sLoreta Neurofeedback Targeting Attention Networks in Table Tennis Athletes Modulates Neural Connectivity and Enhances Visual-Spatial Attention

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Abstract

The aim of this study was firstly to identify alpha band EEG sources playing a functional role in the performance differences between elite and amateur table tennis players use of visuo-spatial cues to guide response selection. EEG was recorded from 206 elite and amateur table tennis athletes from across the International Table Tennis Federation. EEG was obtained during eyes closed (EC) and eyes open rest (EO) and during a 4-minute video task (VT). The VT was filmed from the player's perspective to simulate match-play against a top 100 world ranked player. Participants imagined playing against the on-screen player. Players also completed a visuo-spatially cued version of the Go-NoGo continuous performance 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. 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). Source activity estimates correlated significantly with superior processing speed and perceptual sensitivity under increased processing demands on the vsCPT. 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.

Secondly, we sought to use Neurofeedback (NFB) training, a form of operant conditioning based on reward-learning, to produce measurable changes in the efficiency of visual spatial attention networks within a group of aspiring elite table tennis athletes within an associated region of interest, right BA40.

The relationship of learning during sLoreta NFB (sLNFB) training to a strengthening of connectivity in the targeted cortical network was measured by the EEG activity of fifteen adolescent table tennis players. 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 indicated significant changes in cortical activity in regions related to visuo-spatial and motor processing in addition to regions directly related to learning. Increased response inhibition accuracy on Go-NoGo task was strongly and significantly correlated to post NFB changes in brain activity.

We concluded that the current sLNFB protocol changes cortical activity throughout functionally connected nodes of task-relevant 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, motor control, table tennis.

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1. Introduction

Previous investigations of EEG rhythms related to elite performance across a range of sports have consistently identified the alpha band (8 – 12Hz) as the most salient frequency range for discriminating athletes' performance levels (Babiloni et al., 2008; Sherlin, Gervais, & Walshe, 2011). The alpha rhythm has been demonstrated to play an essential role in visual and motor processing where it is strongly associated with optimal performance (Capotosto et al., 2009; Llanos et al., 2013; Pineda, 2005; Schürmann & Başar, 2001). In particular, task-related increases (synchronisation) in the upper-alpha band (10 – 12Hz) appear to enhance cognitive performance, by inhibiting the influence of 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).

By using elite table tennis player EEG findings from the current study as targets for a Neurofeedback (NFB) protocol (Hanslmayr et al., 2005) we hope to bring about a higher level of responsive motor control – not by influencing the motor system directly, but by targeting the underlying attention and decision-making systems. NFB training is a form of operant conditioning based on reward learning. It is currently recognised as an empirically supported clinical intervention to treat attention deficit hyperactivity disorder (Van Doren et al., 2018). 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 et al., 2014).

1.1. Alpha and Elite performance

Studies employing elite samples of fencers, golfers, gymnasts, karate practitioners and pistol shooters have consistently demonstrated that task-related alpha activity in elite athletes differs significantly from amateur and non-athletes and can predict and differentiate between best and worst performance within elite athletes (Babiloni et al., 2009; Baumeister, Reinecke, Liesen, & Weiss, 2008; Del Percio et al., 2009; Loze, Collins & Holmes, 2001). Taken collectively these findings indicate that both the up- and down-regulation of cortical alpha, in task-related networks, plays a direct functional role in those sports where the integration of perception in control of action is an essential factor in success. It is also likely that the upper-alpha band plays an important functional role in those sports where the perception of the skilled motion of an opposing player must be integrated with the control of the player's own responsive action (Perry, & Bentin, 2009). The ventral attention system and the dorsal attention system work together, acting to guide the selection and generation of an appropriate motor response (Vossel, Geng, & Fink, 2014). Experienced (elite and amateur) players actively watching the table tennis video task are expected to evoke processing in the ventral and dorsal attention networks which are directly related to their level of skill.

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).

1.2. Aims of the study

A first aim of this study is to establish differences in EEG activation patterns between elite and amateur table tennis players' performance related to visuo-spatial processing demands. 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 when actively watching an opposing (world class) player and imagining playing against them in a continuous table tennis match.

We then seek 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 by adopting a unique version of the Go-NoGo task cued by rapid changes at precise visual locations to objectively measure performance on these core cognitive skills.

Subsequently we will prospectively validate the obtained frequency band and cortical region of interest (ROI) using sLORETA (Pascual-Marqui, 2002) EEG source localization to apply alpha NFB directly (in real time) to the estimated activity of the specified cortical source, where we can causally verify whether the observed EEG correlations with performance are indexed via neurofeedback learning. 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 (Caspers 2011).

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.

