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The Effect of Voluntary Modulation of the Sensory-Motor Rhythm During Different Mental Tasks on H Reflex

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Abstract

Objectives: Exploring the possibility of the short-term modulation of the soleus H reflex through self-induced modulation of the sensory-motor rhythm (SMR) as measured by electroencephalography (EEG) at Cz. **Methods:** Sixteen healthy participants took part in one session of neuromodulation. Motor imagery and mental math were strategies for decreasing SMR, while neurofeedback was used to increase SMR. H reflex of the soleus muscle was elicited by stimulating tibial nerve when SMR reached a pre-defined threshold and was averaged over 5 trials. **Results**: Neurofeedback and mental math both resulted in the statistically significant increase of H reflex ($p = 1.04 \cdot 10^{-6}$ and $p = 5.47 \cdot 10^{-5}$ respectively) while motor imagery produced the inconsistent direction of H reflex modulation ($p = 0.57$). The average relative increase of H reflex amplitude was for neurofeedback 19.0 ± 5.4%, mental math 11.1 ± 3.6% and motor imagery 2.6 ± 1.0%. A significant negative correlation existed between SMR amplitude and H reflex for all tasks at Cz and C4. **Conclusions:** It is possible to achieve a short-term modulation of H reflex through short-term modulation of SMR. Various mental tasks dominantly facilitate H reflex irrespective of direction of SMR modulation. **Significance:** Improving understanding of the influence of sensory-motor cortex on the monosynaptic reflex through the self-induced modulation of cortical activity.

Keywords

H reflex, Sensory-motor rhythm, Electroencephalography, neurofeedback, mental math, motor imagery

Highlights

1. Modulation of the sensory-motor rhythm (SMR) through various mental tasks resulted in the statistically significant increase of H reflex amplitude, independent of whether the mental task increased or decreased the SMR amplitude.

2. Motor imagery may influence H reflex through different mechanisms; thus, control of SMR amplitude alone was not sufficient to produce a consistent effect on H reflex amplitude across different participants.

3. For EEG measured in a monopolar derivation, a significant negative correlation existed between SMR power over the motor cortex at Cz and C4 and H reflex amplitude for relaxed open eyes state, neurofeedback and motor imagery.

4.

1. **Introduction:**

The H reflex has been regarded as a valuable tool for investigating the excitability of the spinal reflex pathways (Palmieri et al. 2004, Misiaszek 2003). It is believed that the H reflex can be conditioned through spinal and supraspinal sites (Wolpaw 2007, Thompson and Wolpaw 2014). At the supraspinal level, the sensory-motor cortex has been identified as the main cortical center for H reflex conditioning. It has been shown that the H reflex amplitude is modulated during overt and covert motor tasks (Capaday and Stein 1986, Cowley et al. 2008, Hale et al. 2003, Bonnet et al. 1997). In general, the H reflex amplitude is increased during Motor Imagery (MI) (Cowley et al. 2008, Hale et al. 2003, Bonnet et al. 1997) during which similar neural mechanisms are activated and rules followed as for overt movement (Jeannerod 1995). However, the direction of H reflex change may be affected by the amount of MI practice. For example, in elite speed skaters, who perform mental simulation of voluntary motor actions as a part of athletic training, the soleus H reflex amplitude is reduced during mental movement simulation (i.e., vividly imagining skating movement) (Oishi et al. 1994, Oishi and Maeshima 2004).

The H reflex can also be modulated during a mental task such as Mental Math (MM). MM reduces the alpha rhythm in the posterior and occipital region (Yu et al. 2009). Oishi and Maeshima (2004) observed a significant increase in the H reflex amplitude during MM in non-elite athletes but not in elite athletes. It appears that the mental tasks of MI and MM have differing effects on spinal reflex excitability depending on the athletic training background of the subjects. On the cortical level, both MI and MM decrease the power of 8-12 Hz band measured by electroencephalography ((EEG) Fernandez et al. 1995). However, while MI directly modulates localized sensory-motor rhythm (SMR), MM modulates a wide spread 8-

12 Hz activity as well as activity in the delta band (Harmony et al. 1996). To date, EEG activity and the H reflex have not been measured concurrently during MM or MI tasks.

While both MM and MI result in reduction of SMR, it is an open question how an increase of SMR would affect the H reflex amplitude. Apart from relaxation, which results in an increase of wide-spread alpha rhythm (8-12 Hz), it is hard to define a verbalised mental strategy that would result in SMR increase. Nevertheless, people can be trained to voluntarily modulate their brain activity if visual or auditory feedback is provided in real time. This technique is called 'neurofeedback' (NF) and has been used for treatment of a range of neurological and psychiatric conditions, such as attention deficit hyperactivity disorder, epilepsy, depression, pain, etc (Budzynski et al. 2009, Hassan et al. 2015). Because NF relies on non-verbalised rules, it typically requires training over several daily sessions. For example, in a research study by our group, we trained chronic paraplegic patients with central neuropathic pain to increase SMR over the primary motor cortex of the right hand to reduce sensation of pain (Hassan et al. 2015). They successfully learned the strategy over 3-4 daily sessions. Power in 8-12 Hz band increased predominantly over central areas of the cortex, indicating that patients modulated sensory-motor mu rhythm rather than a wide-spread alpha rhythm. Recently there have been several controlled randomised studies involving patients which demonstrated that people can successfully learn to increase power in the upper alpha (10-12 Hz) frequency band, resulting in improved memory performance (Escolano et al. 2014, Kober et al. 2015). A person can also be trained to decrease SMR using NF. This strategy has been used in brain computer interface studies, where visual feedback increases the degree of event-related desynchronization during MI tasks, hence decreasing the power of the SMR (Sollfrank et al. 2016). However, training to modulate SMR in both directions using non-verbalised strategies would require an even greater number of training sessions. Occasionally people may be able to verbalise their mental NF strategies (relaxation, imagination, singing, praying, and focussing), but strategies vary among people for the same task. It should be mentioned however, that while there is no published literature on modulation of H reflex using NF, other biofeedback strategies, not directly exploiting the activity of brain, have been successfully applied to modulate the amplitude of the H reflex in a desired direction in humans and animals (Wolpaw 2007, Thompson et al. 2009).

The purpose of this study was (i) to explore the possibility of a short term modulation of the soleus H reflex through a self-induced modulation of the SMR rhythm, (ii) to assess whether the direction of H reflex modulation is correlated with the direction of SMR modulation (i.e. increase or decrease in EEG power), and (iii) to assess whether different mental tasks, which modulate SMR in the same direction (i.e. MM and MI) affect the amplitude of the H reflex in a similar way across different cortical locations. We used NF to train subjects to increase SMR, and used both MI and MM to reduce the SMR. Defining the relationship between the self-induced modulation of SMR and the amplitude of H reflex is important for understanding the mechanism through which the sensory motor cortex contributes to the conditioning of the H reflex.

2. **Methods**

2.1. Participants

Sixteen able-bodied volunteers (10 male and 6 female, age 27.9 ± 4.1 years), participated in the study. The exclusion criteria were any known history of neurological disorder or an ongoing injury to the upper or lower limbs. One of the participants was excluded from the study due to the inability to detect H reflex. All participants provided informed consent for the study, which was reviewed and approved by the College of Science and Engineering ethics committee, University of Glasgow. All methods used in the experiment comply with the Declaration of Helsinki.

2.2. Experimental Setup

Throughout the experiment participants' posture and head position were maintained to be unchanged. Participants were seated at a desk, with both legs flexed at the hip (90^o), knee (90^o), and ankle (0^o). During the experiment they were facing a computer screen (15" size) at an approximate distance of 120 cm. Participants kept hands on their thighs. They were instructed to stay still and relaxed throughout the experiment. Figure 1 shows the experimental setup.

A 16 channel biosignal amplifier (g.USBamp, Guger Technologies, Austria) was used to record EEG and electromyogram (EMG). The amplifier consisted of 4 subunits with 4 channels each, which can have separate or common reference and ground. EEG and EMG were recorded with separate reference and ground. EEG sampling frequency was 2400 Hz, and was band-pass filtered between 2 and 60 Hz (and notch filtered at 50 Hz) using 5^{th} order IIR digital Butterworth filter within the g.USBamp device. The reference electrode was attached to the left earlobe, while the ground electrode to the right earlobe. Impedance was kept under 5 kΩ. EEG was recorded from the central, parietal and occipital cortical areas, C3, Cz, C4, P3, P4 and Oz, according to the international 10-20 system (Jasper, 1958). For 5 participants, additional EEG recordings were acquired using electrodes C3, Cz, C4, P3, P4, Oz, C1, C2, CPz and FPz. EMG sampling frequency was 2400 Hz and was band pass filtered between 5 Hz and 500 Hz using 5^{th} order IIR digital Butterworth filter within the g.USBamp device.

Figure 1 about here

For EMG recording, skin was prepared with alcohol swabs and abrasive gel and shaved if necessary. EMG of the soleus muscle was recorded using bipolar surface pre-gelled electrodes with Ag/AgCl sensors (Meditrace,USA, 133, 3cm diameter), placed over the muscle belly with center to center distance of 2cm. The ground electrode was placed at the medial malleolus and reference electrode at the lateral malleolus.

