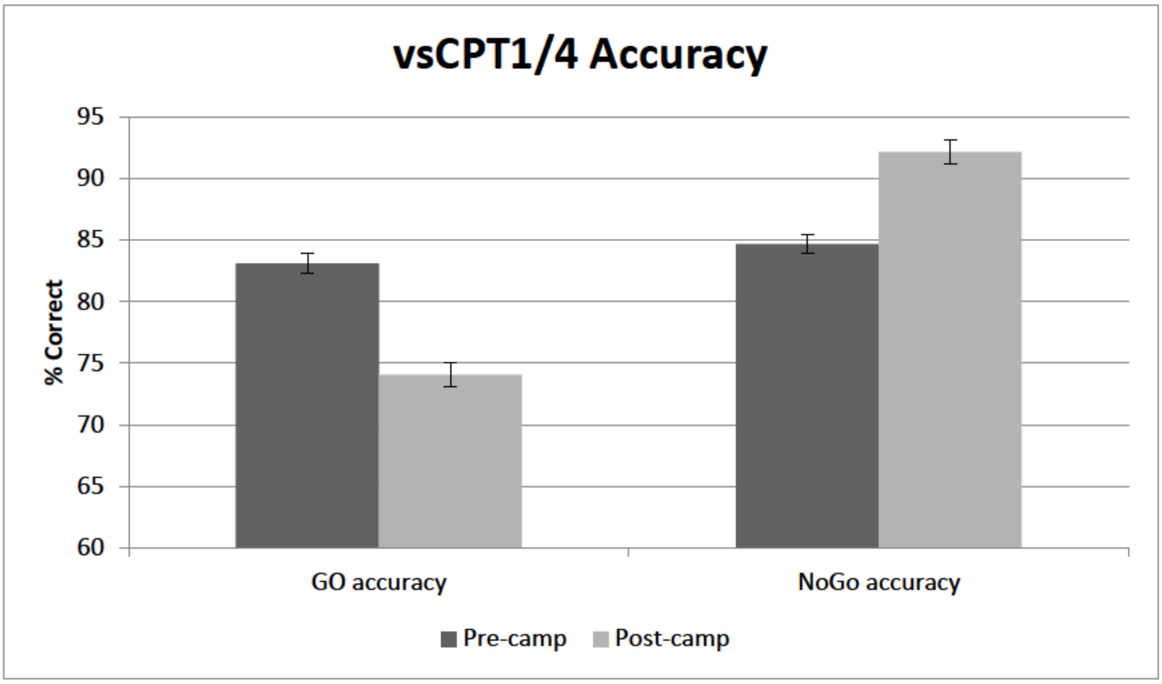


Figure 8. Pre – post training vsCPT accuracy: Experimental and control groups combined.

Participation in the camp resulted in accuracy to vsCPT task Go responses decreasing significantly, while accuracy to NoGo responses increased significantly.

Perceptual sensitivity and reponse bias.

We conducted a mixed model 3 way ANOVA on the signal processing parameter dPrime (Stanislaw & Todorov, 1999) calculated from the vsCPT data. The ANOVA included 2 repeated measures factors, Difficulty with 2 levels (1 circle and 4 circle cue), and Time with 2 levels (pre-training and post training) as well as 1 between groups factor (NFB group versus no NFB group). Mauchly’s test of sphericity was non-significant for the repeated measures factors and hence no correction was applied. There was a significant main effect for Difficulty F (1, 15) = 11.051, p=.005, η_p^2 = .424. As might be expected perceptual sensitivity was significantly higher for the 1 circle cue (M = 2.754, SE = .147) than the 4 circle cue (M = 2.096, SE = .172) version of the vsCPT. Perceptual sensitivity was significantly higher F (1, 15) = 12.501, p=.003, η_p^2 = .455 post training (M = 2.650, SE = .113) than pre training (M = 2.199, SE = .164) however there was no interaction with the NFB group factor suggesting this is a simple practice effect. All other effects were non-significant.

A similar mixed model 3-way ANOVA was conducted on the signal processing parameter response bias (see also Stanislaw & Todorov, 1999) calculated from the vsCPT data. In this case the only significant effect was for Timing, F (1, 15) = 5.496, p=.033, η_p^2 = .268, with a greater tendency to make rather than withhold a response post training (M = 3.575, SE =1 .047) than pre training (M = 1.722, SE = .347).

DAQ self-report of attention during NFB training

NFB training was expected to progressively enhance visual attention to the video (third person perspective) of table tennis match play presented as the training feedback signal in the NFB training task. Therefore, each of the 12 DAQ components of attention was tested for a linear trend across the 4 repeated measures throughout the training period using polynomial trend analysis (Grant, 1956). As there was no specific prediction for which of the 12 dimensions of attentional experience would show a NFB training effect a further Bonferroni correction was carried out to determine significant relationships. Only the linear trend of DAQ-Flexibility (Figure 9), remained significant after correction for multiple testing; *F*(1,9) = 25.52, $p < .001$ (uncorrected), η_p^2 = .739 which is an extremely large effect size.

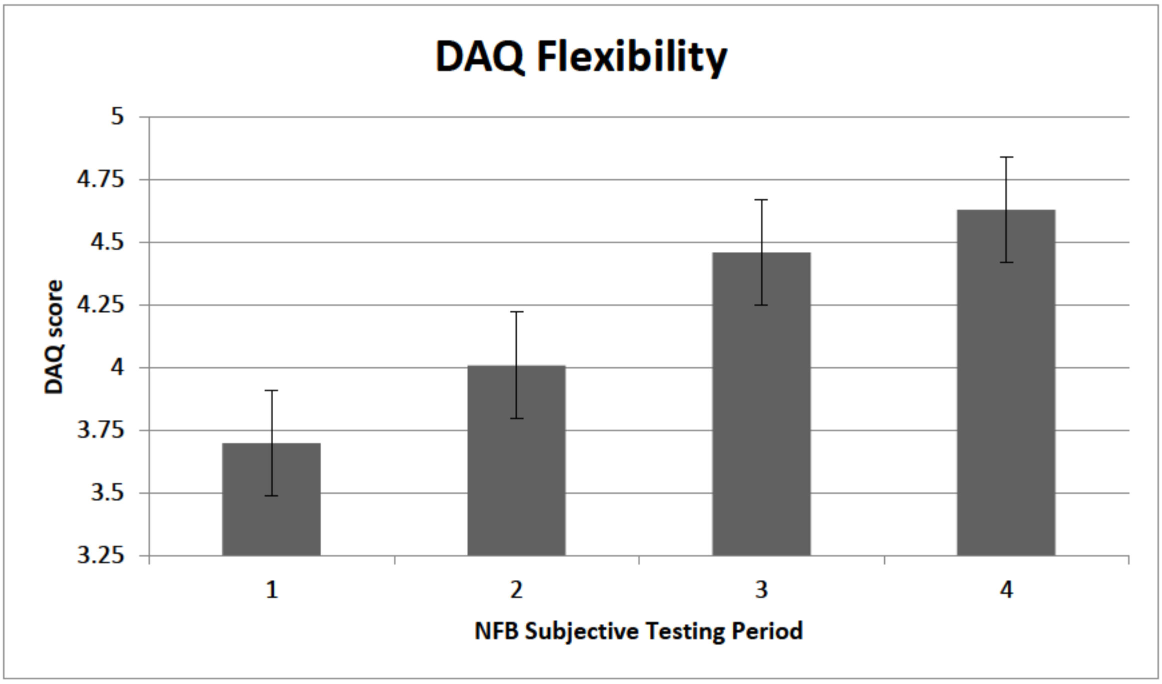


Figure 9. Participants undergoing NFB training self-report of attentional flexibility – after the 1st, 5th, 10th and 15th NFB training session. Values indicate average score given by all

participants (0-5 Likert scale) indicating level of Flexibility of Attention during the NFB training session.

Pre-post NFB differences in EEG related to increasing DAQ Flexibility

Following the discovery of increased DAQ-Flexibility with progressive periods of NFB training a post hoc eLORETA analysis was conducted to determine which, if any, pre-post NFB training changes in cortical source activity were related to increases in DAQ-Flexibility. The change in DAQ Flexibility between the first to the final training session was used as a regressor for the eLORETA estimates of changes in cortical source activity from the pre-NFB training to post-NFB training VT EEG recordings. A cluster of 37 significant voxels was identified in the alpha band at 8.2 Hz (Figure 10). The voxels were located in right precentral gyrus predominantly in BA6. The maximum voxel statistic is located at MNI coordinates (50, -5, 55) and is highly significant $p < .004$. That is, DAQ Flexibility increases during NFB training are associated with increased activity at 8.2 Hz, in right BA6, following the NFB training protocol.

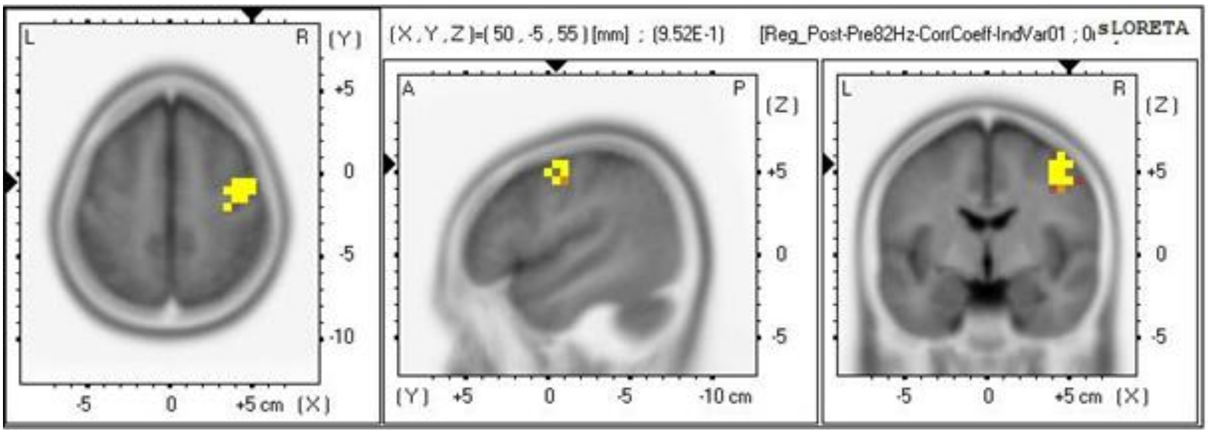


Figure 10. eLORETA images of transverse, sagittal and coronal slices showing right precentral gyrus predominantly in BA6, where a significant increase was found in alpha rhythm at 8.2Hz from Pre- to Post-training camp. DAQ Flexibility increase was used as the regressor for eLoreta estimates of changes in cortical source activity.

Discussion

The aim of this research was to determine whether training a NFB protocol based on EEG differences found between amateur and elite table tennis athletes (Brown et al., submitted), during sport-related cognitive processing could lead to an effective method of enhancing that sport-related cognitive performance. To address this question, five hypotheses were considered.

H1 predicted that NFB training would modulate the targeted neural activity, that is, the time above threshold (TAT) would increase from baseline over the time course of a NFB training session. However, this hypothesis was not supported in the present study, or at least not by a linear increase in TAT across the 5 periods from the beginning to end of each training session. The reason for this lies with the surprising observation that the highest average TAT occurs in the first period of the training session (see Figure 5). Thereafter TAT drops to its lowest point in the second period and rises steadily across each consecutive period until the end of the session (as expected).

H2 predicted that training in the selected NFB protocol would result in post-training increase in the amplitude/power of cortical oscillations in the frequency band trained in the regions selected for training. It was expected that training in the protocol would shift participants' EEG in VT to more closely resemble the prototype of elite (versus amateur) players on which the protocol was based; specifically, that participants would show an increase in the upper alpha band in right BA6 and BA13 (training locations). There was no significant increases in the frequency band trained, in the voxel trained in right BA13 (while actively-watching the table tennis video) from pre- to post-training in the NFB group. Paradoxically there was a significant *decrease* in the amplitude of 11 Hz activity from pre- to post-NFB training in right BA6 but this change was in the opposite direction to that trained by the current NFB protocol. This change did not occur in the control condition indicating that it was an effect of NFB training condition and not merely participation in the table tennis training camp. Similar post-training decreases in target band activity following NFB training to upregulate that activity have previously been reported by Vernon et al. (2003) for a theta band training protocol and also by Pineda et al. (2008) after using a Mu rhythm up-regulation training protocol.

H3 predicted that salient attributes of attentional experience, as measured by the DAQ, would be progressively enhanced during NFB training across the time course of the training sessions. This predicted linear increase was found to be significant for the DAQ dimension of Flexibility even after Bonferroni correction for the full 12 DAQ subscales. The effect was highly significant with an effect size (partial eta squared) of .739.

The vsCPT was designed to tap visual-attention skills specifically relevant to table tennis performance (as demonstrated by Jamieson et al., submitted) and H4 predicted that training in the present NFB protocol would enhance objective performance on this task. This prediction was not supported for the NFB training protocol employed in this study. There was no significant interaction of NFB versus Control with pre- versus post-training effects for any of the vsCPT task objective performance measures employed in this study.

H5 predicted that any attentional changes brought about by the current NFB training protocol would also be systematically related to pre-post NFB training changes in the EEG at nodes in the relevant attentional networks. In the present study this is expected to occur in the active VT condition designed to elicit processing responses in table tennis play-related attention networks. In the case of DAQ Flexibility (self-report measure of the experience of attention processes) the increase of this measure from the first to the last NFB session was significantly related to increases in 8.2 Hz (low alpha) frequencies from pre- to post-NFB training EEG (recorded during active watching table tennis). This relationship was maximally significant in right BA6 with a peak at MNI coordinates (50, -5, 55) (see Figure 11 above). That is, post-NFB training changes in the EEG during performance-related visual processing were directly related to the attentional processes elicited during the NFB protocol itself. This may be an important mechanism for future investigations of how NFB training brings about performance-related changes.

Reward vs punishment

During NFB training participants were reinforced by clear screen images while the specified EEG frequency band in the specified cortical locations remained above threshold. However, this paradigm can also be classified as negative reinforcement when the training signal was below threshold resulting in a degraded (hence frustrating) screen image. The actual NFB method, in retrospect, may have delivered a response contingent negative reinforcement. Note that the average percentage of training time spent above threshold was below 50% (see Figure 5) whereas it is typically above 50% in reward based NFB paradigms. Response contingent positive reinforcement is the norm for NFB and arguably in sports coaching as well. Fundamentally different neural mechanisms underpin learning in positive and negative reinforcement respectively. This issue needs to be carefully evaluated in further studies and an unambiguously positive reinforcement procedure, employing sport specific cues, should be developed and assessed for performance enhancement NFB training.

Learning index does not show a linear trend

The NFB learning index adopted here was the percentage of training time rewarded, evaluated across successive time periods when averaged across all training sessions following the method of Dempster and Vernon (2009). Training sessions were divided into 5 periods of training, of which two minutes preceding the first period was used to set the personal threshold for that training session.

It was expected that the periods of reward (time above threshold) would increase across successive time periods with a linear trend. These results were non-significant but moreover the NFB learning index showed an unexpected trend. When looking at the graph, there is a sharp drop after the first period which then recovers over the remainder of the training periods (see Figure 5). This may be due to the particular hardware-software configuration used to deliver training in this study. Another study, which used BrainTuner software with jammer video mode (but employing a beta-up NFB protocol) also reported a sharp *decrease* in NFB performance between the first and second training periods (Kropotov et al., 2005). Alternatively, it may be that performance during the first training period depletes some resource which rebuilds slowly over the remainder of the session.

Two regions of NFB training

NFB training was simultaneously provided at two different brain regions, however post-training changes were observed in only one of these. In retrospect it may have been a mistake to train activity in two regions simultaneously. NFB training was conducted on an estimated training signal incorporating information from both right BA6 and right BA13 but training related changes were observed only in right BA6. The original frequency domain analysis in Brown et al. (submitted) was conducted over 4 second epochs with no finer temporal resolution. It could be the case that alpha power was not enhanced (in elite versus amateur) over the two regions simultaneously, but that these modulations were locked to specific sequential cognitive processing events which recurred throughout the VT condition. In practice a NFB training signal mixing information from two functionally discrete regions may impair NFB learning to modulate activity at one or both regions. This factor may also have played a role in the unexpected learning index results. Because the learning curve is not based on one source but is the combination of the two sources, the learning index is thus a mix of the two sources. Interpreting the learning index results is therefore a measure that should be interpreted with caution in this particular study.

Time frequency analysis

Since there is no information about the timing of the decrease in alpha power, it may be that performance related increases of power occur over short time intervals but such bursts of alpha activity are poorly targeted by training protocols which only target exceeding a set threshold. Time frequency analysis offers the possibility to feedback the amplitude of specific oscillations time-locked to precise cognitive processing events. With more insight into the time course of relevant functional oscillations, it would even be possible to define event locked NFB protocols. For example, Arns and colleagues (2008) utilized the specific timing of oscillatory power differences in their NFB protocol and were the first to successfully implement customized and concurrent NFB training during task performance. They determined a personalized ‘successful putting’ profile for golfers by comparing the cortical activity associated with successful putt to unsuccessful putts for each participant. These customized EEG patterns were then used as ‘live’ NFB parameters to the golfers during the preparatory time prior to putting. The training parameters varied per person in modulating power combining various frequency bands and results showed an increase in performance (more successful putts) with NFB compared to no NFB. While golf is a closed skill sport with a motion free preparatory period, the continuously flowing neural network activity required by TT (and similar sports) could be trained in the time-frequency domain by an event adaptation of the mental simulation (virtual training) paradigm applied in the frequency domain in the present study.

Decrease in cortical source activity following NFB

The training protocol was intended to increase in mu (upper alpha) power/amplitude in the targeted regions (a network related to motor control) but instead a significant post-training decrease at 11 Hz was observed. Interestingly this was not only the case for the experimental group but also for the control group, albeit at a different cortical region in this extended network. Although this was unexpected since earlier studies confirmed an increase in target band power as an effect of NFB training (Egner & Sterman, 2006; Hammond, 2011; Landers et al., 1991), there were also reported cases where theta power and Mu power decreased even though the aim of the respective NFB training protocols was an increase of power (Vernon et al., 2003; Pineda et al., 2008). One explanation for this decrease is the 'neural efficiency' hypothesis (Del Percio et al., 2008).

