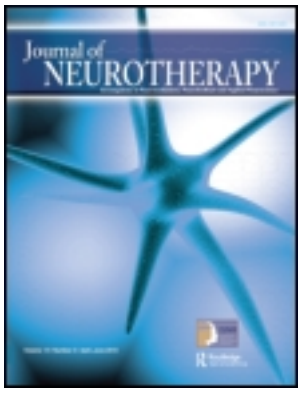


Journal of Neurotherapy
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/wneu20

Comparison of Discrete-Trial-Based SMR and SCP Training and the Interrelationship Between SCP and SMR Networks: Implications for Brain-Computer Interfaces and Neurofeedback

Michiel Kleinnijenhuis MSc [a], Martijn Arns MSc [b c], Desirée Spronk MSc [b], Rien Breteler PhD [d e] & Jacques Duysens MD, PhD [a f g]

[a] Department of Medical Physics and Biophysics, Radboud University Nijmegen, Nijmegen, The Netherlands

[b] Brainclinics Diagnostics B.V., Nijmegen, The Netherlands

[c] Brainclinics Treatment B.V., Nijmegen, The Netherlands

[d] EEG Resource Institute B.V., Radboud University Nijmegen, Nijmegen, The Netherlands

[e] Department of Clinical Psychology, Radboud University Nijmegen, Nijmegen, The Netherlands

[f] SMK-RDE, Nijmegen, The Netherlands

[g] Research Center for Movement Control and Neuroplasticity, Department of Biomedical Kinesiology, Katholieke Universiteit Leuven, Leuven, Belgium

Available online: 08 Sep 2008

To cite this article: Michiel Kleinnijenhuis MSc, Martijn Arns MSc, Desirée Spronk MSc, Rien Breteler PhD & Jacques Duysens MD, PhD (2008): Comparison of Discrete-Trial-Based SMR and SCP Training and the Interrelationship Between SCP and SMR Networks: Implications for Brain-Computer Interfaces and Neurofeedback, Journal of Neurotherapy, 11:4, 19-35

To link to this article: http://dx.doi.org/10.1080/10874200802162808

Comparison of Discrete-Trial-Based SMR and SCP Training and the Interrelationship Between SCP and SMR Networks: Implications for Brain–Computer Interfaces and Neurofeedback

Michiel Kleinnijenhuis, MSc
Martijn Arns, MSc
Desirée Spronk, MSc
Rien Breteler, PhD
Jacques Duysens, MD, PhD

ABSTRACT. *Background.* Operant conditioning of one's slow cortical potential (SCP) or sensorimotor rhythm (SMR) can be used to control epilepsy or to manipulate external devices, as applied in BCI (Brain-Computer Interface). A commonly accepted view that both SCP and SMR are reflections of central arousal suggests a functional relationship between SCP and SMR networks.

Method. The operant conditioning of SCP or SMR was tested with a single electroencephalographic (EEG) channel wireless biofeedback system. A series of trainings taught 19 participants to control SCP or SMR over vertex during 20 neurofeedback sessions. Each session consisted of 96 trials to decrease cortical arousal (SCP positivity/SMR enhancement) and 64 trials to increase cortical arousal (SCP negativity/SMR suppression). In each trial, participants were required to exceed an individual threshold level of the feedback parameter relative to a 500-msec

Michiel Kleinnijenhuis is affiliated with the Department of Medical Physics and Biophysics, Radboud University Nijmegen, Nijmegen, The Netherlands.

Martijn Arns is affiliated with Brainclinics Diagnostics B.V. and Brainclinics Treatment B.V., Nijmegen, The Netherlands.

Desirée Spronk is affiliated with Brainclinics Diagnostics B.V., Nijmegen, The Netherlands.

Rien Breteler is affiliated with EEG Resource Institute B.V. and Department of Clinical Psychology, Radboud University Nijmegen, Nijmegen, The Netherlands.

Jacques Duysens is affiliated with the Department of Medical Physics and Biophysics, Radboud University Nijmegen, Nijmegen, The Netherlands; SMK-RDE, Nijmegen, The Netherlands; and Research Center for Movement Control and Neuroplasticity, Department of Biomedical Kinesiology, Katholieke Universiteit Leuven, Leuven, Belgium.

Address correspondence to: Martijn Arns, MSc, Brainclinics Diagnostics B.V., Bijleveldsingel 34, 6524 AD Nijmegen, The Netherlands (E-mail: martijn@brainclinics.com).

This study was funded by the BIAL foundation (Grant Number 163/04) and supported by Brainclinics Diagnostics B.V. The authors sincerely thank Noemí Sánchez Nácher for her extensive contribution to the training of the participants, Vivian Weerdesteyn for her counsel on the statistics, and Erica Schot-Heesen for her support in the initial phase of the study.

Journal of Neurotherapy, Vol. 11(4) 2007
Available online at http://jn.haworthpress.com

doi: 10.1080/10874200802162808

prefeedback baseline and to hold this level for 2 sec (SCP) or 0.5 sec (SMR) to obtain reinforcement.

Results. Ten of the 19 participants achieved control over their EEG. In the SCP-trained group, 4 of 9 participants increased the differentiation between their SCP responses on positivity-required versus negativity-required trials. SMR suppression and enhancement was achieved by 3 and 4 of the 10 SMR-trained participants. The SMR-trained responders did not show differentiation in their SMR responses, but did show a differentiation in their SCP response—while trained on SMR.

Conclusions. The results showed the proposed method was successful to teach control of SCP or SMR. Bidirectional control was very difficult to achieve with the present SMR training procedure. SCP positivity and SMR enhancement were easier to learn. The results suggest that SMR training modulates excitability thresholds in the striatal-thalamocortical motor loop, whereas changes in the loop's excitability thresholds by SCP training do not affect the thalamic bursting that underlies the SMR.