For EEG, the skin was prepared with a combined abrasive-conductive gel (Abralyt 2000) and EEG was recorded with Ag/AgCl electrodes. The SMR (8-12 Hz) was measured from electrode Cz (corresponding to the primary motor cortex location for legs), or, for EEG recordings with additional electrode sites, using the Laplacian derivative (Hjorth 1975) as described in Equation1. The calculation was performed on-line in Simulink, Matlab (Mathworks, USA).

$$Cz_{LAPLACE} = C_z - \left(\frac{C_1 + C_2 + FC_z + CP_z}{4} \right) \qquad (1)$$

Monopolar recording is known to record mixed activity of both local and distant sources, thus possibly recording both alpha and SMR activity. The Laplacian derivative is a spatial filter which preserves only the activity of the local sources, thus possibly reducing the influence of wide spread alpha rhythm (Hjorth 1975). The reason for two different EEG montages was to compare the effect of modulation of local and distant EEG sources on H reflex. SMR (8-12 Hz) rhythm is an oscillatory activity primarily reflecting sensory-motor processing in the frontoparietal networks (Pineda 2005). An internal event (e.g. imagination of movement) or an external stimulus causes asynchronous firing of the underlying neuronal substrate, i.e. desynchronization, which manifest itself as reduced amplitude of the SMR. Pfurtscheller and Lopes da Silva (1999) describe evoked or induced reduction of central (8-12 Hz) rhythm (here referred to as SMR) as Event Related Desynchronization (ERD), which presents an active state. The increase in the amplitude of this rhythm is a result of synchronous firing of neuronal substrate and is called Event Related Synchronization (ERS). This is considered as an 'idling' state (Kulman et al. 1978, Pfurtscheller and Lopes da Silva

1999) in which a system is not involved in processing sensory input or preparing motor output. The 'occipital alpha' rhythm is an EEG correlate of relaxed wakefulness, best observed with the eyes closed. It is usually found in the occipital, parietal, and temporal regions (Niedermeyer 2010). Increased (synchronized) occipital alpha rhythm can be considered as an `idling rhythm' of the visual area. Both SMR and alpha rhythms contribute to EEG recorded at central regions of the brain, with the occipital alpha thought to be due to the volume-conduction effect, therefore it could be reduced by Laplacian derivation. In this paper, EEG signal in 8-12 Hz range recorded with both montages will be referred to as SMR.

2.3. Measurement of H Reflex

Participants' H reflex was evoked with self-adhesive electrodes (Anode: 9 x 4cm, Cathode: 3cm diameter, Pals platinum, Nidd Vally Medical Ltd, UK). The cathode was placed over the tibial nerve in the popliteal fosse and the anode was placed on the patella. Bipolar electrical stimulator Digitimer (Stimulator Model DS7, England) was used to deliver the 1ms long rectangular pulses. Current intensity was increased in increments of 2 mA to obtain a maximal muscle response (M wave). The exact location of the cathode was determined by hand held bar stimulation electrode (9 mm diameter, AD instruments). The normalized H reflex was chosen on the rising part of the recruitment curve so that the M wave amplitude was approximately equal to 20% of the maximum M wave. Minimum time between two stimuli was 15s to avoid habituation.

2.4 Study Procedure

Prior to the experiment which modulated H reflex, all participants took part in 3 daily NF training sessions, because this technique requires previous training. The NF training sessions will be explained later in the text, in Subsection 2.6. On the fourth day all participants took part in Experiment 1 (as described in Section 2.7), following procedures shown in Fig 2. Five participants took part in the subsequent Experiment 2 (as described in Section 2.8) on the same day, in which Laplacian EEG derivation was applied following the same experimental protocol (Fig 2).

Figure 2 about here

As a part of Experiment 1 and Experiment 2, the H reflex was measured in five conditions: a relaxed state before neuromodulation tasks (PreRelax), during each of three mental tasks in the following order: MM, NF and MI, and in a relaxed state following the three mental tasks (PostRelax). The H reflex was evoked when SMR reached a predefined threshold for at least 0.5s. For the NF task, threshold was set to 60% above the baseline relative SMR power, and for MM and MI task it was et to 80% under the baseline relative SMR power (details on baseline recording provided in Section 2.7). For each experimental condition, the H reflex was evoked 5 times and mean ± standard deviation (SD) values presented in the results. Minimum time between two H stimulus was 15s to avoid habituation. The stimulation parameters were kept constant throughout the experiment.

2.5. Real-Time Data Acquisition and Analysis

Real time data acquisition and processing were performed with g.RTanalyzer (Guger technologies, Austria) in Simulink. A graphical user interface was developed in LabView (National Instruments, USA). Real time data acquisition software, from the same manufacturer as the EEG device, contains a block in Simulink representing the EEG device that can be used to select recording electrode sampling frequency, common ground, and other recording parameters.

The EEG device sends signal in batches, the size of batch depending on the sampling frequency. For 2400 samples/s it is 128. Then, EEG data was down-sampled to 300 samples/s using 'Downsample' block in Simulink (down sample factor, K = 8). To calculate the relative EEG power in 8-12 Hz bands, down sampled EEG recorded at Cz (or Laplacian derivation calculated in Simulink) was bandpass filtered (5^{th} order IIR Butterworth) in 8-12 Hz and 2-30 Hz bands using two independent filter blocks in Simulink. Filtered EEG in both bands was then squared and smoothed/averaged over a half second sliding window (150 samples), updated after each sample (1/300 s), to obtain the band power features. However, because of receiving signals in batches, the sliding window was effectively updated after every 8 samples. Following this, a relative power was calculated by dividing power in 8-12 Hz band with the power in 2-30 Hz band. This value was compared with a reference value for a given task, which was previously calculated based on 2 min EEG recording in the relaxed eyes opened (EO) state, using a graphical user interface developed in LabView. For different tasks, conditions to activate electrical stimulator to elicit H reflex were met when relative power calculated over one sliding window of 150 samples reached the threshold.

2.6. NF Pre- Training

Neurofeedback strategy requires several training sessions in which participants explore the nonverbalized mental strategy that results in a desired outcome (operant conditioning). Prior to Experiment 1, participants were trained to increase SMR amplitude during 3 training sessions organized over three separate days. Throughout SMR training for all participants, the Laplacian derivation was not used. Each session was divided into 6 sub-sessions lasting 5 min each (30 min in total). At the beginning of each NF practice session, monopolar EEG was recorded in EO relaxed state for 2 min. During EO EEG recording, participants were asked to stay still and to concentrate on a small cross in the middle of a computer screen to avoid eyes movement. This EEG was used as the baseline EEG for a subsequent NF training. During NF training, participants were instructed to control a graphical object (bar) on the computer screen using their EEG. A graphical user interface was developed in LabView. Real time data acquisition and processing was performed with g.RTanalyzer in Simulink

The height of the bar was proportional to the power of the SMR and changed color from red to green when the power increased above the threshold, set at 20% above the baseline value (Figure 3). This threshold was lower than during NF experiment, because a threshold set too high in the initial training would result in poor performance and might cause frustration. Electrical stimulation was not applied during NF pre-training sessions.

Figure 3 about here

2.7. Experiment 1

EEG baseline activity in EO state was measured. Participants sat still looking in front of them at a cross at the computer screen for 2min. EEG was visually inspected and portions of EEG exceeding 100 µV were removed before calculating the power of the SMR. Following this, an H reflex recruitment curve was created and stimulation amplitude of H reflex was determined as previously described. Next, participants were asked to perform a maximum isometric dorsiflexion of both feet for 10s, as a reference for defining 60% of maximum voluntary contraction for a subsequent MI task. The raw EMG was observed on the computer screen, its amplitude measured during maximum contraction, and approximate amplitude for 60% of maximum contraction calculated. The participants were verbally informed when their contraction reached that level. Participants performed several real muscle contractions at about 60% of maximum voluntary contraction which facilitated subsequent kinaesthetic imagination (KI) of movement (described in Section 2.7.3).

In Experiment 1, H reflexes were measured in five experimental conditions: PreRelax, NF, MI, MM and PostRelax. Participants were allowed to rest 5 min between each of the conditions.

2.7.1. Measuring H Reflex Amplitude in a Relaxed State

The same procedure was adopted for measuring H reflex amplitude in PreRelax and PostRelax condition. Participants sat still and relaxed in front of a computer screen looking at a cross in the middle of the screen (to minimize saccadic eye movement). Their SMR was monitored, and H reflex was evoked when SMR was within 5% of the baseline SMR measured at the beginning of the experiment for at least 0.5s. At least 15s was allowed between two H reflex evocations to avoid habituation.

2.7.2. Neurofeedback Task

During NF training, participants were instructed to control a graphical object (bar) on the computer screen using their EEG. During the NF condition, participants were asked to increase the SMR amplitude. The size of the bar was proportional to the power of the SMR rhythm and changed the color from red to green when it increased above the threshold (Figure 3), set at 60% above the baseline value. H reflex was automatically evoked when the power of SMR rhythm was 60% above the baseline for at least 0.5s. The H reflex was elicited five times with a minimum inter-stimulus interval of 15s.