2. Methods

2.1. Participants

2.1.1. Elite vs Amateur Comparison

To differentiate elite from amateur EEG during task performance, 206 table tennis players representing elite and non-elite but experienced (amateur) performance from across the International Table Tennis Federation (ITTF) undertook QEEG and ERP testing.

From this group, a sample of 'elite' players was selected by highest World ranking (WR) 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 (N=16). 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 (N=16).

2.1.2. sLNFB Training

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 (N=15, 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.

Prospective participants were first screened for current neurological medications and family history of epilepsy. They were then asked their age, gender, ranking, years played at greater than 10 hours per week, current level of education and email contact details. Ethics approval was granted by the the University of New England Human Research Ethics Committee.

2.2. Measures

2.2.1. 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.

2.2.2. 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 a virtual or simulated task 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".

2.2.3. Visual Spatial Continuous Performance (Go-NoGo) Task (vsCPT)

The vsCPT was specifically developed to assess aspects of visual attention, decision-making and motor control required by the cognitive processing, motor programming, salience detection and motor execution skills of a correct response to the motion of an opposing player. Participants respond (Go) or withhold response (NoGo) to rapidly occurring visual stimuli depending on the spatial location of each stimulus. 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. Stimulus 2, also with an exposure of 100ms, consisted 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).

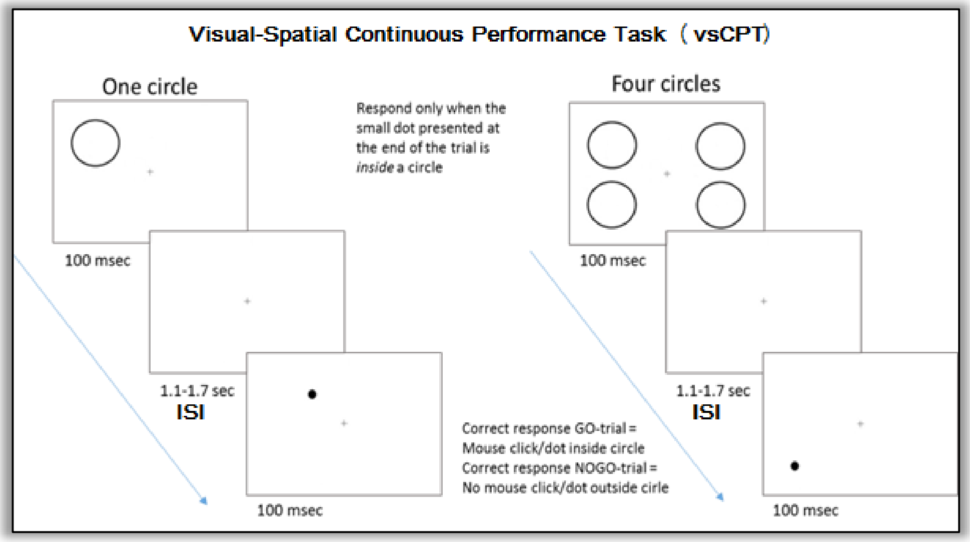

Figure 2. Example of a 'Go' response trial in the vsCPT tasks.

Each circle had 8 possible 'Go' responses and 8 possible 'NoGo' responses. That is, there were 8 different Stimulus 2 dot locations within each circle (Go) and 8 different Stimulus 2 dot locations outside each circle (NoGo). 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.

2.2.4. EEG Recordings and Materials

The EEG was recorded using a stretchable electro-cap (Electro-Cap Inc., USA). Quikcells (Compumedics Neuroscan, Melbourne, Australia) 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).

Ear-clip reference electrodes were attached to the participant using Ten20 electrode paste and connected 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).

2.3. Procedure

2.3.1. Elite vs Amateur Comparison

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, participants were explained the importance of maintaining a relaxed forehead, jaw and minimizing bodily movement during recording. Participants' EEG was recorded from each condition 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)

The order of vsCPT1 and vsCPT4 was counter-balanced across subjects.

2.3.2. sLNFB Training

NFB EEG was recorded in Brain Tuner 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 3). Visual stimulus in the NFB condition was presented on a 117cm flat screen Sony television.

