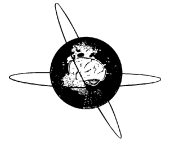




Contents lists available at ScienceDirect

Clinical Neurophysiology

journal homepage: www.elsevier.com/locate/clinph

Shutting down sensorimotor interference unblocks the networks for stimulus processing: An SMR neurofeedback training study

Silvia Erika Kober^{a,c,*}, Matthias Witte^a, Matthias Stangl^a, Aleksander Väljamäe^a, Christa Neuper^{a,b,c}, Guilherme Wood^{a,c}

^a Department of Psychology, University of Graz, Universitaetsplatz 2/III, A-8010 Graz, Austria

^b Laboratory of Brain-Computer Interfaces, Institute for Knowledge Discovery, Graz University of Technology, Austria

^c BioTechMed-Graz, Universitaetsplatz 3, A-8010 Graz, Austria

ARTICLE INFO

Article history:

Accepted 31 March 2014

Available online xxx

Keywords:

Cognitive performance

Cognitive processing

ERP

Functional connectivity

Neurofeedback

Sensorimotor rhythm

HIGHLIGHTS

- This study examined the effects of SMR (sensorimotor rhythm, 12–15 Hz) neurofeedback training on cognitive processing capabilities.
- SMR neurofeedback improved behavioural performance in different cognitive tasks.
- SMR neurofeedback led to a more intense stimulus processing indicated by diverse EEG parameters.

ABSTRACT

Objective: In the present study, we investigated how the electrical activity in the sensorimotor cortex contributes to improved cognitive processing capabilities and how SMR (sensorimotor rhythm, 12–15 Hz) neurofeedback training modulates it. Previous evidence indicates that higher levels of SMR activity reduce sensorimotor interference and thereby promote cognitive processing.

Methods: Participants were randomly assigned to two groups, one experimental ($N = 10$) group receiving SMR neurofeedback training, in which they learned to voluntarily increase SMR, and one control group ($N = 10$) receiving sham feedback. Multiple cognitive functions and electrophysiological correlates of cognitive processing were assessed before and after 10 neurofeedback training sessions.

Results: The experimental group but not the control group showed linear increases in SMR power over training runs, which was associated with behavioural improvements in memory and attentional performance. Additionally, increasing SMR led to a more salient stimulus processing as indicated by increased N1 and P3 event-related potential amplitudes after the training as compared to the pre-test. Finally, functional brain connectivity between motor areas and visual processing areas was reduced after SMR training indicating reduced sensorimotor interference.

Conclusions: These results indicate that SMR neurofeedback improves stimulus processing capabilities and consequently leads to improvements in cognitive performance.

Significance: The present findings contribute to a better understanding of the mechanisms underlying SMR neurofeedback training and cognitive processing and implicate that SMR neurofeedback might be an effective cognitive training tool.

© 2014 International Federation of Clinical Neurophysiology. Published by Elsevier Ireland Ltd. All rights reserved.

1. Introduction

The sensorimotor rhythm (SMR, 12–15 Hz) in the electroencephalogram (EEG) is strongest over the sensorimotor cortex during movement suppression and generated by a thalamo-cortical network. In EEG based neurofeedback training studies, in which participants learn to voluntarily modulate their own electrical

* Corresponding author. Address: Department of Psychology, Karl-Franzens University Graz, Universitätsplatz 2/III, A-8010 Graz, Austria. Tel.: +43 (0) 316 380 8497; fax: +43 (0) 316 380 9808.

E-mail address: silvia.kober@uni-graz.at (S.E. Kober).

<http://dx.doi.org/10.1016/j.clinph.2014.03.031>

1388-2457/© 2014 International Federation of Clinical Neurophysiology. Published by Elsevier Ireland Ltd. All rights reserved.

brain activity by means of operant condition (Skinner, 1945; Hammer et al., 2012), SMR has often been used as feedback frequency since there is evidence that gaining voluntary control over SMR activity is associated with cognitive improvements. However, the meaning of SMR is not fully understood yet (Vernon et al., 2003). SMR activity has been linked to different cognitive functions such as attention, short-term memory, and memory consolidation (Egner and Gruzelier, 2004; Hoedlmoser et al., 2008; Vernon et al., 2003; Vernon, 2005; Tinius and Tinius, 2000; Gruzelier et al., 2006, 2010; Doppelmayr and Weber, 2011). In the present study, we investigated which cognitive processes are responsive to SMR based neurofeedback training and the electrophysiological mechanisms underlying the effects of SMR on stimulus processing capabilities.

Generally, SMR is recorded over central scalp regions over the sensorimotor cortex and has a frequency range of 12–15 Hz. SMR rhythm was first identified during alert motionless waking behaviour over the motor cortex of cats (Serman et al., 1970). In the human brain, SMR emerges also when one is motionless yet remains attentive and is suppressed by movement (Pfurtscheller, 1981). There is evidence that SMR is generated in the somatosensory relay nuclei of the thalamus, commonly known as ventrobasal nuclei (Serman, 1996, 2000). Studies in animals and humans provide evidence on the circuits generating SMR. Firstly, reduced motion in the context of alert attention decreases motor output to the thalamus and the brainstem, resulting in decreased red nucleus activity, stretch reflex activity, and muscle tone. This leads to an attenuation of somatic afferent activity and an increase in oscillatory activity in the loop between the nucleus ventralis-posterior-lateralis and nucleus reticularis of the thalamus. Finally, the afferent pathways from the thalamus to the sensorimotor cortex lead to the development of fast sensorimotor EEG rhythmic activity at this last location. Hence, during SMR activity, the conduction of somatosensory information to the cortex is attenuated or inhibited. Based on these findings, first neurofeedback studies trained patients with epilepsy to voluntarily increase SMR activity and found positive effects on hyper-excitability of the brain (Serman, 1996). Hence, Serman (1996) associated this rhythm with “internal inhibition” since SMR neurofeedback training seems to facilitate thalamic inhibitory mechanisms (Serman, 1996, 2000; Egner and Gruzelier, 2004).

The inhibition of somatosensory information flow to the cortex during increased SMR activity is associated with improved cognitive performance. Serman (1996) proposed that motor activity may interfere with perceptual and integrative components of information processing, since motor activity can disengage visual processing areas of the cortex. In line with this, Pfurtscheller (1992) found reciprocal responses between central and posterior regions of the scalp, which reflected specific task demands. Increase of activation over central sites is associated with corresponding deactivation over posterior sites and vice versa (Pfurtscheller, 1992). Therefore, such a sensorimotor interference with visual processing may hamper cognitive performance (Pfurtscheller, 1992; Serman, 1996). In contrast, voluntary control of sensorimotor excitability by means of SMR based neurofeedback training may facilitate cognitive processing by decreasing such interference and maintaining perceptual and memory functions at the same time (Serman, 1996).

Improvements of cognitive capabilities achieved by SMR training have been related to an overall altered stimulus processing in an unspecific manner (Egner and Gruzelier, 2004; Vernon et al., 2003; Hoedlmoser et al., 2008). Moreover, the effects of voluntary SMR modulation on cognitive performance have been investigated mainly at the behavioural level (Egner and Gruzelier, 2004; Hoedlmoser et al., 2008; Vernon et al., 2003; Vernon, 2005; Tinius and Tinius, 2000; Gruzelier et al., 2006, 2010; Doppelmayr

and Weber, 2011; de Zambotti et al., 2012; but see Kropotov et al., 2005). Empirical evidence that increased SMR activity determines other aspects of electrical brain activity, which are responsible for improved cognitive performance, remains elusive. Hence, we sought to reveal the effect of SMR training on electrophysiological correlates of stimulus processing. Event-related potentials (ERP) in the EEG elicited by stimulus processing were assessed during a short-term memory task before and after 10 neurofeedback training sessions. A memory scanning paradigm developed by Sternberg (1966) has often been used to relate ERP to stimulus processing and memory processes. In this short-term memory task, participants memorise a brief list of memory set items such as digits and a few seconds later indicate whether a target number was a member of the memory set or not (Sternberg, 1966). Early ERP components such as the N1 are sensitive to physical parameters of the stimuli, but also are affected by cognitive factors such as attention (Herrmann and Knight, 2001; Davis, 1964; Picton and Hillyard, 1974; Correa et al., 2006; Fu et al., 2008), expectancy (Starr et al., 1997), and tasks involving short-term memory (Kaufman et al., 1991). The N1 is a negative component peaking around 100–150 ms after stimulus onset with a fronto-central maximum. This component is generally associated with allocation of perceptual resources and sensory processing, such as encoding elementary stimulus features (Heinrich et al., 2007; Juhász et al., 1997). Hence, the N1 amplitude is a valid indicator of stimulus processing. The P3, a positive-going component of the ERP waveform, which peaks within a time window between 300 and 600 ms after an eliciting event at posterior-parietal electrodes, has been regarded as a sign of processes of memory access (Fox et al., 2005; Heinrich et al., 2007; Hinterberger et al., 2004; Keizer et al., 2010). Furthermore, the P3 amplitude has been considered to be closely related to the intensity of cognitive processing (Hinterberger et al., 2004). A stronger stimulus processing leads to increased P3 amplitude. We expected that SMR training improves stimulus processing capabilities indicated by more pronounced ERP amplitudes after repeated neurofeedback training sessions compared to a pre-assessment.

Additionally, we addressed the question about how increased SMR activity should foster stimulus processing. Previous evidence points out that motor activity can disengage visual processing areas of the cortex, which may hamper or interfere with perceptual and integrative components of information processing (Serman, 1996; Pfurtscheller, 1992). Consequently, increased SMR activity should reduce such motor interference by inhibiting the somatosensory information flow to the cortex. To analyse the conceptual and mathematical relation between EEG activity in motor areas and visual processing areas, coherence analysis was employed. High coherence values indicate a functional relationship between different brain areas, which is generally associated with synchronous electrical activity in these regions. Hence, coherence analysis was applied to determine functional brain connectivity between motor and visual processing areas. Only a few prior studies investigated changes in coherence values due to neurofeedback training and found conflicting results (Thornton and Carmody, 2009). Some neurofeedback studies even targeted at increasing coherence values by means of neurofeedback training in neurologic patients and found improvements on neuropsychological measures of attention and problem solving (Thornton and Carmody, 2009; Tinius and Tinius, 2000). However, the placement of the feedback electrodes and the feedback frequency varied between patients in function of lesion location (Tinius and Tinius, 2000). Unfortunately, based on these prior studies no clear conclusion about possible changes in functional brain connectivity as a result of SMR based neurofeedback training can be drawn. However, based on the theory that increased SMR activity should reduce interferences between motor areas and visual processing areas, we tentatively

conclude that after SMR based neurofeedback training the functional connectivity between motor and parietal-occipital brain areas might be reduced. A reduction in connectivity between visuo-motor areas is a sign of reduced mutual interference possibly leading to enhanced stimulus processing as suggested by Serman (1996).