2.7.3. Motor Imagery Task

Following a visual cue on a computer screen, participants were instructed to imagine repetitive ankle dorsiflexion at 60% of the maximum voluntary contraction of the soleus muscle at their preferred pace. They were instructed to imagine feeling muscles in their legs (kinaesthetic imagery) rather than a simple visual imagery because of their distinctive activation of the sensory-motor cortex (Neuper et al. 2005). After each cue, 5s were given to participants to concentrate on the tasks prior to SMR measurement. Visual feedback was not provided for this task. H reflex was evoked when SMR was 80% under the baseline value for at least 0.5s. An H reflex was evoked following each cue. The H reflex was evoked five items with a minimum inter-stimulus interval of 15s.

2.7.4. Mental Mathematics Tasks

During MM, participants were instructed to subtract numbers in intervals of 7 starting from a random large number. H reflex was evoked if SMR was 80% under the baseline value for at least 0.5s. Visual feedback was not provided for this task. The H reflex was evoked five times with a minimum inter-stimulus interval of 15s.

In order to examine whether there is any short term carry-over effect, following the three experimental conditions (MM, NF and MI), participants were asked to relax and sit still while 5 H reflexes were elicited at rest (PostRelax).

2.8. Experiment 2

Five participants took part in Experiment 2. They were given a 10 min rest between Experiments 1 and 2. The same experimental procedure was adopted as in Experiment 1, except SMR was calculated at Laplacian-derived Cz. Current amplitude to evoke the H reflex was kept the same as in Experiment 1. A baseline SMR from $Cz_{LAPLACE}$ was calculated (see Equation 1) from EEG measurement at the very beginning of the experiment, prior to Experiment 1, when it was also recorded from Cz monopolar montage.

2.9. Kinaesthetic and Visual Imagery Questionnaire (KVIQ)

Following Experiments 1 and 2, on a separate day, participants' level of visual and kinaesthetic imagery were tested by using Kinaesthetic and Visual Imagery Questionnaire (KVIQ) (Malouin et al. 2006). KVIQ is divided into two imagery tests: kinaesthetic and visual imagery. Each test comprises 17 questions. Participants were asked to perform a specific movement of a limb or a trunk, which was presented verbally. Then, they were asked to imagine performing the same movement and to rate it on a 5 grades scale, which describes the imagination clarity. For kinaesthetic imagery, 0 meaning no sensation, and 5 meaning as intense a sensation as if executing the action.

2.10. Off line Signal Processing

Offline analysis was performed using Matlab. Normalized power, with respect to power in 2-30 Hz band was calculated for theta (4-8 Hz), SMR (8-12 Hz) beta 1 (12-15 Hz), and beta 2 (16-24 Hz) band. The Pearson correlation test was performed to examine a possible correlation between the H reflex amplitude, normalized with respect to the maximum amplitude for each participant, and the power in all frequency bands for the initial baseline period and all three tasks.

To exclude the influence of background EMG on H reflex, the stability of the background EMG was examined post hoc by calculating the root mean square (RMS) value of the EMG for both 100ms and 2s pre stimulus intervals in all five conditions. The short 100ms period was based on the requirements of studies looking into the modulation of H reflex during MI (Hale et al. 2003). A choice of the 2s period was based on results of biofeedback studies (Thompson et al. 2009) which recommended that background EMG should be stable (i.e. within a predetermined range) for at least 2 seconds before stimulation in order to ensure no effect of EMG backgorund on the H reflex. The relative amplitude of the H and M waves during MM, NF, MI and PostRelax tasks was expressed with respect to the H and M waves during the initial relaxed period (PreRelax) – see equation (2) and equation (3), respectively.

$$H(\%) = \frac{H_{TASK} - H_{PRERELAX}}{H_{PRERELAX}} \quad (2)$$

$$M(\%) = \frac{M_{TASK} - M_{PRERELAX}}{M_{PRERELAX}} \cdot 100 \quad (3)$$

Normalized H reflex amplitude was presented as the percentage of maximum H reflex amplitude for that person. While relative H reflex amplitude presents the H reflex of a task with respect to the H reflex in a relaxed condition, normalized H reflex characterizes a certain task, independent of the baseline value, and can therefore be also calculated for PreRelax period. The former is convenient measure to assess the effect of a mental task on the H reflex, while the latter is more appropriate measure to find a correlation between the amplitude of different brain rhythms and the amplitude of the H reflex.

2.11. Statistical Analysis

A non-parametric test (paired sign rank sum, p=0.05) was used to check whether there was a statistically significant difference between any pair of tasks. A linear correlation between two independent variables was measured using the Pearson correlation test. A correction for multiple comparisons was performed using Holm-Bonferroni correction (Holm 1979). To test whether there existed a statistically significant difference in mean values between more than two variables across repeated measures, a non-parametric Friedman test (non-parametric, repeated measure ANOVA) was used. In cases of several factors e.g. one factor montage and other factor task, as in Section 3.3, Friedman test had to be applied to each factor separately, because it does not allow analysis of interaction between factors. All calculations were performed in Matlab. H reflex was considered stable (no habituation or carry-over effect) if the absolute difference between PreRelax and PostRelax was less than ± 5%.

3. **Results:**

In this section we first present the results of modulation of H reflex and M wave amplitude during all three mental tasks for both monopolar and Laplacian montage. This is followed by the analysis of correlation between the H reflex <u>and</u> EEG power in different frequency bands during MM, NF and MI tasks during Experiments 1 and 2. We subsequently present modulation of power in different frequency bands over the central, parietal and occipital cortex during different mental tasks. Finally, we show results of a correlation between the H reflex and vividness of KI.

3.1. The Variation of Relative H Reflex and M Wave During Neuromodulation Tasks:

The average relative H reflex and M wave amplitudes during different conditions are presented in Figure 4 and Figure 5 respectively. The average relative amplitude increase of H reflex (with respect to PreRelax) was largest during NF (19.0 ± 5.4%, mean ± standard error) followed by MM (11.1 ± 3.6%) and MI (2.6 ± 1.0). During MM, NF, and MI, 12 out of 15 participants achieved modulation of H reflex amplitude larger than 5% in at least one task. During NF the amplitude of H reflex significantly increased as compared to the PreRelax ($p = 1.04 \cdot 10^{-6}$), and similarly during MM as compared to the PreRelax ($p = 5.47 \cdot 10^{-5}$). Low values for the relative H reflex amplitude during MI are due to a fact that in about half participants with significant (> 5%) modulation, the amplitude of the H reflex increased and in the other half it decreased. This resulted in overall non-significant difference compared to PreRelax ($p = 0.57$). There was a statistically significant difference in relative H reflex amplitude between the tasks (MM vs NF $p = 0.037$, MM vs MI $p = 0.0064$ and NF vs MI $p = 1.93 \cdot 10^{-5}$).

There was no statistically significant difference in H reflex amplitude between PreRelax and PostRelax state ($p = 0.69$). In all participants, the H reflex amplitudes PostRelax remained stable (variation less than ± 5%) as compared to the amplitude during PreRelax. This indicates that there was no modulation of H reflex due to habituation.

On a group level, there was no statistically significant difference in M wave amplitude between the baseline level PreRelax and all three tasks together ($p = 0.0723$). There was also no statistically significant difference in M wave amplitude between neuromodulatory tasks (MM vs NF $p = 0.0818$, MI vs NF $p = 0.9305$ and MM vs MI $p = 0.1765$). The M wave for all participants remained stable during all tasks (variation less than ± 5%) compared to the amplitude before the experiment (PreRelax). This indicates the stability of direct efferent muscle response throughout the whole experiment.

Figure 4 about here

Figure 5 about here

The upper figure (P8, in Fig 4 and 5) shows an example in which H reflex increased in all neuromodulatory tasks, in particular during NF, and returned to the baseline value during PostRelax task. The middle figure (P4, in Fig 4 and 5) shows an example in which H reflex decreased during MI and slightly increased during NF. Finally, the bottom figure (P3, Fig. 4 and 5) shows an example with no changes in H reflex during neuromodulatory tasks. Note that in all participants and in all 5 conditions the M wave remained stable. Figure 6 shows the H reflex and M waves during PreRelax, all three neuromodulation tasks, and PostRelax for three representative participants.

Figure 6 about here

3.2. Correlation Between H Reflex and EEG Power for Different Frequency Bands, Tasks and Electrode Locations

For each participant all responses to all 5 stimuli for each task were normalized with respect to the maximum H amplitude. Power of theta, SMR, beta1 and beta 2 for each stimulus were expressed as power normalized with respect to 2-30 Hz band. Beta 1 (12-15 Hz) is called SMR in neurofeedback literature and is used for different neurofeedback protocols (Ros and Gruzelier 2011), and beta 2 (16-24 Hz) is in the frequency range of beta SMR related to the control of movements (Pfurtscheller and da Silva 1999). Midline-frontal theta rhythm (4-8 Hz) is influenced by increased level of concentration and might be involved in all active tasks (Mizuki et al. 1983).

