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Neurofeedback facilitation of implicit motor learning

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ABSTRACT

Background: Mu rhythm desynchronisation via EEG-neurofeedback (NFB) has been previously been shown to induce durable motor-cortical disinhibition for at least 20 min. It was hypothesised that the presentation of a novel procedural learning task immediately after this NFB protocol would boost motor performance.
Method: The protocol consisted of firstly activating the right primary motor cortex with a single session of Mu (8–12 Hz) suppression via NFB for a total of 30 min. Shortly after, and with their non-dominant (left) hand, subjects ($n = 10$) performed the serial reaction time task (SRTT), which is used to assess reaction time improvement over multiple trials. During another occasion (1 week before/after), the same subjects were tested on a different sequence without prior NFB, as part of a counterbalanced control condition.
Results: Compared to a "cross-over" condition without NFB, subjects who received NFB immediately prior to SRTT performance exhibited a significantly faster rate of learning, reflected in a greater reduction of reaction times across blocks ($p = 0.02$). This occurred in the absence of explicit awareness of a repeating sequence. Moreover, no significant differences were observed between conditions in error rate or reaction time variability.
Conclusion: Our results suggest that a single NFB session may be directly used to facilitate the early acquisition of a procedural motor task, and are the first to demonstrate that neurofeedback effects could be exploited immediately after individual training sessions so as to boost behavioural performance and learning.

1. Introduction

Harnessing neuronal plasticity in order to modulate brain function or improve recovery is becoming a rapidly evolving and increasingly viable method in the neurosciences (Moucha & Kilgard, 2006). We had earlier provided original evidence that brain–computer interface control of the electroencephalogram (EEG) via closed-loop "neurofeedback" (NFB) can impact motor-cortical plasticity directly after a 30-min session (Ros, Munneke, Ruge, Gruzelier, & Rothwell, 2010). The question which naturally arose was could there be a behavioural counterpart to this effect in motor performance immediately after NFB? Improving the efficiency and timeliness of NFB application would constitute a significant step forward, methodologically and therapeutically, with respect to approaches exploring the overall effects of multiple sessions on cognitive (Keizer, Verment, & Hommel 2010; Egner & Gruzelier, 2001) or sensorimotor performance (Ros et al., 2009).

The serial reaction-time task (SRTT) was developed to assess learning of perceptuo-motor procedures, or *procedural memory* (Nissen & Bullemer, 1987), where subjects press keys corresponding to stimuli appearing at fixed spatial locations. Here, the stimuli occur within a fixed sequence of considerable length that is usually not identified by the subject. Reaction times to the locations then decrease across consecutive training blocks, but increase to pre-training levels when a switch occurs from the fixed sequence to a truly random appearance of stimuli. The simple nature and application of the SRTT has made it a convenient choice for examining the impact of various interventions on procedural learning. Nitsche et al. (2003) first explored the impact of raising motor cortex excitability with anodal tDCS on SRTT learning, based on previous observations that the motor cortex transiently exhibits an increase in excitability during learning of sequential finger movements (Pascual-Leone, Grafman, & Hallett 1994). The results of the tDCS experiment were striking: online tDCS applied during the course of the experiment (15 min) decreased reaction times in a

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shorter number of trials of the fixed sequence, as well as overall reaction time in the random sequence, when compared to sham stimulation (Nitsche et al., 2003). On the other hand, our prior results point to the feasibility of increasing motor cortex excitability for a period of at least 20 min following a single session of NFB desynchronisation of motor cortex alpha (8–12 Hz) rhythms, also known as Mu rhythms. Based on this overlapping evidence, the aim of the present experiment was to assess whether such an NFB protocol could engender similar advantages in healthy subjects in comparison to a no-treatment condition. Specifically, this protocol was shown to lead to an increase in corticospinal motor evoked potentials (MEPs) and a reduction in short-interval intracortical inhibition (SICI) (Ros et al., 2010): both measures which appear to be linked with successful motor learning (Pascual-Leone et al., 1994; Teo et al., 2009). The temporal window of post-NFB plasticity of at least 20 min (Ros et al., 2010) neatly overlaps with the time needed to complete the SRTT. In order to enable direct comparisons between different neuromodulation methods, the SRTT parameters (block and sequence length, etc.) were kept as closely as possible to the original experiment with tDCS (Nitsche et al., 2003).