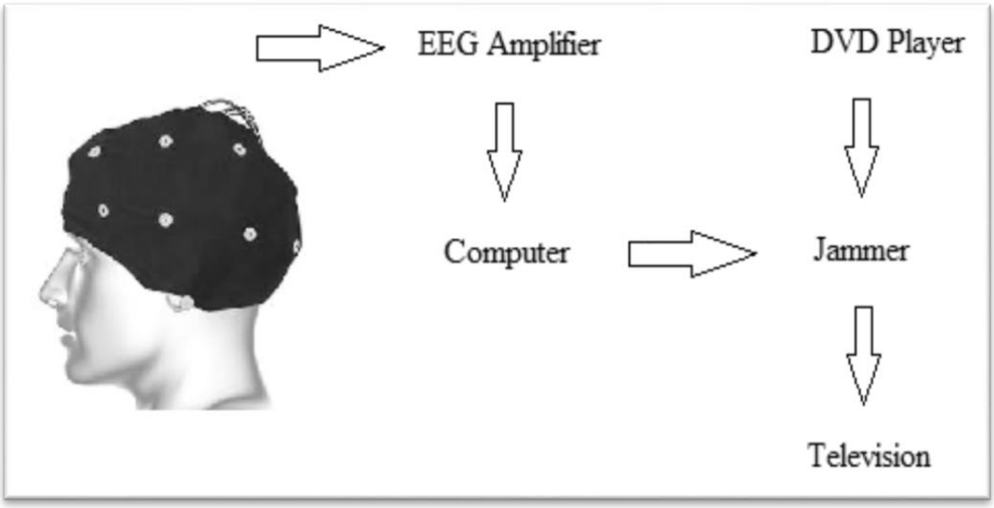

Figure 3. Schematic representation of EEG Amplifier, Computer, Jammer and DVD player interaction.

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.

2.4. Design

2.4.1. Elite vs Amateur Comparison

The experiment was a mixed measures design with between group’s 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).

2.4.2. EEG Data Preparation and Analysis

WinEEG software was used to prepare each EEG file. A common average reference was selected (Bertrand, Perrin, & Pernier, 1985) and a 0.5 – 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 – 30Hz 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 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 et al., 2002). Three-dimensional source space is restricted to cortical grey matter as determined by the Talairach Atlas (Lancaster et al., 2000). Estimated strength and direction of activity in each voxel determine the distribution of current source density (CSD) (Pascual-Marqui, Michel, & Lehmann, 1994). eLORETA estimates maximally smooth CSD distribution for 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 was calculated 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).

2.4.3. sLNFB Training

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. 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).

Neurofeedback: NFB training targeted the upper alpha band (IAF to IAF+2 Hz) in right BA40. 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, one of the world's most accomplished table tennis players. Each NFB session consisted of a two-minute baseline threshold-setting period during which no jamming was applied and the screen was clear. This was followed by five 5-minute training sessions each separated by a one-minute rest period. The threshold for reward was initially set at 90% of the mean amplitude of alpha activity recorded during the baseline period (55% overall reward during training). This was observed to result in less than expected video image being seen. As this may have constrained the rate of learning (due to not being able to actively engage in the match-play with so little clear image) it was decided to set the threshold to 80% mean amplitude of alpha at baseline (giving 60% overall reward during training) from the second session onward. As such, 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 screen clear during the training sessions and relax during the rest periods".

Learning Index (LI): 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 a necessary change in thresholding method).

3. Results

3.1. Elite vs Amateur player EEG source differences

The spectral averages calculated below for EC, EO and VT conditions were entered into eLORETA to compare source activity differences between elite (N=16) and amateur (N=16) groups. Across EC, EO and VT the GFP maxima were very close and lay, as hypothesized, in the narrow upper alpha band.

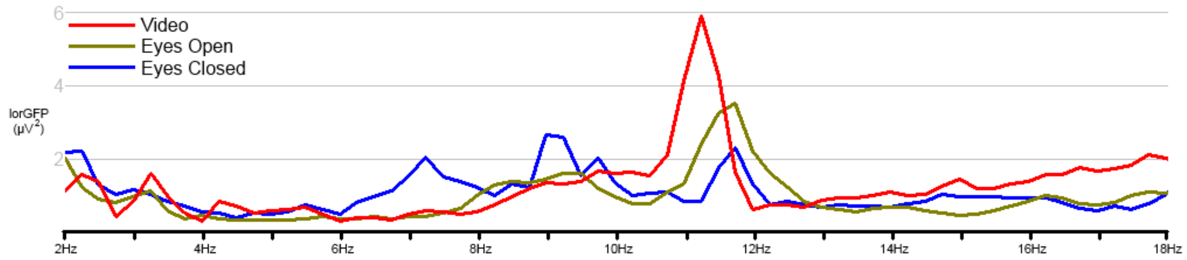

Figure 3. Global Field Power for difference between Elite and Amateur groups during EC Blue), EO (Green) and VT (Red) condition plotted from 2Hz to 18Hz.

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 a minimum at 11.75 Hz (see Figure 4).