For electrodes at the central, parietal, and occipital cortex, a linear regression was calculated between the H reflex amplitude of all participants (5*15=75) and the normalized power of a single frequency band. Figure 7 shows a linear regression between SMR and H reflex for all three mental tasks at Cz. The largest negative correlation was found between the H reflex amplitude and SMR at C4 and Cz (Table 1). A statistically significant correlation existed between H reflex and SMR power for all three tasks and PreRelax. A statistically significant negative correlation was also found between H reflex and SMR for MM at all examined electrode locations. In other frequency bands, a statistically significant correlation was found only between H reflex amplitude and the beta 2 band for NF at Oz ($p = 0.0016$ and $R = -0.3578$). A general conclusion was made that there exists a negative correlation between the H reflex amplitude and the SMR power. Note that larger SMR power characterises synchronised neuronal activity (ERS), which describes the 'idle' state (Pfurtscheller and da Silva 1999), so there is effectively a positive correlation between the active SMR (ERD) and the H reflex amplitude.

The analysis of the contribution of individual participants reveals that in most cases for both MM and MI the same participants had low or high H reflex amplitude (e.g. P2 and P5 had low a H reflex amplitude, and P11, P12, and P14 had high a H reflex amplitude). In addition, the same participant P15 had a very high SMR power for low H amplitude, and removing this single 'outlier' participant would result in nonsignificant correlation between SMR power and H reflex amplitude for MM task ($p = 0.0958$ and $R = -0.2006$) while for MI this correlation would still have remained statistically significant ($p = -0.0363$ and $R = -0.2507$). In case of NF there is less similarity than between MM and MI cases. For example, P6, who for MM and MI had high a H reflex amplitude for low SMR power, during NF had low H reflex amplitude for low SMR power. Participant's P15 results do not appear to be outliers as they overlap with results of P1 and P7.

Table 1 about here

Figure 7 about here

3.3. H Reflex During Monopolar and Laplacian EEG Derivation:

To assess the influence of neuromodulation based on EEG measurement of local and wide spread sources, five participants were asked to repeat the same five tasks (PreRelax, MM, MI, NF and PostRelax) while EEG was recorded from an additional 4 electrodes (see methods). For all five tasks, SMR was calculated from Laplacian-derived Cz. The relative amplitude of the H reflex during monopolar and Laplacian EEG derivations are presented in Figure 8, showing a similar trend except for MI task in P11, and NF tasks in P15. A two way repeated measures Friedman test was performed to compare whether there was a statistically significant difference between monopolar and Laplacian derivation across all five tasks, each task repeated 125 times (5 tasks·5 repetitions·5 persons). The test demonstrated that there was no statistically significant differences between different derivations for all tasks p=0.2099. The same test was applied to compare between five different tasks for both derivations together, with 50 repetitions (2 derivations·5 participants·5 repetitions) resulting in nonsignificant differences among tasks, p=0.0712. When Friedman test was applied to only first four tasks (without PostRelax which is very similar to PreRelax, see Section 3.1) it resulted in a statistically significant difference between tasks p=0.0277.

Linear regression was calculated for both derivations between the normalized amplitude of H reflex and EEG power in theta, SMR, beta 1, and beta 2 band for each task (25 measurements of Laplace derivation, and 25 for monopolar derivation). A statistically significant negative correlation was found in both cases between SMR and the H reflex for the PreRelax (Laplace p = 0.038, R = -0.4172, monopolar p =$6 \cdot 10^{-6}$ and R = -0.7723) and NF (Laplace p=0.0173, R=-0.4717, monopolar p = 0.0013, R = -0.6084). In monopolar derivation only, statistically significant negative correlation was also found for both MM and MI tasks ($p=4.2*10^{-5}$, R= -0.7244 and p= $4.7*10^{-5}$, R= -0.7214) respectively. Though the results of both derivations show similar trends, they are somewhat different from the results on 15 participants with monopolar derivation, probably due to the small number of participants. Although participants practiced NF with monopolar derivation this did not negatively influence their performance during NF with Laplace derivation. The average time to achieve 5 conditions for H reflex stimulation during NF was 16.7 ± 2.1s for monopolar and 15.6 ± 0.8s for Laplace.

Figure 8 about here

3.4. Kinaesthetic Imagery Scores:

The mean value of KI scores across all 17 questions, including MI of different parts of the body, and across 12 participants (participants 6, 10 and 11 were not available for the test) was 3.2 ± 0.6, and it ranged from 1.95 to 4. These results show that on average participants had moderate kinaesthetic imagery (KI=3). To test the relation between the ability of the KI and the variation in H reflex amplitude during MI, a linear regression was calculated between KI score and the relative H reflex amplitude (Fig. 9). The correlation coefficient was moderate (Pearson p = 0.164, R = 0.4282) but was not statistically significant.

Figure 9 about here

3.5 Background Electromyography:

The mean RMS value of background EMG in a period 100ms before each stimulus during all experimental conditions and across all participants was 3.49 ± 1.85 µV (min 1.18 µV, max 9.62 µV). The mean RMS value of background EMG in a period 2s before each stimulus was 3.42 ± 1.84 µV (min 1.30 µV, max 8.72 µV). All values were under 10 µV, which was a benchmark value to determine stability of background EMG in some previous studies (Thompson et al. 2009), showing that H reflex was not modulated due to the modulation of the background EMG activity.

3.6 Modulation of Other EEG Frequency Bands During Mental Tasks:

Figure 10 shows an example of Power Spectral Density (PSD) as a function of frequency over 2-30 Hz range for PreRelax, MM, NF, and MI. PSD was calculated based on 1s of EEG before stimulation, providing 5s of recording for each condition. Although stimulation was based on 0.5s EEG, a period of 1s was chosen for computational reasons as 0.5s provided an overall EEG signal that was too short (only 2.5s). During MM and MI the power in 8-12 Hz was smaller, and during NF it was larger than in PreRelax state. While power was controlled in the SMR band only, it can be noticed that power was also modulated in other frequency bands, most notably in the theta and beta 1 band during MM and MI.

Figure 10 about here

Figure 11 shows power in other frequency bands during modulation of SMR power, across different electrode locations at the central, parietal, and occipital cortex for different mental tasks. It also shows the baseline power across different cortical areas. Asterisks in Fig. 11 mark statistically significant differences between the PreRelax and the various mental tasks across the frequency bands and electrodes, corrected for multiple comparisons. In the SMR band an increase in baseline power can be noticed, starting from the central area towards the parietal and occipital area, though it did not reach a statistically significant level ($p = 0.0683$ Cz vs Oz). While the difference in SMR between the PreRelax and NF was statistically significant for Cz ($p = 1 \cdot 10^{-11}$), it was not significant for Oz ($p = 0.085$). This indicates that although EEG derivation was monopolar, it was the true SMR rather than wide-spread alpha being modulated during this task. Numerical values are provided in Appendix 2.

Significant decrease of the SMR during MM and MI can be noticed across all electrode locations. Wide spread posterior-occipital reduction in SMR activity during MM has been previously reported, and was related to modulation of the alpha rhythm (Yu et al. 2009). Beta 1 power was also significantly reduced for MM at all electrode locations. A wide-spread reduction in SMR during MI can be attributed to aggregation of different processes involved in the transformation from seeing (a visual cue) to doing (Pineda 2005). Beta 1 was significantly reduced ($p = 0.035$) at Cz for MI. Theta band power was significantly reduced at Cz, C3, P4, and Oz during MM, and at Cz, P4, and Oz during MM. Beta 2 power was not significantly modulated by any of the mental tasks.

Figure 11 here

For Laplacian derivation at Cz, during MI, power was on average reduced in the SMR rhythm and theta and beta 2 band (Fig 12). Although SMR and beta 1 are two nearby bands, MI did not result in reduced power in beta 1 band. During NF, the average power increased in SMR, beta 1 and beta 2, as compared to the baseline. Again, although SMR and theta are neighbouring frequency bands, theta band power decreased while SMR power increased. Finally, during MM, power decreased in SMR and theta bands, staying on a similar level as during the baseline in beta 1. On the contrary, beta 2 power increased during MM. Compared to the monopolar montage, NF had a similar effect on the theta, SMR and beta 1 band, MI had the similar effect on the SMR, beta 1 and beta 2 band and MM had similar effect on SMR and theta band. It should however be noted, that largest differences between monopolar recording and Laplacian derivation were in bands in which there was no statistically significant differences between the baseline and the task, in case of monopolar montage shown in Fig 11.

Figure 12 about here

4. **Discussion:**

It is believed that the sensory-motor cortex presents the major supraspinal site for modulation of the H reflex (Wolpaw 2007, Thompson and Wolpaw 2014). However the effect of the self-induced modulation of SMR on the H reflex has not been sufficiently explored.