KEYWORDS. Brain–computer interface, discrete training, epilepsy, neurofeedback, sensorimotor rhythm, slow cortical potential

The efficacy of neurofeedback in the control of seizures in persons with uncontrolled epilepsy has been well documented over the past decades. The most promising approaches to seizure control include neurofeedback of the sensorimotor rhythm (SMR; Sterman, 2000; Sterman & Friar, 1972; Tozzo, Elfner, & May, 1988) and the slow cortical potential (SCP; Kotchoubey et al., 2001; Rockstroh et al., 1993). SMR neurofeedback exercises the patient's regulatory mechanisms in the thalamocortical loop that produces the SMR (Sterman, 2000). Similarly, the proposed mechanism of SCP neurofeedback seizure reduction is an improved regulation of cortical excitability, because positive SCPs reflect a decrease in cortical excitability (Birbaumer, Elbert, Canavan & Rockstroh, 1990).

A second application of neurofeedback methodology is in the field of brain–computer interfacing (BCI). BCI is a technique that uses signals extracted from the brain to control devices (computers) without muscular activity or overt speech. Such control can be beneficial for patients with severe motor disabilities. For example, Birbaumer and colleagues (Birbaumer et al. 1999) developed a spelling device (Thought Translation Device [TTD]) for patients suffering from amyotrophic lateral sclerosis (ALS). The TTD uses self-regulation of the SCP as a means of binary decision strategy. By either increasing or decreasing the SCP relative to a pretrial baseline the patient can choose between selections of letters of the alphabet until the desired letter is selected. Numerous variations on the TTD training protocol have been tested (Birbaumer et al., 1999; Kübler, et al., 1999; Neumann et al., 2004). Several other studies showed that it is possible to operate a BCI with rhythmic activity over the sensorimotor cortex as well. Typically, the mu or beta rhythms are used (Kübler et al., 2005; Pfurtscheller, Flotzinger, Pregenzer, Wolpaw, & McFarland, 1996; Wolpaw, Birbaumer, McFarland, Pfurtscheller, & Vaughan, 2002).

Because both the SCP and the SMR can be regarded as measures of cortical arousal (Nagai, Goldstein, Critchley, & Fenwick, 2004; Sterman, 1982), perhaps they are expressions of the same underlying neurophysiological network. The generating mechanisms of both the SCP (Birbaumer et al., 1990) and SMR (Sterman, 2000) are relatively well understood. Further, the invasive animal studies with SCP (Birbaumer et al., 1990) and SMR (Bazhenov, Timofeev, Steriade, & Sejnovski, 1999) and human functional magnetic resonance imaging studies with SCP (Hinterberger et al., 2003) and SMR (Beauregard & Lévasque, 2006) showed that they share cortical and subcortical structures and rely heavily on regulation

of activity in the striatal-thalamocortical motor loop (Birbaumer, 2006). Therefore, it can be hypothesized that the self-regulation of one of the parameters affects the other (i.e., invoked SCP shifts induce SMR changes and/or SMR changes shift the excitability thresholds of the cortical pyramidal neurons reflected by the SCP). This proposed functional relationship could be further examined with coregistration of SCP and SMR while training one or the other in a neurofeedback training protocol.

Although in recent years significant progress has been made in the field of electroencephalographic- (EEG-) based BCI, the systems commonly employed are traditional full-cap systems, which require significant effort to apply and maintain. Indeed, some of the commonly used techniques (spatial filtering, independent component analysis) require the application of a multitude of electrodes. Because these techniques are cumbersome, the question arises whether a single measurement electrode could be sufficient for BCI systems, which therefore would be easier to apply, and more practical in use. Recent advances in technology have resulted in the development of portable wireless EEG equipment that can measure a limited number of EEG channels (Arns & van Dorsten, 2005). During tele-neurofeedback (patients train at home, supervised by their therapist over the Internet), this equipment can be easily applied by end-users with only minimal training in application of the electrodes and use of the software (Breteler, de Ridder, Monsuwe, & Arns, 2006). A BCI should be applicable to, for example, spinal cord-injured patients and therefore setup should be as simple as possible, such that the end-user is able to apply and operate it with minimal assistance.

The regular approach in clinical neurofeedback is to reward desired behavior in a continuous task execution setting (e.g., in a 5-min run, the advancement of a video is dependent on the feedback variable exceeding a certain threshold level). In BCI, however, a discrete trial method is more appropriate. The nature of the goal that is pursued imposes these different approaches. The aim for clinical neurofeedback is to manipulate EEG power in a designated bandwidth geared toward a clinical outcome, whereas in BCI a transient EEG response is appropriate for controlling a device. Despite the broadly accepted convention to use continuous tasks in clinical neurofeedback, a discrete approach might be a more effective learning method, because it is a key feature of traditional operant conditioning (Ferster & Skinner, 1957; Sterman, M. B., personal communication Oct. 10, 2005).

In this study, we describe a novel approach for the feedback of physiological parameters using a discrete-trial based approach where participants are required to show an increase *or* decrease in the feedback parameter. This approach was developed for the purpose of BCI as well as clinical discrete (EEG) biofeedback training. In the experiment presented here, we focus on the feedback of the SMR and SCPs, as both SMR and SCP control have been proven to be advantageous for epilepsy patients and it was shown that SCP can be used for BCI purposes. This investigation explores whether the 12 to 15 Hz SMR might also be an EEG rhythm suitable for BCI. The specific questions we address in this study with healthy participants are (a) are participants able to voluntarily increase or decrease their SCP or SMR using discrete feedback, (b) do participants show a change in their trained SCP or SMR responses over the course of training reflecting improved skill acquisition, (c) how do the percentages of successful responses of SCP-trained and SMR-trained participants compare over the tasks of increasing and decreasing the SCP or SMR level, and (d) is there evidence for a functional relationship in the networks that generate the SCP and SMR (i.e., do changes occur in one while participants are being trained on the other)?