The intensity of stimulus processing plays a key role in various cognitive functions. Hence, we hypothesise that SMR based neurofeedback training leads to improvements in different cognitive tasks. Firstly, an intense stimulus processing should be related to increased attentional performance. A large body of literature showed that increasing SMR activity voluntarily by means of neurofeedback training has positive effects on attentional performance of healthy participants, individuals with learning difficulties and children with attention-deficit hyperactivity disorder (ADHD) (Egner and Gruzelier, 2004; Tansey and Bruner, 1983; Tansey, 1984, 1985, 1986; Serman, 1996; Lubar and Shouse, 1976; Arns et al., 2009; Vernon et al., 2003; Kropotov et al., 2005; Strehl, 2013; Gevensleben et al., 2014). Secondly, a more intense stimulus processing should affect learning and memory performance. There is ample of evidence that SMR training leads to improved short-term memory performance. Hence, the immediate recall of learned material should be facilitated when relevant information is processed more intensively after SMR training (Vernon et al., 2003; Lévesque et al., 2006; Beauregard and Lévesque, 2006; Kropotov, 2009; Hoedlmoser et al., 2008). Some neurofeedback studies investigated the influence of SMR based neurofeedback training on long-term memory performance and memory consolidation as well. Beside the association between SMR and alert motionless waking behaviour, SMR is similar in location and quality to sleep spindles (Serruya and Kahana, 2008). Sleep spindle activity, which lies in the EEG SMR frequency range, shows a functional significance for declarative memory consolidation (Holz et al., 2012). For instance, Schabus et al. (2004) found a positive relationship between long-term memory performance (overnight storage of learned material) and spindle activity during the night. In this context it is assumed that SMR training facilitates the expression of 12–15 Hz spindle oscillations during sleep and consequently leads to improved memory consolidation (Schabus et al., 2004). Prior neurofeedback studies could only partially support that SMR training improves long-term memory performance (Schabus et al., 2004, 2014; Hoedlmoser et al., 2008). Hence, whether SMR training might improve performance in long-term memory tasks remains an open question.

In summary, prior neurofeedback studies reported positive effects of SMR modulation on different cognitive functions. The majority of these prior studies only investigated the effects of SMR training on single behavioural measures (Hoedlmoser et al., 2008; Vernon et al., 2003). Therefore, the relation between changes in cognitive functions and changes in brain activation patterns such as diverse EEG parameters as a result of neurofeedback training are largely unknown, which is one important gap in the neurofeedback literature (Thornton, 2000; Thornton and Carmody, 2013). To bridge this gap, we used a multi-signal approach including standardised psychometric tests, computerised cognitive tasks and electrophysiological signals to evaluate the specificity of SMR neurofeedback training. Hence, by using such a multi-signal approach we addressed the question about the relation between changes in EEG parameters (ERP and coherence) and cognitive changes as a result of SMR based neurofeedback training. Electrophysiological parameters of the EEG were assessed during cognitive processing as indicators of the intensity of stimulus processing and functional brain connectivity. Finally, to avoid pygmalion effects a double-blind design was used.

The following hypotheses were proposed: We first expect an increase in SMR activity in the experimental group during

neurofeedback training, whereas no changes in SMR activity should be observed in the control group receiving sham feedback. Secondly, we expect that increasing SMR activity voluntarily by means of neurofeedback training leads to a more intense stimulus processing indicated by more pronounced ERP amplitudes after repeated neurofeedback training compared to a pre-assessment in the experimental group. Thirdly, since a reduction in connectivity between visuo-motor areas might be a sign of reduced mutual interference, which may lead to enhanced stimulus processing (Serman, 1996), we hypothesise that after SMR neurofeedback training the functional connectivity between motor and parietal-occipital brain areas might be reduced. Finally, we hypothesise that SMR based neurofeedback training leads to improvements in different cognitive tasks, such as attention, short- and long-term memory tasks, due to a more intense cognitive processing of task relevant stimuli.

2. Material and methods

2.1. Participants

Twenty healthy adults (10 male, 10 female) took part in this study. All participants gave written informed consent and were paid for their participation (100 €). The ethics committee of the University of Graz, Austria approved all aspects of the present study. The age of the participants ranged from 18 to 30 years ($M = 24.40$ yrs., $SE = 1.85$ yrs.). Participants were randomly assigned to two groups, one experimental (EG, $N = 10$) and one control group (CG, $N = 10$), matched for sex in a double-blind design in which neither the experimenter nor the participant were informed whether real SMR feedback was being presented or not. Participants assigned to the experimental group were trained to increase their SMR (12–15 Hz) power, while the control group was shown a playback of the SMR observed at the training session performed by another participant. This session was randomly chosen out of the pool of all available sessions from the experimental group. A participant of the control group never got the playback of a specific session more than once. In order to reduce eye movements and muscle artefacts during the feedback training, all participants received real feedback on Theta (4–7 Hz) and Beta (21–35 Hz) frequency power, which they all – experimental as well as control group – were instructed to reduce. All participants were told that a training protocol was tested to examine whether EEG based neurofeedback training might provide cognitive improvement. At the final disclosure, participants were asked to tell to which group they believe they had been assigned. Independent of their real group assignment, after 10 training sessions, 6 participants of the experimental group and 8 participants of the control group believed that they had been assigned to the experimental group. Since belief to belong to the experimental group was comparable across experimental and control group ($\chi^2(1) = 0.24$, *n.s.*), one may conclude that the double-blind design was effective.

2.2. SMR based neurofeedback training

Ten neurofeedback training sessions were carried out three to five times a week, each session on a different day. On average, participants received training three to four times a week. For the training, Cz was used as feedback electrode recorded by Ag/AgCl electrodes against a left mastoid reference, the ground was placed at FPz. For EEG recording during the training sessions, a g.USBamp 16 channels standard amplifier (g.tec, Graz, Austria) was used. Vertical and horizontal EOG was recorded with three electrodes in total, two were placed on the outer canthi of the eyes and one was placed superior to the nasion. Electrode impedances were kept

below 5 kOhms for the EEG recording and below 10 kOhms for the EOG recording. EEG signals were digitized at 256 Hz and filtered with a 0.5 Hz high-pass and a 60 Hz low-pass filter.

All pre-processing and data analysis of EEG recordings (neurofeedback training data and pre-post electrophysiological parameters) were performed offline using the Brain Vision Analyzer software (version 2.01, Brain Products GmbH, Munich, Germany). Ocular artefacts (eye blinks) were automatically corrected using the algorithm developed by Gratton et al. (1983). After ocular artefact correction, automated rejection of other EEG-artefacts (e.g., muscles) was performed (criteria for rejection: >50.00 μ V voltage step per sampling point, absolute voltage value $\geq \pm 120.00$ μ V). All epochs with artefacts were excluded from the EEG-analysis. To analyse the feedback training data, absolute values of SMR (12–15 Hz), Theta (4–7 Hz), and Beta (21–35 Hz) power in a fixed range were calculated and averaged separately for each 3-min run of each sessions using the Brain Vision Analyzer's built-in method of complex demodulation (method to calculate power).

The neurofeedback system provided visual feedback for increasing SMR power (12–15 Hz) while keeping other frequencies low (Theta: 4–7 Hz, Beta: 21–35 Hz). Therefore, three bars were presented on a screen. The bar in the middle of the screen reflected the SMR power. The bars on the left and the right side of the screen represented Theta activity and Beta activity, respectively. These bands were used to prevent participants from manipulating the SMR amplitude by blinking their eyes, which would increase Theta power, or by voluntarily contracting muscles, which would increase Beta and, consequently, also SMR power (Doppelmayr and Weber, 2011). Online visual feedback was implemented via SIMULINK software (The MathWorks, Natick, USA). The EEG raw signals were band-pass filtered in the respective target bands (6th order butterworth IIR) and squared to obtain power estimates. To ensure a smooth visual feedback a moving average of 256 samples was applied and updated the computer screen at a rate of 10 Hz. Each training session lasted approximately 40 min and included 10 min of preparation, 2 min of eyes-open and 2 min of eyes-closed resting EEG recordings, a 3-min baseline trial in which the participants saw the moving bars but were instructed to relax themselves, and six 3-min feedback runs, where they should try to increase their SMR amplitude while reducing Theta and Beta. Note the distinction between feedback training *session* and feedback training *run*. The term *session* describes the 10 trainings conducted on different days. The term *run* describes the six 3-min feedback runs conducted within one session. Between the feedback runs, short breaks were embedded in which the participants could relax for some minutes and continue training when they had recovered. Additionally, during the feedback runs the individual thresholds of each feedback frequency was delineated as horizontal line at the corresponding bar. The thresholds for the Theta and Beta amplitude were calculated from the data recorded during the baseline trial and were kept constant over all feedback runs (median + 1 SD). The threshold for the SMR bar was adapted after each feedback run on the basis of the immediate previous run (median). The participants' task was to move the bar in the middle of the screen above the previously defined SMR threshold and to keep the bars on the left and the right side of the screen below their thresholds. Participants were rewarded by getting points (displayed on the screen) whenever the SMR amplitude was above the SMR threshold and at the same time both the Theta and the Beta bar were below the Theta and Beta threshold, respectively.

2.3. Pre- & post-assessment

Before and after the neurofeedback training module behavioural parameters were assessed. Therefore, participants performed standardised psychometric tests to assess their short- (VVM2, Digit

Span test forward; Corsi Block Tapping test forward) and long-term memory performance (VVM2), working memory (Digit Span test backwards; Corsi Block Tapping test backwards) and focused auditory attention (Go/No-Go task). To avoid learning effects available parallel forms of the standardised psychometric tests were used in the pre- and post-measurement. Furthermore, to examine electrophysiological parameters during stimulus processing, participants additionally performed the Sternberg paradigm during a 60-channel EEG measurement before and after the 10 training sessions.

2.3.1. Behavioural parameters

Visual and Verbal Memory Test (Visueller und verbaler Merkfähigkeitstest 2 – VVM 2 by Schelling and Schächtele, 2001) assesses short- and long-term memory of visuo-spatial and verbal material. Participants have to remember visuo-spatial and verbal material for up to 24 h. With the VVM 2, decrease in memory performance and the rate of forgetting can be calculated. It contains two subtests: in the subtest 'city map' (visuo-spatial memory) participants have to memorise a route drawn on a map and then mark it on the same map during recall; in the subtest 'construction' (verbal memory) a description of a building is presented to participants, worded in syntactically simple sentences and participants have to learn names, numbers, and propositional contents. Participants have to memorise the visuo-spatial or verbal material for two minutes. Afterwards, there is an immediate recall phase (short-term memory: VVM2 city map 1, VVM2 construction 1). 24 h later there is a further recall phase (long-term memory: VVM2 city map 2, VVM2 construction 2). In pre- and post-test assessment parallel forms of the VVM 2 were used. The subscale city map is an internally consistent measure, with Cronbach's alpha coefficients between 0.85 and 0.97. The subscale construction also shows good values in reliability between 0.79 and 0.85.

The Corsi Block-Tapping test (CBTT) (Schellig, 1993) is a standardised subtest of the Vienna Test System (Schuhfried, 2011). It assesses the so called "immediate block span", which is associated with visual short-term memory capacity and implicit visuo-spatial learning. The participant views nine irregularly positioned blocks on a large sheet of paper and the experimenter taps on a number of these blocks in turn. Afterwards, the participant is required to tap on the same blocks in the same order (forward – short term memory) or backwards. The backwards task assesses working memory performance. The number of blocks increases by one after three items. When the participant makes an error in three successive items the test stops. The CBTT shows good values in reliability between 0.81 and 0.89 (Schuhfried, 2011).