As originally formulated with regard to sport performance, the neural efficiency hypothesis postulates that experts show a reduction in the neural activity directly involved in skill related processing due to *more* efficient cortical function which is observed as higher alpha (less ERD) during skill execution (Del Percio et al., 2008). Yet in the current study increases in upper alpha during VT were observed in both the experimental (NFB plus intensive training) in right BA6 and control (intensive training) groups in right BA40[2]. In both cases these findings contradict the original neural efficiency hypothesis. If neural efficiency has increased than reduced upper alpha (post training) must mean that these oscillations are directly contributing to task efficiency, perhaps through inhibitory control, rather than merely indicating a reduction of active processing (Jensen & Mazaheri, 2010). Furthermore the mechanism by which upper alpha contributes to skill related processing must itself have become more efficient during upper alpha NFB training (experimental group) or physical training (control group). After training, less oscillatory activation *in upper alpha* is needed to meet the same cognitive processing demands. These results may be explained if increased neural efficiency is linked to the timing related inhibition of specific processing regions by upper alpha in skilled cognitive processing.

Previous findings suggest increased timing control of burst firing in upper alpha may play an important role in such enhanced efficiency. Pineda et al. (2008) conducted two studies with an autistic sample using NFB to train *up* the Mu rhythm (8-13Hz in study 1; 10-13Hz in study 2). Post-NFB testing showed a *decrease* in Mu power along with behavioural improvements. The authors reported that even though overall Mu power decreased, session logs showed increasingly frequent high amplitude bursts. They added that "Mu appears in 'packets' and sustaining high amplitudes does not appear to be possible and may not be beneficial" (Niedermeyer, Goldszmidt, & Ryan, 2004; as cited in Pineda et al., 2008). In the current study we are using an athlete sample rather than an autistic sample. However, regulation of the timing of Mu oscillations to incoming stimuli may be a key element differentiating the two populations. Whilst the autistic population may have a phase-locking

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[2] Right BA40 (inferior parietal cortex) is an area in which high level visual and other sensory information is integrated into a representation of the visual scene in space relative to the physical body of the observer and is seen as a part of the dorsal 'where' visual pathway (Glezerman, 2013).

deficit to incoming sensory stimuli compared to the normal population; likewise, the elite table tennis population may possess a more finely tuned phase-locking ability than the non-elite population. If so, then in both cases, training would lead to increased timing control of short bursts of Mu power but overall lower average Mu power.

Better at NoGo and worse at Go

Despite the failure of the vsCPT to discriminate at a behavioural level between the experimental and control groups, there were two noteworthy significant results. Post training both groups made significantly fewer errors on NoGo-trials, and were significantly slower on Go-trials. This cannot be explained by a simple practice effect since, if being the case, participants would have improved overall in the task. Surprisingly there was no significant change in either the perceptual sensitivity or response bias measures of 'signal detection theory' (Neath & Surprenant, 2003). Rather it appears that a higher threshold of evidence is required to decide on the presence of a Go stimulus resulting in slower reaction times (due to a longer period of evidence accumulation to reach response threshold). As a consequence, they also decide more often not to respond to the NoGo trials, hence increasing accuracy on these trials.

Dimensions of Attention Questionnaire

A highly significant effect was found for the linear trend for increased DAQ Flexibility during sessions as training progressed. The increase in DAQ Flexibility demonstrated a very large effect size which remained significant even after a Bonferroni correction for the 12 DAQ subscales. The increase in DAQ Flexibility across training sessions was further found to be significantly associated with a post-training increase in 8.2 Hz (low alpha) activity in the precentral gyrus (BA6). For the moment the DAQ dimension of Flexibility can only be interpreted in terms of the face validity of the self-report items which comprise it. A representative item from the DAQ Flexibility of attention dimension is: *"I felt it very difficult to move and focus my attention; my mind kept returning to certain impressions." versus "I was easily able to move, control, and focus my attention on whatever impression that came into my mind"*. Such questions seem to be tapping into the capacity to relinquish the current focus of attention as a new focus becomes salient. This flexibility in the flow of attention improves as NFB training progresses. Moreover, not only did it improve, but it was systematically related to alpha band changes in the EEG from beginning to the end of the training period, albeit in the *lower* alpha band.

Conceptually this may describe an interaction between the dorsal attention network and ventral attention network as briefly described previously. The ventral attention network causes a shift from the current focus of the dorsal attention system by letting go of the current object of attention. The arrival of a new salient stimulus then leads to a new focus on that stimulus and selecting that new salient object as the focus of attention. When translating these findings to table tennis, the DAQ dimension of Flexibility seems highly relevant. Flexibility in attention enhances the possibility of split second perceptual-motor decision-making that is required at critical junctures in any competitive encounter. Although it is not possible to ascertain whether this increase of DAQ Flexibility is a result of NFB training or by the table tennis training camp itself (control group did not participate in the DAQ assessment), it is a remarkable finding that corresponds closely to the cognitive visual attention demands of playing table tennis.

Conclusion

In conclusion, the current study did not find behavioural evidence of an enhancement in sport related cognitive performance by means of the upper alpha sLORETA Neurofeedback training protocol used here. However, the active VT viewing task provided a successful method to assess EEG patterns linked to visual attention and cognitive control networks specifically related to table tennis performance to measure pre-post NFB effect. The decrease in Mu pre-post NFB demonstrated in this study supports the decrease found in a previous Mu-NFB study (Pineda et al., 2008). Taken together the decreases in Mu found following both upper alpha NFB training and intensive skill training alone point to a fundamental extension of the neural efficiency hypothesis of the role of alpha in skilled performance to include efficiency in the timing control of alpha burst firing (and resulting decreased time averaged alpha power).

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Statement of Originality:

We, the PhD candidate and the candidate’s Principal Supervisor, certify that the following text, figures and diagrams are the candidate’s original work.

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Statement of Contribution by Others:

Trevor Brown	70%
Dr Graham Jamieson	15%
Ian Evans	5%
Quirine Tordoir	10%

Chapter 5

Cortical Changes Following Upper-Alpha sLORETA NFB Training in Table Tennis Athletes are Linked to Performance Enhancement on a Visuo-Spatial GoNoGo Task

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Abstract

Background: Previously we identified evoked brain responses during a visuo-spatial GoNogo task that were closely associated with Table Tennis players' world rankings. We also found upper-alpha band activity in anterior attention network nodes of players during virtual play was related to performance on this task. Here we seek to test the effects sLoreta Neurofeedback (sLNFB) training protocol designed to enhance upper-alpha activity in a parietal hub of visual selection for action on performance in this same visuospatial response selection task in a group of nationally ranked table tennis players.

Method: The relationship of learning during sLNFB training (upper alpha band (Individual Alpha Frequency (IAF) to IAF+2 Hz) in right BA40 (inferior parietal lobule, MNI coordinates 50 -50 55) to a strengthening of connectivity in the targeted cortical network, the electroencephalographic (EEG) activity of fifteen adolescent table tennis players was recorded pre- and post sLNFB training. A learning index was used to establish a relationship between sLNFB training, learning, and post-sLNFB EEG. A motor decision (Go-NoGo) task was undertaken pre- and post-NFB training to determine if changes in cortical activity translated to improved visuo-spatial cued motor control performance.

Results: Results indicated significant changes in cortical activity in regions related to both visuo-spatial processing and motor control. Increased accuracy of visually guided response inhibition was strongly and significantly correlated to post NFB changes in brain activity.

Conclusion: The current sLNFB protocol changes cortical activity throughout functionally connected nodes of visual and motor action-selection networks. Furthermore, some of these changes are directly related to behavioural performance enhancement depending on cognitive processing within these networks. The findings provide support for sLNFB training as a tool for enhancing visuo-spatial and motor processing performance in aspiring elite table tennis players.

Keywords: sLoreta Neurofeedback, alpha, upper-alpha, inhibition-timing, visuo-spatial attention, performance enhancement, table tennis.

Introduction

Neurofeedback (NFB) training is a form of operant conditioning based on reward learning. It is currently recognised as an empirically supported clinical intervention to treat medication resistant epilepsy (Sterman & Egner, 2006). Unlike in clinical practice where the aim of NFB training is to reduce symptoms, the field of sports psychology has great interest in the potential of NFB training to enhance performance (Wilson & Peper, 2011). Elite athletes compared to amateur and non-athletes have been found to have different patterns of alpha cortical activity associated with peak performance (Babiloni et al., 2008; Del Percio et al., 2009). The alpha rhythm is functionally associated with aspects of attention, visual and motor processing, and optimal motor performance (Klimesch, 1999; Loze, Collins, & Holmes, 2001; Min & Herrmann, 2007; Babiloni et al., 2008). As such, there is a major focus on determining whether alpha NFB protocols can be used to alter connectivity strength in visual-motor attentional networks required for elite performance and ultimately improve behavioural performance (Ring, Cooke, Kavussanu, McIntyre, & Masters, 2014). The purpose of this study is to assess whether adaptations to a recently developed alpha NFB protocol (Brown, Jamieson, Tordoir, & Evans, submitted) with table tennis players would enhance the efficiency of visual spatial attention networks related to elite table tennis performance.

The Alpha Rhythm

Alpha (8-12Hz) activity is typically strongest when recorded at posterior cortical locations. Because alpha is most pronounced in an eyes closed, relaxed state of wakefulness and suppressed when the eyes are opened, it was traditionally considered an “idling” rhythm generated while the brain was at rest (Klimesch, 2012; Klimesch, Sauseng, & Hanslmayr, 2007; Schürmann & Başar, 2001). Similarly, increases in a second alpha rhythm, ‘tau’, detectable only from magnetoencephalography (MEG) recordings over the auditory cortex in the temporal lobe, correlate with deactivation in the auditory cortex after reduced acoustic stimuli. And, thirdly, and also independently from other alpha rhythms, ‘Mu’ is detected by EEG recordings over the motor cortex and increases in power with the reduction in motor related task demands (Klimesch, 1999).

In his seminal work on alpha, Klimesch (1999) determined that there are functional sub-bands within the alpha range with modulation of lower alpha (7-10Hz) frequencies related to general arousal and upper alpha (10-12Hz) to semantic processing. Further, he determined that peak alpha (the highest amplitude frequency within the alpha band) varies greatly between individuals and that low peak alpha (~7.5Hz) is associated with neurological disorders and aging. In contrast, high peak alpha (~10-12.5Hz) is frequently associated with individuals of high intelligence and elite athletes (Klimesch, 1999; Babiloni et al., 2009; Klimesch, Sauseng, & Hanslmayr, 2012). Because the distribution of activity within the alpha band varies between individuals and the peaks at either end of the frequency band can resemble neighbouring bands such as theta/alpha and alpha/beta, Klimesch (1999) developed the individual alpha frequency (IAF) method. This approach first calculates an individual's dominant alpha frequency (IAF) then considers frequencies up to 4Hz below IAF as lower alpha and anything 2Hz above IAF as high alpha (Klimesch, 1999). Since Klimesch (1999) introduced IAF, it has become widespread practice in the EEG literature to calculate IAF for all subjects (Babiloni et al., 2009; Capotosto et al., 2009; Min & Herrmann, 2007).

The in-depth study of alpha has also revealed that it plays an essential role in visual and motor processing and is strongly associated with optimal performance (Capotosto et al., 2009; Llanos, Rodriguez, Rodriguez-Sabate, Morales, & Sabate, 2013; Pineda, 2005; Schürmann & Basar, 2001). Unlike other frequencies which synchronise in response to task demands, alpha responds to stimuli with one of two actions; synchronisation or desynchronisation (Klimesch, 2012). It is thought that alpha enhances cognitive functioning by synchronising in task-irrelevant areas to inhibit processing of distracting stimuli (termed "event-related synchronisation" or "ERS") (Klimesch, 1999, 2012; Pfurtscheller & Lopes da Silva, 1999). Alpha has also been shown to desynchronise in response to stimuli (termed "event-related desynchronisation" or ERD) or in anticipation of a response (Klimesch, 1999, 2012; Pfurtscheller & Lopes da Silva, 1999). Event-related desynchronisation is thought to reflect cortical activation, releasing an area from inhibition to allow for processing of information (Klimesch, 1999, 2012). While Babiloni et al. (2009) and Klimesch et al. (2007) agree that high ERS is related to effective processing of cognitive and visual information and how intelligent or skilled a subject is, there remains conjecture about the optimal level of ERD. Babiloni et al. (2009) and Del Percio et al. (2009) argue that less ERD is associated with optimal cognitive performance ("neural efficiency" hypothesis) while Klimesch (1999) and Klimesch et al. (2007) argue that greater ERD is predictive of superior performance.

Alpha in athletes

The study of the relationship between the alpha rhythm and elite athletes has revealed that elite athletes differ significantly from amateur and non-athletes in terms of cortical alpha activity (Babiloni et al., 2008; Del Percio et al., 2007a; Del Percio et al., 2007b). This difference is clear between elite, amateur, and non-athletes and also within athletes (Loze et al., 2001). Babiloni et al. (2008) measured the EEG activity of expert golfers and found significant differences in upper alpha activation (10-12Hz) between successful and unsuccessful putts. The differences were most evident in the right primary sensory-motor cortex (visuo-spatial processing) with greater reduction in alpha power associated with successful putts. As a control measure they compared the alpha power of the unsuccessful putts and found that putts closest to the hole (least error) compared to those that were further away (most error) were associated with less activation. These findings support the idea that alpha activity is related to optimal skilled motor performance (Babiloni et al., 2008).

In another study, alpha activity in elite and non-athletes was compared during the judgment of performance of observed sporting actions (Babiloni et al., 2009). Fifteen rhythmic gymnasts and 10 non-athletes watched a series of videos of elite gymnasts performing routines and were asked to judge the artistic/athletic performance of each video. During the viewing of the videos, EEG readings indicated less alpha ERD (higher alpha power) in the right visuo-spatial areas of the elite athletes suggesting that judgment of observed sporting performance requires less cortical activation in athletes than it does in non-athletes (Babiloni et al., 2009). These findings are in line with the “neural efficiency” hypothesis. Del Percio et al. (2009) found less alpha ERD (higher alpha power) in the right parietal areas of expert karate and fencing athletes compared to non-athletes and suggested that this is associated with increased efficiency in the areas of the brain related to visuo-spatial attention and processing. Singh-Curry and Hussein (2009) propose this area of the brain, in particular right Brodmann area 40 (inferior parietal lobule; BA40), is essential for sustained attention to task goal and detection of successive stimuli.

Further to this, Rizzolatti and Matelli (2003) suggest that BA40 functions as a “ventro-dorsal” component of the dorsal visual stream responsible for action organisation and understanding as well as space perception. Caspers et al. (2011) support the idea of this “ventro-dorsal” pathway due to the location of BA40 noting that it is in a prime position to integrate information about the “where” aspect of stimuli (dorsal stream) and “what” action to take (ventral stream). Based on functional connectivity with the primary visual cortex (V1) and the premotor cortex (BA6), Caspers et al. (2011) describe BA40 as necessary for spatial and non-spatial attention and motor preparation. Singh-Curry & Husain (2009) also highlight that upper alpha (Mu) levels in the rIPL play an important role in the successful discrimination between targets and non-targets. Further analysis of functional connectivity reveals connections between BA40 with inferior frontal and posterior temporal regions of the cortex in addition to connections with the insula (Caspers et al., 2013).

Consistent with the importance of ventral and dorsal network interaction in sport related visual-spatial processing, Brown, Jamieson, Tordoir, Evans, & Cooper (submitted a) found that the EEG frequency spectrum in a group of elite table tennis players differed maximally from an amateur group in a narrow range of the upper alpha band (peaking at 11.25Hz) with greater source activity (in elite players) localised within right BA6 (a functional node of the dorsal attention network) and right BA 13 (a functional node of the ventral attention network) during active visual processing of an opposing player’s motion. The difference in upper alpha activity was elicited by a task requiring table tennis players to watch a video of an elite player from a player’s perspective and actively imagining playing against him. The amplitude of that narrow upper alpha band during this motor related processing (Mu) was significantly correlated with superior processing speed and perceptual sensitivity together with reduced response bias on a visual-spatial Go-NoGo task designed to assess the integration visuo-spatial cues with response selection (motor control), a core cognitive demand of elite table tennis performance (Brown et al., submitted a; Brown, Jamieson, Tordoir, Evans, & Cooper, submitted b). The task requires correct identification of changes in spatial arrays (cf. motion cues) to guide correct motor responses and the avoidance of impulsive responses to highly similar but misleading spatial signals. Jamieson et al., (submitted) have since identified an ERP (cortical processing) component during responses to this task, that correlates (*r*=.9) with player world rankings.

In a follow-up study, Brown et al (submitted b) employed a NFB protocol using real-time source localisation (sLoreta NFB) to train upper alpha in both right BA6 and right BA13 in aspiring elite table tennis players. It was hypothesised that by rewarding an increase in this narrow band Mu rhythm, that post NFB training, testing would reveal an increase in that Mu rhythm during a virtual-play condition. However, after 15 NFB sessions players showed a decrease in Mu band amplitude in regions of right BA6 measured during the pre-post sLORETA NFB training video task condition. The authors argued that this decrease was the result of enhanced functional efficiencyof these upper alpha oscillations (possibly via improved timing control) leading to lower time-averaged band power following NFB training. That study did not find changes in right BA13 suggesting that, when information from 2 cortical sources are combined in a single feedback signal, operant conditioning effects may occur at only one of those sites. Thus while sLORETA NFB (sLNFB) training at a key network node may induce changes in other connected nodes it may be counterproductive to train multiple sources in a single protocol. The low percentage of training time (<50%) rewarded for participants in that study may also have limited the NFB training effects. The current study sought to address both these methodological issues.

Current Research and Hypotheses

The current study aimed to extend the findings of Brown et al. (submitted) on the application of sLNFB training to enhance sport performance in elite athletes. Given the proposed functional role of alpha activity in optimal sport performance, and in related cognitive processing throughout the ventral and dorsal attention networks, the current experiment targeted right BA40 which has been proposed to be the early locus of interaction between ventral and dorsal processing streams. It intends to build upon the lessons of the previous study by focusing sLNFB training on only one EEG source and by setting a lower reward threshold for NFB participants. This NFB methodology uses sLORETA (Pascual-Marqui, 2002) EEG source localization to apply alpha NFB directly (in real time) to the estimated activity of a specified cortical source (see Brown et al., submitted a, submitted b).

If learning to self-regulate the selected EEG signal occurs during NFB training, we expect there to be an increase in mean time participants' spent above the reward threshold as training progresses. Further, we expect that the effect of the sLNFB training protocol will extend beyond the target node to other connections in its functional network. Therefore, we predict significant changes in post-training compared to pre-training EEG activity in further nodes of the extended visual-motor attentional network. We also expect changes in post-NFB training EEG related to the learning that has occurred during NFB training. We predict that post NFB performance improvements on the visual-spatial Go-NoGo task will be closely related to the changes in brain activity which follow training on the current NFB protocol.