The present study explores the effect of short term modulation of SMR using different mental strategies on the H reflex amplitude of the soleus muscle. From the literature, it is known that mental tasks, including MM, can induce unspecific facilitation of motor evoked potential (Rossi et al. 1998). Our recent study shows that upregulation of SMR power by NF over the motor cortex, results in increased SMR power primarily over the central areas of the cortex (Hassan et al. 2015). However, it is not known how it affects H reflex. In this study, the effect of MM and NF on the H reflex was excitatory despite the opposite direction of modulation of the SMR rhythm. Both tasks significantly increased the H reflex. MI also resulted in modulation of H reflex but in about one half of participants with significant modulation (amplitude change larger than ±5%) it caused an increase, while in the other half a decrease of H reflex amplitude. The comparable values of the baseline H reflex before and after the experiment in the current study indicate that there was no carry-over effect following a single session of three mental tasks.

Modulation of H reflex was largest during NF. To the best of our knowledge, there is no published study providing information about the change in cortical excitability during NF task. However, Ros and Gruzelier (2011) studied the effect of suppression of monopolarly recorded 8-12 Hz rhythm over C3 on corticospinal tract excitability following 30 min NF training. Motor evoked response to transcranial magnetic stimulation was used as a measure of excitability. They noticed no significant change in corticospinal tract excitability immediately after NF, followed by a significant increase in excitability 15 min after NF. In the current study, participants were asked to increase SMR power for 5 min only and no significant difference was noticed between PreRelax and PostRelax baseline H reflex.

An rTMS study showed that stimulation with 1Hz increased 8-12Hz band power over the sensory-motor cortex as the result of ERS of neuronal activity (Brignani et al.2008), while stimulation with 5Hz caused ERD. Another rTMS study showed that stimulation with 1Hz caused increase in H reflex (Centonze et al. 2007), while stimulation with 5Hz caused reduction of H reflex, resulting in reduced spasticity in patients with multiple sclerosis. Results of these studies show that 1Hz rTMS stimulation is related to both ERS and increase in H reflex. This indicates a possible relation between ERS (increased 8-12 Hz power) and increased H reflex. If we hypothesise that NF and rTMS result in a similar effect on SMR power, then the effect of NF would be similar to ERS, i.e. inhibition of cortical networks (Kuhlman 1978, Neuper et al. 2006), which results in increased H reflex. In patients with spinal cord injury, total or partial loss of communication between the brain and monosynaptic loops in the spinal cord results in spasticity (Decq 2003, Pikov 2007), which can manifest itself as an exaggerated H reflex (Thomas and Filed Fotte 2009). In our recent NF study (Hassan et al. 2015) with spinal cord injury patients, we noticed increased spams in legs during NF training from C3/C4 and Cz in people with an incomplete injury. The NF protocol involved upregulation of 8-12 Hz and downregulation of theta and beta (20-30 Hz) band power using monopolar EEG montage. A post hoc analysis revealed that 8-12 Hz rhythm was increased over the central area indicating that it was most likely the SMR rhythm.

It is of interest that while NF resulted in H reflex increase, largest increases were noticed for smaller increases of SMR. This apparent decoupling between the global effect of NF and a specific relation between SMR and H reflex might indicate that some more factors, apart from SMR, are involved in modulation of H reflex during NF.

During MM a significant increase in H reflex amplitude was noticed. It is believed that the mechanism for increasing H reflex during MM is caused by stress which heightens sympathetic outflow (Kamibayashi et al. 2009). Sympathetic outflow enhances the stretch reflex response in the relaxed soleus muscle in humans (Kamibayashi et al. 2009). It is of interest that reduced power during both MM and MI was noticed over the parieto-occipital region. It has previously been reported that mental math affects the wide spread alpha rhythms over the parieto-occipital region (Yu et al. 2015). This indicates that MM actually modulated the alpha rhythm rather than the SMR. However, in experiments with Laplacian derivate, which should reduce the influence of a wide-spread alpha rhythm on the stimulation-triggering SMR measurement, increase in H reflex during MM was noticed in some cases. Thus, MM probably modulated both SMR and the alpha rhythm. On the other hand, a wide spread cortical reduction of 8-12 Hz rhythm during MI over the central, parietal, and occipital regions might be the consequence of a volume-conduction effect or may reflect a complex process of transformation of seeing (a visual cue) into doing (Pineda 2005).

Previous studies demonstrated that the effect of MI on the H reflex depends on the level of fitness (Oishi 1994, Bonnet et al. 1997, Hale et al. 2003, Oishi and Maeshima 2004, Cowley et al. 2008). In our study the level of fitness was not measured, but participants belonged to a general population. However, a moderate, though non-significant, positive correlation ($p = 0.4282$, $R=0.164$) was noticed between the kinaesthetic imagery score and the H reflex amplitude during MI. Although we asked participants to perform MI at 60% of maximum contraction of the soleus muscle it is possible that this varied among participants. Hale et al. (2003) found that MI practice rather than the intensity of imagination influenced H reflex amplitude, as it increased throughout the experiment including repeated MI sessions. The inconsistent results on the influence of MI on H reflex indicate that although MI produces consistent decrease of SMR, the SMR power is likely not the only factor influencing the H reflex amplitude. In a recent study on rats by Boulay et al. (2015) two mechanisms were proposed through which the activity of the sensory-motor cortex may influence H reflex. These two mechanisms were associated to a distinctive relation of H reflex with two frequency bands. The first, probably mediated by presynaptic inhibition, results in H reflex increase with increased activation of SMR (8-12 Hz). The second, which is probably mediated via the motoneuron itself as well as changes elsewhere in the spinal cord, has the opposite effect. A more active sensory-motor cortex in lower gamma band (45-85 Hz) results in lower H reflex. This could explain why, in some cases, H reflex was reduced during MI. A limitation of the current study is that gamma band activity was not recorded, making it impossible to test this hypothesis. In addition, it is not known to what extent results in humans and rats are comparable.

A recent study by Takemi et al (2015) analyzed the influence of ERD during MI on the excitability of the human spinal motoneurons, as measured by the presence of F wave. Although the intensity of ERD (5% or 15%) had no impact on the results, increasing SMR during MI task had an overall excitatory effect. A difference between F and H waves is that the F wave is elicited at supramaximal M wave amplitude and is caused by an antidromic stimulus in the motor pathways, meaning it requires higher current than H reflex and does not involve the sensory pathways. In our study H reflex activated both sensory and motor pathways, and intensity of ERD was 80% - much higher than that used by Takemi et al. (2015).

Analysis of the power spectrum during all three tasks showed that modulation of SMR was accompanied by the modulation of EEG in other frequency bands. Significant reduction in theta and beta 1 power was noticed over the central cortex for MI, and over central, parietal, and occipital cortex for MM. These frequency bands might independently affect H reflex. We therefore calculated a correlation between the H reflex and modulation of power in different frequency bands over the central, parietal, and occipital cortex. A statistically significant negative correlation between H reflex and EEG power was found for SMR band only. It was present for all three mental tasks and PreRelax at electrode locations Cz and C4 located over the primary motor cortex. This effectively means that ERS was negatively and ERD positively related to the H reflex amplitude, confirming results of Boulay et al. (2015).

A possible limitation of the study is that only NF included visual feedback and direct conscious self-regulation of SMR. This may have influenced wider cortical networks, including the occipital cortex, however in this study we found no significant modulation of 8-12Hz rhythm at Oz during NF. Since people use various mental strategies for NF, the set of mental tasks used to increase the SMR during NF is probably less homogeneous than mental tasks used to reduce SMR with MM and MI. To the best of our knowledge there is no verbalized rule that can be used to increase 8-12 Hz rhythm, apart from relaxation which typically affects the parieto-occipital alpha rhythm (Niedermeyer 2005). Additionally, the duration of NF training prior to the study was relatively short. We did however check the participants' ability to self-regulate their brain waves through post hoc analysis of PSD during NF.

Furthermore, another limitation is that we used monopolar derivation for most of participants, which probably records a mixture of sensory-motor rhythm and alpha rhythm. In Experiment 2 of this study, the Laplacian derivation was used to exclude the effect of a wide spread alpha rhythms modulation in 5 participants. A Friedman test failed to demonstrate a statistically significant difference between monopolar and Laplacian derivation, indicating that either the modulation of a relative H reflex amplitude was not clearly affected by the origin of 8-12 Hz rhythms, or that both approaches recorded dominantly SMR. A regression analysis between SMR and H reflex amplitude showed a significant negative correlation for

PreRelax and NF in both cases, while a negative correlation for MM and MI was found for monopolar montage only. The NF result confirm the result of our previous study in which we recorded multichannel EEG during NF (Hassan et al. 2015), and showed that NF tasks predominantly modulated the central 8-12Hz rhythm, i.e. SMR. The absence of significant correlation for both MM and MI tasks for Laplacian derivation is probably a combination of two factors, the small number of participants and possibility that wide spread alpha, rather than SMR was modulated. Unfortunately, due to the small number of participants we had to apply a nonparametric statistic which did not allow us to analyse between factors 'derivations' and 'tasks' to draw conclusions about which of five tasks was influence by different derivations.