METHOD

Participants

There were 19 participants in this study (9 male, 10 female). All participants were recruited according to the normative subject

profile of the Brain Resource International Database (Gordon, 2003) in which exclusion criteria include a history of neurological, psychiatric, or psychological disturbances; motoric, hearing, or vision impairments; and serious medical conditions. Every participant gave informed consent prior to the study. The study was approved by the Institutional Review Board (METC Noord Holland; number M05–010).

EEG Recordings

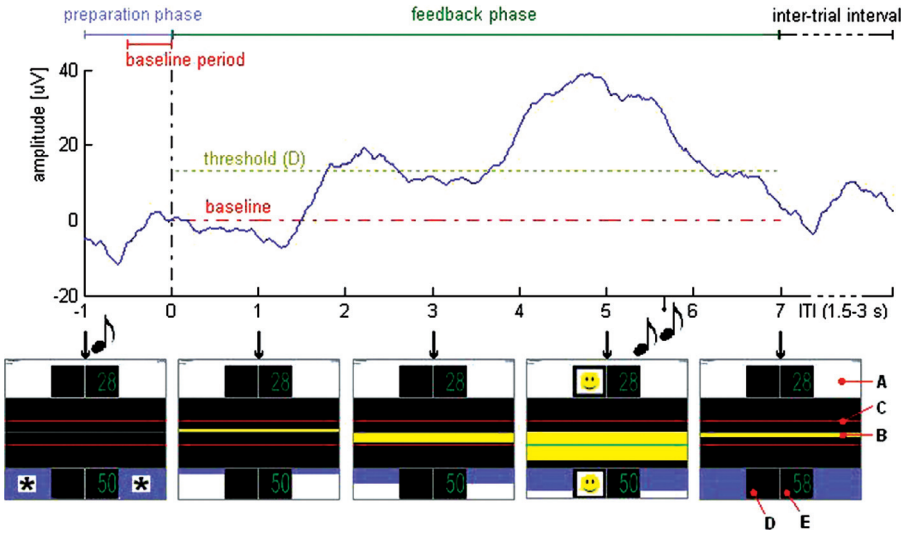
Data recording was achieved using personal computers (Pentium IV processors) and BioExplorer software (V1.3). A custom open source design was programmed in the BioExplorer software environment. The used design and manual can be downloaded from http://www.brainclinics.com.

The participants' EEG was recorded from Cz referenced against linked mastoids [(A1 + A2)/2] using the wireless two-channel bipolar Brainquiry PET SCP with active electrodes. The second channel of the device was used for recording vertical eye-movement activity (vEOG). The EOG electrodes were placed on the sagittal midline 1 cm above and below the outer canthus of the right eye. The ground electrode was placed on AF3. EEG and EOG were recorded with a sampling frequency of 200 Hz. Disposable pre-gelled $Ag/Ag^{+}Cl^{-}$ electrodes (Arbo electrodes H124SG, Tyco) were used for EEG recording. Ten-20 electrode paste was applied on the Cz recording site. All electrode sites were prepared with alcohol and Nuprep abrasive gel.

Procedure

The participants received 20 neurofeedback training sessions in which they were trained to self-regulate either their SCP ($n = 9$) or SMR ($n = 10$). The experiment spanned a total of 8 weeks with three training sessions per week and no more than one session per day. The sessions were divided into four 7-min runs of 40 discrete trials each. After two runs, participants were encouraged and informed on their progress during a 1- to 2-min pause. Trials were separated by variable intertrial intervals (1.5–3 sec) with no task requirement and stimuli. Before the experiment, the participants were instructed on the functions of the various elements of the feedback window (Figure 1) and the task requirement. The basic mechanisms of neurofeedback were explained, but participants were not provided with a

FIGURE 1. The time course of a SCP in a D trial and the feedback window.



strategy to control the SCP or SMR. Instead, participants were asked to stay focused on their task and try to find a strategy for themselves by closely observing the feedback and trying to relate this to internal states. A hint was provided stating that the feedback parameter was related to arousal. The participants were further instructed to minimize movement of body, head, hands, and eyes. This instruction was repeated if necessary.

During the trials, two conditions were mixed pseudorandomly (i.e., during every session one of six trial sequences was used). In the sequences, the "down" (D) trials (which required lowering the level of cortical arousal: SCP positivity/SMR enhancement) and "up" (U) trials (heightening arousal: SCP negativity/SMR suppression) were randomly mixed with the D condition comprising 60% of all trials and the U condition comprising 40% of all trials. The asymmetric distribution of D trials and U trials was introduced, because previous work by Hinterberger and colleagues (Hinterberger, T., personal communication May 5, 2005) indicated that increasing cortical arousal was easier to learn compared to decreasing cortical arousal. In addition, because reduction of epileptic seizures is mediated by lowering the cortical excitability level, emphasizing the D condition was hypothesized to be more useful and safer. Furthermore, intertrial intervals (1.5, 2.0, 2.5, or 3.0 sec) were mixed randomly in the sequences. The six trial sequences were randomized over sessions, and this randomized order was counterbalanced over participants by inverting the order in half of the participants in each group.

Participants were seated behind a 17-in. TFT monitor displaying the feedback window wearing headphones. In a trial, the participant had to either increase or decrease SCP or SMR (12–15 Hz). Figure 1 shows the time course of a SCP in a D trial and the feedback window as the participant would see it at different time points throughout the trial. The start of a trial was indicated by a brief tone delivered through the headphones. The trials were divided in a preparation phase and a feedback phase. In the preparation phase, the trial type was indicated to the participant by the blinking (see* in Figure 1) of two blue rectangles (A in Figure 1) in either the upper (U trial) or lower half (D trial) of the feedback window. In the feedback phase, the amount of time that was left to perform the task was indicated in the rectangles that were used to indicate trial type in the preparation phase. The task requirement was to reach an individually determined threshold (C in

FIGURE 2. The detailed overview of the core of real-time data processing.