Method

Participants

Fifteen adolescent table tennis players were recruited from the Integralnytenistolowy Table Tennis Camp in Miedzyzdroje, Poland (conducted by former Polish National Team coach, Jurek Grycan). Subjects were six females and nine males aged 13-17 years old (*M*=13.8, *SD*=1.15), right handed, who practiced table tennis (TT) at least 12 hours per week. One participant withdrew on the first day and their data were not included in the analysis. The participant was subsequently replaced with another eligible participant.

Materials and Procedure

Ethics approval was granted by the University of New England Ethics Committee, Australia. All materials related to experimental information, consent, and instructions were provided in English and Polish. Written consent was received from both parents/guardians and participants. EEG data was collected using 19 channel Ag/AgCl electrode caps (Electro-Cap International, Eaton, Ohio) placed according to the international 10/20 system. EEG signals were amplified by a Mitsar 21-channel system amplifier (Mitsar-EEG systems, Saint Petersburg, Russia) and recorded at a sampling rate of 250Hz. Linked left and right ear lobes were used as the reference and the ground electrode was located at FCz. Impedance for all electrodes was achieved below 10kOhms. Quantitative EEG was recorded in WinEEG version 2.91.54 (Mitsar-EEG systems, Saint Petersburg, Russia) on a Toshiba Satellite Pro Notebook computer (Intel Core 2 DUO CPU). NFB EEG was recorded in BrainTuner version 1.5.19 software and a jammer (USB interface adapter; Mitsar-EEG systems, Saint Petersburg, Russia) was connected from the laptop to the DVD player to jam the screen during NFB training (Figure 1). Visual stimulus in the NFB condition was presented on a 117cm flat screen Sony television.

EEG data preparation. Using WinEEG, the common average reference was selected and a 0.5 to 30Hz band-pass filter was applied. Artefacts from physiological (eye movements/blinks, skin potentials) and non-physiological (electromagnetic interference, electrode popping) sources were removed with independent components analysis (ICA). ICA decomposes the data into maximal information independent components (which extends beyond the simple linear independence of principal components analysis) based on selected parameters (Stone, 2002). Automatic artefact detection thresholds were set for the recording at the following bandpass settings: 0-30Hz +/- 70µV, 0-1Hz +/- 50µV, 20-30Hz +/- 35µV. Time segments of +/- 300 ms were marked in the recording around these artefacts and excluded from further analysis. EEG was then visually inspected for any remaining artefacts, and contaminated EEG was manually removed. Each 4-minute recording segment was then divided into artefact free epochs of 4000 ms. For the resulting epochs power spectra from 0.5 to 30 Hz with a frequency resolution of 0.25 Hz were calculated in WinEEG by Fast Fourier Transform. These were then averaged for each participant in each condition.

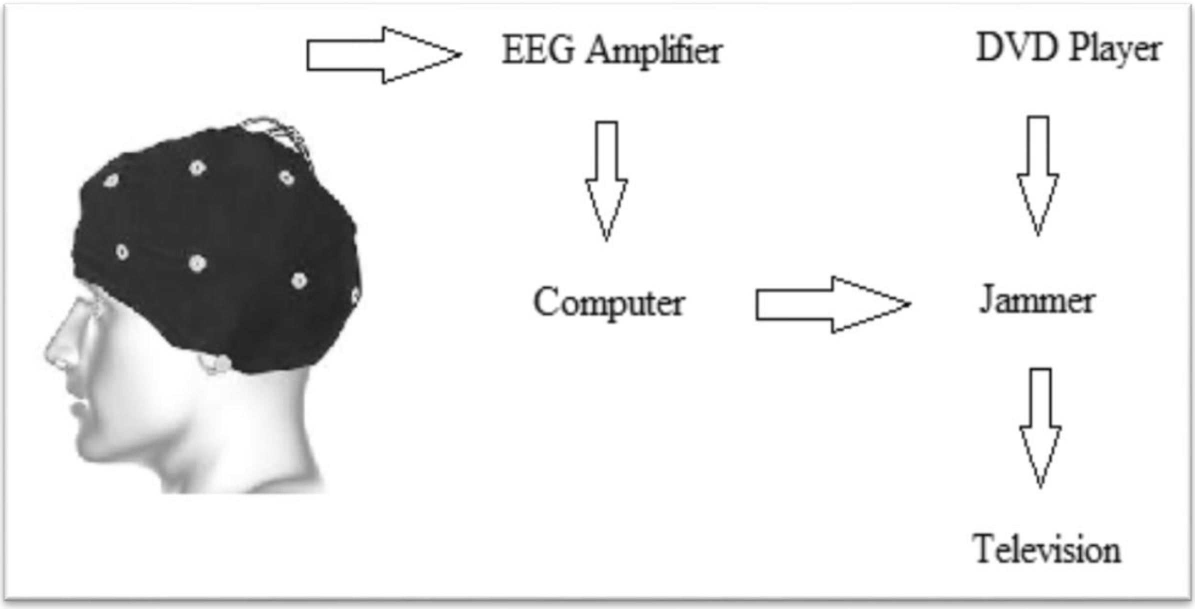

Figure 1. Schematic representation of EEG Amplifier, Computer, Jammer and DVD player interaction. The EEG amplifier receives input from the participant, sending it to the computer. The computer uses BrainTuner software to assess real-time EEG relative to sLNFB protocol parameters. The Jammer receives input from the computer instructing it to 'Jam' the signal flowing from the DVD player to the Television screen when the participant's EEG does not exceed threshold.

Baseline EEG. Participants were seated 47cm away from the screen. Four minutes of baseline EEG was collected for three conditions: eyes closed (EC), eyes open (EO), and watching a table tennis video (VT). Participants were instructed to relax during EC, to focus on a fixation cross for EO and imagine playing against the opponent in VT (Figure 2). Following collection of baseline EEG, independent alpha frequency (IAF) was computed for each participant with an individual’s dominant alpha frequency during eyes closed baseline recordings selected as their peak alpha (Klimesch, 1999).

Figure 2. A still frame from the EEG Table Tennis Video condition.

Standardised low-resolution brain electromagnetic tomography (sLORETA).

sLORETA is a method of zero error EEG source localisation that measures voltage potentials at various positions on the scalp (electrodes) and applies signal processing techniques to estimate the source of activity (Grech et al., 2008). Using a realistic cortical model represented by 6,239 voxels with 53mm spatial resolution, sLORETA computes images of standardised current source density (CSD) within three-dimensional cortical space based on the changes in the distribution of electrical potentials. The sLORETA images represent standardised electric activity at each voxel with an increase or decrease in cortical activation representing an increase or decrease in CSD (Pascual-Marqui, 2002). The sLORETA software package was used to perform the statistical analyses. The methodology used is non-parametric. It is based on estimating, via randomisation, the empirical probability distribution for the max-statistic (e.g. the maximum of a t or F statistic), under the null hypothesis. This methodology corrects for multiple testing (i.e., for the collection of tests performed for all electrodes and/or voxels, and for all time samples and/or discrete frequencies). Due to the non-parametric nature of the method, its validity need not rely on any assumption of Gaussianity.

Neurofeedback. NFB training targeted the upper alpha band (IAF to IAF+2 Hz) in right BA40 (inferior parietal lobule, MNI coordinates 50 -50 55). Participants each received 14 sessions of NFB training over a 10-day period. The visual stimulus was a DVD of table tennis matches played by Jan-Ove Waldner, the world's most accomplished table tennis player. Each NFB session consisted of a two-minute baseline period, for the purpose of setting the training threshold, during which no jamming was applied and the screen was clear. This was followed by five training sessions, of 5-minutes each, separated by one-minute rest periods. The threshold for reward was initially set at 90% of the mean amplitude of the target band in the ROT (region of training) recorded during the set-up period. This was designed to result in the reward (a clear image) being presented about of 55% of the time. However, during the first training session this was observed to result in a much lower percentage of time rewarded than expected. As this may have constrained the rate of learning it was decided to lower the training threshold to 80% for the second and subsequent training sessions (theoretically corresponding to a reward about 60% of the time if there is no change between baseline and training periods). As such, learning index (see below) data from the first session of NFB for each participant were not included in the analyses. Participants received real time feedback of cortical activity through the clear (estimated EEG source activity above threshold) or jammed (estimated EEG source activity below threshold) screen. The DVD was paused during rest periods. Participants were instructed to try to make the images on the screen clear during the training sessions and to relax during the rest periods.

Learning Index (LI). In this study a learning index was developed to assess the extent to which each participant improved their control of the target EEG signal contingent upon NFB training (training related learning). This was calculated as the mean percentage of time spent with the training signal above the alpha threshold in session 14 (end of training) minus the mean of session two (start of training; session 1 being removed from analysis due to the change in threshold reported above).

Go/NoGo task. The Go/NoGo task was completed on a DELL laptop running Windows XP. Visuo-spatial reaction time, accuracy, and response inhibition were measured using a unique form of the Go/NoGo task. The task required a response decision based on visual-spatial stimulus location and had two levels of difficulty. The simple version of the visual-spatial continuous performance task (vsCPT1) consisted of a fixation cross on a white background followed by a circle that flashed in one corner of the screen for 100 ms. A black dot appears 1,100 to 1,700 ms after the circle disappears. As seen in Figure 3 below, participants were instructed to click the left mouse button as quickly as possible if the black dot appeared inside of where the circle had been (Go condition) or not respond if the dot was outside of the circle (NoGo condition). The more difficult version (vsCPT4) followed the same process however four circles would appear, one in each quadrant of the screen, simultaneously. Each Go/NoGo task lasted 10 minutes and consisted of 96 Go trials and 96 NoGo trials. Task order was alternated between participants to control for task order effects with one being completed before the baseline recording and the other completed after the baseline recording.

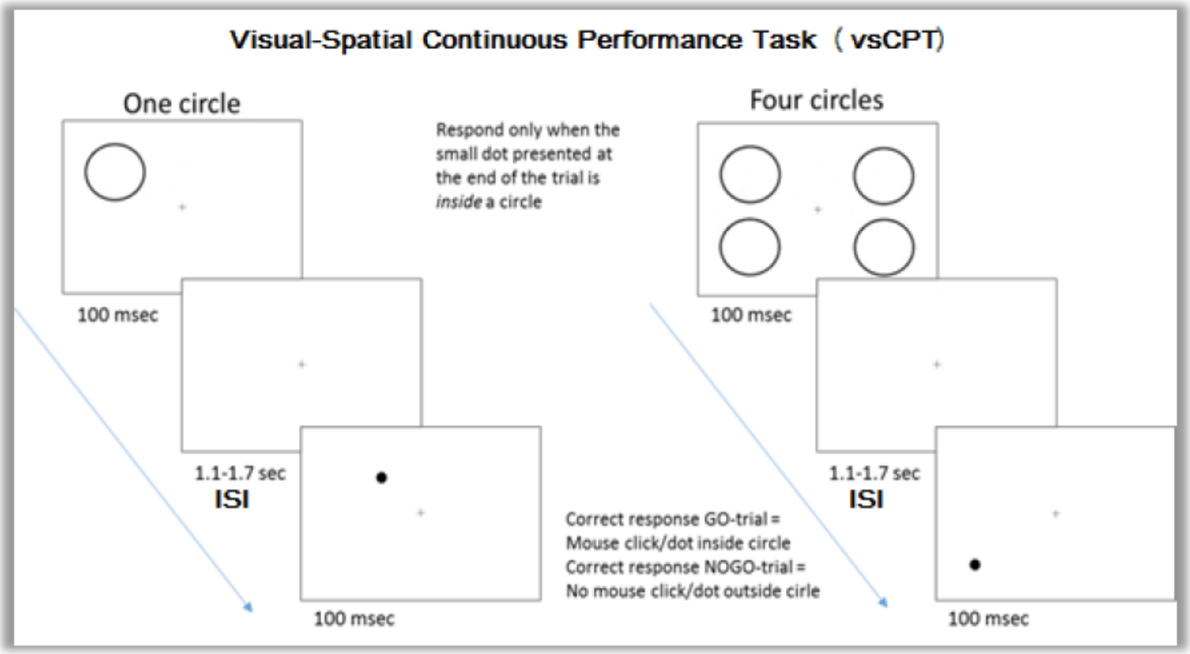

Figure 3. Example of a 'Go' response trial in the two vsCPT tasks. Each circle had 8 possible 'Go' responses and 8 possible 'NoGo' responses. Of the 192 trials, there were 96 'Go' and 96 'NoGo' responses. Quasi-randomisation ensured that there were never more than four 'Go'or four 'NoGo' responses in succession. ISI: Inter-stimulus-interval.

Results

A mixed model ANOVA was used to investigate if the rate of reward (percentage of time above threshold) increased over time both within and between NFB training sessions. Mauchly's test indicated the assumption of sphericity was met. As seen in Figure 4, average time above threshold (equivalent to reward) climbed consistently from the second until the fifth time period within a session. However, because of the drop observed after the first period there was not a significant increase across the entire training period $F(4, 13) = 1.45$, $p = .228$.

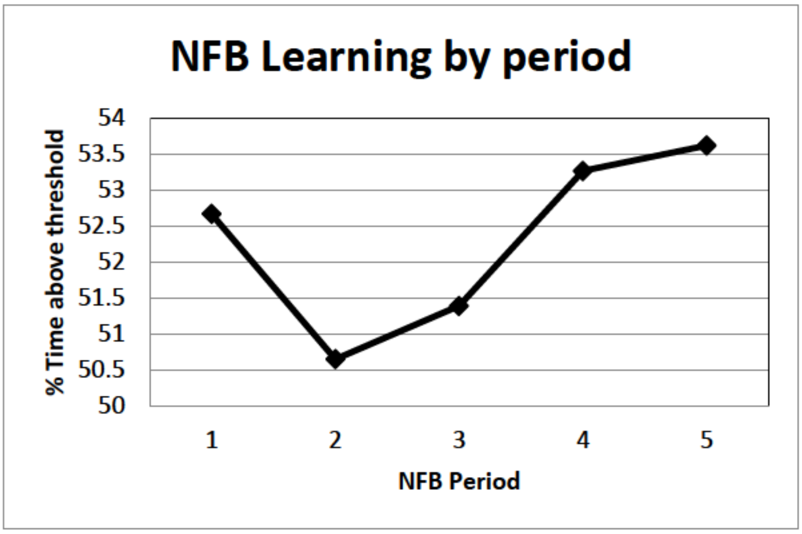

Figure 4. Percentage of time spent above the reward threshold within sessions.

Polynomial trend analysis of the time spent above threshold across sessions, excluding the first session, (Figure 5) was also not significant, $F(12, 13) = 1.428$, $p = .157$.

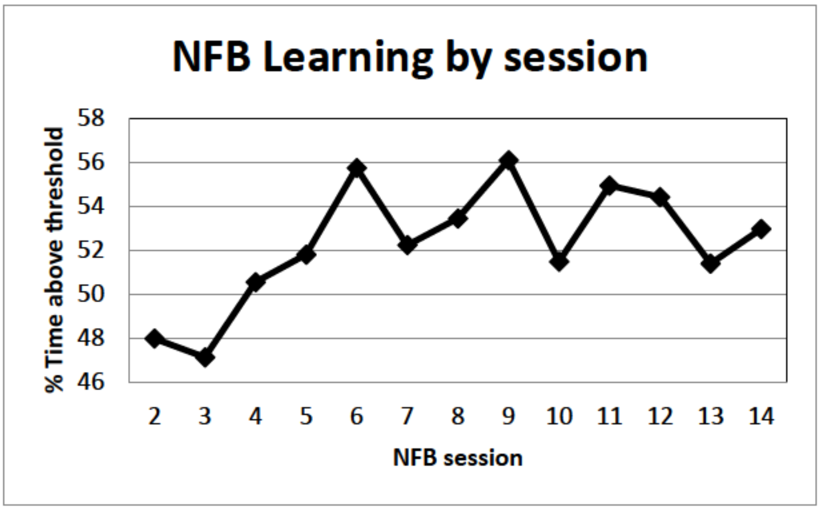

Figure 5. Percentage of time spent with signal above the reward threshold for training sessions 2 through 14.

EEG Source Activity Changes Following SLNFB

Spectral analysis of the EEG data was performed using the eLORETA software package (Pascual-Marqui et al., 2011). Changes in cortical activation post- compared to pre-NFB training were tested using one-tailed paired sample t-tests. Statistical significance was set at α=.05 for all analyses.

Eyes closed. A significant decrease in activity maximal at 12.87Hz, bordering alpha and beta frequency bands was found in the eyes closed condition, *t*(14) = -4.30, *p* = .004. Significant voxel changes were located in right BA 19 and BA 7 (specifically the precuneus in the parietal lobe and cuneus of the occipital lobe respectively) which lie along the right dorsal ("where") visual processing stream (Figure 6).

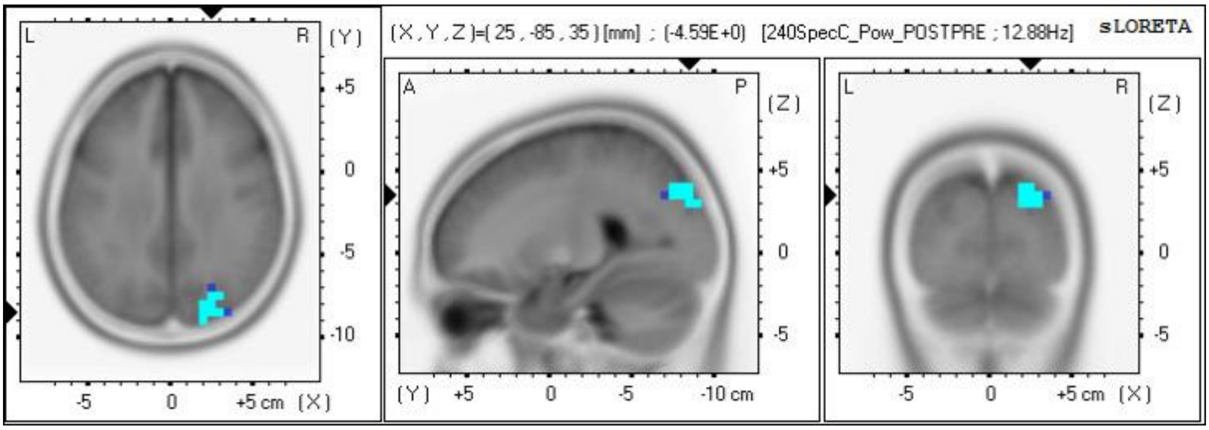

Figure 6. eLORETA images of transverse, sagittal and coronal slices showing right BA19 and BA7 where maximal differences in EEG activity were observed in post- compared to pre-NFB training. Blue indicates post-training amplitude decrease.