2. Materials and methods

2.1. Experimental design

In total, 10 healthy subjects (age: 35.7, SD: 12.7, right handed, 6 female) participated in this experiment. Each subject performed the SRTT task (lasting approx. 20 min) on two different days in a counterbalanced design denoting 2 experimental conditions. The first condition consisted of receiving a 30 min NFB session immediately *before* performance of the SRTT task with the left hand. The NFB protocol was set-up to suppress Mu (8–12 Hz) amplitude at right motor cortex (electrode site C4). Thus it paralleled the protocol used in our last study which demonstrated increased corticomotor excitabilities (Ros et al., 2010). The second condition was a control assessment consisting of only SRTT performance without prior NFB, in order to discriminate whether the NFB intervention has any beneficial effects over a strictly 'no-treatment' condition, which may be appropriate for medical or neurorehabilitation settings. The conditions were separated by at least 7 days and consisted of two entirely different motor sequences in order to control for any possible practice or plasticity effects.

2.2. Serial reaction time task (SRTT)

Subjects were seated in front of a 15″ computer screen at eye level and a keyboard. They were instructed to independently press a series of four keys ('C', 'G', 'H', and 'M') with a different finger of the left hand (little finger for 'C', ring finger for 'G', middle finger for 'H', and index finger for 'M'). An asterisk appeared in one of 4 positions that were horizontally spaced on a computer screen and permanently marked by white dots. The subjects were told to press the key corresponding to the horizontal location of the active asterisk as quickly and accurately as possible. After a button was pushed, the asterisk disappeared and reappeared 500 ms later in a new location, independent of a correct or incorrect response. The experiment consisted of 8 blocks of 120 trials each. In blocks 1 and 6, the sequence of asterisks followed a random order, and asterisks were presented equally frequent in each position and never in the same position in two consecutive trials. In all other remaining blocks (2–5 and 7–8), an identical 12-key sequence of asterisk positions was repeated 10 times (e.g. cgcmghmchgmh). Subjects were not told about the repeating sequence at any point in the experiment. After the experiment however, they were asked whether they were aware of any repeating pattern, and if so, to write it down. The experiment was conducted in a counterbalanced NFB/control condition within-subject design.

2.3. Apparatus and EEG analysis

EEG signals were recorded using a NeXus-10 DC-coupled EEG amplifier using a 24-bit A-D converter (MindMedia, the Netherlands), and visual NFB training was carried out with the accompanying Biotrace+ software interface on an Intel DualCore computer with a 15″ screen. The EEG used for feedback was sampled at 256 Hz with Ag/AgC electrodes at the right primary motor cortex (electrode site C4) referenced to the contralateral mastoid. The scalp area was carefully scrubbed with NuPrep abrasive gel, followed by application of Ten20 electrode paste. The ground electrode was placed on the right arm. The signal was IIR bandpass filtered to extract Mu (8–12 Hz) amplitude (μV peak–peak) with an epoch size of 0.5 s. Reward thresholds were set to be 70% of the time below the initial Mu mean amplitude (baseline). The first baseline was recorded during a 3-min eyes open EEG recording at rest immediately before the start of feedback, and the second 3-min immediately after the end of training. Regrettably, 80% of the recorded EEG training data was lost due to a hard disc failure on the laptop computer (8 out of 10 subjects). This unfortunately compromised the possibility of conducting statistical analyses on the EEG data. With respect to the neurofeedback training strategy, subjects were given no explicit verbal instructions and were told to be guided by the feedback process instead. This was achieved via a collection of different visual displays/games whose control reflected the modulation of the trained EEG amplitude. This consisted of five visual feedback games (MindMedia Biotrace+, Netherlands), which were played in a random order for approximately 6 min each (mandala, space invaders, mazeman, bugz, puzzles). In each game, the start/stop movement of the sprite(s) would be dependent on whether Mu levels were below or above the reward threshold, respectively. We used multiple games to counteract boredom and maximise participant engagement.