The present study provides an important and novel first step in exploring the effect of modulation of SMR during neuromodulation tasks on H reflex amplitude in the able-bodied population. It is however based on the measurement of the immediate effect of a single session of neuromodulation. Repeated experiments over an extended period would be necessary to understand the long-term changes of H reflex induced via prolonged modulation of brain activity. The results of the study are also relevant for the design of brain-computer interface rehabilitation strategies, which are based on cortical activation to promote restoration of the neural activity in the cortico-spinal tract. Very often MI is combined with functional electrical stimulation (FES) to promote simultaneous activation of sensory and motor pathways (Kim et al, 2015, King et al. 2015, Vuckovic et al. 2015). Results of this study, in particular results concerning MI, should inform future design of such BCI-FES studies.

5. Conclusion

Short term voluntary modulation of SMR from Cz resulted in modulation of H reflex amplitude of the soleus muscle. The excitatory effect on H reflex was independent of the direction of modulation of the SMR rhythm. Increasing SMR through NF produced the largest increase in the H reflex. Decreasing SMR through MI had an inconsistent effect on the H reflex, indicating possible concomitant influence of other EEG rhythms present in the same area of the cortex or the influence of sub-cortical centres. All three mental tasks also resulted in modulation of the theta and lower beta band power in the central, parietal, and occipital cortex; however, a significant correlation with H reflex was found mainly for SMR. A single neuromodulation session produced only a short term modulation of the H reflex.

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Conflict of interest: none

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Tables

Table 1: Linear correlation (p and R values) between relative H reflex amplitude and SMR power across different conditions and different electrode locations. PreBL: baseline before the experiment, NF: neurofeedback, MM: mental math, MI: motor imagery. Bold marks statistically significant values.

	PreBL		MM		NF		MI	
	p	R	p	R	p	R	p	R
C3	0.0793	-0.2039	**$6.95*10^{-6}$**	**-0.4932**	0.1447	-0.17	0.0903	-0.197
Cz	**$6.42*10^{-4}$**	**-0.3853**	**$2.40*10^{-4}$**	**-0.412**	**0.0325**	**-0.2472**	**$9.67*10^{-4}$**	**-0.3734**
C4	**0.0108**	**-0.2928**	**0.0031**	**-0.3376**	**0.0337**	**-0.2456**	**0.0336**	**-0.2458**
P3	0.2711	-0.1287	**0.005**	**-0.3212**	0.0755	-0.2065	0.2526	-0.1337
P4	0.1849	-0.1548	**$2.43*10^{-6}$**	**-0.5138**	0.0854	-0.2	0.4196	-0.0946
Oz	0.9749	$3.7*10^{-3}$	**0.0054**	**-0.3181**	0.555	-0.0692	0.4437	-0.0898

Figure legends:

Figure 1. The experimental setup diagram. Participants sit straight looking towards the computer screen. Visual feedback was provided during NF task only. During each of the tasks, computer calculated power of SMR recorded by EEG device and based on its value activated the stimulator to elicit H reflex.

Figure 2. Experimental protocol for Experiments 1 and 2. Sensory-motor rhythm (SMR) refers to the normalized power in the 8-12 Hz band measured from Cz in either monopolar (Experiment 1) or Laplacian derivation (Experiment 2). Threshold SMR of each condition was measured with respect to a corresponding baseline SMR (BSMR). An H reflex was evoked when SMR reached a threshold for 0.5s. Numbers in boxes describing conditions present corresponding threshold values to evoke H reflex.

Figure 3. Visual feedback during neurofeedback. Bars represent normalized power of SMR averaged over 0.5s sliding window. When SMR was above the threshold (20% above the baseline for pre-training, 60% for Experiments 1 and 2), the color of the bar was green, otherwise it was red.

Figure 4: Relative H wave amplitude with respect to the values in relaxed state before the neuromodulatory tasks (PreRelax). The horizontal dashed lines mark ± 5 % change of the H reflex amplitude compared to the PreRelax; MM: mental mathematics; NF: neurofeedback; MI: motor imagery: PostRelax: relaxed state following all neuromodulatory tasks. Error bars present a standard error.

Figure 5: Relative M wave amplitude with respect to the values in relaxed state before the neuromodulatory tasks (PreRelax). The horizontal dashed lines mark ± 5 % change of the H reflex amplitude compared to the PreRelax; NF: neurofeedback; MI: motor imagery:

PostRelax: relaxed state following all neuromodulatory tasks. Error bars present a standard error.

Figure 6: The H and M wave for two baseline periods before (PreRelax) and after (PostRelax) neuromodulation tasks and during neuromodulation tasks (MM, NF and MI) for three representative participants (**A**: highest increase in H reflex, **B**: highest decrease in H reflex and **C**: no change in H reflex). The black thin line represents the M and H reflex for each stimuli and the black thick line represents their average.

Figure 7. Linear correlation between SMR measured and normalised H reflex amplitude for different mental tasks. MM ($p = 2.4 \cdot 10$-4, $R = -0.412$), NF ($p = 0.0325$, $R = -0.2472$) and MI ($p = 9.6 \cdot 10^{-4}$, $R = -0.3734$) and. The combination of different symbols and colours presents contribution of a single participant.

Figure 8: Relative H wave amplitude for all three neuromodulation tasks (MM, NF and MI) during two EEG recording derivations (Laplacian and monopolar).

Figure 9. A linear regression between KI score and the relative H reflex amplitude during MI across all 12 participants (3 out of 15 participants did not take part in this test).

Figure 10. EEG power as a function of frequency averaged across 15 participants in Experiment 1. PreRelax: relaxed state before the experiment; MI: motor imagery; NF: neurofeedback; MM: metal math.

Figure 11: Relative EEG power at different frequency bands (Fig A-D) during different mental tasks over several electrode locations. A: Theta band (4-8Hz), B: SMR (8-12 Hz), C: Beta 1 (12-15 Hz), Beta 2 (16-24 Hz). PreBL: baseline power before the experiment, MM: mental math, NF: neurofeedback, MI: motor imagery. Asterisks above bars indicate tasks

which significantly modulated power as compared to the baseline value. Initial statistical significance level p = 0.05 was corrected for multiple comparisons for each single band/electrode.

Figure12 Relative EEG power at different frequency bands during different mental tasks over Cz electrode location during Experiment 2. PreRleax: baseline power before the experiment, NF: neurofeedback, MM: mental math, MI: motor imagery.

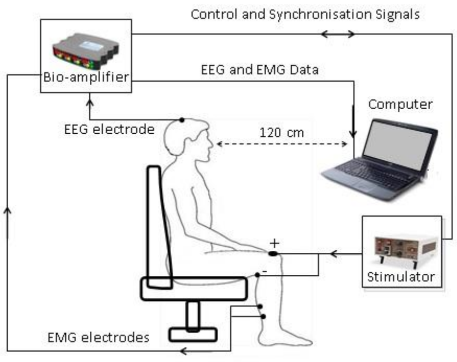
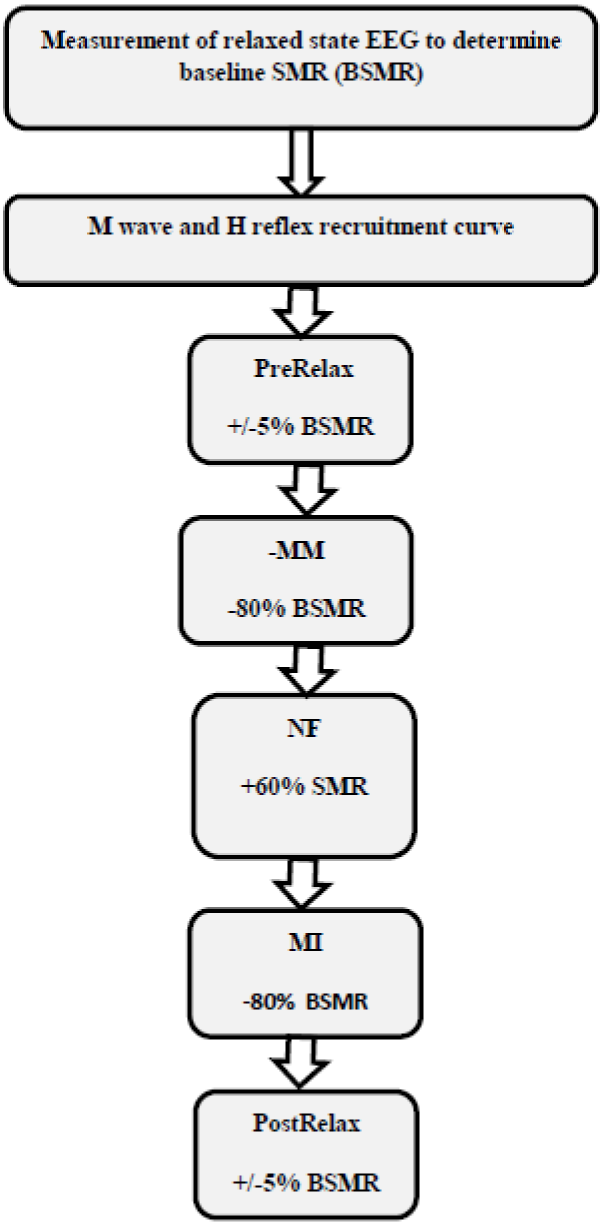

Control and Synchronisation Signals
Bio-amplifier
EEG and EMG Data
Computer
EEG electrode
120 cm
+
-
Stimulator
EMG electrodes