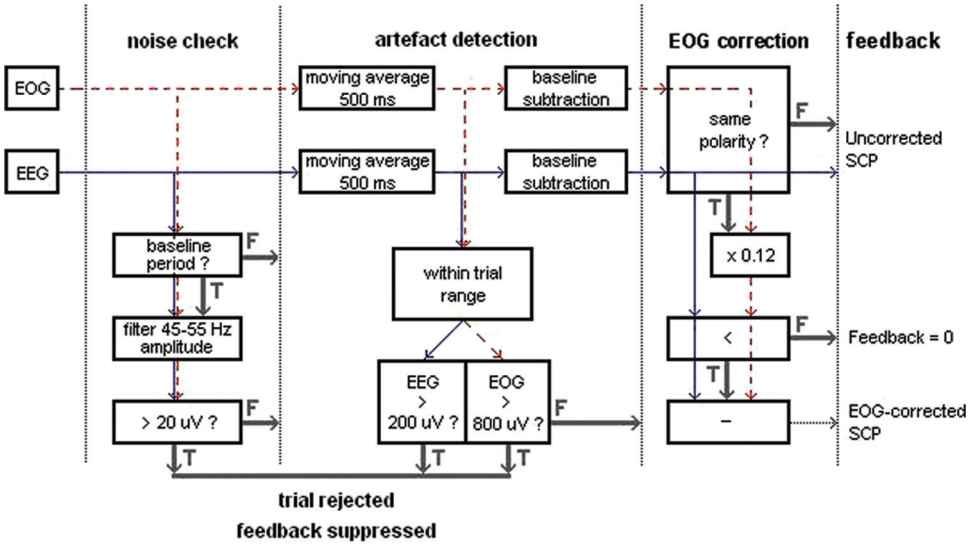


Figure 1) level of the feedback parameter relative to the 500-msec prefeedback baseline and to hold this level for at least 2 sec for SCP (Hinterberger, T., personal communication May 5, 2005) or 0.5 sec for SMR (Sterman, M. B., personal communication Oct. 10, 2005).

EEG Filter Settings and Feedback

SMR was filtered from the raw EEG using a sixth order Butterworth IIR 12 to 15 Hz bandwidth filter. The feedback was based on an average period of 500 msec. SCP was filtered using a 500-ms moving average FIR filter. A detailed overview of the core of real-time data processing (noise check, artifact rejection and EOG correction) is provided in Figure 2. SMR data processing did not include EOG correction, but featured both the noise check and artefact detection identical to the SCP data processing. On a positive outcome of either the noise or artefact check the feedback bar would disappear for the remainder of the trial and the trial was excluded from analysis and success percentages calculation.

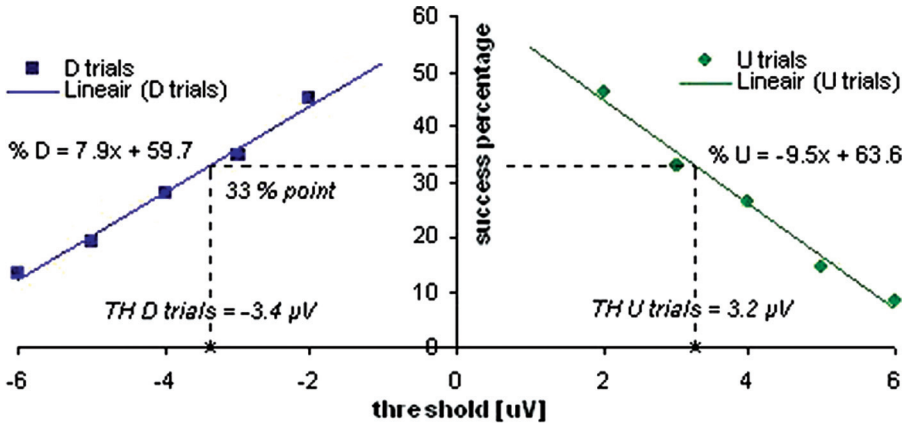
Real-time feedback was provided by displaying a yellow bar (B in Figure 1) the height of which was proportional to the level of the feedback parameter (SCP or SMR amplitude) relative to the average 500-msec prefeedback baseline SCP/SMR level. The prefeedback baseline level was set at the vertical midline of the window, and the visible range of the bar was set such that it was proportional (3x) to the—individually different—threshold values, resulting in an identical visual display for all participants. Arousal increases (negative SCPs and SMR decreases) were scaled to be displayed in the upper half of the window and arousal decreases (positive SCP shifts and SMR increases) were displayed in the lower half. In the intertrial-interval and the preparation phase, no feedback was provided.

Reinforcing feedback in the form of two "smiley" faces (location D in Figure 1) was given when the participants reached the appropriate threshold. When the task was completed successfully, the participant heard a reinforcing sound, delivered through the headphones. In addition, feedback on performance was provided continuously by displaying the percentage of successful trials in a run for U and D trials separately (E in Figure 1). These percentages were updated after every trial.