2.4. Data analysis

2.4.1. SRTT

In each trial, response time (RT) was recorded from the appearance of the asterisk until the first button was pushed by the subject. Mean RT was calculated for each subject for each block of a given experimental condition (NFB vs. control, 8 blocks each). Along with incorrect responses, response times of less than 200 ms or more than 3000 ms were discarded, or those that were above 3 standard deviations of the individual subject's mean block response time. In addition, the standard deviation of subject RTs in every block was calculated as an index of variability of response. Lastly, an error rate (ER) was calculated to assess the number of incorrect responses versus correct responses in each block and experimental condition. Statistical analyses were conducted for the absolute values of RT, standard deviation of RT, and ER with a within-subject repeated measures ANOVA (CONDITION × BLOCK; 2 × 8). In cases where sphericity of the ANOVA data was violated, a Greenhouse–Geisser correction was automatically used from SPSS. Post hoc paired sample Student's *t*-tests (two-tailed) were performed on RT, ER, and standard deviations between blocks to explore learning effects. Additionally, since RT differences between blocks 5 (fixed sequence) and 6 (random sequence) represent a relative measure of procedural learning, a within-subject repeated measures ANOVA (CONDITION × BLOCK; 2 × 2) was performed to test for an interaction between the NFB and control condition. Thus, a confirmed interaction indicates that a significant difference exists between factor combinations.

3. Results

After the experiment, out of the 10 subjects, only one noted that there may have been a repeating sequence. However, she was unable to explicitly recall the sequence when asked to write it down. *t*-Test revealed no significant differences in overall RT between the two different *sequences*, or as a result of experimental condition *order*. Potential training effects were further discounted by a lack of a significant interaction ($p < 0.05$) in an ANOVA between CONDITION × (condition) ORDER.

3.1. Mean reaction time (RT)

Results for absolute RTs are shown in Fig. 1A. A within-subject repeated measures ANOVA (CONDITION × BLOCK; 2 × 8) disclosed a lack of a significant main effect for CONDITION ($F(1, 9) = 3.7$, $p = 0.08$), with perhaps a trend for a lower overall RT for the neurofeedback (NFB, 521 ms) vs. control (555 ms) conditions. A significant main effect for BLOCK ($F(7, 63) = 2.2$, $p = 0.05$) pointed to a decrease in RT across blocks. Overall RT for random blocks 1 and 6 was 560 and 551 ms, respectively, whereas the overall RT for fixed sequence blocks 2, 3, 4, 5, 7 and 8 was 536, 524, 538, 531, 536, and 529 ms, respectively. Moreover, a significant interaction effect ($F(7, 63) = 2.7$, $p = 0.02$) was observed for CONDITION × BLOCK. This suggests a quantitative difference between the dynamic reduction of RTs across blocks of the neurofeedback and control conditions. As depicted in Fig. 1A, the NFB intervention appears to induce a more rapid decrease in RT especially in the early fixed sequence blocks 2, 3, 4 and 5; exploratory analyses using Fisher's LSD (Least Significant Difference) paired *t*-tests indicated significantly reduced RTs between NFB vs. control conditions in block 2 ($t_9 = 2.4$, $p = 0.04$), block 3 ($t_9 = 3.2$, $p = 0.01$), block 4 ($t_9 = 2.3$, $p = 0.05$), and 5 ($t_9 = 3.6$, $p < 0.01$), as shown by asterisks in Fig. 1A.

A separate analysis between fixed (block 5) and random blocks (block 6) via a 2 × 2 ANOVA (CONDITION × BLOCK) revealed a reliable interaction ($F(1, 9) = 8.5$, $p = 0.02$), with an insignificant main