Eyes open. A significant decrease in beta activity at 24.25 Hz was found in the eyes open condition, *t*(14) = -4.67, *p* = .007. Changes were located in right BA13 (insula), 43 (precentral gyrus), 22 (superior temporal gyrus), and 41 (transverse temporal gyrus; Figure 7).

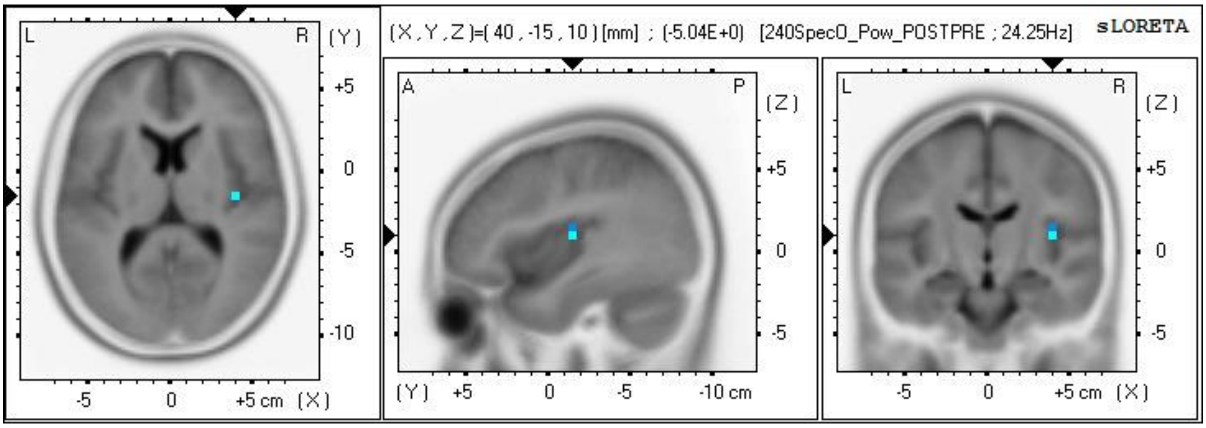

Figure 7. eLORETA images displaying right BA13, 43, 22, and 41 where maximal differences in EEG activity were observed in post- compared to pre-NFB training in the eyes open condition. Blue indicates post-training amplitude decrease.

Table tennis video. Alpha band activity at 9.25 Hz decreased in the VT condition, *t*(14) = -4.98, *p* = .002, in right BA24 (dorsal anterior cingulate cortex) and 23 (posterior anterior cingulate cortex; Figure 8). This corresponds with regions directly involved in response conflict, error monitoring, and reward learning (Braver, Barch, Gray, Molfese, & Snyder, 2001; Bush et al., 2002).

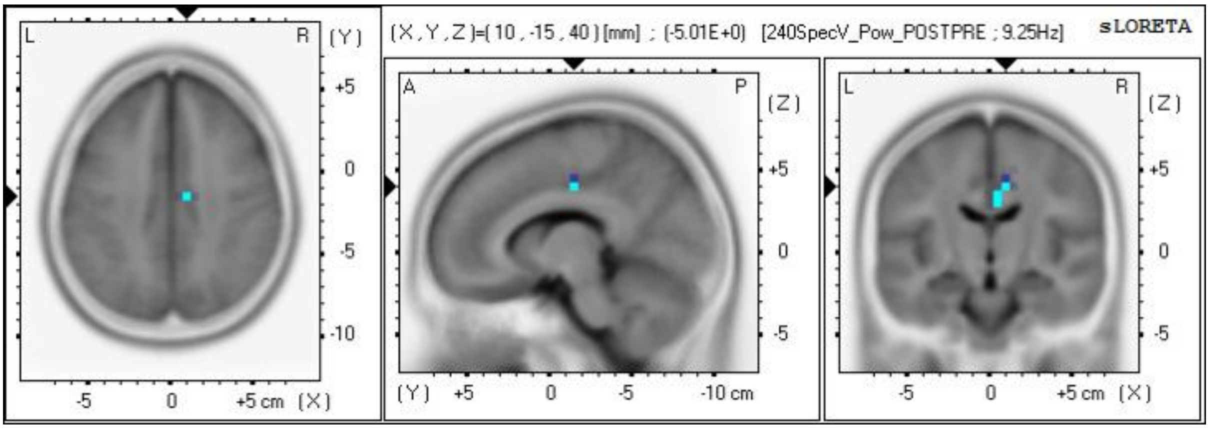

Figure 8. eLORETA images displaying right BA24 and 23 where maximal differences in EEG activity (9.25 Hz) during the VT condition were observed in post- compared to pre-NFB training. Blue indicates a post-training amplitude decrease.

Close inspection of results for each eLORETA analysis above showed that irrespective of significance, EEG source activity at most voxels *decreases* across all frequencies from 1 – 30 Hz, from pre to post NFB training in EO, EC and VT testing conditions.

Learning Index (LI) and Change in EEG Source Activity. A strikingly large effect was found for a regression analysis exploring the relationship between the LI and EEG activity. The LI was found to significantly predict changes in alpha band activity at 8.5 Hz in left BA24 (anterior cingulate cortex) and 32 (dorsal anterior cingulate cortex) in post-NFB eyes open condition, $r = -0.93$, $p = .011$, showing that as reward time increased across training sessions, low-alpha activity decreased post training in this motor control region (Figure 9).

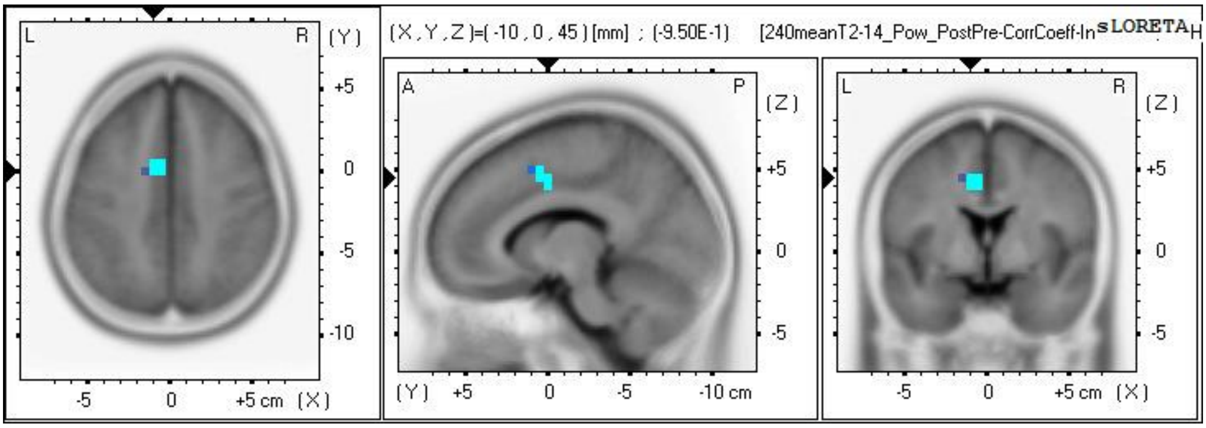

Figure 9. eLORETA images displaying right BA24 and 32 where maximal differences in EEG activity during eyes open were observed in post- compared to pre-NFB training as a function of the NFB learning index. Blue indicates a post-training reduction in activity as the LI increases.

Pre-post NFB differences in CAR EEG

For the mean band amplitude in the range 10.5 – 11.5 Hz obtained from the CAR channel we conducted a repeated measures 2-way ANOVA. The first repeated measure factor was Baseline condition which has 3 levels: Eyes Closed (EC), Eyes Open (EO) and Table Tennis Video (TTV). The other repeated measures factor Time had 2 levels; pre training and post training. There was a significant effect for Baseline condition F (2, 28) = 12.276, p<.001, η_p^2 = .467. Consistent with findings in the Danish study the mean band amplitude falls from EC (M = .872, SE = .077) to EO (M = .723, SE = .072) and almost as much again to TTV (M = .614, SE = .046). There was no significant effect for Time and no significant interaction effect between Baseline condition and Time. Global cortical differences amplitude in this band amplitude do not appear to respond to or interact with (cortically localised) sLNFB training.

Visuospatial Continuous Performance Task (Go/NoGo) Behavioural Analyses

Accuracy and reaction time.

At face value these performance parameters are the most ecologically valid (meaningful) for real world success in elite table tennis players. The Go-NoGo data were analysed using SPSS (Version 20). Visual inspection of histograms indicated assumptions of normality and normality of difference scores were not violated. Paired samples t-tests were used to compare pre- and post-NFB training scores for the Go-NoGo task as it was expected each of these basic performance measures would improve due to the practice effect which accompanies retesting. There was improved accuracy on vsCPT1 NoGo from pre (*M* = 87.00, *SD* = 5.22) to post (*M* = 91.27, *SD* = 4.28), with a mean difference of 4.27 (*SD* = 4.30), *t*(14) = 3.84, *p* = .002. There was also improved accuracy on vsCPT4 NoGo from pre (*M* = 76.00, *SD* = 10.50) to post (*M* = 85.33, *SD* = 6.01), with a mean difference of 9.33 (*SD* = 7.29), *t*(14) = 4.94, *p* < .001. This indicated enhanced response inhibition performance.

Performance decreased on vsCPT4 Go accuracy from pre (*M* = 65.86, *SD* = 12.82) to post (*M* = 59.80, *SD* = 13.17), a mean difference of -6.06 (*SD* = 10.76), *t*(14) = -2.18, *p* = .047; and vsCPT4 response time increased pre (*M* = 483.33ms, *SD* = 82.12) to post (*M* = 516.46 ms, *SD* = 82.13), *t*(14) = 2.64, *p* = .019, a mean difference of 33.13 milliseconds (*SD* = 48.64). Accuracy decreased slightly on the vsCPT1 Go trials however the changes were not significant (*M* = -3.46, *SD* = 14.83), *t*(14) = -0.90, *p* = .381. No significant changes were found for response time on the vsCPT1 Go trials (*M* = -10.53ms, *SD* = 62.70), *t*(14) = -0.65, *p* = .526. Unlike response inhibition neither response initiation nor reaction time showed post training improvements.

Perceptual sensitivity and response bias.

Signal detection theory, which calculates measures of perceptual sensitivity and response bias, provides a framework widely adopted in the analysis of perceptual performance tasks (Stanislaw & Todorov, 1999). Therfore we also analysed these performance parameters. A repeated measures 2-way ANOVA was conducted on the signal processing parameter dPrime calculated from the vsCPT data. The 2 repeated measures factors were Difficulty with 2 levels (1 circle and 4 circle cue), and Timing with 2 levels (pre-training and post training). Mauchly’s test of sphericity was non-significant for the repeated measures factors and hence no correction was applied. There was a significant main effect for Difficulty F (1, 14) = 35.162, p<.001, η_p^2 = .715. As might be expected perceptual sensitivity was significantly higher for the 1 circle cue (M = 2.489, SE = .118) than the 4 circle cue (M = 1.783, SE = .132) version of the vsCPT. Perceptual sensitivity was significantly higher F (1, 14) = 33.042, p<.001, η_p^2 = .702 post training (M = 2.366, SE = .132) than pre training (M = 1.906, SE = .100). The interaction effect was non-significant.

A similar repeated measures 2-way ANOVA was conducted on the signal processing parameter response bias calculated from the vsCPT data. There was a significant main effect for Difficulty F (1, 14) = 11.126, p=.005, η_p^2 = .443 with a greater tendency to make rather with hold a response in the one circle (M = 2.969, SE =.529) than the 4 circle (M = 1.936, SE = .342) condition. There was also a significant effect was for Timing, F (1, 14) = 10.249, p=.006, η_p^2 = .423, with a greater tendency to make a positive response post training (M = 3.244, SE =.651) than pre training (M = 1.661, SE = .218). The interaction effect was non-significant.

sLNFB training EEG changes related to performance improvements

Accuracy on NoGo trials improved significantly from pre to post NFB training on both 1 circle and 4 circle cued trials. For 1 circle cued NoGo trials this improvement was found to have a large and highly significant negative correlation (*r* = -.690, *p* = .004) with the pre to post NFB training decrease in 9.25 Hz (low-alpha) activity at the peak voxel in right BA24 (dorsal Anterior Cingulate Cortex) reported in the VT (table tennis video) result above. A negative correlation in this case indicates that the larger the post NFB decrease in source activity the greater was the post improvement in accuracy of response inhibition.

Discussion

This study aimed to determine if learning to self–regulate the selected EEG activity actually occurs throughout the period of NFB training and whether the alpha training protocol employed alters related activity at other functionaly related network nodes. In addition, learning (the LI) was expected to be related to specific cortical changes. Finally, it was expected that NFB linked changes in cortical activity would be related to performance improvements on the visuo-spatial Go-NoGo task. Although a trend was found for a linear increase in the LI over time both within and between NFB sessions this was not significant and so the first hypothesis was not supported. An important limitation of the study however, was the small sample size and corresponding low power to detect effects. In particular negative findings should be considered cautiously until they can be tested with a larger sample size. Furthermore, NFB is based on a form of operant conditioning that positively reinforces desired behaviours. However, the reinforcement delivered by the screen jammer used in the current experiment may also be experienced as negative reinforcement when participants were not producing selected EEG activity above threshold, because a degraded (hence frustrating) image was presented at that time. Negative reinforcement operates via distinct neural mechanisms to reward learning, and if present would represent a major departure from standard NFB procedures. Frustration due to the negative feedback received during jamming may have had a limiting effect on the rate of NFB learning.

Although there were no significant post-NFB training changes in the EEG in the region trained (right BA40), the second hypothesis regarding change in related cortical network activity was supported. As found by Haller et al. (2013) and Scharnowski et al. (2014), the current study elicited changes in processing regions that are functionally connected to the region that was trained. The regions in which change occurred are all nodes in a functional network linking visuo-spatial, attentional and motor control processes. Further, each of the regions in which change occurred has direct corticocortical connections and/or indirect connections via cortico-striatal-pallido-thalamo-cortical loops with right BA40.

In the eyes closed condition, the voxels indicating post-training decrease in upper alpha/lower beta (12.9 Hz) activity were in right BA19 and BA7. Both regions have direct and indirect connections to BA40 and are essential for motor imagery and coordination of visually guided movement (Cavanna & Trimble, 2006). This frequency is essentially that of the classic sensori-motor rhythm (Sterman & Friar, 1972). Given that increased beta activity is associated with difficulty initiating movement (Salmelin and Hari, 1994, as cited in Davis, Tomlinson, & Morgan, 2012) and suppression of beta is associated with cortical excitability and anticipation (Buchholz, Jensen, & Medendrop, 2014), these results suggest that the participants were primed to process motor related visual information.

The decrease of high beta (24.25 Hz) activity in the eyes open condition in right BA13, 43, 22, and 41 is indicative of greater activation in motor processing areas. Brodmann area 43, which is anatomically overlying and richly connected to posterior BA13, has been found to have strong functional connection with BA40 and is essential for sensorimotor processing, control of action, and somatosensory processing (Eickhoff et al., 2010). In BA13, the voxels indicating change are located in the dorsal-posterior insula. Cauda et al. (2011) identified this area of BA13 as essential for the integration of information from somatosensory and proprioceptive afferents and motor control with substantial efferent projections to supplementary motor cortices. Post NFB changes in BA13 (the insula) in the present study support the findings of Haller et al (2013) who conclude that NFB elicits changes in the insula due to its role in introspective awareness, an essential requirement for self-regulation during NFB training.

The functional role of changes in BA22 and BA41, which are related to auditory processing, is less clear. However, the small number of voxels indicating change and their proximity to BA13 suggest the changes are anatomically related as opposed to functionally related. Further, BA22, 41, and 13 receive afferent input from the same thalamic nuclei (medial geniculate nucleus; MGN) making each region sensitive to changes in the oscillatory activity originating in MGN (Rodgers, Benison, Klein, & Barth, 2008).

In the VT condition, during which participants were to imagine playing against a virtual opponent, the post NFB training reduction of alpha power at 9.25Hz may indicate less cortical inhibition and increased processing related to mental responses while watching the video of the world ranked opposing table tennis player. This finding is consistent with Babiloni et al. (2009) who found that elite athletes show less cortical activation while watching skilled athletic performance compared to non-athletes. The changes in right BA23 in this condition are particularly relevant as this region is associated with visuo-spatial orientation, monitoring changes in the environment, and switching attention, all of which are essential for successfully returning an opponent’s shot (Vogt, Vogt, & Laureys, 2006;

Pearson, Heilbronner, Barack, Hayden, & Platt, 2011). In addition to this, BA23 has afferent connections with multiple thalamic nuclei and as such is sensitive to changes in cortical activity originating in the mediodorsal, ventral anterior, ventral lateral and central latocellular nuclei (Vogt et al., 2006). Changes were also found in right BA24 (dorsal anterior cingulate cortex (dACC)) an area involved in detection of response conflict, error monitoring, and motor learning (Braver et al., 2001). Braver et al. (2001) also outlined the role of the dACC in response inhibition, a key requirement in both table tennis play and performance on the Go-NoGo task.

Due to the limited availability of player/participants, change in the NFB learning index (LI) rather than a control group, was employed to identify NFB learning effects as distinct from test-retest/practice effects. The LI was used to establish if there was a relationship between learning during NFB, and post training change in the EEG. The effect size of the maximum voxel statistic was strikingly large (r^2=.86). Unlike the right hemispheric changes found pre versus post NFB training in the eyes closed, eyes open, and VT conditions, the LI related changes in the eyes open condition occurred in the left hemisphere. Increase in LI throughout training was strongly associated with a decrease in low alpha in left BA32 and BA24.

Closer inspection of the positive and negative max-voxel statistics for all pre versus post NFB training comparisons revealed the direction of change in local cortical activity across almost all voxels, in all conditions and in all frequencies irrespective of statistical significance. This suggests the need for some form of synthesis between Del Percio et al.'s (2009) and Babiloni et al's (2009) neural efficiency hypothesis and inhibition-timing accounts of the alpha rhythm (Mathewson et al., 2011). This was initially proposed by Brown et al. (submitted B) in order to explain the paradoxical effects of alpha NFB training where alpha in functional networks declined following both NFB and physical skill training. On this account alpha NFB training increases control over the timing (and intensity) of alpha burst-firing. Consequently, the recruitment of alpha in the functional role of inhibition-timing control during cognitive processing becomes more efficient. Related cognitive processing becomes more efficient: lowering the resource requirements for synchronised brain activity directly implementing cognitive processing; and lowering the time averaged amplitude of alpha recruited in inhibition-timing control in support of those processes. The present findings indicate that following practice with this (upper) alpha sLNFB training protocol, less cortical resources are recruited in network nodes which carry out information processing of a type required during elite table tennis performance.