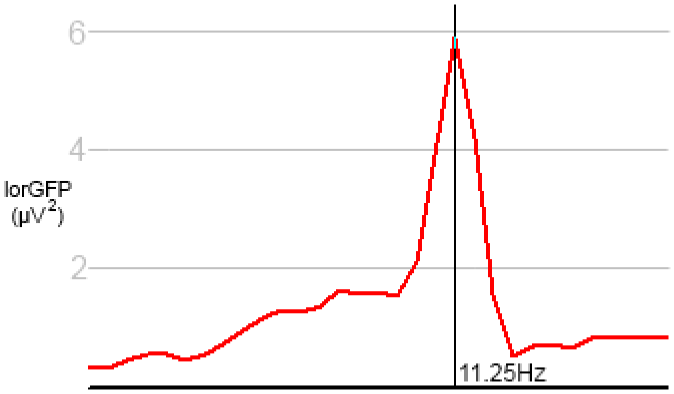

Figure 4. Maximum Global Field Power difference between Elite and Amateur groups during VT condition at 11.25Hz.

The maximum voxel statistic for the difference in activity between groups in the VT condition occurs at 11.25 Hz is (log F = 5.96, p = .38). This activity is greater in the elite than the amateur group. The world ranked and the amateurs were not found to be significantly different in this (or any other) EEG source frequency measure in this study. 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).

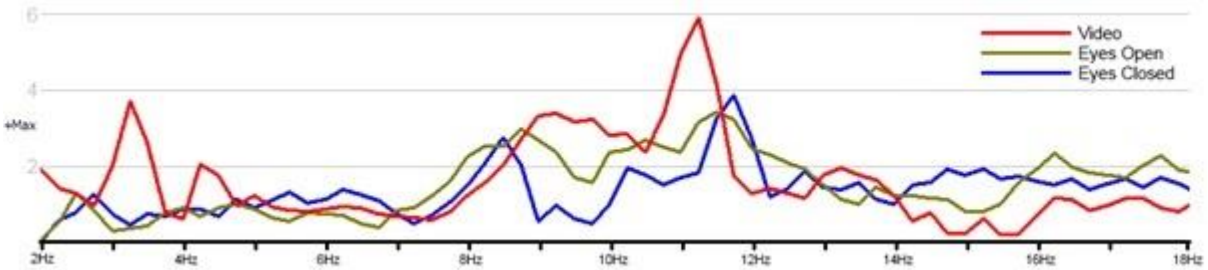

Figure 5. Maximum voxel statistic (log F ratio) for Elite > Amateur comparison in EC, EO and VT plotted from 2Hz to 18Hz.

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; 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).

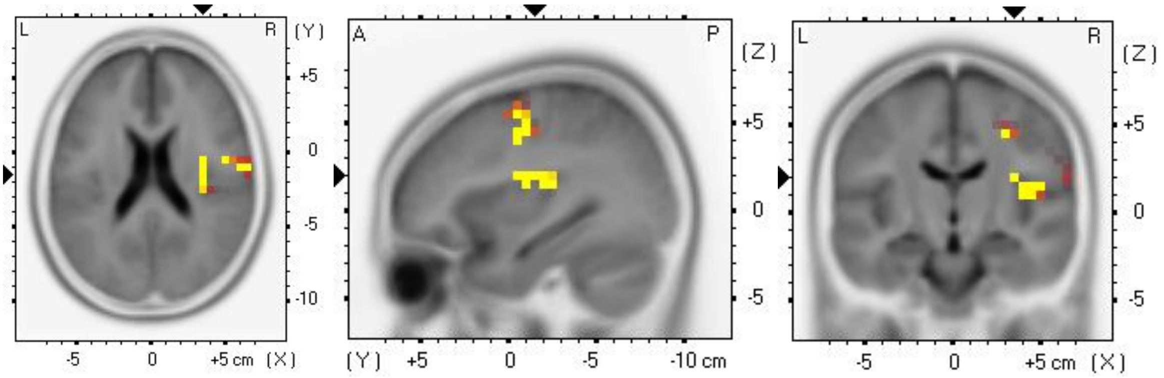

Figure 6. eLORETA images of transverse, sagittal and coronal slices showing top 100 voxel log F ratio for differences between elite and amateur groups from 10.50Hz – 11.75Hz. All voxels lie within right BA13 and BA6. Black arrows on the axes mark the eLORETA maximum voxel difference at MNI (35 -15 20).

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. 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 vsCPT.

3.2. Elite versus amateur player behavioural relationship to EEG sources

Performance on the vsCPT is summarized 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 (vsCPT4).

3.3. sLNFB Training

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 7, 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.