Threshold Procedure

Each participant was provided with individually determined threshold settings for the D and U conditions that would start them at 33% successful trials (the chance level that was chosen according to the hypothesis that the number of rewards [one third] would be sufficient to accomodate

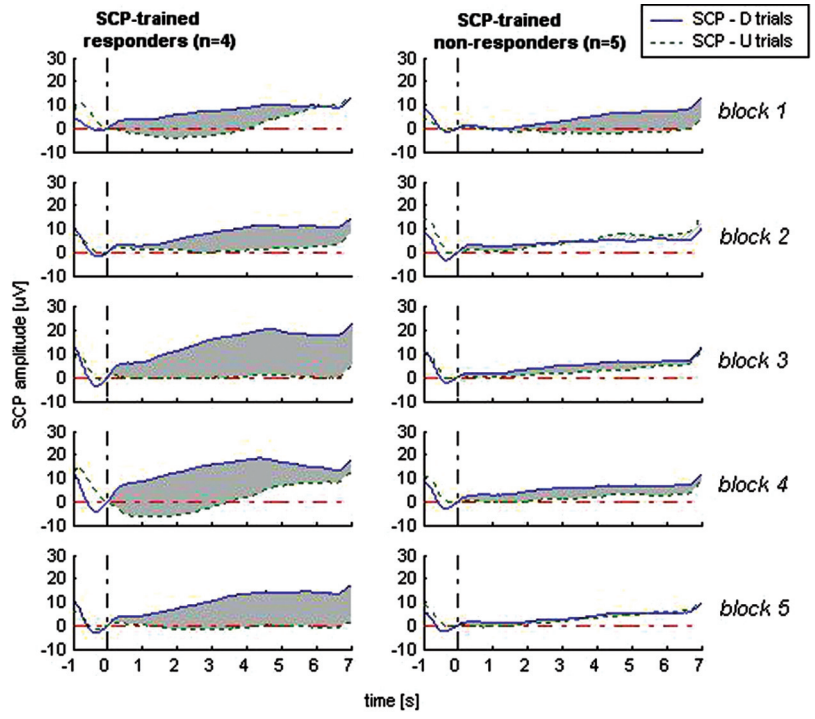
FIGURE 3. Example of individual thresholds setting by linear regression.



learning but low enough to challenge participants). This standardized the procedure by establishing personal thresholds. These personal thresholds were determined based on two pretraining sessions. In the first pretraining session, thresholds were set to a prefixed value (–10 μV and 10 μV for the SCP group; –4 μV and 4 μV for the SMR group). Every run in a session is associated with a percentage of successful trials, which is dependent on the threshold value. The BioExplorer software package features a "playback" function: the possibility to rerun the session data, with (the same or) different parameters for data processing. Employing this function, the success percentages of a run in case different threshold settings would have been used were simulated with five different threshold settings (±4, 6, 8, 10, 12 μV for the SCP group; ±2, 3, 4, 5, 6 μV for the SMR group), thus rerunning the session five times for each of the pretraining sessions with different threshold settings. The resulting success percentages were averaged over the runs of the first pretraining session yielding an average success percentage for each of the threshold settings. Then, a linear regression was carried out on the averages for D trials and U trials separately (see Figure 3). The thresholds for the second pretraining session were taken as the level of the feedback parameter with which 33% of trials would be successful according to the linear regression of the first session.

The playback procedure was repeated for the four runs of the second session, resulting in another four success percentages for each threshold setting, thus a total of eight success percentages was obtained from the two pretraining sessions for each of the threshold settings. The success percentages of the pretraining sessions were averaged over the eight runs, arriving at an average pretraining success percentage for each threshold setting. Again, a linear regression was conducted, now on the average pretraining success percentages. The thresholds for the training sessions were fixed at the level that predicted 33% successful trials.

FIGURE 4. Grand-average SCP responses for D and U trials over the blocks for the SCP responders and non-responders.



Physiological Responses

The physiological data (EEG and EOG) were processed using BioReview, Matlab, and SPSS software. Invalid trials were excluded from analysis. An entire run was excluded when more than 10 trials were invalid and an entire session was discarded if more than two runs were excluded. The raw signals were filtered offline with the same filter specifications as in the real-time implementation. The EEG was corrected for eye-movement influences offline according to the procedure of Gratton, Coles, and Donchin (1983). The 500-msec prefeedback baseline was subtracted from every trial for SMR and corrected SCP. Grand-average SCP and SMR amplitudes were obtained by averaging D and U trials separately in five blocks of four sessions. To quantify physiological responses, the integral between the grand averages of the D/U trials and the baseline was calculated for the feedback phase. Integrals P_D and P_U of the D and U trials, respectively, are defined as

$$P_D = \int_a^b GA_D dt \qquad P_U = \int_a^b GA_U dt$$

where GA_D and GA_U are the grand-averages of the D and U trials, respectively. These performance measures are calculated for both SCP and SMR in the interval t = [a,b] = [0,7] s. Repeated measures analyses of variance (ANOVAs) ($2 \times 5 \times 2$ [Group $\times$ Block $\times$ Trial Type]) were performed on the integrals P_D and P_U for both the SCP and SMR response. The significance level was set at $\alpha = .05$.

Performance

The participants' performances were analyzed with SPSS software. The percentages of successful trials (for every run) were averaged in five blocks of four sessions. The averaged success percentages were entered in a $2 \times 5 \times 2$ (Group $\times$ Block $\times$ Trial Type) repeated measures ANOVA.

RESULTS

Physiological Responses

Analysis of the data of the individual participants indicated large variability between the participants. The SCP-trained participants ($n = 9$) can be divided in two relatively homogeneous groups based on their ability to control their SCP (the criterion was a larger slope of a least-squares linear regression for P_D as compared to P_U over blocks; see also Figure 6 for the group example). First, there is a group of four participants who were able to increase the differentiation between their SCP responses on D and U trials over the blocks (responders; Figure 4).

The increase in differentiation (shaded area) was primarily caused by SCP increases in the D trials (4 participants). One participant was able to also progressively decrease his SCP in the U trials over the blocks. Second, 4 participants showed essentially the same response in all sessions, and 1 participant even showed a decrease in differentiation.