The final hypothesis, that changes in cortical activity following NFB would be related to visuo-spatial Go/NoGo task performance enhancement, was partially supported. Significant performance improvements were observed only for accuracy on the NoGo trials. In the absence of a control group it cannot be ruled out that these were simple practice effects. However, a similar practice effect would be expected for Go trial accuracy and for reaction times if that was the explanation of these results but those were not observed. For the 1 circle cue NoGo trials there was a very significant relationship with a large effect size (r^2=.48) between pre – post NFB changes at right dACC and increased accuracy over the same time period. In this case NFB related changes in brain activity are directly related to changes in performance. The non-significant relationship in the case of the 4 circle cue NoGo trials may be due to the marginal significance of that original behavioural result.

NFB related decreases in alpha band activity were linked to increased functional connectivity of this region (dACC) with other nodes of the salience (attention control) network and to decreased mind wandering during an oddball task were reported by Ros et al. (2013). This region has previously been identified as a core node in a network linked with global field power (hence the topographic expression) of the upper alpha band (Sadahiani et al., 2010). Whereas Sadaghiani et al. (2010) and Ros et al. (2013) interpret their results as due to changes in activity of a network which regulates tonic alertness, the absence of NFB related changes in average (CAR) upper alpha band activity in this study suggest a wider role in regulating specific responses to specific cues. This interpretation is further supported by the specific link observed with improvements in NoGo or response inhibition accuracy rather than to more general attentional performance (which would be expected if EEG changes corresponded to an increase in vigilance).

In summary, this experiment indicates that similar NFB training protocols, targeting specific nodes in a performance related functional network, elicit similar changes in cortical activity and that these changes occur across task-relevant network nodes (cf Haller et al, 2013; Scharnowski et al., 2014). In this case, visuospatial, motor, and attentional control networks are richly connected to the region targeted by sLORETA NFB training (BA40) were involved in addition to regions of the brain directly associated with reward learning. The results support previous paradoxical findings that up-training of the upper alpha band may result in widespread decreases in the local power of many synchronised cortical oscillations (cf Pineda et al., 2008). Research with larger samples and the inclusion of control groups are required to further explore changes related to indices of learning during NFB training and extend findings from table tennis players to the wider sporting communities. Future research may benefit from the inclusion of phenomenological measures to explore participants' experience during the NFB sessions and how their subjective experience is related to the success of NFB training, cortical changes and ultimately, behavioural change. This experiment demonstrated that NFB training elicits changes in cortical activity which extends through structural and functional connections to other nodes of task-relevant networks. Furthermore, some of these changes are directly related to behavioural performance enhancement on a paradigm previously demonstrated to tap cognitive processes related to table tennis performance.

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Statement of Originality:

We, the PhD candidate and the candidate's Principal Supervisor, certify that the following text, figures and diagrams are the candidate's original work.

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Statement of Contribution by Others:

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Dr Graham Jamieson	10%
Ian Evans	10%
Natalya O’Keefe	10%

Chapter 6 - Conclusions

6.1. Summary of Results

Human EEG research dates to the 1920's and the seeds of what is now known as Neurofeedback (NFB) to the 1960's. Continuing improvements in our understanding of human psychology, the neuroscience of learning and electronic technology, gave birth to the fast-evolving field of neuromodulation. To date, the application of neuromodulation techniques has been overwhelmingly geared towards use within the clinical population. Given the relatively sparse research in the performance enhancement field (Park, Fairweather, & Donaldson, 2015) the purpose of this thesis was to bring together some of the most recent advances in technology and theory to conduct EEG analysis and NFB training for performance enhancement within a fast-paced and open-action sport – table tennis.

Table tennis requires on-going attention to assess the spatial location (relative to oneself) and interpret the motion (e.g., spin) of a moving ball. Additionally, and possibly more importantly as a player evolves, an elite table tennis player also focuses attention on the moving opponent. The elite player assesses the meaning of opponent's movement for salience, relevant or non-relevant motions, deception (feints) and integrates all of this information in a split second in order to select and prepare a response (motor planning) and finally, execute a motoric response.

This thesis was aimed at assessing the neural circuitry underpinning the psychological skills vital to an elite player *prior* to the execution of a motor response – Phase 1. The subsequent aim was to use information gained from Phase 1 to conduct NFB with aspiring elite table tennis players – Phase 2. Chapter 6 will discuss the neural circuitry of elite performance identified in Phase 1 (Chapters 2 and 3) and the changes in regulation of that neural circuitry elicited by the NFB protocols in Phase 2 (Chapters 4 and 5).

Phase 1 – EEG Indicators of Elite Performance

In phase 1 of this study, the aim was to identify EEG measures that could be used as indicators of elite performance and subsequently as targets for Neurofeedback (NFB) training. In Chapter 2, a group of elite table tennis players was compared to a group of lower level but experienced 'amateur' players while actively participating in a table tennis viewing task (VT), while sitting passively with eyes open and with eyes closed. Maximal cortical source differences (higher activity in the elite compared to the amateur group) in a narrow frequency band of 10.50 to 11.75 Hz were located by eLORETA at right Brodmann Area (BA) 13 and right BA6. This comparison was constrained by the similarity of the elite and amateur groups in experience level. In future research it will be useful to include an additional group of novice table tennis players to extend the contrast. However, the the aim of this comparison was to identify candidate structural features of the EEG (underlying sources and frequencies) separating these groups. The functional meaning of these focal group differences in EEG activity was examined in relation to performance on an objective task (vsCPT) designed to assess cognitive skills specifically demanded by table tennis play.

Source activity in the identified frequency band and at the location of maximal group difference in each of these clusters (right BA13 and right BA6) while engaging in the mental activity of simulated table tennis play (the VT condition) was found to be significantly related to superior response speed and perceptual discrimination at the higher processing load (vsCPT4) and reduced response bias at the lower processing load (vsCPT1) of a separate visuo-spatial (Go-NoGo) continuous performance task. This same cortical source activity was also found to be significantly positively related to perceptual sensitivity (d' prime in signal detection theory) for 4 circle cued trials and significantly negatively correlated with response bias (c in signal detection theory) following 1 circle cued trials.

The precentral gyrus (right BA6), part of the dorsal attention network, is involved in cognitive processes such as spatial working memory and spatial attention (Tanaka, Honda, & Sadato, 2005). This brain region selects between sources of sensory input to be utilized in the control of motor responses (Chouinard & Paus, 2010). The insula (right BA13) is known to be a central hub in the ventral attention network, supporting coordination and evaluation of task performance and playing a crucial role in judging the significance of a stimulus. Thus, elite players actively watching the table tennis video show greater activity in the ventral and dorsal attention network nodes than non-elite club players.

This theoretical analysis presumes that the ventral attention system and the dorsal attention system work together, acting to guide the selection and generation of an appropriate motor response. It was further suggested that the high amplitude mu generated by elite table tennis players in right BA13 and right BA6 during the VT condition represents an example of pulsed-inhibition allowing for the selection of what *not* to allow into awareness. The inhibition-timing mechanism of alpha phase may be allowing for top-down control of visual processing and inhibition within the dorsal and ventral network, synchronised to the speed of a table tennis game. Thus upper alpha band EEG source differences between elite and amateur athletes in play related conditions are likely to be a key performance indicator for this sport. They also present the opportunity to train the underlying neural circuitry in an attempt to enhance visuo-spatial performance in table tennis players.

In Chapter 3, the relationship of the ERP from each condition of the Go-NoGo task to world rankings was analysed in a group of 16 world ranked player engaged in international competition in Europe in the summer of 2013. The behavioural version of partial least squares (PLS; McIntosh, & Lobaugh, 2004) was a particularly suitable tool for this analysis. PLS identified components of the vsCPT ERPs that were very strongly related to the competitive performance (world rankings) of these elite players. This was found across all conditions of the vsCPT and a common set of processes appeared to present in each case. These results strongly support the validity of the vsCPT as a measure of cognitive neural network processes required for elite performance in table tennis athletes.

Phase 2 – Neurofeedback for Performance Enhancement

Chapter 4 began the training phase of this program of studies. A NFB protocol was designed using the MNI coordinates differentiating Elite from Amateur table tennis players in Phase 1. Nineteen nationally ranked players undertook intensive table tennis training (5 hours per day), while ten of those players made up the experimental group and also participated in 15 x 30 minute NFB sessions.

NFB training based on estimated EEG source activity at right BA13 and right BA6 within the 10.5-11.5 Hz (upper alpha) bandwidth resulted in a significant decrease in source activity at 11.25Hz in right BA6 post training camp. The Dimension of Attention Questionnaire category ‘Flexibility of Attention’, when used as a regressor, correlated significantly with an increase in 8.2Hz lower alpha activity in BA6 during the VT condition post-NFB. Behaviourally, vsCPT results showed improved accuracy to NoGo stimuli in both 1 and 4 circle cue conditions.

It was discussed that the decreases in Mu seen post NFB, and supported by a previous Mu NFB study (Pineda et al., 2008), might be the result of a change in the frequency of Mu 'packets' (short high amplitude bursts) throughout the epoch, and the timing relationship of these upper alpha oscillations relative to incoming stimuli. Together with improved behavioural accuracy to NoGo stimuli, results suggest a regulation of the inhibitory and timing roles of upper alpha when engaged in the mental activity of the table tennis viewing (VT) task.

Possible limitations of that study included the unknown impact of training two source locations simultaneously and that participants achieved a percentage time above threshold below 50% (that is, the target activity measure decreased during training). The impact of video mode as the NFB presentation method was suggested as possibly providing negative feedback resulting in the non-significant 'learning' over the course of NFB periods. Furthermore, individual alpha frequency (IAF) was not calculated for participants. As such, adjustments were made to the Chapter 5 study in which IAF was calculated, baseline NFB threshold was adapted to induce a higher percentage reward and only one source location was targeted for training.

Results from the second NFB study (Chapter 5) in which training targeted EEG source activity right BA40 at IAF-IAF+2Hz showed, once again, a significant post training decrease in source activity, but this time across all three conditions (Eyes Open, Eyes Closed and VT). As in the previous NFB study, behavioural results showed an increased accuracy to NoGo stimuli.

Eyes Closed changes in visual (dorsal) stream at right BA19 and right BA7 (decrease in low beta 12.87Hz) point to a more relaxed but primed visual system. More extensive changes occurred in Eyes Open condition, revealing a decrease in high beta 24.25Hz in right BA43, 13 and 22, and are indicative of greater activation in motor processing areas.

With regard to Eyes Open changes post NFB, BA43, which anatomically overlays BA13, has been found to have strong structural and functional connections with BA40 and is essential for sensorimotor processing, control of action, and somatosensory processing (Eickhoff et al., 2010). In BA13, the voxels indicating change are located in a dorsal-posterior position. Cauda et al. (2010) identified this area of BA13 as essential for sensorimotor processing and integration with significant connections to pre-sensori- and supplementary motor cortices. Further, findings that changes in BA13 (the insula) were present support the findings of Haller et al., (2013) who suggest that NFB elicits changes in the insula due to its role in introspective awareness, an essential requirement for self-regulation during NFB training.

The functional role of changes in BA22 and BA41, which are related to auditory processing, is less clear. However, the small number of voxels indicating change and their proximity to BA13 suggest the changes are anatomically related as opposed to functionally related. Further, BA22, 41, and 13 receive afferent input from the same thalamic nuclei (medial geniculate nucleus; MGN) making each region sensitive to changes in the oscillatory activity originating in MGN (Rodgers, Benison, Klein, & Barth, 2008).

An exploration into the relationship between the LI and EEG activity found the LI significantly predicted decreased alpha activity at 8.5Hz in BA24 (anterior cingulate cortex) and 32 (dorsal anterior cingulate cortex; dACC) in post-NFB eyes open condition. The changes located in left BA32 and BA24 in the low alpha frequency suggest a release from inhibition in regions directly related to reward learning (Bush et al., 2002). The particularly high *r*-score in the sLORETA analysis in voxels in BA24 is a reminder of the importance of the dACC in learning but especially in response conflict.

In the active (VT) condition, during which participants were to imagine playing the opponent, the reduction of alpha power at 9.25Hz indicates (on average) less cortical inhibition and may represent increased processing and readiness to respond while watching the video. This finding suggests that players have become more efficient at recognising and processing sensory stimuli, requiring less inhibitory involvement from alpha oscillations. The changes in right BA23 in this condition are particularly interesting as this region is associated with visuo-spatial orientation, monitoring changes in the environment, and switching attention, all of which are essential for successfully returning an opponent's shot (Vogt, Vogt, & Laureys, 2006; Pearson, Heilbronner, Barack, Hayden, & Platt, 2011). In addition to this, BA23 has massive afferent connections with multiple thalamic nuclei and as such may be sensitive to changes in cortical activity originating in the mediodorsal, ventral anterior, ventral lateral and central latocellular nuclei (Vogt et al., 2006). Changes were also found in right BA24 (dACC) an area essential for response conflict, error monitoring, and learning (Braver et al., 2001). Braver et al. (2001) also outlined the role of the dACC in response inhibition, a key requirement in both table tennis play and performance on the Go-NoGo task.

Most importantly pre – post NFB training reduced 9.25 Hz activity, at the maximum voxel, during the VT condition was strongly and significantly correlated with pre – post NFB training increases in NoGo accuracy following the 1 circle cue. Thus the changes in cortical activity following this NFB training protocol have been directly linked to sport related performance enhancement in this study.

6.2. Discussion - Phase 1: EEG Indicators of Elite Performance

Table tennis is a fast-paced sport. The ball travels at around 100km/h over a distance of around 3 metres, giving players approximately 200 ms to react from the time the ball leaves the opponent's racket. To select the correct response a player must learn to read the meaning of the opposing players' motion and identifying the salient differences in visual information at speed, not only by observing ball trajectory, but also from the bodily movements of the opponent. To do this requires domain specific perceptual learning and rapid selection from these perceptual processes to guide motor decisions.

Perceptual learning is a form of implicit learning gained through practice (ie. skill acquisition) which allows one to tune perception to efficiently select relevant sensory signals. It ultimately determines one's success when adapting and interacting with the dynamic and complex environment. A recent study on perceptual learning has shown that ongoing electrical oscillations in the alpha frequency band (8–12 Hz), is able to predict up to 64% of the observed variability in the learning outcome in a perceptual task (Freyer et al., 2013). The recently observed coupling of gamma amplitude and alpha phase dynamics (Palva & Palva, 2007) may be expected to play an important role here as will be discussed in a later section (6.4 Future Directions).

Features of alpha correlated with perception and learning have been well documented including event-related de/synchronisation (ERS/ERD), inhibition-timing mechanisms, pre-stimulus alpha influences on performance and neural efficiency (Pfurtscheller, Stancak, & Neuper, 1996; Hanslmayer et al., 2007; Babiloni et al., 2006; Mathewson et al., 2009; Del Percio et al., 2008; Capotosto et al., 2009). The core properties of organised neural activity measured by the EEG, frequency, amplitude/power and phase, have been observed to vary systematically according to task (visual detection, visual discrimination, visual-spatial attention, somatosensory detection), cortical region (occipital, frontal, parietal, sensorimotor/parietal), event (stimulus, response) and time interval (Sigala, Haufe, Roy, Dinse, & Ritter, 2014). In current models the observed functional roles of the alpha rhythm emerge from its capacity to effect transient inhibition of information processing at specific locations and at specific time intervals related to ongoing cognitive operations, for example to facilitate detection of changes at spatial locations where salient stimuli are expected, as in the top-down control of visual processing by the DAN (Händel, Haarmeier, & Jensen, 2011). Additionally, it is widely observed that brain regions that are activated during a task exhibit event-related desynchronisation (ERD), whereas regions associated with task irrelevant and potentially interfering processes exhibit event-related synchronisation (ERS) in the alpha band (Pfurtscheller et al., 1996). Both experimental findings and computational models point to the functional role of alpha band activity, in the sensory processing, as regulating the temporal and spatial flow of information processing related to higher cognitive functions such as perceptual learning (Sigala et al., 2014).

Klimesch (2012) reviews and integrates experimental findings on alpha by highlighting the close connection between the effects of alpha on the inhibition and timing of information flow and the two fundamental functions of attention, the suppression or selection of independent processing streams. He goes on to suggests that, through the combination of these functional roles, alpha facilitates and controlls cognitive access to task relevant information represented in a so-called Knowledge System (KS) which comprises, not only long-term memory, but also includes procedural and implicit perceptual knowledge. Alpha's effects on the timing and inhibition of access to information acts to control the processing of responses to incoming stimuli by gating access to the KS of activated memory encoding and perceptual learning processes. Further details of the proposed mechanisms involved in his account go beyond the scope of this thesis (for a full review see Klimesch, 2012) however it is clear that the phase in the temporal cycle of alpha oscillations plays a pivotal role in the selection of information from continuous sensory processing as in perceptual learning. Klimesch's (2012) analysis of the functional role of alpha in the control of selective access to one's KS provides a helpful framework for understanding the results found in Phase 1 of this thesis relating to the role of narrow upper alpha band activity in the performance of elite table tennis players.

Greater upper alpha band activity, found in elite than amateur table tennis players during mental play (VT), reported in Chapter 2, was focussed in right BA 6 and right BA 13 which are involved in extended networks of motor control (including the dorsal and ventral attention networks). This brain activity was then demonstrated to be directly related to the highly efficient identification and selection of salient visual stimuli for motor control on the vsCPT in these same skilled participants. Our finding supports previous research which has found alpha increases over parietal areas when a task engages processing in the ventral visual stream (Jokisch, & Jensen, 2007) and that semantic processing (stimulus meaning) is associated with changes in upper alpha (10-12Hz) activity (Klimesch et al., 1994). In terms of Klimesch’s (2012) model, the increased upper alpha activity shown by elite table tennis players (compared to amateurs) may be interpreted as reflecting not only increased top-down inhibitory control and selection of sensory information, but also a gating process allowing an increased ability to find what meaningful in that performance context from the continuous stream of visual stimuli based upon access to existing KS representations (Figure 1). Consider that the comparison ‘amateur’ group were matched for experience level (years playing table tennis) but showed lower table tennis performance and lower amplitude upper alpha. It would follow, from Klimesch’s (2012) account, that the amateur group’s lower upper alpha activity in these regions during the processing of continuous responses to changing meaningful visual information indicates less effective inhibition of irrelevant sensory information coupled with decreased access to related KS representations (giving rise to a lower level of perceptual learning efficiency). That is the amateur group was not using upper alpha as efficiently in regulating response related stimulus processing. Future research assessing alpha phase resetting differences, to salient visual stimuli) between these groups with a task allowing for the assessment of time-locked processing responses to stimuli would assist in determining the functional role of phase timing differences in upper alpha between elite and amateur athletes in addition to the amplitude differences reported here.