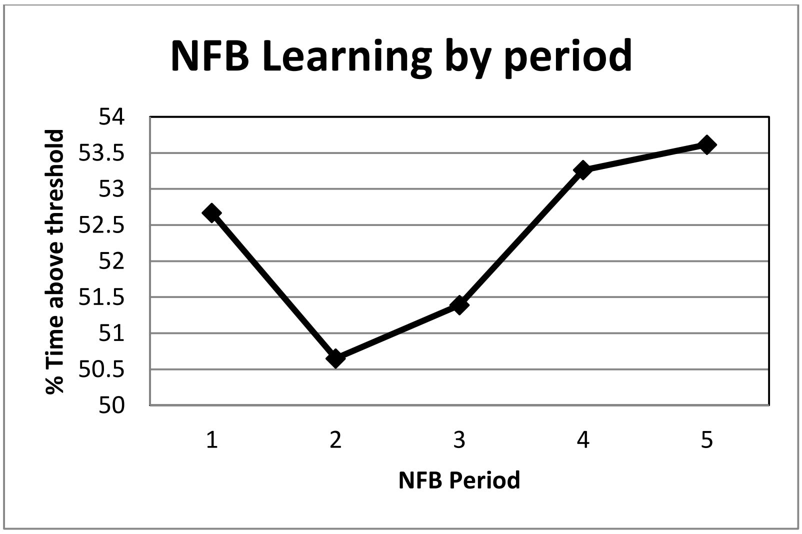

Figure 7. Percentage of time spent above the reward threshold within sessions.

Polynomial trend analysis of the time spent above threshold across sessions, excluding the first session, (Figure 8) was also not significant, $F(12, 13) = 1.428$, $p = .157$.

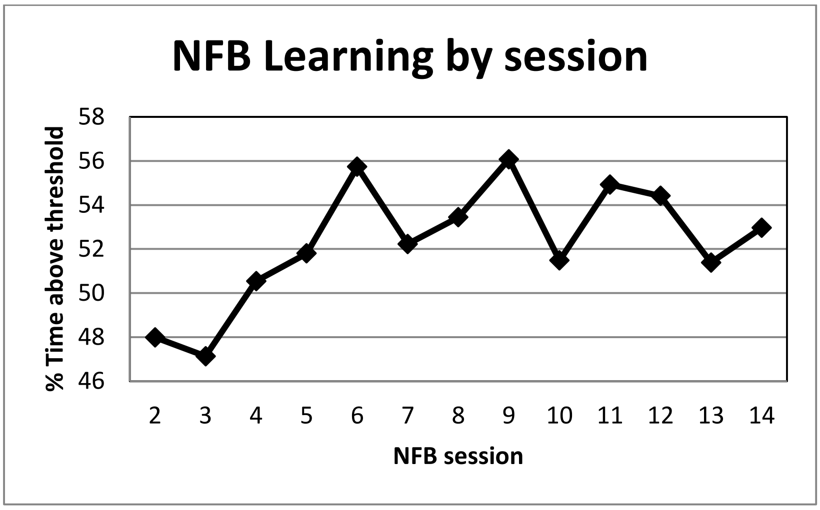

Figure 8. Percentage of time spent with signal above the reward threshold between Sessions two and 14.

3.4. EEG source activity

Spectral analysis of the EEG data was performed using the sLORETA 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.

3.4.1. Eyes Closed

A significant decrease in activity at 12.87Hz, bordering alpha and beta frequency bands was found in the eyes closed condition, t(14) = -4.30, p = .004. Significant changes were located in right BA 19 and BA 7 (Figure 9).

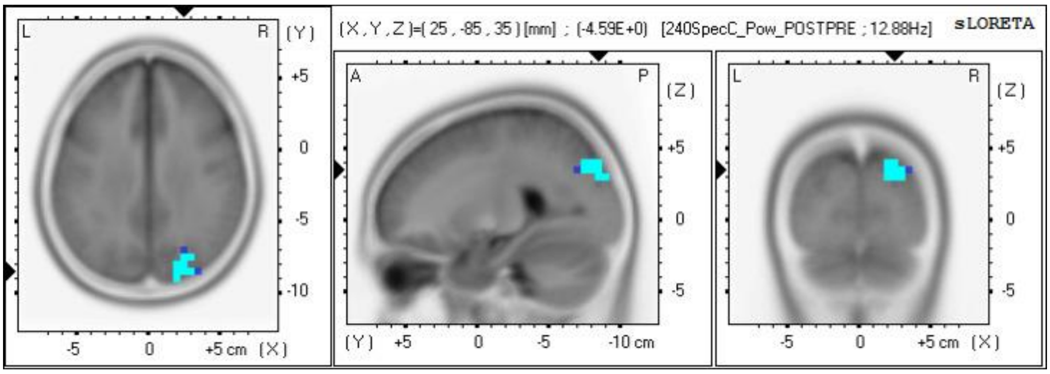

Figure 9. sLORETA images of transverse, sagittal and coronal slices showing right BA19 and BA7 where maximal differences in EEG activity were observed in post- compared to pre-NFB training. Blue indicates a reduction of cortical activation.