Figure 1



Measurement of relaxed state EEG to determine baseline SMR (BSMR)
M wave and H reflex recruitment curve
PreRelax
+/-5% BSMR
-MM
-80% BSMR
NF
+60% SMR
MI
-80% BSMR
PostRelax
+/-5% BSMR

Figure 2

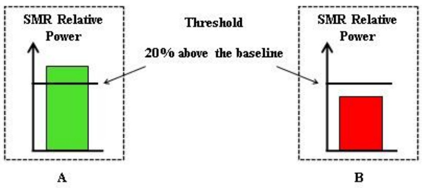
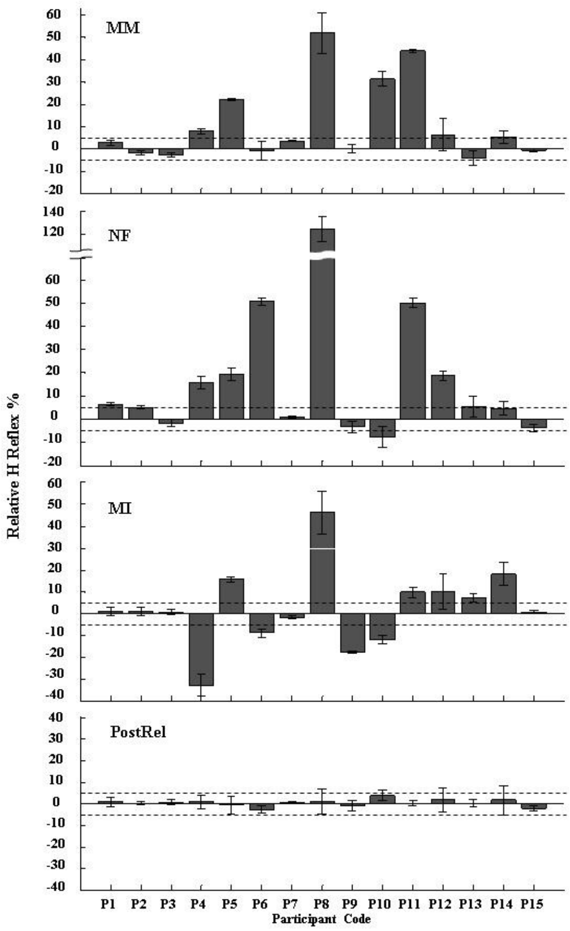

SMR Relative Power
Threshold
20% above the baseline
SMR Relative Power
A
B

Figure 3



MM
NF
MI
PostRel
Relative H Reflex %
P1 P2 P3 P4 P5 P6 P7 P8 P9 P10 P11 P12 P13 P14 P15
Participant Code

Figure 4

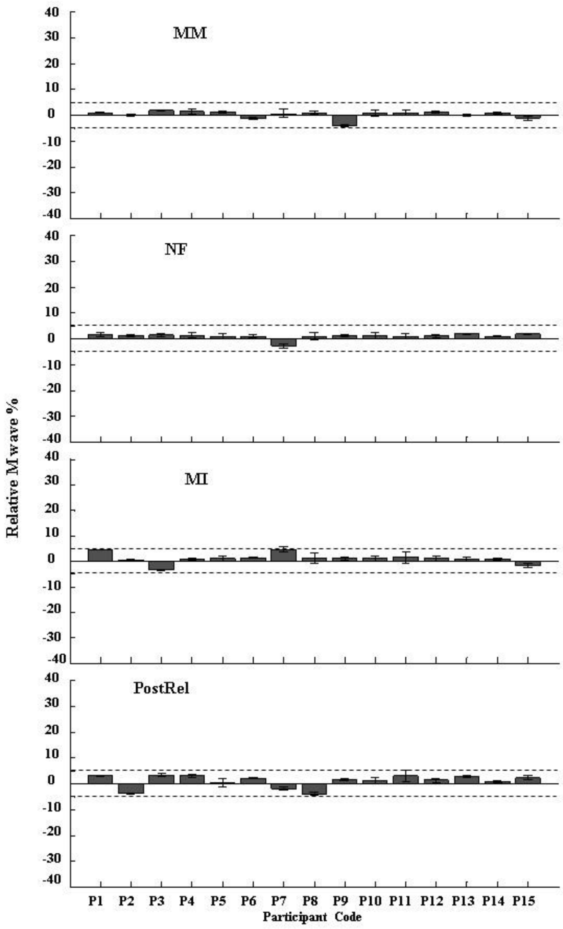

MM
NF
MI
PostRel
Relative M wave %
40
30
20
10
0
-10
-20
-30
-40
P1 P2 P3 P4 P5 P6 P7 P8 P9 P10 P11 P12 P13 P14 P15
Participant Code

Figure 5

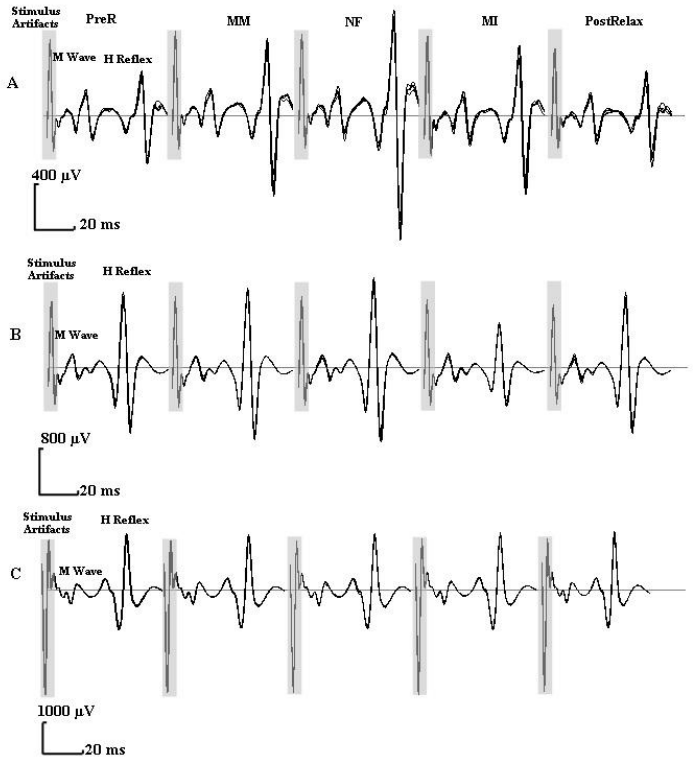
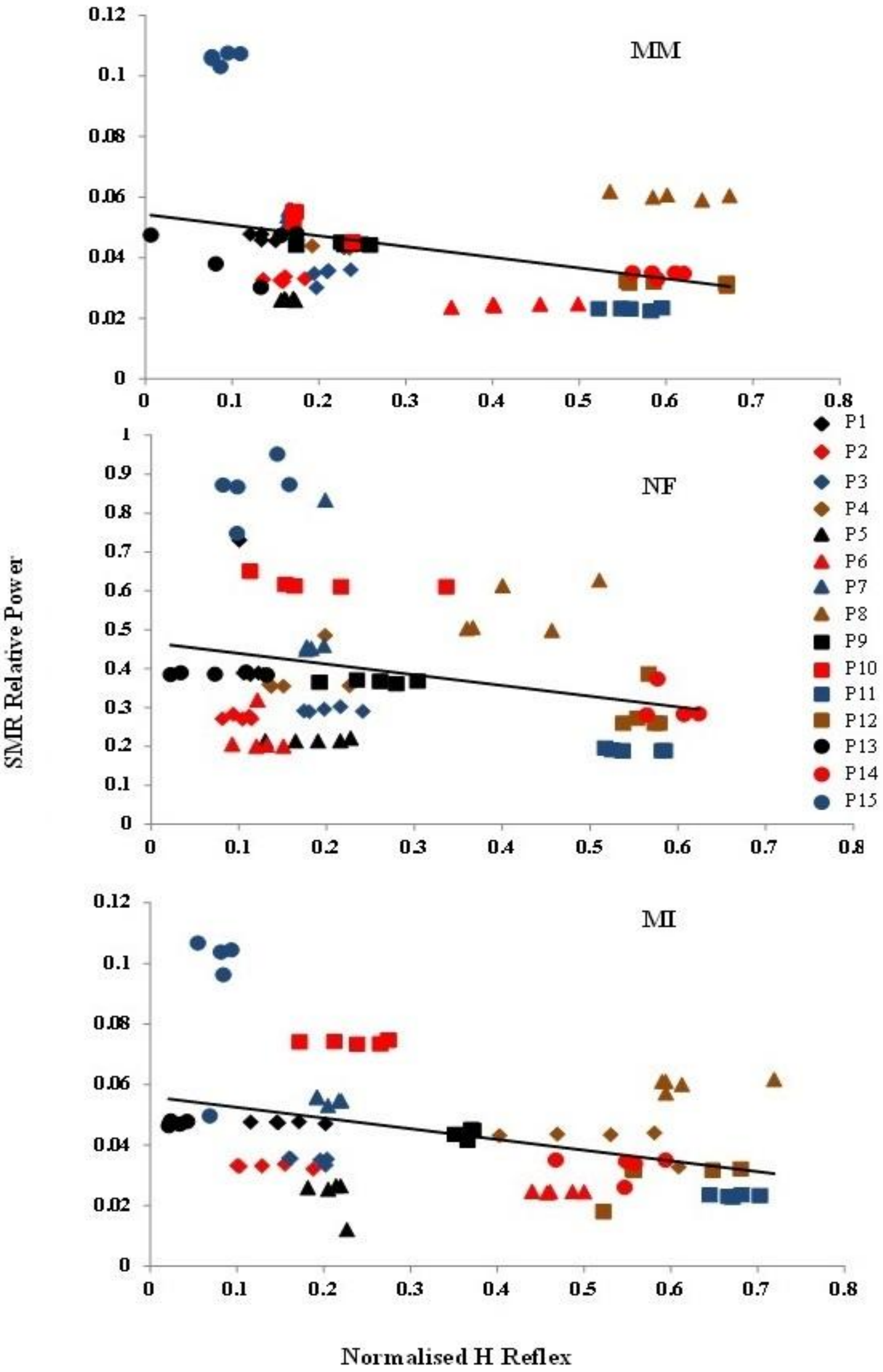
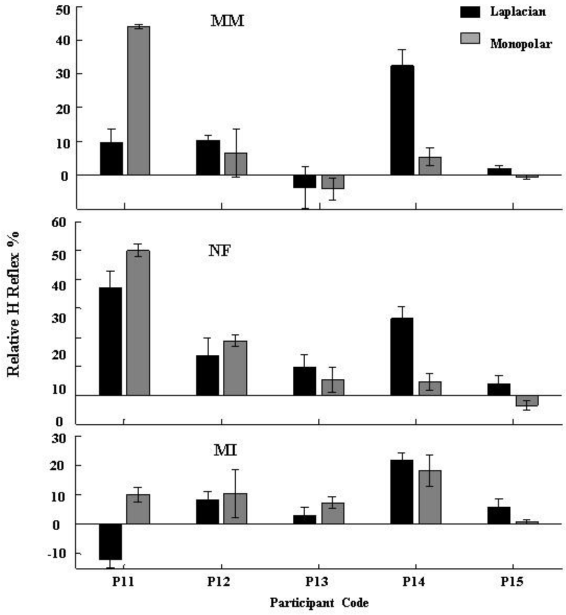