The Digit Span test is a common measure for the working memory's number storage capacity. Participants are presented with a series of digits (e.g., '8, 3, 4') followed by immediate recall of these digits. If the recall is correct, they are provided with an extended list (e.g., '9, 2, 4, 0'). A person's digit span is defined as the length of the longest list a person can remember. In the forward task, participants are required to recall the digits in the given order (short-term memory), whereas in the backwards task, participants have to recall the sequence of digits backwards (working memory).

Focused auditory attention was examined using an auditory two-stimulus Go/No-Go task. Two tones, a frequent 1200 Hz tone (standards) with a probability of 0.8 and an infrequent 2000 Hz tone (targets) with a probability of 0.2, were used as stimuli. Intervals between stimuli were 1000 ms, the stimuli were presented in a randomized order. The participants had to press a button with the right hand as fast as possible whenever a target tone appeared. In sum, 60 target tones and 240 standard tones were presented.

2.3.2. Electrophysiological parameters

For pre- and post-training EEG measurement, EEG was recorded by Ag/AgCl electrodes from 60 electrode positions according to the

extended 10–20 electrode placement system against a linked mastoid reference, the ground was placed at FPz. For EEG-recording, a BrainAmp Standard amplifier (Brain Products GmbH, Munich, Germany) was used. Vertical and horizontal EOG was recorded with three electrodes in total, two were placed on the outer canthi of the eyes and one was placed superior to the nasion. Electrode impedances were kept below 5 kOhms for the EEG recording and below 10 kOhms for the EOG recording. EEG signals were digitized at 500 Hz and filtered with a 0.01 Hz high-pass and a 100 Hz low-pass.

After a 2-min eyes-open and eyes-closed resting measurement, the Sternberg paradigm was performed. The Sternberg paradigm is a short-term memory task in which one can determine between stimulus encoding/processing and memory retrieval. Each trial started with the presentation of a fixation cross in the middle of the screen for 2 s. Afterwards, a “memory set” of either 4 (e.g., 5682) or 6 digits (e.g., 146372), which should be memorised, was presented for 1 s (encoding phase), followed by another fixation cross presented for 2 s. Then a single probe digit was presented for 250 ms (retrieval phase) followed by a fixation cross presented for 1250 ms. Afterwards, the question “yes or no?” appeared at the screen for a maximum duration of 1500 ms. When this question appeared at the screen the participant was required to give an answer by pressing one of two buttons. If the probe was a member of the preceding set (target), the participant had to press “F” with the left hand. If the probe wasn’t a member of the preceding memory set (non-target), the participant had to press “J” with the right hand. The duration of the presentation of the question “yes or no?” was response terminated, hence, as soon as the participant gave an answer the next trial started. The probability that the probe was a member of the preceding set was 0.5.

2.3.2.1. Event-related potentials. To investigate possible changes in the intensity of stimulus processing due to SMR based neurofeedback training, we analysed ERP in the EEG as response to stimulus encoding (presentation of the memory set, 4 and 6 digits) and memory retrieval trials (presentation of the single probe digit, analysed separately for targets and non-targets) of the Sternberg paradigm. ERP were derived by extracting the period from 200 ms prior to 1000 ms following stimuli onset, relative to a 200 ms pre-stimulus baseline. Mean area amplitude was obtained by averaging the amplitude of the signal for the following latency windows: N1 = 110–150; P3 = 300–600 ms after stimulus onset. N1 amplitude was most prominent over FCz and P3 amplitude was most prominent over Pz. Therefore, these two electrode positions were used for analysing ERP data respectively. Preliminary assessment of lateral electrode positions did not reveal any hemispheric differences. Hence, only midline electrode positions were evaluated. Preliminary analysis revealed no differences in ERP amplitudes elicited in the 4 or 6 digit conditions. Therefore, the 4 and 6 digit conditions were analysed together.

2.3.2.2. Functional brain connectivity. Coherence analysis was applied to assess functional brain connectivity between motor areas and frontal and parietal brain areas during stimulus encoding. A functional relationship between different brain areas is generally associated with synchronous electrical activity in these regions. A quantitative measure for this synchrony is the EEG coherence between signals recorded from electrode pairs as a function of frequency (Varela et al., 2001). For the coherence analysis, the baseline period of the Sternberg task was used since SMR activity was strongest during baseline. For each segment, EEG power spectra were calculated using Fast Fourier Transformation (FFT). FFT was computed for each data segment with maximum resolution of ~0.98 Hz. Furthermore, a 10% Hanning window was applied including a variance correction to preserve overall power. Next,

computation of coherence r between two channels $c1$ and $c2$ at a given frequency f was based on FFT transformed complex data C according to

$$r(c1, c2)(f) = \frac{|CS(c1, c2)(f)|^2}{|CS(c1, c1)(f)||CS(c2, c2)(f)|}$$

with cross (respectively auto) spectra CS averaged over i data segments by

$$CS(c1, c2)(f) = \sum C1_i(f)C2_i(f)^*$$

(Brain Products GmbH, 2009).

The EEG was analysed in the SMR frequency, which was also used as feedback frequency during training. Coherence between an electrode pair was defined as the cross spectral density function normalised by individual auto spectral density functions (also called ‘power spectra’) (Nunez et al., 1997). The coherence value r represents a generalisation of the Pearson product correlation coefficient to variables expressed in the frequency domain (Thornton and Carmody, 2009). A resulting value of 0 indicates no correlation in frequency, whereas a resulting value around 1 indicates an ideal constant correlation. The r values we present indicate the coherence in the SMR band 12–15 Hz. Coherence is a measure of the dependency of the data between two individual channels over time. Coherence estimates were derived for the SMR band for five electrode pairs (Cz–Fz, Cz–FCz, Cz–CPz, Cz–Pz, Cz–POz) to assess if there is a functional connectivity between Cz, which was used as feedback electrode during training and where SMR power was maximal, and frontal and parietal brain regions. In order to normalise the distribution of the correlation measures, coherence values were Fisher’s z -transformed, and means were inverse transformed for reporting. For statistical analysis, a paired-sample t -test comparing coherence values between pre- and post-test was applied separately for each pair of electrodes.

2.4. Statistical analysis

For statistical analysis, paired-sample t -tests were used to compare the results of the pre- and post-assessment (dependent variables: behavioural parameters and electrophysiological parameters N1 and P3 amplitude, Fisher’s z -transformed r) separately for the experimental and control group. Note that preliminary analysis (independent samples t -tests) revealed no differences in behavioural parameters and electrophysiological parameters between the experimental and control group during the pre-test. The probability of a Type I error was maintained at 0.05. Holm corrections for multiple comparisons were applied (Holm, 1979). The advantage of using a t -test instead of analysis of variance (ANOVA) is that t -tests do not require the fulfilment of so many assumptions as the other methods (e.g., assumptions about the distribution of data, which cannot be determined properly based on samples smaller than $N = 100$). Finally, the use of sets of t -tests is a consecrated practice largely recommended for intervention studies in statistics manuals (Katz, 2010; Bonate, 2000).

In order to analyse the time course of SMR power over the ten training sessions and six runs within sessions respectively in more detail, we conducted regression analysis separately for the experimental and control group (predictor variable = session/run number; dependent variable = SMR power).

To investigate the relationship between SMR activity and behavioural/electrophysiological parameters, Pearson correlations were calculated separately for the experimental and control group. To check whether correlation coefficients differ significantly, the correlation coefficients were Fisher’s z -transformed and compared using z -tests.

3. Results

3.1. SMR neurofeedback training outcome

The regression analysis of absolute SMR power (predictor variable = run; dependent variable = SMR power) revealed significant changes of SMR power over the training runs within sessions only in the experimental group. For the experimental group, this regression model revealed a significant positive slope across runs ($F(1,5) = 48.98, p < 0.01$) and explained 90.74% of variance of SMR power over the training runs. Hence, the experimental group was able to voluntarily increase their SMR amplitude over the feedback runs within the sessions. For the control group, no significant changes in SMR power over the training runs could be found ($F(1,5) = 0.16, ns.$). Fig. 1 illustrates the time course of SMR power over the training runs for both groups. There were no significant changes in absolute SMR power over the feedback training sessions neither in the experimental ($F(1,5) = 0.02, ns.$) nor in the control group ($F(1,5) = 0.07, ns.$).

Furthermore, we analysed the time course of Beta and Theta power over the training runs averaged over all training sessions as well (Fig. 1). The regression model for Beta was significant in the experimental group ($F(1,5) = 17.61, p < 0.01$) but not in the control group ($F(1,5) = 0.63, ns.$). With the regression model, 77.88% of variance of Beta power over the training runs could be explained in the experimental group (Fig. 1). Hence, the time course of Beta power over training runs was comparable with the time course of SMR power. Theta power did not change significantly over the training runs in both groups (EG: $F(1,5) = 0.19, ns.$, CG: $F(1,5) = 0.13, ns.$).

3.2. Effects of SMR neurofeedback training on behavioural and electrophysiological parameters (pre- & post-assessment)

3.2.1. Behavioural parameters

Pre-post comparisons revealed that only the experimental group showed significant improvements in their behavioural performance between pre- and post-test, whereas the control group showed no significant changes over time (Table 1), except for the VVM2 subscale construction 1. The experimental group showed a substantial improvement in the VVM2 subscale construction 1 (from an average T -score of 46.50 during the pre-test to 54.40 during the post-test), which assesses immediate memory recall

performance. The control group also showed significant higher values in the subscale construction 1 during post-(average T -score of 55.90) compared to pre-assessment (average T -score of 52.70), but this average increase in 3.2 T -scores (difference value between pre- and post-test) was significantly lower as the improvement of 7.90 T -scores in the experimental group ($t(18) = -2.55, p < 0.05$). The experimental group also showed an improved performance in the subscale construction 2, assessing delayed memory recall performance, after training compared to the pre-test. Furthermore, the experimental group improved their auditory focused attention performance as assessed with the Go/No-Go task after the training compared to the pre-measurement. For the CBTT and the DS test which assess working memory performance, the t -tests revealed no significant results. In Table 1, the results of the behavioural tests are depicted, separately for both groups and the pre- and post-assessment.

3.2.2. Electrophysiological parameters – event-related potentials

During the encoding phase, the N1 amplitude was significantly higher during the post-compared to the pre-measurement in the experimental group ($t(9) = 2.36, p < 0.05$), whereas the control group showed no changes in N1 amplitude during stimulus encoding between pre- and post-measurement ($t(9) = 1.05, ns.$) (Fig. 2). For the N1 mean area amplitude at FCz during the retrieval phase, the statistical analysis revealed no significant effects (EG: pre: $M = -0.01 \mu V, SE = 0.22$; post: $M = -0.20 \mu V, SE = 0.58$; $t(9) = 0.28, ns.$; CG: pre: $M = 0.16 \mu V, SE = 0.20$; post: $M = -0.01 \mu V, SE = 0.33$; $t(9) = 0.66, ns.$).

For the P3 mean area amplitude at Pz during the encoding phase, statistical analysis indicated higher P3 amplitude values during stimulus encoding in the post- compared to the pre-measurement in the experimental group ($t(9) = -3.42, p < 0.01$) but not in the control group ($t(9) = -1.02, ns.$) (Fig. 3). For the P3 mean area amplitude at Pz during the retrieval phase, the statistical analysis revealed no significant results, except the P3 amplitude was higher for targets ($M = 6.51 \mu V, SE = 0.73$) than for non-targets ($M = 5.15 \mu V, SE = 0.67$) in both groups and during the pre- and post-measurement ($t(19) = 5.33, p < 0.01$).