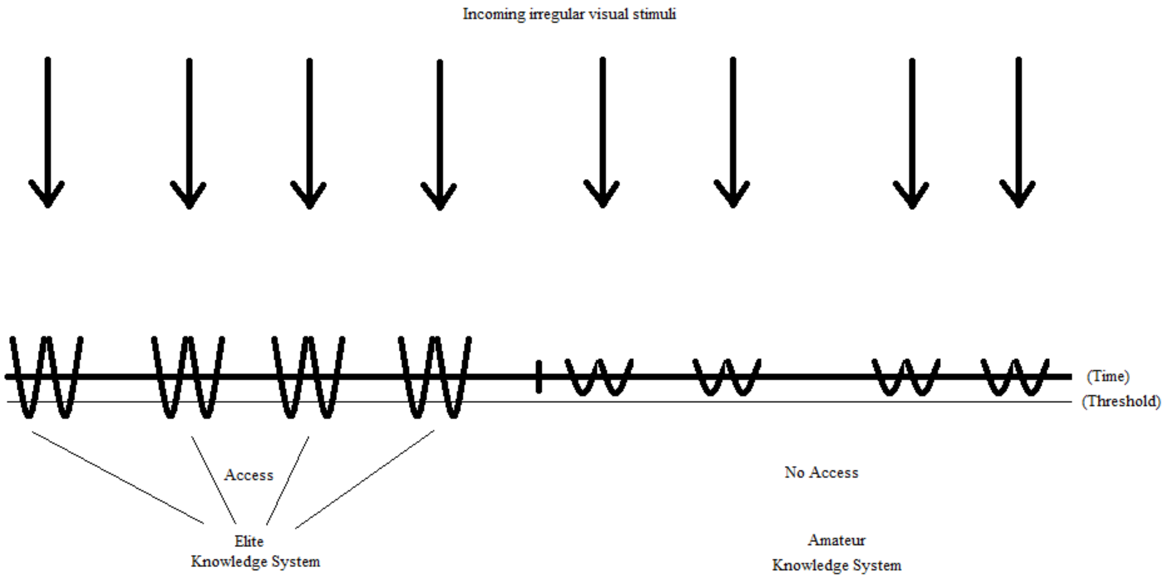

Figure 1. Gated inhibition, phase-locked to incoming stimuli, but with increased amplitude regulating access to specific Knowledge System representations at corresponding time points. This allows a player to successfully process the meaning of stimulus events in relation to learned KS representations in real-time.

6.3. Discussion – Phase 2: Neurofeedback for Performance Enhancement

6.3.1. Video mode – positive and negative reinforcement

The use 'video mode' as the presentation method for feedback in our sLORETA NFB studies was designed to induce in the participant an active state of mental processing as similar as possible to that of actually playing table tennis (but without producing movent artefacts). It was our intention to provide feedback to participants while actively processing incoming visuo-spatial sensory information of sport-specific significance related to their personal experience. Watching a table tennis video reproduced as closely as possible the pre-post testing (VT) task described in Chapter 2, and used throughout this thesis, which guided the selection of the frequency band and subsequent cortical regions for sLORETA NFB training.

It was proposed (Chapter 4), that this presentation mode of the sLORETA NFB may have provided both contingent positive and contingent negative feedback. Contingent *negative* feedback would occur when the signal from the video was distorted to indicate EEG was not meeting the required NFB parameter threshold. This changing feedback signal could be viewed as a form of alternating negative and positive reinforcement with unknown effects for learning outcomes. It remains unknown as to whether participants responded to the jamming of the screen as negative feedback, or to unjamming as positive feedback, or both. Frustration during the NFB training was not reported by participants; however, they were not directly questioned by the experimenters regarding this issue. In the future, it would be useful to assess participants' feelings of reward and frustration here and to compar them to other presentation modalities. While Krigbaum, & Wigton (2014) discuss efficacy of different NFB techniques regarding protocol construction and parameter calculation (QEEG-guided NFB, z-score-NFB, slow-cortical-potential NFB), the author is unaware of any literature regarding an objective comparison of modern NFB presentation methods. Previous research has used video mode sucessfuly with ADHD clients (Kroptov et al., 2005; Kroptov et al., 2007; Ahmadlou, Rostami, & Sadeghi, 2012; Ogrim & Hestad, 2013) but without assessing the efficacy of the video mode nor the possible role of negative reinforcement. The Neuroguide system, widely employed by clinicians, uses video mode coupled with z-score sLoreta NFB (Koberda, Moses, Koberda, & Koberda, 2012; Koberda, Koberda, Bienkiewicz, Moses & Koberda, 2013).

The increase in percentage of time above threshold across sequential training periods, averaged across NFB sessions and across participants, was not-significant (Chapter 4 – Figure 5, pg 115) and (Chapter 5 – Figure 4, pg 147) in either of the NFB studies. However, post hoc inspection of results across both studies shows a clear pattern of linear increase, consistent with learning, from period's two to five after an initial drop between periods one to two. That is the introduction of NFB training to the mental activity engaged in players by viewing the table tennis video results in an early desynchronization in the narrow upper alpha band activity in the ROT and subsequent increase in this activity (NFB learning) occurs following this initial drop off (see below).

In Chapter 5 (Chapter 5 – Figure 5, pg 147) time above threshold (here averaged across time periods and across partciapants) showed a clear pattern of linear increase, consistent with progressive learning, between NFB sessions 2 – 6 which was then maintained until session 14 (the final training session). Importantly, the increase in time above threshold from the second to the final training session strongly predicted post NFB EEG changes in regions related to the control of attention to stimulus features required to select between competing motor responses. This confirms that learning during the NFB protocol administered had an effect on cortical activity and that these schanges occurred in regions engaged in the cognitive control functions elicited by table tennis play. Therefore, it is concluded that the video mode of NFB presentation has been successful in learning to self-regulate selected neural activity and in bringing about related changes in functional cortical network hubs.

6.3.2 Time above threshold (TAT) as a measure of NFB training performance

The percentage of time above training threshold during either each training period (within a session) or each training session is the standard index of training performance in clinical NFB practice, and is widely employed for this purpose in the experimental literature (Dempster & Vernon, 2009). Alternative indexes of training performance reported in the NFB research include the number of successive time segments during training in which the training parameter increases (or decreases depending on the protocol) (Egner & Gruzelier, 2001). The relative merits of these and other measures of learning performance during NFB training is the subject of a separate research program at the University of New England. However preliminary analysis of results from that project indicate a high correlation between each of these 3 operationally distinct indexes (Macnamara, Jamieson & Evans, in preparation). The measure used here, percentage TAT, was chosen because of its widespread acceptance amongst NFB practitioners, the end users or this research. However, based on available findings (Macnamara et al.) it is reasonable to expect a very similar pattern of results had either of the major alternative measures been employed.

The training threshold was set at a level which was designed to be exceeded about 55% of the time during the baseline period in Chapter 4 and 60% in Chapter 5. In both Chapter 4 and Chapter 5 average time above threshold during NFB training never exceeded these levels. Looking at the averages for each training period it appears that in the first period TAT was maintained at about (but slightly below) the level of the (immediately preceding) baseline period. During the second training period time above threshold declined sharply and then recovered linearly across the remainder of the session to be slightly below that of the baseline period. It can be inferred that the addition of NFB training to the baseline condition resulted in a drop in synchronised oscillatory activity for a short time period in the frequency band being trained (a narrow band within the alpha range) in the ROT.

This phenomenon may be a parallel to that reported by Qualls and Sheehan (1981) in the biofeedback literature. They found using EMG biofeedback (muscle relaxation) that for high trait absorption trainees focusing on the biofeedback signal actually interfered with the targeted muscle relaxation and that this relaxation was facilitated by learning to adopt self-generated mental strategies. Tellegen (1981) interpreted the former result as an effect of the active mental demands or ‘instrumental set’ imposed by the biofeedback task and the latter result as the effect of adopting an effortless “experiential set”. It is noteworthy for this parallel that DAQ Absorption (a state rather than a trait measure) showed a significant increasing linear trend across training sessions F (1, 9) = 12.97, p < .006, η_p^2 = .665 (uncorrected) in the Danish study.

High levels of cortical alpha band activity are closely linked to states of deep relaxation such as when falling asleep and are inhibited by active sensory processing (Klimesch, 1999). It may be the case that, within the alpha band, engaging in NFB training actively suppresses cortical activity compared to non NFB baseline conditions. In that case what participants are learning during (wide or narrow band) alpha enhancement NFB protocols is to consciously facilitate this cortical activity in conditions which actively inhibit it. However such learning will still be reflected in systematic increases in TAT across a series of successive training periods within a session.

The extent to which the NFB task suppresses cortical alpha may differ for different ROT. For example, is this effect limited to primary (exteroceptive) sensory cortices and those (higher order) regions with which they functionally interact? This is an important issue for alpha facilitation NFB applications which should be addressed by future research.

6.3.3. NFB training and the regulation of cortical alpha

Before we proceed to a deeper interpretation of the results it is necessary to revisit current understandings of the overlapping neurophysiological mechanisms which underlie NFB and the modulation of the cortical alpha rhythms. Through NFB training, individuals learn to voluntarily raise or lower their own cortical neural activity within specific regions at particular frequency bands to obtain various desired behavioural and cognitive outcomes (Vernon et al., 2003; Gruzelier & Egner, 2005). For NFB to be effective, sources of cortical activity must be open to operant conditioning (Sterman, 1996; Vernon, 2005). The major regulators of alpha generation targeted as a potential candidate mechanism for eliciting cortical changes observed in NFB training are the cortico-striatal-pallido-thalamo-cortical loops (Babiloni et al., 2009; Sterman, 1996). These loops are involved in the relay and modulation of sensory motor information and its subsequent integration in higher cognitive processes (Guillery & Sherman, 2002). Functionally distinct thalamic nuclei (Figure 2 below) receive incoming signals from specific sensory modalities (first order relay), pyramidal axons from cortical layers V and VI (higher order relays), and the basal ganglia. These signals are then relayed to functionally specific cortical areas for further processing (Guillery & Sherman, 2002). The inputs to the thalamus from the globus pallidus of the basal ganglia and cortical layer VI pyramidal neurons play a modulatory role controlling the firing rate of thalamocortical relay neurons, in turn affecting information flow back to the cortex (Lee & Sherman, 2008). For example, visual stimuli received via the retina travel along the optic tract into the lateral geniculate nucleus (LGN) of the thalamus. The LGN relays the information directly to the primary visual cortex (V1). In turn, axons in layer VI of the visual cortex provide feedback to the pulvinar nucleus of the thalamus which in turn projects these inputs to further visual processing areas (Burman & Wurtz, 2008). Similar connections provide the basis for oscillatory activity within multiple parallel cortico-striatal-pallido-thalamo-cortical loops.

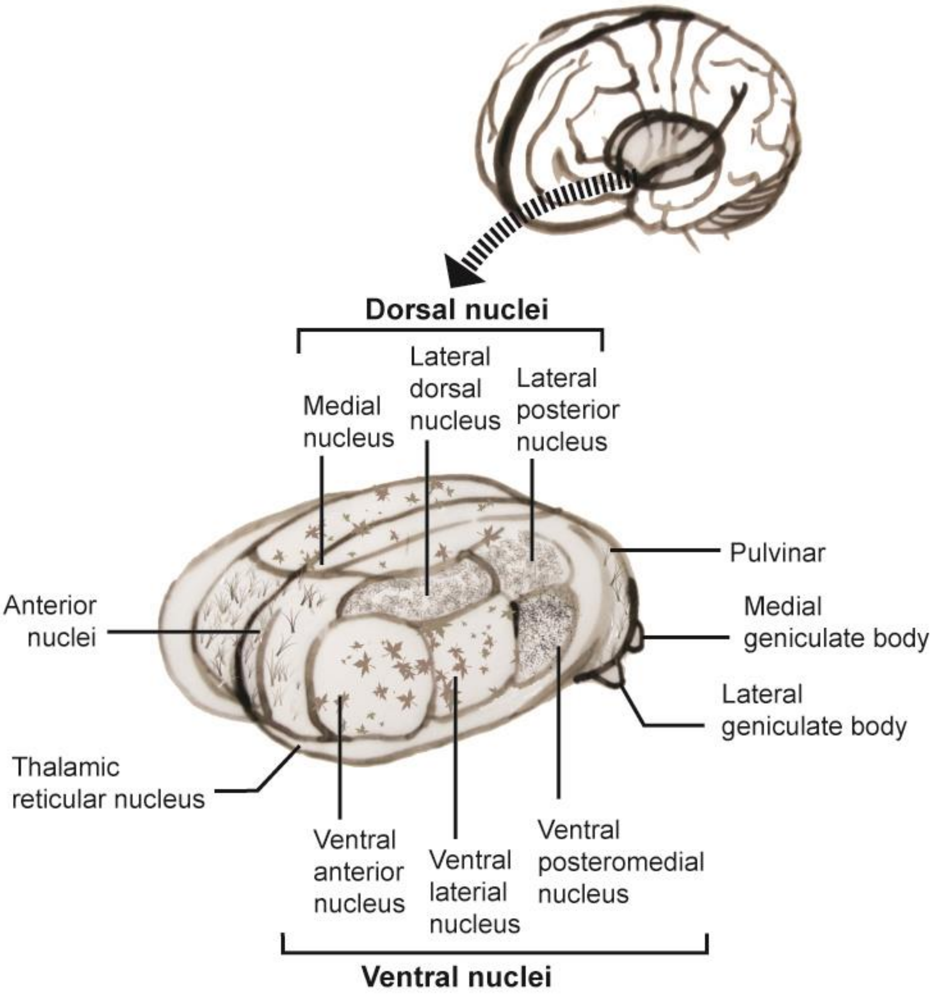

Figure 2. The anatomy of the thalamus. The functionally distinct nuclei of the thalamus operate as part of a feedback loop receiving input from specific sensory modalities, relaying the information to the cortex and receiving feedback from these same cortical targets and from basal ganglia connections before feeding forward the information to additional areas of cortex.

Information flow between the thalamus and the cortex is modulated by the firing rate of the thalamic relay cells (Lee & Sherman, 2008). When a relay cell is depolarized for 100ms, excitatory post synaptic potentials (EPSP) activate action potentials that communicate information on a single input/output basis, faithfully transmitting the incoming signal uninterrupted from the thalamic nuclei to the cortex (Lee & Sherman, 2008). Rhythmic alpha waves are generated when the globus pallidus inhibits the thalamus, causing thalamic relay cells to switch from tonic firing to burst firing. During burst firing of a cell, a series of two to 10 action potentials are activated that interrupt the communication between the thalamus and cortex (Crunelli & Hughes, 2005). The activity of burst firing neurons is detected on the scalp EEG as rhythmic alpha waves (Crunelli & Hughes, 2005). Figure 3 provides a basic diagram of the cortico-striatal-pallido-thalamo-cortical loop involved in the relay of motor information.

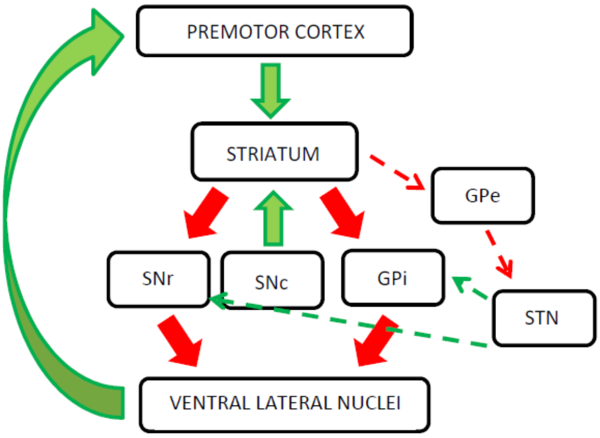

Figure 3. Preparing and executing motor movements — a basic representation of the communication in the cortico-striatal-pallido-thalamo-cortical loops. Red and green arrows depict inhibitory and excitatory relationships respectively. Solid arrows represent a direct pathway of influence (activation increases movement) while broken lines represent an indirect path (activation decreases movement). The premotor cortex sends excitatory signals to the striatum. When activated, the striatum inhibits the SNr and GPi, in turn inhibiting the inhibitory effect the SNr and GPi exert over the thalamus (ventral lateral nuclei project to the cortical regions associated with planning and execution of movement). Release of inhibition of the thalamic nuclei allows the thalamus to communicate information back to the premotor cortex (McFarland & Haber, 2002). SNr = substantia nigra pars reticulata; SNc = substantia nigra pars compacta; GP = globus pallidus internal; Gpe = globus pallidus external; STN = subthalamic nucleus.

In terms of trainability of cortical activity, the striatum in the cortico-striatal-pallidothalamo-cortical loop (Figure 3) receives massive dopaminergic input from the substantia nigra pars compacta (SNc) making it particularly responsive to reward. As such, it is considered to play an essential role in learning motor sequences and procedural skills (Kreitzer & Malenka, 2008). It is thought that through NFB training, cortical networks are undergoing a form of neural plasticity modulated by activity reverberating in these loops, in effect changing the connectivity ('neurons that fire together wire together') between task relevant areas (Haller et al., 2013; Scharnowski, Rosa, Golestani, Hutton, & Josephs, 2014). Haller et al. (2013) investigated the changes in functional connectivity that occurs after real-time fMRI (rt-fMRI) NFB targeting the auditory cortex. They found changes in connectivity not only in the auditory processing networks but also in visual processing areas and the insula. They suggest that changes in the insula in particular are related to the introspective awareness required to self-regulate during NFB training. Another study utilising NFB via fMRI explored the effects of this form of training on visual perception (Scharnowski et al., 2014). Scharnowski et al. (2014) found that training in the visual cortex elicited change in connectivity between the visual cortex and the superior parietal lobe (SPL). The SPL is involved in directing visuo-spatial attention and the increased connectivity with this area likely facilitates greater top-down control over visual processing areas (Scharnowski et al., 2014).