Stimulus Artifacts
PreR
MM
NF
MI
PostRelax
M Wave
H Reflex
A
400 µV
20 ms
Stimulus Artifacts
H Reflex
B
M Wave
800 µV
20 ms
Stimulus Artifacts
H Reflex
C
M Wave
1000 µV
20 ms

Figure 6



MM
NF
MI
SMR Relative Power
Normalised H Reflex
P1
P2
P3
P4
P5
P6
P7
P8
P9
P10
P11
P12
P13
P14
P15
0.12
0.1
0.08
0.06
0.04
0.02
0
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8

Figure 7



MM
NF
MI
Laplacian
Monopolar
Relative H Reflex %
Participant Code
P11
P12
P13
P14
P15

Figure 8

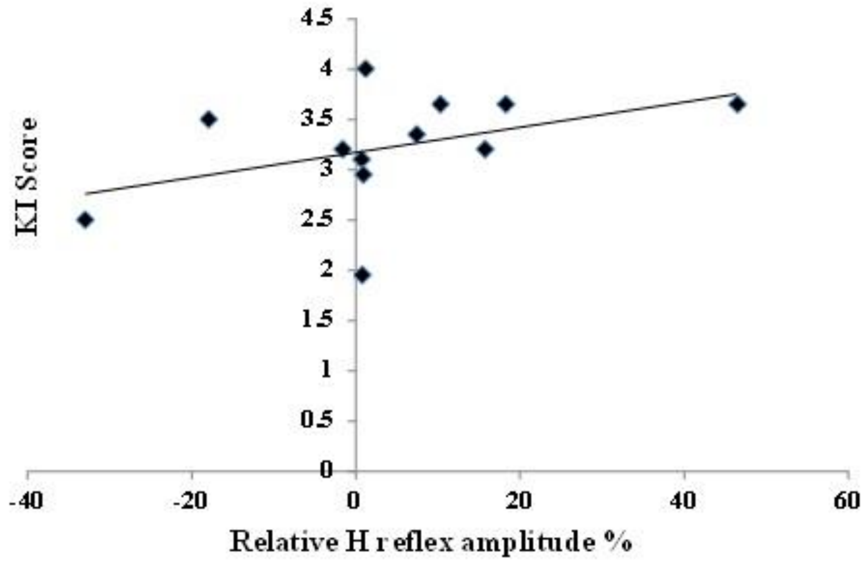
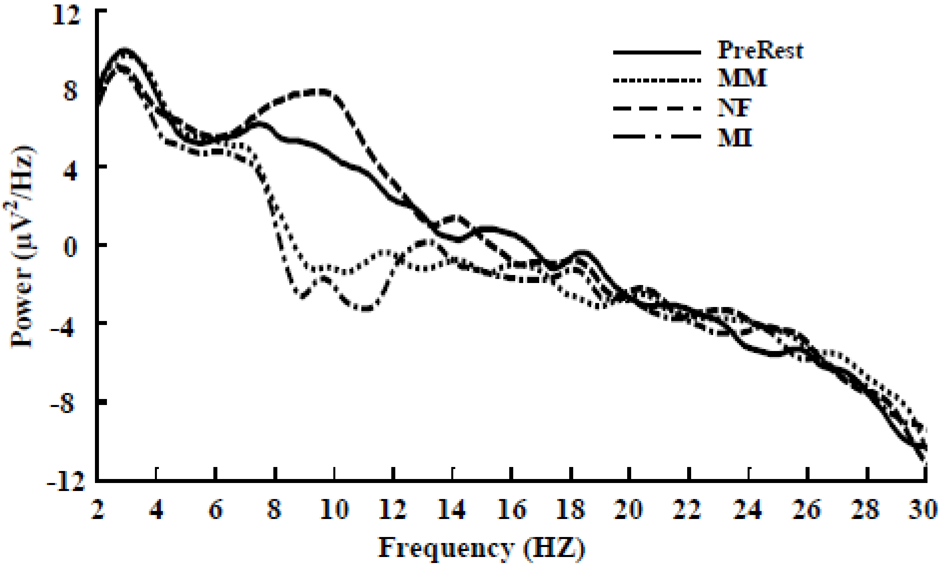

4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
KI Score
-40
-20
0
20
40
60
Relative H reflex amplitude %

Figure 9



12
8
4
0
-4
-8
-12
Power (μV²/Hz)
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
Frequency (HZ)
PreRest
MM
NF
MI

Figure 10

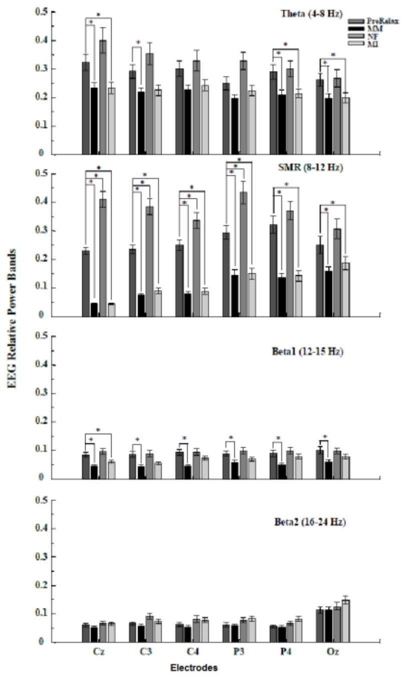

Theta (4-8 Hz)
PreRelax
MM
NF
MI
SMR (8-12 Hz)
Beta1 (12-15 Hz)
Beta2 (16-24 Hz)
EEG Relative Power Bands
Cz
C3
C4
P3
P4
Oz
Electrodes

Figure 11

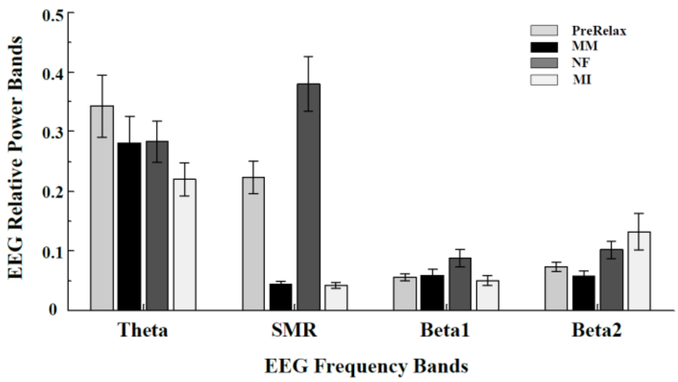

0.5
0.4
0.3
0.2
0.1
0
EEG Relative Power Bands
PreRelax
MM
NF
MI
Theta
SMR
Beta1
Beta2
EEG Frequency Bands

Figure 12