3.2.3. Electrophysiological parameters – functional brain connectivity

The coherence analysis revealed a lower SMR coherence between motor areas (Cz) and parietal-occipital electrodes (CPz,

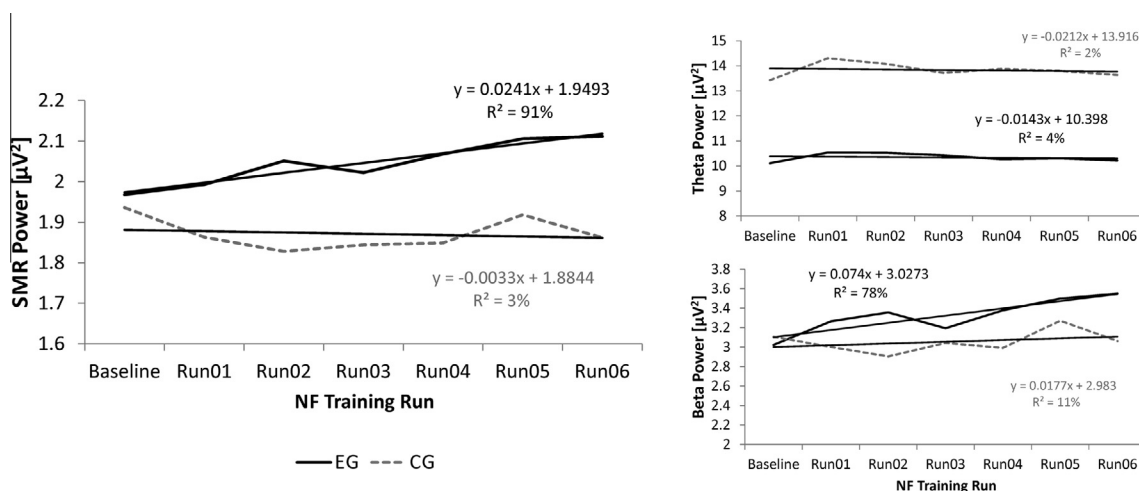
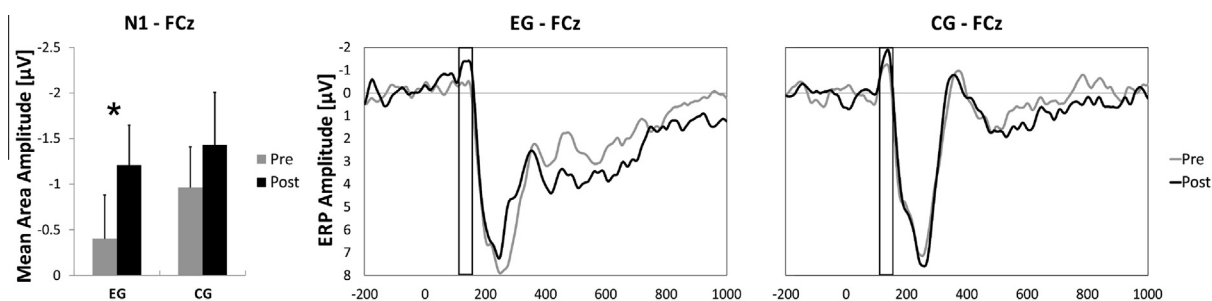
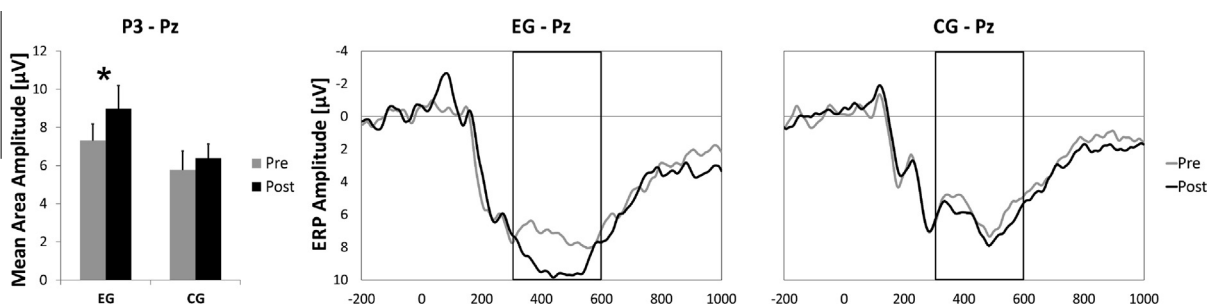


Fig. 1. Time course of SMR (left panel), Theta (upper right panel), and Beta (lower right panel) power over the neurofeedback training runs, averaged over all 10 neurofeedback training sessions, presented separately for the experimental and control group. The experimental group showed a linear increase in SMR power values over the training runs, which could not be seen in the control group.

Table 1Means and standard errors of the behavioural data and the results of the statistical analyses (*t*-tests) of the pre-post comparison, separately for each group.

	Experimental group (N = 10)		<i>t</i> -value (df) <i>p</i> -value	Control group (N = 10)		<i>t</i> -value (df) <i>p</i> -value
	Pre	Post		Pre	Post	
	Mean (SE)			Mean (SE)		
CBTT forward (raw scores)	8.90 (0.71)	9.40 (0.78)	−0.64 (9) 0.54	10.60 (0.50)	11.10 (0.61)	−0.89 (9) 0.40
CBTT backwards (raw scores)	9.30 (0.50)	9.60 (0.45)	−0.56 (9) 0.59	10.00 (0.67)	9.40 (0.62)	1.03 (9) 0.33
Digit span forward (raw scores)	10.80 (0.57)	10.80 (0.51)	0.00 (9) 1.00	10.90 (0.66)	11.20 (0.76)	−0.67 (9) 0.52
Digit span backwards (raw scores)	8.10 (0.43)	8.80 (0.47)	−1.91 (9) 0.09	9.30 (0.54)	9.80 (0.60)	−0.76 (9) 0.64
VVM2 city map 1 (<i>T</i> -scores)	43.20 (4.27)	45.60 (3.77)	−1.30 (9) 0.23	53.50 (3.37)	52.20 (2.89)	0.49 (9) 0.63
VVM2 city map 2 (<i>T</i> -scores)	43.40 (4.87)	47.10 (3.67)	−1.44 (9) 0.18	49.50 (3.59)	49.90 (3.18)	−0.17 (9) 0.87
VVM2 construction 1 (<i>T</i> -scores)	46.50 (2.30)	54.40 (2.10)	−5.57(9)** 0.00	52.70 (2.70)	55.90 (2.76)	−2.71 (9)* 0.02
VVM2 construction 2 (<i>T</i> -scores)	44.80 (3.13)	48.70 (2.74)	−2.78 (9)* 0.02	47.60 (2.08)	49.40 (2.51)	−0.75 (9) 0.47
Sternberg error rates (relative frequency)	0.06 (0.01)	0.04 (0.01)	2.26 (9) 0.05	0.06 (0.01)	0.03 (0.01)	2.25 (9) 0.05
Go/No-Go error rates (relative frequency)	0.02 (0.01)	0.00 (0.00)	2.86 (9)* 0.02	0.01 (0.00)	0.02 (0.01)	−0.76 (9) 0.47
Go/No-Go reaction times (ms)	360.57 (14.31)	366.11 (14.82)	−0.57 (9) 0.59	328.29 (9.05)	314.40 (10.80)	2.05 (9) 0.07

Significant results are marked with asterisks (**p* < 0.05, ***p* < 0.01).**Fig. 2.** Left panel: means and SE of the N1 mean area amplitude (FCz) during the encoding phase averaged for target and non-target conditions, presented separately for the experimental (EG) and control group (CG) and the pre- and post-measurement. Middle and right panel: Grand average event-related potentials during the encoding phase from FCz for the experimental (EG) and control group (CG), presented separately for the pre- and post-measurement. The analysed latency windows are marked with rectangles: N1 = 110–150 ms after stimulus onset (=second 0). Significant differences are marked with asterisks (**p* < 0.05).**Fig. 3.** Left panel: means and SE of the P3 mean area amplitude (Pz) during the encoding phase averaged for target and non-target conditions, presented separately for the experimental (EG) and control group (CG) and the pre- and post-measurement. Middle and right panel: grand average event-related potentials during the encoding phase from Pz for the experimental (EG) and control group (CG), presented separately for the pre- and post-measurement. The analysed latency windows are marked with rectangles: P3 = 300–600 ms after stimulus onset (=second 0). Significant differences are marked with asterisks (**p* < 0.05).

Pz, POz) after 10 neurofeedback training sessions compared to the pre-measurement in the experimental group (Fig. 4). Hence, after repeated SMR based neurofeedback training, functional brain connectivity between motor areas and parietal-occipital brain regions during stimulus processing was reduced. In the control group, no changes in SMR connectivity between the pre- and post-test were observed. The SMR connectivity between motor areas and frontal brain regions (Cz–Fz, Cz–FCz) did not change between pre- and post-assessment (all *p* > 0.05; EG: Cz–Fz pre: *r* = 0.65, *SE* = 0.04; Cz–Fz post: *r* = 0.65, *SE* = 0.04; Cz–FCz pre: *r* = 1.16, *SE* = 0.06; Cz–FCz post: *r* = 1.21, *SE* = 0.05; CG: Cz–Fz pre: *r* = 0.64, *SE* = 0.06;

Cz–Fz post: *r* = 0.63, *SE* = 0.07; Cz–FCz pre: *r* = 0.98, *SE* = 0.13; Cz–FCz post: *r* = 1.03, *SE* = 0.13).