6.3.4. Theoretical implications of current NFB findings

As an interpretation of the results of Phase 1, we posit that upper alpha oscillations within the fronto-parietal networks of attention are facilitating an athlete's ability to select and interpret ongoing perceptual information in relation to their pre-existing knowledge system (KS) and thus to process and utilise the visual cues salient to response selection and motor control both at a faster rate and with greater precision. If this is the case, training aspiring athletes to control their upper alpha band activity in those networks has the potential to assist them to more efficiently utilise continuous, meaningful visual information, with rapid access to relevant KS representations, for effective selection of motor responses. In any case, the result from Phase 1 of this thesis pointed to high upper alpha power in these networks differentiating elite from amateur performance which was thus selected as the target frequency band for sLORETA NFB training. Previously Zoeful et al. (2011) trained participants in the upper alpha band via NFB and showed increased cognitive (top-down) control in a mental rotation task (a form of visuo-spatial information processing). In Chapter 4 and Chapter 5 of this thesis upper alpha training was followed by heightened accuracy of no-go responses (top-down inhibitory control) to visuo-spatial stimuli during the vsCPT.

The amplitude of alpha activity correlates negatively (i.e. decreases) with increased efficiency of information processing in multiple domains, including perceptual learning (Babiloni et al., 2010). On this account increased neural efficiency leads to decreased activation (lower task related alpha desynchronization) and hence higher alpha levels in more expert performers. The results of Chapter 2 may also be considered as another example of this pattern of findings described by the neural efficiency hypothesis. In that case the alpha rhythm plays no causal role in performing skilled behaviours and modulation of alpha band rhythms will not facilitate enhancement of skilled performance. Ros et al. (2010) provided evidence of a causal link by combining NFB training and localised TMS pulses to show that a NFB trained decrease in alpha oscillations contribute significantly to cortical plasticity in the motor evoked potential, thereby causing changes in cortico-spinal excitability. The authors suggest that the plasticity effects they observed are best explained by mechanisms related to long-term and short-term potentiation, which interact with alpha oscillations in the context of perceptual learning.

In a similar way, in chapters 4 and 5, we sought to demonstate functional performance enhancement following NFB training to upregulate the narrow alpha band activity observed to be elevated during virtual play in the elite table tennis players in Chapter 2. The use of cortically specific NFB training in conjunction with pre-post training neuroimaging assessment (and eLORETA must be considered an EEG based neuroimaging modality) allows us to directly link pre-post NFB changes in local neuronal activity to changes in behaviour and cognition. This was the strategy adopted in Phase 2 employed sLORETA NFB to train the alpha networks identified in Phase 1, where results were evaluated using eLORETA as the source imaging method.

At this point, however, one key limitation of the Chapter 4 study should be pointed out. Alpha plays differing functional roles depending on the time sequence of cortical events and the location of the alpha source. The study in Chapter 4 trained both right BA6 and right BA13 simultaneously. While this ‘double barrelled’ approach to NFB training was closer to the empirical differences reported in Chapter 2 it was consequently impossible to disentangle whether observed changes resulted from training at one or the other nodes or both combined. Interpretation of results of the NFB study in Chapter 4 must keep this in mind. This said, however, rewarding the signal generated from either two (Chapter 4) or one (Chapter 5) network sources consistently resulted in a post NFB decrease in upper alpha at right BA6 (a major node in the executive network) in the VT condition.

The larger spatial scale (spanning centimetres) of neural networks connected by alpha oscillations (von Stein, & Sarnthein, 2000) means that phase differences in alpha oscillations are expected between causally connected network nodes. The flow of functional processing from one node to the other would depend on consistent phase differences, which were not explicitly trained in that study. An important extension of the NFB study in Chapter 4 will be to target performance enhancement employing the temporal phase relationsips amongst the spatial nodes of the neural network identified in Phase 1 in NFB training. While these capacities are targeted for the next round of development this approach is beyond the constraints of the hardware/software platform available in the current studies.

As previously discussed in Chapter 4 and 5, an upper alpha decrease was seen in a previous study by Pineda (2008) after rewarding power increases during NFB and has been seen previously in other frequencies (e.g. Vernon et al., 2003, in theta band). Upper alpha generally appears over motor cortex in ‘packets’ or spindles, synchronising from hundreds to thousands of milliseconds and then disappearing. Analysis of the dynamic features of these packets would require time-frequency analysis time-locked to specific processing events. The current assessment task (VT) can in principle be developed to permit this form of analysis. However, the video jammer (presented using ongoing table tennis matches) feedback mode is unsuited to training these signals. The videos used to present the table tennis matches comprised of ‘rallies’ of varying length interspersed by periods of no play – as in a real match – and it was therefore impossible to analyse at which moments of the video the upper alpha ‘packets’ synchronised relative to incoming meaningful stimuli. Even if event triggers were built into that process degraded visual input significantly disrupts processing in the networks which are the target of such training. While such developments are planned for a future round of research, discussion of the results to date will be constrained by the technological limitations of current NFB methods.

The decreases in upper alpha band activity following NFB training reported in these studies is paradoxical. The conventional understanding of NFB training is that the effect of training should be to enhance intrinsic (i.e. resting state) activity in up regulated frequency bands (Ros, Baars, Lanius, & Vuillemier, 2014). Ros et al. (2014) argue that similar paradoxical effects following NFB may be explained by the concept of homeostatic plasticity according to which perturbations of functional intrinsic rhythms either up or down away from an optimal set point may result in performance decrements and/or compensatory shifts in oscillating neural networks against the direction of the perturbation (in this case up regulation of upper alpha by our NFB training protocols) and towards the optimal set point. On this interpretation elevated upper alpha (relative to less skilled table tennis players) was already optimal and NFB training to up regulate this activity has triggered a post training homeostatic response to lower these levels to maintain optimal performance. However if such a mechanism lies behind current results then one would expect resting levels of mean (CAR) upper alpha band activity to be higher in elite compared to club players (Chapter 2) or that mean (CAR) training band amplitude would be significantly reduced following NFB training (Chapter 4 and Chapter 5) however in each case results were not only non-significant but far from significance.

Insofar as the current paradoxical effects of NFB training are also linked with performance improvements (e.g. Chapter 5) these findings are also inconsistent with the neural efficiency hypothesis (Del Percio et al., 2008). However upper alpha also decreased over the period of intensive table tennis training in the control (non NFB) group, at another network node, right BA40, in Chapter 4, which is also inconsistent with the neural efficiency hypothesis. In Chapter 5 post NFB alpha training EEG activity consistently declined (albeit non significantly) across the observed frequency range from 1 – 30 Hz across the cortex during intrinsic network activity (eyes closed and eyes open resting) *and* active skill related processing (the VT condition). One possible explanation for these findings is that less upper alpha is required to achieve the same level of control after learning due to greater efficiency in skill execution.

Given the functional role of alpha in the timing of processing and the modulation of attention we seek to interpret these post NFB training changes in the EEG as the result of increased efficiency in control of (and through) the process of inhibition-timing itself. If the timing (as well as the location) of cortical upper alpha plays an essential role in the efficiency of ongoing cognitive processes, then greater precision in the timing of this alpha activity can in principle result in reduced upper alpha amplitude in control related activity (Chapter 4 and Chapter 5) *and* reduced (non-alpha) cortical processing activity (Chapter 5). We call this *the inhibition-timing neural efficiency hypothesis*.

If, as appears likely, the inhibition-timing role of cortical alpha is coordinated by the burst firing of thalamic relay neurons then it is apparent that, where effective, both physical skill training and current NFB protocols will enhance the efficiency of this control. In that case, the effect of training is to increase the precision of the packets of cortical alpha produced during skilled performance. This precision will be expressed as greater amplitude, greater topographic specificity and increased timing control of cortical alpha. The effect of training this mechanism over time will be greater processing efficiency and thus lower amplitudes in higher (beta, gamma) and lower (delta, theta) frequencies in processing related networks (particularly during active processing). Because of its pulsed nature, improved precision in the timing of control related cortical alpha band activity can in principle give rise to decreased amplitudes when averaged across epochs. *This is the inhibition-timing neural efficiency hypothesis.* While admittedly speculative it is proposed here in order to explain paradoxical features of the current series of studies. Specific testing of this hypothesis in relation to NFB training will require the adoption of EEG time-frequency analysis methods and the development of NFB protocols which employ features of time-frequency activity of cortical upper alpha (and other frequency bands).

6.3.5. Resting state network and extended motor network change

The cortical changes evoked by the alpha NFB protocols used in Chapters 4 and 5 are evidence for wider cognitive control extended motor network involvement in these NFB training protocols. Results from Chapter 4 showed that NFB training aimed at right BA13 and right BA6 within the 10.5 – 11.5 Hz bandwidth (Chapter 4) resulted in a significant decrease in source activity at 11Hz in right BA6. The Dimension of Attention Questionnaire category ‘Flexibility of Attention’, when used as a regressor, correlated significantly with an increase in 8.2Hz (lower alpha) activity in BA6 during the VT condition post-NFB training.

Results from the second NFB study (Chapter 5) aimed in right BA40 showed a significant decrease in source activity in RSNs and active (VT) conditions. As outlined in section 6.1.2, RSN changes during Eyes Closed involved right BA19 and right BA7. RSN changes during Eyes Open involved right BA13, 43, 22, 41, and correlating with the LI, left BA24 and 32. Active (VT) changes post NFB involved right BA6, 24 and 23.

Given the EEG changes found in the RSN and active condition post NFB, it seems that the use of the upper alpha sLORETA NFB protocols in this study has had a lasting effect on cortical organisation not only while a player is playing (or simulating) table tennis but also at rest, supporting previous findings (see Sigala et al., 2014) of training influences on multiple resting state networks (RSNs). The alpha NFB protocol combined with watching and playing table tennis has recruited involvement from the integrated action of the dorsal (right BA19 and 7) and ventral (BA13) attention networks, motor planning (right BA6, 43, 22) reward learning (BA32, 24), and orienting the body in space via the cingulate motor areas (BA23). But more specifically, our results point to a highly targeted *activation* network (during VT changes occurred in right BA6, 24 and 23 – right supplementary motor, ACC and PCC), and more global changes taking place within *RSNs* (within right BA19, 7, 13, 43, 22, 32), supporting previous research indicating a reconfiguration of brain networks between task and resting state conditions (Di, Gohel, Kim, & Biswal, 2013).

To conclude, intrinsic oscillatory activity in motor and cognitive control network nodes with functional roles in sensory processing, reward learning, perceptual learning, inhibitory control, conflict and error monitoring, attention switching, visuo-spatial orientation, introspective awareness and self-regulation, in both active sport specific mental processing and resting states show signicant changes following training on the sLORETA NFB protocols employed here in Chapter 4 and Chapter 5. All of these functional nodes are engaged in psychological skills that are essential components of the fast-paced decision-making required in table tennis and other fast-paced continuous sports for simultaneously monitoring an opponent and the ball, planning and executing a motoric response.

6.4 Future Directions

Our results show that upper alpha is higher in magnitude in elite players and I have argued that this is an example of a more efficient inhibition-timing mechanism. I have argued that alpha oscillations become more precisely phase-locked to incoming visual stimuli through NFB training and that alpha oscillations may directly precede and/or straddle the anticipated relevant movement by the opponent (in order to sharpen focus by inhibiting irrelevant sensory information). One obvious next question arises. In such a fast sport as table tennis, whereby one may have as little as 200 ms to react, does one alpha oscillation (~100 ms) carry one data-point of sensory information from the thalamus to the cortex? It is well established that our visual system works by taking saccades of visual information (3-5 saccades per second, 200-300 ms apart), controlled by the frontal eye fields and placing them together to give us the impression of seeing movement (Fischer, & Weber, 1993). Purcell, Schall, Logan, & Palmeri, (2012) show that adjustments in the level of gated-inhibition can control trade-offs in speed and accuracy that optimize visual search performance. Is it the case that one alpha oscillation, then, carries one saccade of visual information? If so, how would an elite athlete generate the impression of movement over such a short time-span required in, for example, a sport like table tennis?

It is at this point the interaction between frequency bands becomes pivotal in extending our understanding. Relating to predictors of perceptual learning outside the alpha band, Palva and Palva (2007) describe the importance of cross-bandwidth analysis and the timing interaction between, for example, gamma (30-70Hz) and alpha oscillations. A recent study by Spaak, Bonnefond, Maier, Leopold, & Jensen (2012) showed an "intimate relationship" between alpha and gamma band dynamics within the primate V1 cortical microcircuits. Driven by deep layer alpha generators, gamma band activity in superficial granular and supragranular layers is modulated in a suppressive, phase-specific manner (Spaak et al., 2012). Furthermore, gamma has been found to be phase-locked to both theta and alpha oscillations (Belluscio, Mizuseki, Schmidt, Kempter, & Buzsáki, 2012; Osipova, Hermes, Jensen, & Rustichini, 2008). Jensen, Gips, Bergmann, & Bonnefond (2014) reiterate the inhibitory role of alpha oscillations to control information processing overload and combine this with the coupled processing of gamma waves. They propose, as one of the key processes by which oscillations of different frequencies interact in order to coordinate information processing, that bottom-up gamma oscillations are selected by being 'nested' within the positive phase of a top-down alpha wave, phase-locked to prioritise anticipated sensory information of maximum relevance. In the case of a fast-paced ball sport, this would explain the perception of continuous movement experienced over a short period (~200 ms) of time, if processing of visual information were timed at the rate of a gamma frequency (>30Hz, ie. at least 6 visual frames within 200 ms).

An interesting point regarding post NFB results was the change in Eyes Closed EEG at 12.88Hz in right BA 19 (precuneous) and BA 7 (cuneous); and Eyes Open EEG, at 24.25Hz in right BA13 (insula), 43 (precentral gyrus), 22 (superior temporal gyrus), and 41 (transverse temporal gyrus). Klimesch (2012) discusses the interaction between bandwidths as representing "harmonics" of the brain involving a balanced "coupling" together of bandwidths which represent different aspects of processing. Palva, Palva and Kaila (2005) have shown that phase-coupling between alpha band (at approximately 10 Hz) and beta-band (at approximately 20 Hz) oscillations changes in a task dependent manner, are spatially distinct and are often associated with wide range network oscillations. Viewed in this way, changes in RSN within visual processing areas at ~12Hz and cognitive control areas at ~24Hz may indicate frequency coupling involvement in the wide range motor network being elicited in the alpha NFB protocol used in this study.

Future analysis of the database of table tennis players acquired in this study focused upon the gamma/alpha frequency interaction (frequency-power relationships) may assist in understanding how players achieve the impression of continuity as the ball comes towards them. If we consider that Gamma frequency (30-70Hz) would enable 3-10 frames per 100 ms, we begin to comprehend the basis of a player's ability to track a speeding ball. The database of 206 table tennis players could be mined further to assess the role of this process.

In order to elucidate just what sensory aspects of an opponent and at what exact time-points an elite TT player is processing or inhibiting information, time-locked measures would need to be used. However, it must be remembered that by breaking down a table tennis rally into 'shots' we will not be capturing the flowing elements of the sport. It may not be that the brain has time to trigger alpha's inhibitory-timing mechanism in the same way for one shot as it does for multiple sequential shots in a TT rally. To assess this the task would need to involve full 'rallies' incorporating several shots, with each 'shot' being the point at which a player hits the ball which would then send a trigger code to the EEG acquisition device. In a fast-paced sport such as table tennis this would be a technological feat in itself. The development of an event-related potential sequence of 'shots' to imitate a 'rally' would perhaps elicit ongoing visual attention in a life-like manner and may be more practical in the meantime (e.g. Jin et al., 2010). A motoric response based on anticipating the direction of an opponent's shot would elicit visual-spatial attention processing and ensure participant involvement. Either of these time-locked tasks may assist in making a step towards understanding the time-frequency interaction underpinning elite TT performance.

6.4.1. Future performance enhancement NFB training in the field

The obstacles encountered in the data gathering 'fieldwork' provided a good understanding of what working with athletes would be like in the future. In short, not many athletes or coaches respect neuroscience yet, or appreciate its potential value in performance enhancement.

Coaches generally report simply repeating the training methods they themselves used as players.

Results have shown definite promise for successful implementation of NFB into a performance enhancement training schedule in the future. Extended NFB training (for example 2 days per week ongoing) would be less demanding than the 2 times per day asked of players in this thesis. At that rate, players may not become bored with it, but actually look forward to sitting down and watching some elite table tennis. Firstly, educate athletes on the benefits of sport psychology training in, for example, ‘warming up the brain’ before playing (neuroscience is still considered ‘pie in the sky’, so explanations would need to be very practical/understandable). Secondly, athletes are already pushed for time, so it would need to be it easy, fun and portable so they can do it while travelling, or resting after training. NFB training would ideally incorporate a ‘fun’ aspect to it, for example, developing a game/simulation style presentation method. Development of NFB training for athletes must be capable of applying the split-second timing involved in most sports.

NFB technology is constantly evolving. One would need a time-locked NFB device to assist an elite TT player to learn to regulate alpha phase to oncoming visual stimuli quickly and efficiently. In 2008, Arns, Kleinnijenhuis, Fallahpour, & Breteler established a NFB protocol in which the training parameters were based on personalized event-locked EEG profiles. These EEG profiles were created by recording EEG during golf-putting sessions in which successful putts and unsuccessful putts were compared for each person individually, resulting in a personalized and customized NFB protocol for each player. A personal event-locked EEG frequency profile was determined for successful versus unsuccessful putts and used to derive personalized target frequencies for the NFB training protocol. Furthermore, NFB training was given in a real-life golf setting. During a session, participants received feedback on their brain pattern through a go/no-go tone which was terminated when their EEG signal was above or below the target thresholds determined by their personalized profile for successful versus unsuccessful putts. Participants were required to putt within 1.5 seconds of the termination of the go/no-go tone. The percentage of successful putts were significantly larger (on average 25% larger) for sessions where the participants received this NFB compared to the sessions without NFB training (Arns et al., 2008). Table tennis, or similar continuous sports, might benefit from a similar (yet to be developed) NFB technology whereby players were playing a simulation-style game similar to the VT task used in this thesis. Frequent auditory feedback would be provided on the power and phase of the player's EEG based on personalised 'optimal' EEG relative to performance in a previously established assessment.

Another possibility of giving time-locked feedback to players in an ongoing method would be ERP-based NFB. Kropotov and colleagues (2011) recently produced some encouraging results when they used the P3b ERP component as the NFB parameter (a positive evoked wave occurring approximately 300 milliseconds after stimulus located in the centro-parietal cortex in response to the engagement of an executive system operation). The referencing method of ERP component localisation was replaced by the recently designed and previously described Independent Component Analysis (ICA). The low signal to noise ratio of a single independent component of the ERP was significantly amplified in order to distinguish each single trial from raw EEG.