In the group of the SMR-trained participants ($n = 10$), the number of responders ($n = 6$) was higher than in the SCP-trained group (Figure 5). Three of 10 participants were able to progressively decrease their SMR in the U trials (U trial responders), and 4 participants showed consistent increases in SMR amplitude in the D trials over the blocks (D trial responders). One participant was able to differentiate his response between D and U trials.

Further, Figure 5 shows that, in the first 2 sec of the feedback phase, the U trial responders (left column) exhibit an increasingly suppressed SMR response in the U trials (dashed trace) over blocks. However, roughly the same decreasing trend is seen in the D trials (solid trace), where this response is inappropriate. Moreover, the SMR in the D trials is even more suppressed compared to baseline than it is in the U trials. An opposite—but similar—pattern is seen for the D trial responders (right column). These participants also showed a suppression of SMR compared to baseline in the

FIGURE 5. Grand-average SMR responses for D and U trials over the blocks for the SMR U trial responders and D trial responders.

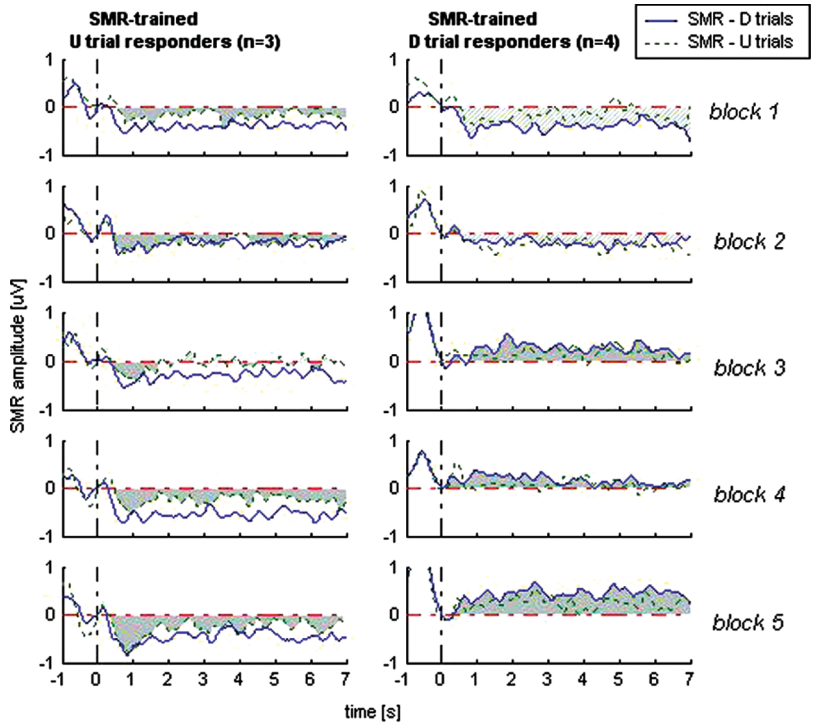
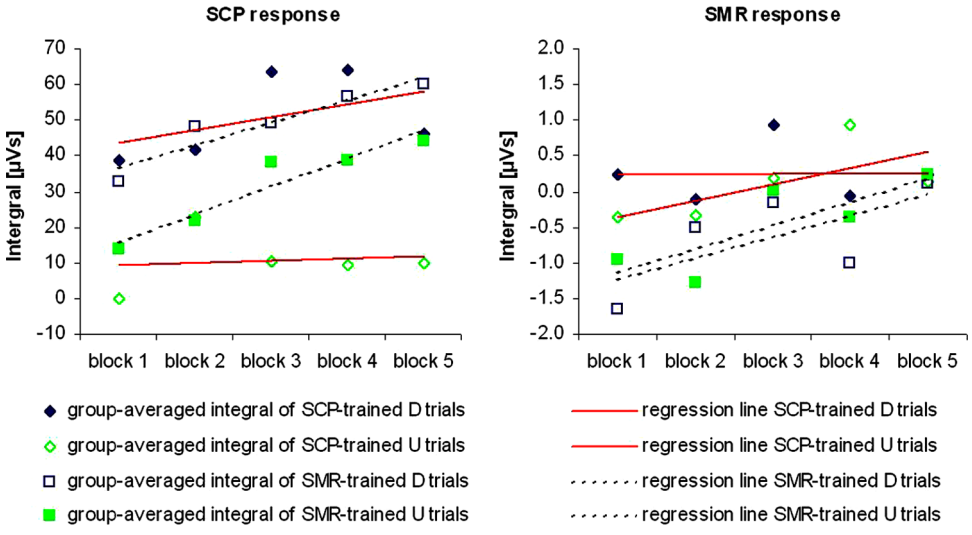
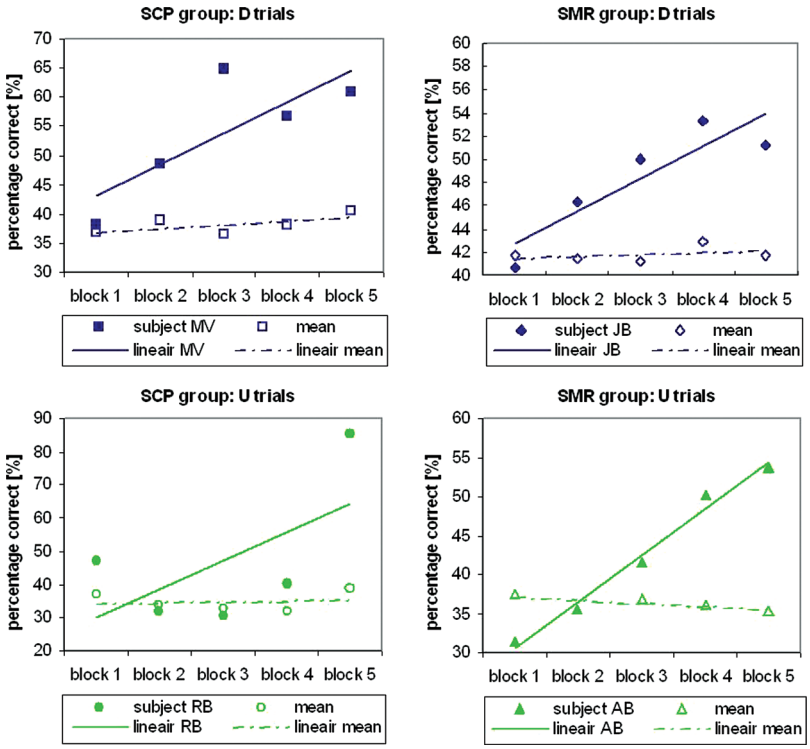