3.3. Relationship between SMR activity and behavioural/ electrophysiological parameters

3.3.1. Relationship between neurofeedback performance and electrophysiological parameters (ERP)

To investigate whether the EEG neurofeedback performance was related to the electrophysiological parameters assessed during the pre- and post-assessment, we correlated the SMR power during

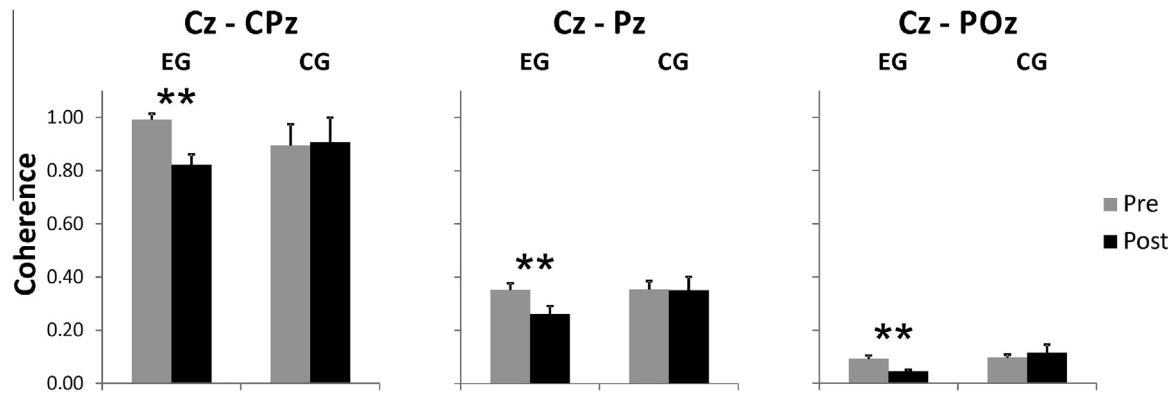


Fig. 4. Coherence values (M and SE) in the SMR band (12–15 Hz) for the electrode pairs Cz–CPz, Cz–Pz, and Cz–POz, presented separately for the experimental (EG) and control group (CG) and the pre- and post-measurement. After neurofeedback training, coherence values were lower in the EG than during the pre-measurement. In the CG, no changes in coherence values between pre- and post-test could be found. Significant differences are marked with asterisks (** $p < 0.01$).

training with the ERP amplitudes. We correlated the SMR power of the first training session with the ERP amplitudes assessed during the pre-test and the SMR power of the last training session was correlated with ERP amplitudes assessed during the post-test. At the beginning of the neurofeedback training (session 1) these correlations revealed no significant results (EG: P3: $r = 0.23$, ns ; N1: $r = -0.11$, ns ; CG: P3: $r = -0.13$, ns ; N1: $r = -0.37$, ns). However, at the end of the training (session 10) the experimental group showed a positive correlation between SMR power during the training and P3 amplitude during stimulus encoding ($r = 0.66$, $p < 0.05$) and a negative correlation between SMR power during the training and N1 amplitude during stimulus encoding ($r = -0.65$, $p < 0.05$). These results demonstrate that an increased SMR power at the end of the neurofeedback training was associated with increased P3 and N1 amplitudes during stimulus processing in the Sternberg task. Hence, there was a relationship between the intensity of stimulus processing and SMR activity after participants of the experimental group gained voluntary control over SMR. For the control group, the same correlation analysis revealed no significant results (P3: $r = 0.10$, ns ; N1: $r = 0.14$, ns).

3.3.2. Relationship between neurofeedback performance and behavioural parameters

Furthermore, we investigated possible relationships between the neurofeedback performance and behavioural parameters. At the end of the training (session 10), a higher SMR power was positively correlated with the performance in the VVM2 construction 2 ($r = 0.60$, $p = 0.07$), although it was not significant at the $\alpha = 0.05$ level, and negatively correlated with the Sternberg error rates ($r = -0.71$, $p < 0.05$) and Go/No-Go reaction times ($r = -0.70$, $p < 0.05$) only in the experimental group during the post-assessment (same correlations for CG: VVM2 construction 2: $r = 0.05$, ns ; Sternberg error rates: $r = -0.31$, ns ; Go/No-Go reaction times: $r = -0.01$, ns). Hence, higher SMR activity at the end of the neurofeedback training was specifically related to increased short- and long-term memory performance (Sternberg task, VVM2 construction 2) and attentional performance (Go/No-Go task). Working memory performance (Digit Span, CBTT) did not correlate with SMR power during neurofeedback training (all other $p > 0.05$).

3.3.3. Relationship between SMR power and electrophysiological parameters during stimulus processing

Furthermore, we were interested in the relationship between the SMR activity during the Sternberg task and the electrophysiological parameters assessed during stimulus encoding. Therefore, we correlated the SMR power during the baseline period of the

Sternberg task at Cz (–600 to –400 ms before stimulus encoding), where SMR power was highest, with the ERP amplitudes elicited during stimulus processing of the same task, separately for the pre- and post-assessment. During the pre-assessment, the ERP amplitudes did not show any significant relationship with SMR power (all $p > 0.05$). However, after 10 neurofeedback training sessions we found a significant positive relationship between the SMR power briefly before stimulus processing and the P3 amplitude during stimulus processing in the experimental group ($r = 0.77$, $p < 0.01$) but not in the control group ($r = -0.11$, ns). These correlations differed significantly between the experimental and control group ($\text{sigma}Z = 0.53$, $Z = 2.15$, $p < 0.05$). Hence, increased SMR activity prior to the beginning of a new trial was associated with more pronounced P3 amplitude. This indicated stronger stimulus processing in participants receiving SMR training. Between the N1 amplitude and SMR power we found a negative but not significant correlation for the experimental group ($r = -0.47$, ns) during the post-test. A negative correlation implied that higher N1 amplitude was associated with increased SMR power. The control group showed a low and non-significant positive correlation between N1 amplitude and SMR power ($r = 0.31$, ns). The correlations between N1 amplitude and SMR power differed significantly between both groups ($\text{sigma}Z = 0.53$, $Z = -1.56$, $p < 0.05$). In Fig. 5, the scatter plots of these correlations are presented.

4. Discussion

The present study investigated the effects of SMR based neurofeedback training, where participants should learn to voluntarily increase SMR activity by means of visual feedback, on sensorimotor interference and stimulus processing. SMR activity has been related to the promotion of inhibitory mechanisms effective over thalamo-cortical networks. Moreover, increased SMR activity has been associated with improved cognitive processing capabilities due to reduced motor interference, consequently leading to improvement in various cognitive functions (Sterman, 1996, 2000; Egner and Gruzelier, 2004). We assessed electrophysiological correlates of stimulus processing at two time-points: before and after repeated SMR based neurofeedback training. Moreover, we examined whether repeated SMR neurofeedback training improves different cognitive functions such as short- and long-term memory, attention and working memory compared to sham feedback. Modulating SMR activity voluntarily had positive effects on behavioural and electrophysiological parameters in the experimental but not in the control group. In the following, we will discuss these results in more detail. Firstly, we will discuss the

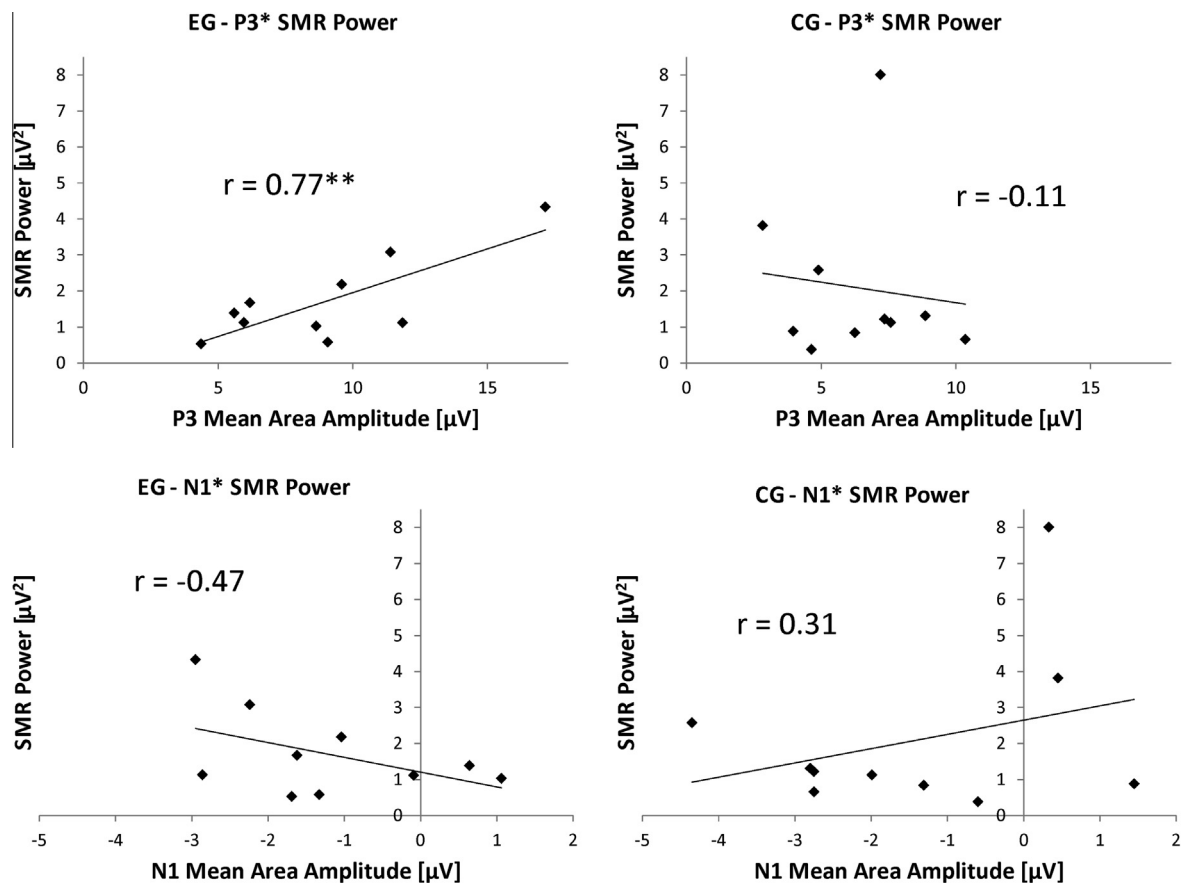


Fig. 5. Scatter plots. Results of the correlations between SMR power during the baseline period of the Sternberg task (-600 to -400 ms before stimulus encoding) and ERP (P3 and N1) during stimulus encoding, presented separately for the experimental (EG) and control group (CG) during the post-measurement. Note that preliminary z-transformation of the data revealed no statistical outliers (Stevens, 2002). Significant differences are marked with asterisks ($^{**}p < 0.01$).

efficiency and specificity of SMR training. More precisely, we want to know if the experimental group was able to voluntarily increase SMR activity. Secondly, we will focus on the effects of SMR based neurofeedback training on cognitive performance, comparing our behavioural results with prior neurofeedback studies. Thirdly, we will try to explain the cognitive improvements following SMR neurofeedback training by means of electrophysiological data. Therefore, we will discuss changes in electrophysiological parameters, which are indicators of the intensity of stimulus processing, due to SMR based neurofeedback training.

4.1. Efficiency of SMR neurofeedback training

The experimental group receiving real feedback about their SMR activity showed an increase in SMR power over the training runs. Participants receiving sham feedback showed no changes in SMR power over time. These results reflect successful SMR based neurofeedback training in the experimental group (Gruzelier et al., 2006; Vernon et al., 2003; Hoedlmoser et al., 2008; Schabus et al., 2014).

We did not find any consistent changes in SMR power over the 10 training sessions. However, other authors also have failed to report significant changes in SMR power over different sessions (Vernon et al., 2003; Vernon, 2005), while finding robust modulations of SMR power within sessions. According to Dempster and Vernon (2009), focusing on within sessions changes may be a more useful approach in identifying changes resulting from neurofeedback training (Dempster and Vernon, 2009). The present findings do not conflict with past findings as those studies reporting

inter-session changes either used ratios of the power within two or more frequency bands or relied on relative power changes (Ros et al., 2013; Gruzelier et al., 2010; de Zambotti et al., 2012; Kober et al., 2013). In contrast, our measure of absolute SMR power represents a more direct index of brain activity. A generalised increase of this index over sessions actually would not have been expected and plays no clear physiological role in cognition. Gaining voluntary control over SMR activity by means of neurofeedback training does not necessarily imply that the SMR baseline level of a feedback user has to change. The purpose of the present study was to show that modulating SMR activity voluntarily at a given time (within a neurofeedback training session) has effects on cognitive processing capabilities, which we could show on the behavioural and electrophysiological level. Hence, our results proved evidence that SMR based neurofeedback training has an impact on the capacity of individuals to adaptively modulate SMR activity according to task demands and not merely to increase the average SMR signal.