3.4.2. 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 10).

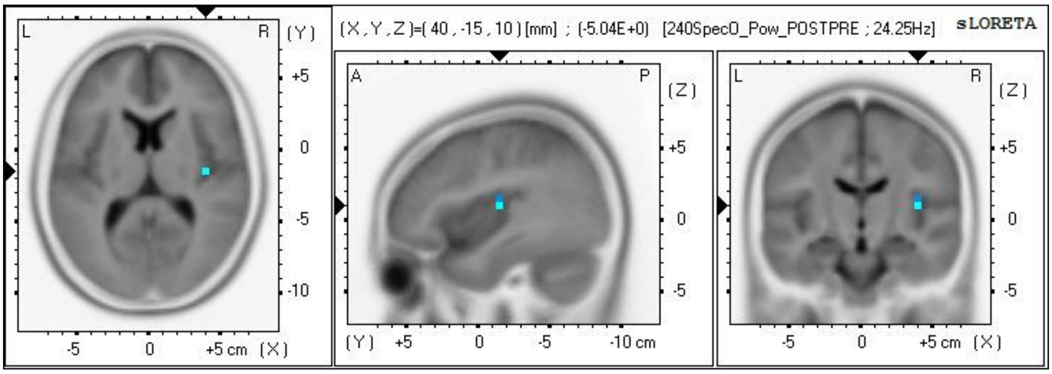

Figure 10. sLORETA images displaying right BA13, 43, 22, and 41 where maximal differences in EEG activity were observed in post- compared to pre-NFB training in the eyes open condition. Blue indicates a reduction of cortical activation.

3.4.3. Table Tennis Video

Alpha 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 11).

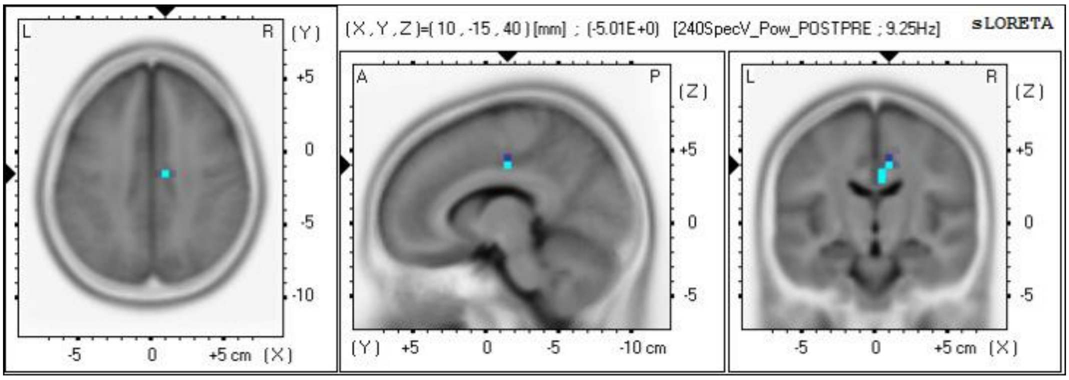

Figure 11. sLORETA images displaying right BA24 and 23 where maximal differences in EEG activity (9.25 Hz) during the VT condition were observed in post- compared to pre-NFB training. Blue indicates a reduction of cortical activation.

3.4.4. Learning Index (LI) and Change in EEG Source Activity

A large effect was found for a LI, a regression analysis exploring the relationship between the Neurofeedback learning by session and EEG source change. The LI was found to significantly predict changes in alpha activity at 8.5 Hz in BA24 (anterior cingulate cortex) and 32 (dorsal anterior cingulate cortex) in post-NFB eyes open condition, r = -0.93, p = .011, showing that as learning in this NFB protocol increased across training sessions, post training alpha activity decreased in regions sensitive to response conflict (Figure 12).