The goal of the ERP NFB was to generate higher amplitude of the P3b component generated over the parietal cortex compared to a previously calculated baseline average recorded from that individual during a Go-NoGo CPT. If the generated ERP was higher than baseline, a '+' sign was immediately presented on the screen to the individual, if not, a '-' sign was presented. A sham control group underwent the same process in which a different individual's ERP recording was used to provide false feedback. The effect of one 20 minute session of ERP NFB did not result in significantly higher amplitude of the P3b component for either the experimental or control group. However, 2 of the 10 subjects were able to discriminate between the sham and real feedback conditions and managed to significantly increase their P3b component. Furthermore, both sham and real feedback groups significantly decreased the amplitude of another component called the Slow Positive Wave (SPW) generated in the parahippocampal gyrus. Results of this study showed that it is quite difficult to learn to control the P3b component in one session. However, results also show that 2 subjects were able to achieve increase of the P3b component, and that the effort made by both real and sham groups of trying to control their ERPs resulted in significant increase in amplitude of the SPW component.

In the future, real-time ERPs might be calculated during an ongoing table tennis simulation task in which players play against an opponent, anticipating direction and responding via a button press. Players would receive continued feedback on the screen visually, or via auditory feedback, based upon their ERP latency and magnitude compared to a previously established baseline. Use in the field of portable, dry-cell headsets would enable players (and coaches) to quickly and easily record their EEG, linked via Bluetooth, to a hand-held device. These technologies are already being developed (e.g. Emotiv) and the signal quality is improving as we speak…

The future of performance enhancement brain training looks bright.

6.5. References

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Statement of Originality:

We, the PhD candidate and the candidate's Principal Supervisor, certify that the following text, figures and diagrams are the candidate's original work.

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Statement of Contribution by Others:

Trevor Brown	80%
Dr Graham Jamieson	20%

Appendix

From athlete to researcher

My life as a professional athlete in France was abruptly over due to injury. My table tennis career – after representing Australia in two Commonwealth Games and an Olympics – was quite suddenly just a distant memory. What to do now? I had enjoyed my undergraduate studies in Psychology throughout my sporting career and had even found some of the sport psychology tools quite useful during competitions such as breathing regulation and hear rate variability biofeedback. But most importantly, I had been introduced to one particular psychological tool right at the end of my career through my 4th year Psychology Honours thesis – Neurofeedback (NFB). Should I accept the challenge of bringing exposure of this promising technique to the world of elite table tennis? When have I ever knocked back a challenge?

After my 4th year Honours thesis pilot study returned promising results for the use of NFB for performance enhancement with table tennis athletes at the English Institute of Sport I applied, and was accepted, into this PhD program. Presentation of my 4th year thesis at the Australian Cognitive Neuroscience Society conference in 2012 during my first year of PhD, combined with my literature review, provided essential information assisting me in the conceptualisation of my pending project. Importantly, I realised that the sport performance literature was focussed primarily on elite performance biomarkers measured by scalp EEG of *closed-action* sports. A literature review also revealed very little in the way of EEG *source localisation* research and not a great deal of NFB (or any other form of brain-training) research within the peak performance field – but it had been increasing over the last 5 or so years (see review by Park, Fairweather, & Donaldson, 2015). Consequently, it was apparent that this field was where I could make my contribution, having access to athletes of high quality at my fingertips – a rare commodity in the EEG research world and one probable reason for the lack of studies undertaken compared to the clinical population. My focus was beginning to take shape – EEG biomarkers in athletes using source localisation, followed by EEG source NFB training for performance enhancement!

This tightening of focus then led to the question of how behavioural data would be measured for both EEG biomarker identification and pre-post NFB analysis. In discussion with my supervisor, it was decided that behavioural data could be obtained using a theoretically relevant Go-Nogo task that we would devise and create ourselves. Consequently, this novel task would result in behavioural time-locked EEG responses to stimuli (Event-Related Potentials), and reaction-time and accuracy data.

It took one final meeting to place me on my methodological path. Dr Leslie Sherlin (who, at the time, was President of the International Society for Neurofeedback Research) confirmed for me that source localisation NFB using Low Resolution Electromagnetic Topography (loreta) was being used successfully (see Cannon & Lubar, 2011) and introduced me to my first major methodological question – what would be the best way to present real-time EEG feedback to *athletes*?

One major lesson learnt from my 4th year thesis was that, as opposed to the clinical population, athletes are an impatient bunch! So, when Dr Sherlin introduced me to a type of feedback modality called ‘video mode’ (see section *1.8 NFB delivery method*) which would give EEG feedback in such a way as to keep athletes interested for long-enough to give the operant conditioning time to take effect. I naturally jumped at the idea. We could use table tennis videos to keep athletes interested in the NFB sessions while providing the feedback. Furthermore, watching table tennis should, through mirror neuron activation, elicit the relevant EEG being targeted within the NFB training protocol.

However, this left me with a decidedly difficult problem – does technology exist that fulfils all my methodological requirements? For my research to go ahead I required hardware and software that interfaced smoothly and would accommodate continuous EEG acquisition, ERP task creation, presentation and acquisition, and provision of loreta NFB using video mode.

NFB technology and feedback modalities

The lack of choice in EEG technology astounded me and, in fact, since beginning my research in 2012 many advances have been made in this area (for example Neuroguide loreta NFB). For decades, NFB had provided auditory feedback through ‘beeps’ when points were scored (time above threshold) and visual feedback where points equalled ‘success’ within the game (for example, BrainMaster/EEGer for basic games, and more recently Zukor Air for 3D skateboarding and flying games). However, video mode had been used successfully with inattentive (ADHD) clients (Kropotov et al., 2007) and was now an accepted modality of NFB presentation.

Having met Professor Juri Kropotov in London for a workshop in 2010, I was fortunate to already have some understanding of the capabilities of the Mitsar system. The Mitsar 201 amplifier would interface with the EEG acquisition software WinEEG and the ERP task presentation program PsyTask which also allowed creation of novel ERP tasks. Furthermore, the Mitsar 201 amplifier would interface with BrainTuner software providing Loreta NFB presented with video mode. I had found my system. But as with all technology, once purchased I shortly began to understand the limitations associated with the Mitsar system.

Initially, I began testing the equipment using pre-installed ERP tasks. The set-up required that a serial cable from the control computer be connected to a 'slave' computer which would present the task stimuli to the participant. The serial cable required a particular serial-to-USB-port adapter and its corresponding 'driver' to be correctly installed. This was set-up initially by technicians at UNE and sent to me for use with athletes in the field. However, upon arrival at my residence, the computer would routinely change the allocated comport, or not identify the driver for the serial-to-USB-port adapter whenever connected up. It was quickly discovered that these issues had been occurring for other users of this system and Mitsar had just released replacement software called EEGStudio. This new software presented the ERP task on a monitor connected to the control computer, avoiding the complicated and unreliable serial cable and 'slave' computer set-up. EEGStudio would run as the EEG acquisition software and the monitor required use of a calibration kit for auditory and visual stimulation presentation to be accurately recorded. It seemed that I had resolved the problem and would travel around Europe with a monitor instead of a second PC.

Unfortunately, EEGStudio software had not returned sufficiently accurate results according to Professor Kropotov who, at a conference on the Gold Coast in 2013, noted that bugs still needed to be fixed with the software. He recommended that, for accuracy of data, I continue to use the 'slave' computer method. So taking his advice I stuck with the two-computer method – it would seem that I was destined to become an I.T. expert and learn to set-up and troubleshoot any PC problems on a daily basis throughout my data acquisition travails in Europe. An example of this problem occurred without resolution was in the third and final experiment in Poland when Natalya O'Keefe, a UNE 4th year student who was assisting me, arrived with her computer and slave computer in Poland a day prior to commencing the NFB experiment. To our dismay the slave-PC connection was no longer working after having been set-up and tested at UNE before leaving. As it was the day before the experiment would start, there was not enough time to correct the problem, even through multiple telephone communications with UNE technicians. The pre-NFB QEEG data acquisition procedure that had been planned down to the minute, incorporating multiple tasks per participant whilst working around their table tennis training sessions and eating times, needed to be adapted the night before starting! As a result, Natalya recorded all Attentional Network Tasks on her PC and I recorded all QEEG/ERPs on mine, which was unfortunate for Natalya's EEG experience but did not decrease the optimal amount of data acquisition.

During the above-mentioned conference in 2013 Professor Kropotov provided further assistance as we discussed my ERP task in depth. Professor Kropotov also provided technical assistance in creation of the task as some of the Psytask parameters were unknown to me (not specified in the manual) and were constraining my task design.

After phase 1 testing was complete and 206 athletes had been recorded, data analysis began at the University of Essex, UK and limitations were encountered immediately with our software. WinEEG did not provide usable spectral data for statistics to be created unless it was exported to Matlab (which required the purchase of an expensive add-on) but in any case it was too late to work through this. Raw data could be exported to Loreta from WinEEG for source localisation and this was the preferred and most useful method of data analysis in preparation for the loreta NFB to come.

In hindsight, perhaps NeuroScan hardware would have been a better choice for EEG acquisition as perhaps it provides a more reliable set-up for ERP acquisition and a 31-channel EEG cap obviously provides more data than a 19-channel system. Scan 4.1, the associated software for Neuroscan, may also have provided a more user-friendly analysis method for spectral data. However, using one amplifier for EEG acquisition and another for NFB sessions was impractical, especially when travelling so intensely, not to mention monopolising UNE resources. I needed one system to do it all. Mitsar was it!

Data gathering in Europe – Trials and tribulations

From what I'm told, research never runs smoothly or, at least, never goes completely according to plan. My experience was no different and I didn't make it any easier for myself by choosing to gather data from elite table tennis athletes across the other side of the world for over three months.

Firstly, funding had to be obtained before even setting off, so an application for the K & D Mackey travelling scholarship was sought and obtained. The planning and logistics involved in the two European trips required the management of literally hundreds of people including athletes, coaches, tournament administrators and International Table Tennis Federation officials. For example, the organiser of the World Table Tennis Championships in Paris initially accepted, but then subsequently refused, to accommodate me. The president of the ITTF sport science department stepped in and backed me up, and several other ITTF officials also became involved. Unfortunately, the situation became political between two members of the ITTF who had been at loggerheads for some years. I had to tread very carefully and was (mistakenly) seen to be representing Table Tennis Australia for the research project when my only official role for the World Championships was that of Head Coach for that one tournament – I learnt a lot about international relations, dual relationships and politics in a very short period of time.

It all turned out fine, fortunately, and Paris was our first stop where, two days prior to the World Championships, I presented my 4th year Honours thesis at the ITTF Sport Science Congress. This presentation gave me exposure to other coaches, ex-players and researchers within the table tennis field enabling me to build credibility and have support for the subsequent experiment. Consequently, many coaches sent their players to be tested and provided me with feedback about how to deal with athletes who were completely naïve to EEG research.

Another bonus of the previously mentioned ACNS conference in Brisbane in 2012 was my meeting there with Ms Quirine Tordoir, a Neuroscience Masters student from the University of Amsterdam. She was at the University of Queensland for an internship and was looking for a second research project involving EEG. As it turned out, I became her Master's thesis supervisor, in exchange for assistance with the experiment in Europe. The advantage of this was that more data would be acquired in phase 1 (EEG biomarker identification), and more NFB sessions would be undertaken during the NFB experiment in phase 2. I taught Quirine EEG acquisition and NFB methodology, including all the technical aspects of using the hardware and software, plus the procedures we would be using. This provided Quirine with the practical experience and data she needed for her degree, and also gave me experience in supervising a Masters student both for the practical and theoretical work involved in EEG research.

Technical issues plagued data collection incessantly throughout the three and a half month trip, for example electrode cap breakages whereby an electrician was sought in Poland and emergency soldering was undertaken assisted by Google translate. Quikcell Electrode cap materials were running out and were ordered in advance but were stopped by customs in Warsaw as they were accompanied by electrolyte powder that attracted suspicion from customs. Therefore, recording was delayed for some days as release of the material was negotiated and paid for!

Catching planes, trains and driving through Europe with expensive equipment, checking into hotels when not speaking the language provided constant challenges. The settings for EEG recording were not ideal in some cases and required enormous flexibility and adaptability relating to temperature, light, room-size, power sources, athletes attending recordings directly after training and therefore sweating profusely! At some locations we dealt with coaches who were interested and others who were not which required considerable social grace and understanding of cultural differences.

Our phase 1 data collection ended with our arrival at the University of Essex, UK. Our goal was, in 4 weeks, to clean and analyse the acquired data to provide the protocol for the upcoming NFB experiment in Denmark. My goal for phase 1 data collection had been 60-100 athletes. In actual fact, we collected 206 table tennis player's EEG data. The data cleaning and analysis job was going to be enormous as, simultaneously, I was in the process of finalising the pending NFB experiment which required obtaining consent forms in advance, securing a player training schedule so I could work my own schedule around theirs', not to mention travel, food and accommodation for Quirine and myself. On top of that, I had never used the BrainTuner software or Jammer device so needed to familiarise myself with it in Essex. Overall, a frantic 4 weeks in Essex resulted, and an eLoreta analysis between an age and gender matched group of elite vs amateur players provided us with our NFB protocol for the experiment in Denmark.

Upon arrival and set-up in Denmark, the allocated room was giving us some technical difficulties. For some reason our EEG was being contaminated when any device (PC, DVD or TV) was plugged into mains power. One whole day of thick, black EEG ensued as we tried using extension cords, changing rooms, anything we could think of to see a nice clean signal. Finally it was found that a 100-110Hz filter solved the problem, cleaned up our signal, and did not affect the frequency bandwidth being used. Phew!

The NFB experiment went relatively smoothly thereafter apart from one thing. The service task used in my 4th year pilot study was a motor execution, closed-action skill that was relevant for the previous research. However, it had become irrelevant in the preceding days of data analysis as it was found that our elite vs amateur analysis revealed salient sensory detection and inhibition was now our main focus. A new behavioural task was briefly discussed but not implemented in Denmark. Fortunately the DAQ and ERP task provided us with subjective and objective behavioural measures respectively.

Back to Australia

Further data analysis began immediately and due to our success at obtaining so much data in Europe, QEEG reports now needed to be provided to 206 people as was promised in repayment for their participation! Each player received a report outlining their Mu voltage (calculated by Mu synchronisation over C4 in the VT condition compared to EO resting condition) compared to the average within their respective age cohort and compared to the elite group, plus their ERP task behavioural performance. This was an enormous task!

Data analysis of the NFB experiment followed the QEEG reporting and it was time to begin preparation of the final data collection phase – another NFB experiment drawing on lessons learnt from the previous one in Denmark. Those lessons learnt included firstly, using only one training location; secondly, using IAF to set individualized training frequency protocols; and, thirdly, the use of the Attentional Network Task – but more on that later.

Introducing… Natalya O’Keefe! I was very fortunate to once again have some assistance in my second European trip by way of a UNE 4th year student interested in NFB. Funding was sought for my flight and provided by the School of BCSS at UNE, and we were off for another 5 weeks. But it wasn’t that simple. Once again, organisation for the experiment was full of surprises, including obtaining consent forms for underage participants at the last minute, accommodation issues, scheduling of participant NFB sessions and the newly devised behavioural task pre-post NFB. The new behavioural task had been carefully devised to be ecologically valid with regard to salience detection and motor preparation for table tennis players and was administered in the form of what is known in the table tennis world as ‘multi-ball’. In such a task, the ball ‘distributor’ will stand at one end of the table with a basket full of table tennis balls and hit them onto the other side for the player to retrieve. The player was instructed to observe the ball ‘distributor’ and play the ball back onto the other side of the table. In this way, the player would observe the relevant (and irrelevant) body movements of the 'distributor', identify and select salient movements, and consequently move quickly towards the ball for optimal retrieval.

Unfortunately, late participant arrivals resulted in the behavioural task being administered at around 11pm for some participants, and even one participant had to be postponed until the next day. However, the disparity in task administration times, motivation by participants and the huge effect of the training camp upon table tennis improvement in both experimental and control groups meant that results were not included in the article. One of the limitations of dealing with young teenagers in an experiment is their emotional instability. Many players clearly displayed their desire simply to leave the camp and get home. Although results, upon quick inspection, showed a larger average improvement in the experimental group versus the control group, we did not feel that task variables were controlled enough for use within the article.

Frequency of NFB sessions

One final methodological issue to be considered from this project and considered for future research is the number of NFB sessions administered to each participant. It is clear that NFB research displays a large disparity in number of sessions administered, some as many as 40 sessions at a frequency of twice per week for 20 weeks (Russell-Chapin et al., 2013). However, due to the time constraints and man-power of researchers, 40 NFB sessions is often not realistic. Certainly in our case staying in Poland for 20 weeks was out of the question and it is simply not feasible to have access to a large number of athletes in one place at any one time other than during an officially organised intensive training camp like those in Denmark and Poland in this project.

Fortunately, the literature also provides examples of fewer NFB sessions, some as few as 1 session (see Ros et al., 2013) are supported by fMRI results showing that plastic brain change has taken place directly related to alpha connectivity in the salience network. In their study of 34 healthy participants, Ros et al. (2013) examined whether during the performance of an attentional task, the functional connectivity of 36 distinct fMRI networks would be plastically altered after a 30-minute session of voluntary reduction of alpha (8-12Hz) rhythm (n=17) versus a sham-feedback condition (n=17). Compared to sham-feedback, NFB induced an increase of connectivity within the salience network (dorsal anterior cingulate focus), which was detectable 30 min after termination of training. This increase in connectivity was negatively correlated with changes in ‘on-task’ mind-wandering as well as resting state alpha rhythm. Crucially, there was a causal dependence between alpha rhythm modulations during NFB and at subsequent resting state, not exhibited by the SHAM group. Ros et al. (2013) concluded that their study provided neurobehavioral evidence for a temporally direct, plastic impact of NFB on a key cognitive control network of the brain.

However, the methodological question remains, how often and how many sessions are practical in the real world of an athlete’s training schedule? We encountered all types of motivation for participation in the study, with some athletes happy to come for NFB twice per day, while a couple of others were bored after a few days and it was felt that they participated because they believed it was good for them and they wanted to keep their coach happy. The latter, fortunately, was an exception to the rule, and most players reported a willingness to participate. General consensus though, was that watching table tennis was the interesting part. My conclusion, methodologically, is that the video mode was vital in motivating continued participation and that any more than 10-12 days straight would have been asking too much. To be implemented into an athlete’s regular training routine long-term, NFB two times per week, in my opinion, would be the desired frequency so as not to induce boredom in the athlete. Whether or not a frequency of twice per week, compared to daily NFB, would provide differing results would be a question for further research