Beside a linear increase in SMR power, the experimental group also showed a linear increase in Beta power over the training runs. Although participants were instructed to reduce this frequency band, a linear increase in Beta power in the experimental group is in line with prior SMR based neurofeedback studies showing a concomitant Beta change with SMR power modulation (Schabus et al., 2014; Ghoshuni et al., 2012). It is assumed that changes in adjacent frequency bands such as Beta are also associated with improvements in cognitive functions (Ghoshuni et al., 2012).

No changes in Theta power over the training runs were observed. Hence, changes in SMR power over training runs cannot

be led back to ocular artefacts such as eye blinks, which would have increased Theta power, too.

4.2. Effects of SMR based neurofeedback training on cognitive performance

To investigate whether SMR based neurofeedback training leads to improvements in various cognitive functions, all participants performed standardised psychometrical tests to assess possible changes in short- and long-term memory performance, working memory and attention before and after ten training sessions.

4.2.1. Memory – immediate recall

Participants who were trained to up-regulate their SMR frequency showed significant improvements in their performance in an immediate recall task. Hence, after SMR neurofeedback training, the experimental group improved their ability to memorise and retrieve verbal information after a short delay. These results are in line with prior SMR based neurofeedback studies showing that SMR training affects the short-term retrieval of verbal information such as word lists (Vernon et al., 2003). This result supports our initial assumption that training participants to enhance their SMR activity may facilitate cognitive processing of task relevant stimuli (Serman, 1996). An improved short-term memory performance might be the result of such an altered stimulus processing.

However, we did not find any memory improvements for visuo-spatial material as assessed with the VVM2 subscale city map. This might indicate that SMR training is specific for verbal memory and not for visuo-spatial memory. Prior SMR neurofeedback studies mainly used verbal materials to investigate memory functions (Vernon et al., 2003; Hoedlmoser et al., 2008; Schabus et al., 2004, 2014). A study by Doppelmayr and Weber (2011) is one of the rare examples examining effects of SMR training on spatial abilities. SMR based neurofeedback training led to performance improvements in a spatial rotation task. The authors explained their findings based on the theory proposed by Serman (1996). The SMR training might have led to an improved regulatory control of the somatosensory and sensorimotor pathways, which in turn led to a more efficient attentional processing. Consequently, a better cognitive integration of task-relevant stimuli follows, which might be necessary to perform well in the spatial rotation task (Doppelmayr and Weber, 2011). However, the spatial rotation task used by Doppelmayr and Weber (2011) and the subscale city map of the VVM2 are not directly comparable, since in the subscale city map visuo-spatial information has to be remembered and no mental rotation transformation has to be performed.

In the forward span tasks of the CBTT and Digit Span test we did not find any performance changes between pre- and post-test. These tasks assess visual or numerical short-term memory capacity. In contrast to our results, Lévesque et al., (2006) found improvements in the Digit Span test (forward) after neurofeedback training compared to a pre-test. However, these authors used a combined SMR and Beta based neurofeedback training. Hence, based on their study design it is not clear whether increases in SMR or Beta activity caused the performance improvements in the Digit Span test (forward) (Lévesque et al., 2006; Beauregard and Lévesque, 2006).

The structure of the different memory tests we used is conceptually different. The construction task favours elaborative rehearsal strategies while the subtest city map and the span tasks favour more maintenance rehearsal strategies (Craik, 2002; Lockhart, 2002). In the subtest construction of the VVM 2 participants listen to a story about a building. Afterwards, different details, which could not be anticipated during the listening phase, should be retrieved. Hence, the deeper the semantic associations that have been formed during the listening phase, the easier it is to make

content associations and remember relevant information (Craik, 2002; Lockhart, 2002). In contrast, in the subtest city map one has to remember a path drawn in a map without any deeper semantic cues. Engaging in deeper rehearsal strategies in this task is therefore difficult and would not be efficient since all relevant information is available as superficial stimulus features. The same applies to the forward tasks of the CBTT and Digit Span test. Hence, these specific effects show that particularly tasks demanding higher depth of stimulus processing are sensitive to SMR modulations.

In the Sternberg task, which is a short-term memory task as well, changes in behavioural performance did not reach significance (see Table 1). Both groups showed decreased error rates in the Sternberg paradigm after training compared to the pre-test. Although no changes in neurofeedback training performance between pre- and post-assessment could be found, SMR power during neurofeedback training was related with the performance in the Sternberg task only during post-assessment. A higher SMR power during the last training session was related to an improved performance in the Sternberg task only in the experimental group. Hence, this result provides further evidence of the association between SMR oscillatory activity and short-term memory performance.

How can one explain this apparent contradiction between Digit Span and Sternberg with respect to effects of SMR on short-term memory? It is well established that Arabic numbers are processed deeply and not only after their phonological or visual surfaces (Nieder and Dehaene, 2009) even in those tasks requiring only phonological processing (Knops et al., 2006). The deep meaning of numbers (i.e., their abstract magnitude) is activated in a very automatic fashion (Eger et al., 2003) and largely independent of consciousness (Dehaene and Naccache, 2001; Naccache and Dehaene, 2001). If the deep meaning of numbers is activated regardless of the task at hand, why no effect of SMR was obtained in the Digit Span task? As pointed out by Knops et al. (2006), the effects of number semantics can be small and more difficult to detect in tasks requiring free recall such as the Digit Span. The Digit Span test may thus not be optimal to reveal SMR-memory effects. However, in more sensitive tasks requiring only the recognition of Arabic numbers, such effects are more evident (Knops et al., 2006).

4.2.2. Memory – delayed recall

The experimental group also improved their memory performance in a delayed recall task after training compared to the pre-test. In this subtest, verbal material should be remembered for 24 h. In contrast, the control group that received sham feedback showed no changes in long-term memory performance. Consistent with the short-term memory results, memory improvements were only observed for verbal material (subtest construction 2) and not for visuo-spatial material (subtest city map 2).

Prior studies investigating the effects of SMR based neurofeedback training on long-term memory performance and memory consolidation reported no concise results (Hoedlmoser et al., 2008; Schabus et al., 2004, 2014). These studies hypothesised that increasing SMR activity by means of real-time feedback facilitates the expression of 12–15 Hz spindle oscillations during sleep, which should foster memory consolidation over-night leading to increased long-term memory performance. Although sleep quality was increased after training, no long-term memory improvements could be observed (Hoedlmoser et al., 2008).

However, in the present study positive effects of SMR based neurofeedback training on long-term memory performance were found. Our interpretation is that a more intense cognitive processing of task relevant information due to increased SMR activity might also foster the transfer of learned material from short- to long-term memory. Furthermore, SMR activity at the end of the

training was positively correlated with the performance in the VVM2 construction 2 during the post-test. Furthermore, the good psychometric properties of most tasks applied here contributed positively to reliably detect genuine effects in cognitive performance.

In line with the findings about the effects of SMR based neurofeedback training on immediate recall performance, only performance improvements in the subtest construction could be found. This further strengthens the assumption that SMR neurofeedback training is beneficiary for the recall of details out of a larger set of information and not for the exact recall of information in a given order as required in the subtest city map.

4.2.3. Attention

Beside improvements in short- and long-term memory performance, the SMR group also improved their performance in the focused auditory attention task. After training, the experimental group made no errors any more compared to the pre-test. The control group again showed no performance changes. In line with our findings, [Doppelmayr and Weber \(2011\)](#) also found improved performance in a simple choice reaction task comparable with the Go/No-Go task used in the present study after SMR neurofeedback training. The authors argue, that increased SMR amplitudes should be related to improved control of the somatosensory and sensorimotor pathways, which explains more accurate processing in reaction time paradigms ([Doppelmayr and Weber, 2011](#)). Our results support the findings of the large body of literature showing that SMR training leads to improvements in attentional processing as well as reductions of inattentive behaviour in healthy participants and participants with ADHD ([Egner and Gruzelier, 2004](#); [Tansey and Bruner, 1983](#); [Tansey, 1984, 1985, 1986](#); [Vernon et al., 2003](#); [Sterman, 1996](#); [Lubar and Shouse, 1976](#); [Arns et al., 2009](#); [Kropotov et al., 2005](#)). We did not find any improvements in reaction times due to SMR based neurofeedback training. However, in the last training session SMR activity was correlated with reaction times in the Go/No-Go task, which again could only be found in the experimental group. Participants showing higher SMR power during neurofeedback training responded faster to target stimuli.

4.2.4. Working memory

Furthermore, we assessed possible changes in working memory performance due to SMR training. To the best of our knowledge, there are no SMR based neurofeedback studies investigating training-related changes in working memory performance. Note that some neurofeedback studies used short-term memory tasks but called them working memory tasks ([Vernon et al., 2003](#)). For instance, [Vernon et al. \(2003\)](#) linked the cued recall task to working memory performance. However, in our point of view this task was no working memory task since words had to be memorised and retrieved after a short delay, but the stimuli did not have to be mentally transformed. In contrast, working memory refers to the structures and processes used for temporarily storing and manipulating information.

In the present study, we did not find any effects of SMR based neurofeedback training on working memory performance. In the backwards tasks of the CBTT and Digit Span test we found no changes in performance between pre- and post-test. Studies investigating the effects of EEG neurofeedback on working memory performance trained other frequency bands such as Alpha (about 8–12 Hz), Upper Alpha (about 10–12 Hz), or the Alpha peak frequency ([Nan et al., 2012](#); [Angelakis et al., 2007](#)). For instance, [Nan et al. \(2012\)](#) found that performance in the Digit Span test forward and backwards correlated positively with Upper Alpha power after neurofeedback training. Generally, increased SMR activity should facilitate cognitive processing by decreasing motor

interference and maintaining perceptual and memory functions at the same time ([Sterman, 1996](#)). However, a more intensive stimulus processing does not necessarily mean that subsequent mental manipulation of information, as required in working memory tasks, is improved too. This might explain why we found positive effects of SMR training on short-, long-term memory, and attentional performance, but not on working memory performance.

In summary, we could show that SMR based neurofeedback training leads to improvements in multiple cognitive functions using standardised psychometric tests. These behavioural results support the findings of prior EEG based neurofeedback studies ([Egner and Gruzelier, 2004](#); [Hoedlmoser et al., 2008](#); [Vernon et al., 2003](#); [Vernon, 2005](#); [Tinius and Tinius, 2000](#); [Gruzelier et al., 2006, 2010](#); [Doppelmayr and Weber, 2011](#)). However, our aim was to go beyond these behavioural measures and to investigate electrophysiological underpinnings of cognitive processing, which might change due to SMR training. Based on our theoretical model, we assumed that these general improvements of cognitive capabilities can be explained by an overall altered stimulus processing as indicated by changes in ERP and functional brain connectivity parameters. Hence, SMR based neurofeedback training should improve cognitive performance via a more intensive stimulus processing.