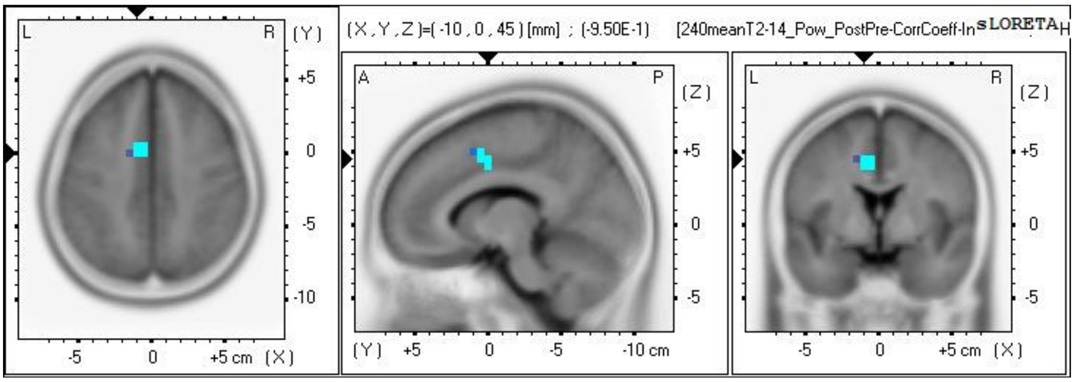

Figure 12. sLORETA images displaying right BA24 and 32 where maximal differences in EEG activity during eyes open were observed in post- compared to pre-NFB training as a function of the learning index. Blue indicates a reduction of cortical activation.

Inspection of max voxel statistics for each eLORETA analysis, shows that even when it is not significant the magnitude of EEG source activity decreases across all frequencies and all voxels from pre to post NFB training in all testing conditions (see Table 1).

Table 2 *Voxel t-statistic of the maximal change in cortical activity at any voxel after NFB training*

	Pre>Post		Pre<Post	
Condition	*t*	*p*	*T*	*p*
Eyes Open	4.655	.005	-4.688	.984
Eyes Closed	4.273	.004	-4.291	.986
VT	4.976	.014	-4.976	.825

Note. Voxels represent 3-dimensional cross sections of cortical tissue.

3.5. Behavioural Data

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. 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 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.

3.6. Behavioural change and NFB change

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.

4. Discussion

We sought to identify functional 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 (GFP) 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 indicating that this amateur group (club players in tournament competition) is similar to the elite group in cortical processing during VT (and hence in future studies, a less skilled control group is to be preferred). It would not be reasonable to conclude that there is no relationship between cortical activity during mental play and the processing skills of elite players, given the differences in results between resting states (EO, EC) and the active condition (VT). The amateur group were not novices but rather highly experienced club players participating in European competitions. The groups were maximally differentiated at this (upper-alpha band) frequency in the VT condition. This result does identify those structures within EEG source frequency space that are most related to the differences between the elite and amateur groups during simulated table tennis play. The functional role of this activity at these cortical sources, in the cognitive processing required by table tennis, may nevertheless be assessed through their capacity to predict individual differences in independent behavioural performance measures.

GFP plots directed EEG source analysis of the VT condition to focus on the narrow frequency band of 10.50 – 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 BA13 and right BA6. These then were the variables tested for external validity. Source activity in the identified frequency band, at the location of the 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 (designed to elicit core cognitive processing demands of table tennis play).

4.1. Function of upper-alpha source activity differences during simulated table tennis play

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 mental activity 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 the specific frequency bands and functional network nodes related to the cognitive demands of 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 BA13 and right BA6.

BA13 corresponds to the insula, which is the core node of the 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). That is, BA13 plays a critical role in the initial detection of salient stimuli, to which attention is then directed in order for the motor control networks to select an appropriate response. BA6 is located within the premotor cortex and plays an important functional role in deciding which sources of visual information will guide the selection of motor responses (Chouinard & Paus, 2010). The functional significance of upper-alpha activity at these sources for mapping salient visual spatial stimulus events to motor control and response selection during the VT condition was 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). However, the magnitude of group differences in the eLORETA comparison was 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 novices (as distinct from amateur) table tennis players in future studies.

4.2. Ventral and dorsal 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). The insula (BA13) supports the switching of processing resources to respond to new salient stimuli detected in the environment. The insula is 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, the interaction of ventral and dorsal stream during behavioural tasks 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 conceptual analysis of the interaction between the ventral and dorsal attention networks as a key component of table tennis performance, which provided the rationale for the design of the study.

4.3. Upper-alpha, inhibition-timing and elite motor control

The frequency range (10.50 – 11.75Hz) in which group differences were localized 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; Del Percio et al., 2007b; see also Loze et al., 2001). Our finding of increased upper-alpha in the VT task condition supports Llanos et al.'s (2013) finding that mu (upper alpha frequency) 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 an important 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). The current study found that upper-alpha was greater in the elite than the amateur group when participants engaged in the task of watching the table tennis video and actively imagining playing against this virtual opponent. It is likely that this upper-alpha activity was engaged in cognitive processing to integrate relevant aspects of the visual stimuli (the opposing players' motion) in preparation of responses, as direct execution of that movement is excluded from the paradigm. This interpretation is strongly supported by the significant relationship of this upper-alpha source activity with performance in the vsCPT.