FIGURE 6. The group-average of PD and PU of the SCP (Diamonds, Solid Lines) and the SMR-trained group (Squares, Dashed Lines) for the SCP response (Left Panel) and the SMR response (Right Panel).



first block in both trial types but gradually changed their response in the feedback phase to a SMR enhancement. Again, they showed this in the D trials (the required response) as well as in the U trials (the inappropriate response).

FIGURE 7. Success percentages for the mean across participants and best-performing participant over blocks.



The ability to regulate the SCP and SMR across session blocks was quantified by calculating the integrals P_D and P_U between the baseline and the grand-averages for the feedback phase per block for both the SCP-trained group and the SMR-trained group.

Figure 6 shows the group-averaged P_D and P_U of the SCP (diamonds, solid lines) and the SMR-trained group (squares, dashed lines) for the SCP response (left panel) and the SMR response (right panel). Of interest, the integrals of the SCP response show a differentiation for both the SCP-trained and SMR-trained participants, but there was a large difference in the evolution of this differentiation. For the SCP-trained participants, it can be observed that the SCP differentiation (the difference between the integrals of the D and U trials) increases over blocks (left panel; solid lines). In contrast, for the SMR-trained participants the SCP differentiation is constant over blocks (left panel; dashed lines are parallel) but shows a nonspecific increasing trend (left panel; equal positive slope of the dashed lines). Unlike for the SCP-trained participants, the difference between D and U trials does not grow larger over blocks for the SMR-trained participants. Thus, whereas the SCP-trained participants learn to increasingly differentiate their SCP response on D and U trials over blocks, the SMR-trained participants only show a positive shift in their SCP level, equal for both D and U trails.

The integrals of the SMR response are undifferentiated (i.e., there is no net area between the grand averages of the D and U trials) for both the SMR-trained group (right panel; dashed lines) and SCP-trained group (right panel; solid lines). Therefore, the SMR-trained participants did not learn to differentiate their SMR response between D and U trials and the SCP-training did not elicit consistent changes in the SMR in the SCP-trained participants. In the SMR-trained group, both integrals P_D and P_U show the same trend towards positivity, that

is, from a suppression of SMR in the first block to the absence of a SMR response in the last block.

The integrals of SCP response and SMR response were both entered in a $2 \times 5 \times 2$ (Group $\times$ Block $\times$ Trial Type) repeated measures ANOVA. For the SCP response, a significant effect of Trial Type was found, $F(1, 17) = 20.050$, $p < .001$. This indicates that participants differentiated in their response to U and D trails. It could not be shown that this differentiation was larger for the SCP-trained group as compared to the SMR-trained group (nonsignificant Trial Type $\times$ Group interaction), $F(1, 17) = 2.984$, $p = .102$. Furthermore, a significant main effect of block was found, $F(4, 14) = 4.666$, $p = .013$, and demonstrates a more positive general SCP level relative to baseline over the blocks, which was the same in the SCP-trained group and the SMR-trained group (nonsignificant Block $\times$ Group interaction), $F(4, 14) = 1.007$, $p = .437$, and occurred in both D and U trials (nonsignificant Trial Type $\times$ Block interaction), $F(4, 14) = 1.198$, $p = .355$. Post hoc contrasts indicated a quadratic increase over blocks, $F(1, 17) = 12.246$, $p = .003$, which showed that the increase in SCP level becomes smaller quadratically over blocks. Consequently, the increase in SCP positivity is much larger from Block 1 to Block 2 as compared to from Block 4 to Block 5. The three-way interaction Trial Type $\times$ Block $\times$ Group was also significant, $F(4, 14) = 3.708$, $p = .029$. Post hoc contrasts revealed that this interaction occurred in Block 2, where the SCP differentiation in the SCP-trained group is reduced compared to the other blocks and the SCP differentiation in the SMR-trained group is increased compared to the other blocks. Therefore, the three-way interaction did not provide compelling evidence for the hypothesis that the SCP differentiation showed a larger increase over blocks in the SCP-trained participants compared to the SMR-trained participants. The ANOVA on the SMR response yielded no significant effects. This result indicates that, in the group average, the SMR response in the feedback phase did not deviate from the pretrial baseline in either the SMR-trained or SCP-trained participants and that no progress was made across blocks.

Performance

The performance of the participants was evaluated separately. The task for the participants was to increase the percentage of successful trials. The criterion for a successful trial was to exceed a personalized threshold level of the trained parameter for 2 sec (SCP) or 0.5 sec (SMR). The success percentage (the percentage of trials within a run in which the criterion was reached) was fed back continuously to the participants and updated after every trial. The mean success percentages of the five blocks are shown in Figure 7 for the D and U trials of the SCP-trained and SMR-trained groups separately. Although three of the four graphs show an increasing trend over experimental blocks, the increases in success percentages were modest.