4.3. Effects of SMR based neurofeedback training on cognitive processing due to reduced motor interference

To directly investigate the effects of SMR based neurofeedback training on cognitive processing capabilities, we examined electrophysiological parameters during stimulus processing before and after neurofeedback training for the first time. SMR training affected early (N1) as well as late (P3) ERP during stimulus encoding. After the training, participants of the experimental group showed higher N1 amplitudes during stimuli processing compared to the pre-measurement. The N1 amplitude is generally associated with automatic stimuli processing and encoding ([Kok, 1997](#); [Näätänen et al., 2011](#)). However, there is also evidence that N1 amplitude is modulated by cognitive factors, especially attention. Increased attention allocation leads to higher N1 amplitudes, indicating a stronger and more pronounced stimulus processing ([Herrmann and Knight, 2001](#); [Davis, 1964](#); [Picton and Hillyard, 1974](#); [Correa et al., 2006](#); [Fu et al., 2008](#)). Consequently, in the experimental group increased N1 amplitudes after training compared to the pre-test seem to be related to a more intensive encoding of the digits that should be memorised in the Sternberg task. In contrast, participants receiving sham feedback did not show changes in the intensity of stimulus processing. Furthermore, there is evidence that N1 amplitude decreases with increasing memory load and task demands due to a memory load-dependent increase in inhibition from prefrontal cortex due to a cognitive overload ([Golob and Starr, 2000](#); [Conley et al., 1999](#)). In the present study, N1 amplitude increased comparing post- and pre-test only in the SMR group but not in the sham group. Thus, one specific effect of SMR neurofeedback training can be assumed in a reduced cognitive load during short-term memory processes.

The P3 amplitude also increased after SMR based neurofeedback training compared to the pre-assessment. Larger P3 amplitudes are related to a more intensive stimulus processing, stronger attention allocation, and decreased cognitive load ([Kok, 2001](#); [Polich, 2007](#)). Hence, larger P3 amplitudes in the SMR group after repeated neurofeedback training compared to pre-assessment indicate again that SMR based neurofeedback training fosters cognitive processing capabilities. In the Sternberg paradigm, there is evidence that task manipulation such as stimulus degradation, which affects the encoding stage, influences P3 amplitude. The P3 amplitude decreases with stimulus degradation, indicating a

diminished stimulus encoding (Kok, 2001). In the present study, no external task manipulation was conducted between pre- and post-assessment. Hence, changes in P3 amplitude between these two measurements in the experimental group might be related to internal changes of stimulus processing capabilities. As for the N1, the sham group showed no prominent changes in P3 amplitude between pre- and post-test. Thus, enhanced stimulus processing was found only as a task-specific effect of SMR based neurofeedback training.

In summary, the results of the ERP analysis strongly support our initial hypothesis: Increased SMR activity seems to be associated with a more intensive stimulus processing (Sterman, 1996). After repeated SMR neurofeedback training, participants of the experimental group showed pronounced ERP amplitudes during stimulus encoding, indicating a stronger processing of task relevant information. Participants receiving sham feedback did not show changes in stimulus processing capabilities.

To demonstrate the specific effect of SMR based neurofeedback training on the intensity of cognitive processing, amplitudes of ERP elicited by stimulus encoding during the Sternberg task were correlated with SMR activity during neurofeedback training and with SMR activity briefly before stimulus encoding in the Sternberg task. Only in the experimental group, increased SMR power at the end of the training was associated with increased P3 and N1 amplitudes. The same relationship was found for SMR power during the Sternberg task and ERP amplitudes in the post-test. These results of the correlation analysis strongly indicate that there is a positive relationship between SMR activity and stimulus processing.

So far, we could show that SMR based neurofeedback training led to a more intensive stimulus processing, which seems to be beneficial for the performance in various cognitive tasks. But the question why increased SMR activity should foster stimulus processing is still not answered. Therefore, we also investigated the effects of SMR based neurofeedback training on functional brain connectivity. Based on the assumption made by Sterman (1996) that motor activity can disengage visual processing areas of the cortex (Sterman, 1996; Pfurtscheller, 1992), which may hamper or interfere with perceptual and integrative components of information processing, we assumed that the coherence between motor areas and parietal-occipital brain areas may also change due to SMR based neurofeedback training. SMR neurofeedback should shut down such sensorimotor interference, which might lead to a reduced coherence between motor areas and visual processing areas of the brain. Our results of the coherence analysis fully support this assumption. Only the experimental group receiving SMR neurofeedback training showed a reduced coherence between motor areas (Cz) and parietal-occipital brain regions (CPz, Pz, and POz), which are involved in visual stimulus processing (Birbaumer and Schmidt, 2006), after repeated training sessions compared to the pre-measurement. Hence, the functional connectivity between motor and parietal-occipital areas was reduced due to SMR based neurofeedback training. Consequently, increased SMR activity might reduce motor interference as indicated by the reduced coherence values after SMR training. This is in line with Buch et al. (2012) who showed that decreasing the sensorimotor rhythm by means of motor imagery leads to increased connectivity between parietal-frontal visuomotor areas. Such parietal-frontal functional networks are recruited during motor execution as well as imagery (Buch et al., 2012). Generally, there is evidence that coherence in the SMR frequency range between motor and visual areas increases during visuomotor tasks (Erla et al., 2012; Lin et al., 2012). This functional link between motor and visual brain regions is assumed to subservise sensorimotor integration. However, during stimulus encoding in the Sternberg task no sensorimotor integration is necessary, only visual processing is needed. Therefore, an increased coherence between motor areas and visual

processing areas indicating sensorimotor integration might hamper visual stimulus processing.

Finally, it seems that stimulus processing is improved during increased SMR activity, because increased SMR activity inhibits the somatosensory information flow to the motor cortex as indicated by the reduced functional brain connectivity after SMR training. Consequently, visual stimulus processing is less disturbed by motor interference. And finally, a more intensive stimulus processing leads to improved performance in different cognitive tasks. Our study provides first empirical evidence for this assumption.

5. Conclusion

In the present study we implemented a multi-signal approach including standardised psychometric tests, computerised cognitive tasks and electrophysiological signals to evaluate the specificity of SMR based neurofeedback training. We could show that voluntary control over SMR activity by means of neurofeedback training led to specific improvements in the quality and intensity of stimulus processing, which could be observed in paper-and-pencil tasks as well as in EEG parameters. Our results provide evidence for a relation between changes in EEG parameters (ERP and coherence) and cognitive changes as a result of SMR based neurofeedback training. Moreover, the mechanism regulating the effects of SMR on stimulus processing involve decoupling sensorimotor networks from visual processing areas. This mechanism shuts down sensorimotor interference and consequently unblocks resources from other networks to be employed in stimulus processing.

Our findings and the results of prior neurofeedback studies showing positive effects of SMR based neurofeedback training on cognitive performance in healthy participants implicate that SMR neurofeedback training might be an effective cognitive rehabilitation tool. Hence, EEG based neurofeedback should be taken into account to plan rehabilitation of patients with cognitive impairments. Recently, a few studies tried to use EEG based neurofeedback training to enhance learning and memory in neurologic patients with cognitive impairment (Haddadi et al., 2011; Thornton, 2000; Thornton and Carmody, 2009; Tinus and Tinus, 2000).

Future studies replicating the present results in a larger sample may provide more information regarding the degree of functional specificity characteristic of SMR neurofeedback training, which may have been overestimated in the present investigation.

Acknowledgements

This work is supported by the European STREP Program – Collaborative Project no. FP7-287320 – CONTRAST. Possible inaccuracies of information are under the responsibility of the project team. The text reflects solely the views of its authors. The European Commission is not liable for any use that may be made of the information contained therein.

The authors are grateful to Iris Tomantschger, Mathias Leitner, Tanja Jauk, and René Stefitz for data acquisition.

The authors declare that they have no competing interests.

References

- Angelakis E, Stathopoulou S, Frymiare JL, Green DL, Lubar JF, Kounios J. EEG neurofeedback: a brief overview and an example of Peak Alpha Frequency training for cognitive enhancement in the elderly. *Clin Neuropsychol* 2007;21:110–29.
- Arns M, de Ridder S, Strehl U, Breteler M, Coenen T. Efficacy of neurofeedback treatment in ADHD: the effects on inattention, impulsivity and hyperactivity: a meta-analysis. *Clin EEG Neurosci* 2009;40:180–9.
- Beauregard M, Lévesque J. Functional magnetic resonance imaging investigation of the effects of neurofeedback training on the neural bases of selective attention and response inhibition in children with attention-deficit/hyperactivity disorder. *Appl Psychophysiol Biofeedback* 2006;31:3–20.