Functional MRI studies have demonstrated that cortical alpha has an inverse relationship with local metabolic rate (Lipp et al., 2012). Extending this finding to the results of the present study would indicate that the increased upper-alpha observed in BA6 and BA13 is evidence of a decrease in processing activity in these regions. This, in turn, could be interpreted in terms of the neural efficiency hypothesis (Babiloni et al., 2009) which argues that greater efficiency in processing (which accompanies expertise) results in less processing activity and hence less desynchronisation in alpha. However, some studies of the mu-rhythm show more, not less, desychronisation while others (as in this case) show a functional increase in alpha (see above). Here, as in the wider literature on the cognitive roles of alpha (Cooper et al., 2003; Jensen, & Mazaheri, 2010; Klimesch, Sauseng & Hanslmayr, 2007; Klimesch, 2012), it is by no means apparent that an increase in alpha (or upper-alpha) is functionally equivalent to a decrease in desynchronisation, which is what the neural efficiency hypothesis specifically predicts. The finely tuned timing of motor control required in table tennis, requiring split-second accuracy of sensory processing, suggests that the inhibitory role of upper-alpha may be related, not so much to neural efficiency, but to the timing role of these oscillations (Mathewson et al., 2011).

Mathewson et al. (2011) have introduced the 'pulsed inhibition' hypothesis as an alternative explanation of the functional role of alpha in the timing, selection of relevant information and the inhibition of irrelevant sensory information. They propose 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, the voltage of an alpha oscillation was higher (more positive) when stimuli were detected, whereas it was lower (more negative) when stimuli were undetected. In this way, the authors posit, brief visual events occurring in a particular phase of ongoing oscillations do not reach awareness, while those in the opposite phase do.

According to this theory, top-down signals from fronto-parietal areas control alpha oscillations when inhibition of some part of visual space, time, or 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). We suggest that the increased amplitude of upper-alpha 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 would allow for top-down control of visual processing synchronized to the speed of a table tennis game.

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. Therefore, it was 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 understanding the functional role 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 could assess the proposal that the pulsed-inhibition mechanism underlies the functional role of the alpha increases observed within elite table tennis athletes.

Our results regarding differences between elite and amateur players should be interpreted with some caution due to a relatively small number of electrodes (19 electrodes) being used. In view of the transfer to the realistic head model in eLORETA, clearly a larger number of electrodes would have made spatial resolution higher and more reliable.

4.4. sLNFB Training

The second aspect of this study aimed to determine if learning to self–regulate selected EEG activity occurs throughout the period of NFB training and whether the alpha protocol applied leads to altered activity at other nodes in the targeted network. The learning index (LI) was expected to be related to the extent of cortical changes. Finally, it was expected that NFB related changes in cortical activity would be related to performance increases 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.

Given the two key locations of difference between elite versus amateur groups (right BA13 and right BA6) and the difficulties and unknowns surrounding the use of sLNFB at 2 locations simultaneously, it was decided to train one location (right BA40) given its established role as a hub within both ventral and dorsal attention networks. 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 cortico-cortical 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 may 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 et al., 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, Vogt, & Laureys 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 comparison to 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 global reduction of cortical activity across all voxels, in all conditions and in all frequencies irrespective of statistical significance. This provides further support for the synthesis of Del Percio et al.’s (2009) and Babiloni et al’s (2009) neural efficiency hypothesis with inhibition-timing account of the alpha rhythm (Mathewson et al., 2011). On this account, alpha NFB training may be increasing 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. Additionally, 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 time improvement, but these 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.

4.5. Time frequency analysis

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.

5. Conclusion

Elite table tennis players were found to differ from lower-level but experienced 'amateur' players by showing greater upper-alpha power in right BA13 and BA6 during mental operations similar to those of actual play. This same activity was shown to be related to superior performance on the vsCPT, which objectively measures key visual-motor integration 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, upper-alpha is highly responsive to operant conditioning (Pineda, 2005) which enables voluntary control of this rhythm to be learnt within a brief period of time. Consequently, upper-alpha is particularly suitable for modulation by Neurofeedback training.

The sLNFB experiment supported previous research that indicates that similar NFB training protocols elicit change in cortical activity and that these changes occur across task-relevant network nodes (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), 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 overall decreases in the power of synchronised cortical oscillations (Pineda et al., 2008). Research with larger samples and the inclusion of control groups are required to further explore indices of learning across NFB training and extend generalisation from table tennis players to the wider sports community. Future research may benefit from the inclusion of phenomenological measures to explore what participants are experiencing during the NFB sessions and how their subjective experience is related to success of 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 devised to elicit cognitive processing within these networks.

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