- Birbaumer N, Schmidt R. *Biologische Psychologie*. sixth ed. Heidelberg: Springer-Verlag; 2006.
- Bonate PL. *Analysis of pretest–posttest designs*. Boca Raton: Chapman & Hall/CRC; 2000.
- Brain Products GmbH. 2009 *BrainVision Analyzer 2.0.1 User Manual*, third ed. Munich, Germany.
- Buch ER, Modir Shanechi A, Fourkas AD, Weber C, Birbaumer N, Cohen LG. Parietofrontal integrity determines neural modulation associated with grasping imagery after stroke. *Brain* 2012;135:596–614.
- Conley E, Michalewski HJ, Starr A. The N100 auditory cortical evoked potential indexes scanning of auditory short-term memory. *Clin Neurophysiol* 1999;110:2086–93.
- Correa A, Lupiáñez J, Madrid E, Tudela P. Temporal attention enhances early visual processing: a review and new evidence from event-related potentials. *Brain Res* 2006;1076:116–28.
- Craik FIM. Levels of processing: past, present and future? *Memory* 2002;10:305–18.
- Davis H. Enhancement of evoked cortical potentials in humans related to a task requiring a decision. *Science* 1964;145:182–3.
- de Zambotti M, Bianchin M, Magazzini L, Gnesato G, Angrilli A. The efficacy of EEG neurofeedback aimed at enhancing sensory-motor rhythm Theta ratio in healthy subjects. *Exp Brain Res* 2012;221:69–74.
- Dehaene S, Naccache L. Towards a cognitive neuroscience of consciousness: basic evidence and a workspace framework. *Cognition* 2001;79:1–37.
- Dempster T, Vernon D. Identifying indices of learning for alpha neurofeedback training. *Appl Psychophysiol Biofeedback* 2009;34:309–18.
- Doppelmayr M, Weber E. Effects of SMR and Theta/Beta neurofeedback on reaction times, spatial abilities, and creativity. *J Neurother* 2011;15:115–29.
- Eger E, Sterzer P, Russ MO, Giraud A, Kleinschmidt A. A supramodal number representation in human intraparietal cortex. *Neuron* 2003;37:719–25.
- Egner T, Gruzeliér J. EEG Biofeedback of low beta band components: frequency-specific effects on variables of attention and event-related brain potentials. *Clin Neurophysiol* 2004;115:131–9.
- Erla S, Faes L, Nollo G, Arfeller C, Braun C, Papadelis C. Multivariate EEG spectral analysis evidences the functional link between motor and visual cortex during integrative sensorimotor tasks. *Biomed Signal Proces* 2012;7:221–7.
- Fox DJ, Tharp DF, Fox LC. Neurofeedback: an alternative and efficacious treatment for attention deficit hyperactivity disorder. *Appl Psychophysiol Biofeedback* 2005;30:365–73.
- Fu S, Zinni M, Squire P, Kumar R, Caggiano D, Parasuramana R. When and where perceptual load interacts with voluntary visuospatial attention: an event-related potential and dipole modeling study. *NeuroImage* 2008;39:1345–55.
- Gevensleben H, Kleemeyer M, Rothenberger LG, Studer P, Flaig-Rohr A, Moll GH, et al. Neurofeedback in ADHD: further pieces of the puzzle. *Brain Topogr* 2014;27:20–32.
- Ghoshuni M, Firoozabadi M, Khalilzadeh MA, Hashemi Golpayegani MR. The effect of sensorimotor rhythm enhancing neurofeedback on power of adjacent frequency bands. *Biomed Eng-App, Bas C* 2012;24:307–12.
- Golob E, Starr A. Age-related qualitative differences in auditory cortical responses during short-term memory. *Clin Neurophysiol* 2000;111:2234–44.
- Gratton G, Coles MG, Donchin E. A new method for off-line removal of ocular artifact. *Electroencephalogr Clin Neurophysiol* 1983;55:468–84.
- Gruzeliér J, Egner T, Vernon D. Validating the efficacy of neurofeedback for optimising performance. *Prog Brain Res* 2006;159:421–31.
- Gruzeliér J, Inoue A, Smart R, Steed A, Steffert T. Acting performance and flow state enhanced with sensory-motor rhythm neurofeedback comparing ecologically valid immersive VR and training screen scenarios. *Neurosci Lett* 2010;480:112–6.
- Haddadi P, Rostami R, Moradi A, Pouladi F. Neurofeedback training to enhance learning and memory in patients with cognitive impairment. *Procedia – Soc Behav Sci* 2011;30:608–10.
- Hammer EM, Halder S, Blankertz B, Sannelli C, Dickhaus T, Kleih S, et al. Psychological predictors of SMR-BCI performance. *Biol Psychol* 2012;89:80–6.
- Heinrich H, Gevensleben H, Strehl U. Annotation: neurofeedback – train your brain to train behaviour. *J Child Psychol Psychiatry* 2007;48:3–16.
- Herrmann CS, Knight RT. Mechanisms of human attention: event-related potentials and oscillations. *Neurosci Biobehav R* 2001;25:465–76.
- Hinterberger T, Neumann N, Pham M, Kübler A, Grether A, Hofmayer N, et al. A multimodal brain-based feedback and communication system. *Exp Brain Res* 2004;154:521–6.
- Hoedlmoser K, Pecherstorfer T, Gruber G, Anderer P, Doppelmayr M, Klimesch W, et al. Instrumental conditioning of human sensorimotor rhythm (12–15 Hz) and its impact on sleep as well as declarative learning. *Sleep* 2008;31:1401–8.
- Holm S. A simple sequentially rejective multiple test procedure. *Scand J Stat* 1979;6:65–70.
- Holz J, Piosczyk H, Feige B, Spiegelhalder K, Baglioni C, Riemann D, et al. EEG sigma and slow-wave activity during NREM sleep correlate with overnight declarative and procedural memory consolidation. *J Sleep Res* 2012;21:612–9.
- Juhász C, Kamondi A, Szirmai I. Spectral EEG analysis following hemispheric stroke: evidences of transhemispheric diaschisis. *Acta Neurol Scand* 1997;96:397–400.
- Katz M. *Evaluating Clinical and Public Health Interventions: A Practical Guide to Study Design and Statistics*. New York: Cambridge University Press; 2010.
- Kaufman L, Curtis S, Wang J, Williamson S. Changes in cortical activity when subjects scan memory for tones. *Electroenceph Clin Neurophysiol* 1991;82:266–84.
- Keizer AW, Verschoor M, Verment RS, Hommel B. The effect of gamma enhancing neurofeedback on the control of feature bindings and intelligence measures. *Int J Psychophysiol* 2010;75:25–32.
- Knops A, Nuerk H, Fimm B, Vohn R, Willmes K. A special role for numbers in working memory? *fMRI Study NeuroImage* 2006;29:1–14.
- Kober SE, Witte M, Ninaus M, Neuper C, Wood G. Learning to modulate one's own brain activity: the effect of spontaneous mental strategies. *Front Hum Neurosci* 2013;7:1–12.
- Kok A. Event-related-potential (ERP) reflections of mental resources: a review and synthesis. *Biol Psychol* 1997;45:19–56.
- Kok A. On the utility of P3 amplitude as a measure of processing capacity. *Psychophysiology* 2001;38:557–77.
- Kropotov JD. *Quantitative EEG, Event-Related Potentials and Neurotherapy*. first ed. Amsterdam: Elsevier; 2009.
- Kropotov JD, Grin-Yatsenko VA, Ponomarev VA, Chutko LS, Yakovenko EA, Nikishina IS. ERPs correlates of EEG relative beta training in ADHD children. *Int J Psychophysiol* 2005;55:23–34.
- Lévesque J, Beauregard M, Mensour B. Effect of neurofeedback training on the neural substrates of selective attention in children with attention-deficit/hyperactivity disorder: a functional magnetic resonance imaging study. *Neurosci Lett* 2006;394:216–21.
- Lin C, Shaw F, Young K, Lin C, Jung T. EEG correlates of haptic feedback in a visuomotor tracking task. *NeuroImage* 2012;60:2258–73.
- Lockhart RS. Levels of processing, transfer-appropriate processing, and the concept of robust encoding. *Memory* 2002;10:397–403.
- Lubar JF, Shouse MN. EEG and behavioural changes in a hyperkinetic child concurrent with training of the sensorimotor rhythm (SMR): a preliminary report. *Biofeedback Self-Reg* 1976;3:293–306.
- Näätänen R, Kujala T, Winkler I. Auditory processing that leads to conscious perception: a unique window to central auditory processing opened by the mismatch negativity and related responses. *Psychophysiology* 2011;48:4–22.
- Naccache L, Dehaene S. The priming method: imaging unconscious repetition priming reveals an abstract representation of number in the parietal lobes. *Cereb Cortex* 2001;11:966–74.
- Nan W, Rodrigues JP, Ma J, Qu X, Wan F, Mak P, et al. Individual alpha neurofeedback training effect on short term memory. *Int J Psychophysiol* 2012;86:83–7.
- Nieder A, Dehaene S. Representation of number in the brain. *Annu Rev Neurosci* 2009;32:185–208.
- Nunez PL, Srinivasan R, Westdorp AF, Wijesinghe RS, Tucker DM, Silberstein RB, et al. EEG coherency. I: statistics, reference electrode, volume conduction, laplacians, cortical imaging, and interpretation at multiple scales. *Electroencephalogr Clin Neurophysiol* 1997;103:499–515.
- Pfurtscheller G. Central beta rhythm during sensorimotor activities in man. *Electroencephalogr Clin Neurophysiol* 1981;51:253–64.
- Pfurtscheller G. Event-related synchronization (ERS): an electrophysiological correlate of cortical areas at rest. *Electroencephalogr Clin Neurophysiol* 1992;83:62–9.
- Picton T, Hillyard S. Human auditory evoked potentials II. Effects of attention. *Electroencephalogr Clin Neurophysiol* 1974;36:191–9.
- Polich J. Updating P300: an integrative theory of P3a and P3b. *Clin Neurophysiol* 2007;118:2128–48.
- Ros T, Théberge J, Frewen PA, Kluesch R, Densmore M, Calhoun VD, et al. Mind over chatter: plastic up-regulation of the fMRI salience network directly after EEG neurofeedback. *NeuroImage* 2013;65:324–35.
- Schabus M, Gruber G, Parapatics S, Sauter C, Klosch G, Anderer P, et al. Sleep spindles and their significance for declarative memory consolidation. *Sleep* 2004;27:1479–85.
- Schabus M, Heib DP, Lechinger J, Griessnerberger H, Klimesch W, Pawlizki A, et al. Enhancing sleep quality and memory in insomnia using instrumental sensorimotor rhythm conditioning. *Biol Psychol* 2014;95:126–34.
- Schellig D. Corsi Block-Tapping test. *Wiener Testsystem (Vienna Test System)*. Mödling: Schuhfried; 1993.
- Schelling D, Schächtele B. *VVM. Visueller und Verbalen Merkfähigkeitstest*. Göttingen: Hogrefe; 2001.
- Schuhfried G. *Wiener Testsystem (Vienna Test System)*. Mödling: Schuhfried; 2011.
- Serruya M, Kahana MJ. Techniques and devices to restore cognition. *Behav Brain Res* 2008;192:149–65.
- Skinner B. The operational analysis of psychological terms. *Psychol Rev* 1945: 270–7.
- Starr A, Aguinaldo T, Roe M, Michalewski HJ. Sequential changes of auditory processing during target detection: motor responding versus mental counting. *Electroencephalogr Clin Neurophysiol* 1997;105:201–12.
- Sterman MB. Physiological origins and functional correlates of EEG rhythmic activities: implications for self-regulation. *Biofeedback Self-Reg* 1996;21:3–33.
- Sterman MB. Basic concepts and clinical findings in the treatment of seizure disorders with EEG operant conditioning. *Clin Electroencephal* 2001;31:45–55.
- Sterman MB, Howe RC, Macdonald LR. Facilitation of spindle-burst sleep by conditioning of electroencephalographic activity while awake. *Science* 1970;167:1146–8.
- Sternberg S. High-speed scanning in human memory. *Science* 1966;153:652–4.
- Stevens J. *Applied Multivariate Statistics for the Social Sciences*. Fourth ed. Mahwah, New Jersey London: Lawrence Erlbaum Associates; 2002.
- Strehl U, editor. *Neurofeedback: Theoretische Grundlagen – Praktisches Vorgehen – Wissenschaftliche Evidenz*. Stuttgart: Kohlhammer; 2013.
- Tansy MA. EEG sensorimotor rhythm biofeedback training: some effects on the neurologic precursors of learning disabilities. *Int J Psychophysiol* 1984;1:163–77.
- Tansy MA. The response of a case of petit mal epilepsy to EEG sensorimotor rhythm biofeedback training. *Int J Psychophysiol* 1985;3:81–4.

- Tansey MA. A simple and a complex tic (Gilles de la Tourette's syndrome): their response to EEG sensorimotor rhythm biofeedback training. *Int J Psychophysiol* 1986;4:91–7.
- Tansey MA, Bruner RL. EMG and EEG biofeedback training in the treatment of a 10-year-old hyperactive boy with a developmental reading disorder. *Biofeedback Self-Reg* 1983;8:25–37.
- Thornton K. Improvement/rehabilitation of memory functioning with neurotherapy/QEEG biofeedback. *J Head Trauma Rehabil* 2000;15:1–13.
- Thornton KE, Carmody DP. Traumatic brain injury rehabilitation: QEEG biofeedback treatment protocols. *Appl Psychophysiol Biofeedback* 2009;34:59–68.
- Thornton KE, Carmody DP. The relation between memory improvement and QEEG changes in three clinical groups as a result of EEG biofeedback treatment. *J Neurotherapy: Investig Neuromodulation, Neurofeedback Appl Neurosci* 2013;17:116–31.
- Tinius T, Tinius K. Changes after EEG biofeedback and cognitive retraining in adults with mild traumatic brain Injury and attention deficit hyperactivity disorder. *J Neurother* 2000;4:27–43.
- Varela F, Lachaux J, Rodriguez E, Martinerie J. The brainweb: phase synchronization and large-scale integration. *Nat Rev Neurosci* 2001;2:229–239.
- Vernon DJ. Can neurofeedback training enhance performance? An evaluation of the evidence with implications for future research. *Appl Psychophysiol Biofeedback* 2005;30:347–64.
- Vernon D, Egner T, Cooper N, Compton T, Neilands C, Sheri A, et al. The effect of training distinct neurofeedback protocols on aspects of cognitive performance. *Int J Psychophysiol* 2003;47:75–85.