Nevertheless, a number of participants did manage to increase their success percentage considerably, in one or both trial types. To illustrate this, the best performers in both trial types of both groups are included in the plots of Figure 7. In the SCP-trained group four participants increased by more than 2.5% per block on D trials. On the U trials, there were 3 SCP-trained participants with an increase rate larger than 1.5% per block with 1 participant achieving even an increase in success percentage of more than 8.5% per block. For the SMR participants, 2 participants achieved an increase of more than 2.5% per block on D trails and 2 participants increased more than 1.5% per block on U trials.

To investigate if the participants were able to increase their success percentage, a $2 \times 5 \times 2$ (Group $\times$ Block $\times$ Trial Type) repeated measures ANOVA was performed on the success percentages. In spite of a large number of participants showing the correct average physiological responses it cannot be concluded from the results of this analysis that the two groups of participants were able to improve their performance, as judged from the increase of their success percentage,

as the ANOVA did not demonstrate any significant effects.

DISCUSSION

A novel approach for single electrode SMR and SCP training was used on the basis of discrete feedback trials, employing automated online correction for EOG and a method for the derivation of personalized threshold settings. This approach was tested in an experiment that aimed to teach 19 participants to self-regulate their SCP or SMR amplitude through neurofeedback. More than half of the participants (10 of 19) were able to acquire some control over their SCP or SMR response, with the results showing distinctive interindividual differences. The SCP responders ($n = 4$) were mainly successful in SCP positivity trials, and SMR responders ($n = 6$) were successful in either SMR uptraining ($n = 4$) or SMR downtraining ($n = 3$), and 1 participant was able to master both conditions.

Consistent with previous studies, not all participants were able to gain control over their SCPs. In a study on healthy individuals by Rockstroh, Elbert, Birbaumer, and Lutzenberger (1990), less than half (21 of 45) of the participants mastered the skill of SCP self-regulation. This is very comparable to the results we observed in this study (4 of 9 participants). Hinterberger et al. (2004) reported successful regulation in 6, 4, and 2 participants in three groups of 18 participants receiving visual, auditory, and combined feedback, respectively. In contrast to our study, these studies used full-cap EEG systems for training their participants. The variability in the success of self-regulation of the SCP is also observed in patients with epilepsy (Rockstroh et al., 1993; Strehl et al., 2006) and patients with ALS (Neumann & Birbaumer, 2003).

A decrease in SCP differentiation of the SCP-trained responders was observed in the last blocks of the experiment. Because the acquisition of the skill of self-regulation is motivationally dependent (Kleinman, 1981) and oral reports from the participants in our experiment indicated a decrease in motivation throughout the second half of the experiment, we consider this to be a likely explanation for the performance decrease. For future research, a performance dependent monetary reward (Elbert, Rockstroh, Lutzenberger, & Birbaumer, 1980) or the coupling of participants to introduce a competitive element in the experiment (Parente & Parente, 2006) might boost the participants' motivation to maximize their performance.

One of the questions that may be answered with our experiment is whether SCP or SMR training has the most potential for BCI and epilepsy treatment. In total, 4 of 9 SCP-trained participants were successful, whereas in the SMR-trained group, 6 of 10 participants responded to the training procedure. SMR suppression or enhancement could be increased over the course of the training by, respectively, 3 and 4 SMR-trained participants. However, these participants showed the same response to both the D and U trials. This inability to differentiate suggests that it is difficult to switch between SMR enhancement and suppression on a very short time scale. We are unaware of previous research investigating SMR enhancement and suppression switching on a trial-by-trial basis. Sterman and Shouse (1980) were successful in both enhancing and suppressing SMR in single participants but not on a trial-by-trial basis. They switched contingencies after 3 months of rewarding SMR enhancement to rewarding SMR suppression and did not use discrete trials.

Of interest, in the SMR-trained group it was observed that the SMR enhancement trials were associated with larger SCP positivity compared to the SMR suppression trials. In contrast, the SCP-trained participants did not show equivalent changes in SMR response (Figure 6). Our data therefore support the notion that there is a relation between the SCP and the SMR. A possible relation between SCP and SMR was also proposed by Kotchoubey, Busch, Strehl, and Birbaumer (1999). They did not find consistent changes in EEG power spectra in their SCP-trained epilepsy patients but attributed the observed posttraining changes in delta,

theta, alpha, and beta frequency bands to nonspecific changes in the participants' brain state. A similar nonspecific effect can be concluded from our data, because we observed a constant SCP differentiation in the SMR-trained responders over the course of the experiment, whereas the SMR response was either increasing (enhancement trial responders) or decreasing (suppression trial responders). In addition, directional differentiation between the enhancement-required and suppression-required trials was observed for SCP but not for SMR. We suggest that SMR control sensitizes the striatal-thalamocortical motor loop, which causes modulation of excitability thresholds in this loop and thereby SCPs. On the other hand, the modulation of the loop's excitability thresholds by invoked SCPs does not appear to cause changes in the bursting behavior of the thalamic nuclei responsible for the generation of the SMR. This could imply that SMR training should be favored over SCP training for the purpose of epilepsy treatment, as SMR training would improve both the control over SMR mechanisms as well as excitability thresholds. However, the SCP seems to be the more sensitive parameter because we observed SCP differentiation between arousal-increasing and arousal-decreasing trials, whereas we did not detect SMR differentiation.

In theory, it is possible that the SCP differentiation in the SMR-trained participants originates from a source outside the brain (EMG/EOG contamination). However, EMG contamination is unlikely because it can be expected that the SMR response would be most highly affected by EMG artefacts. Because we observed a very similar SCP response (that was constant over blocks) in the enhancement trial responders and the suppression trial responders of the SMR-trained group while the SMR response of these groups developed in directions opposite to each other, we can exclude the involvement of EMG. It is possible that the EOG correction procedure is inadequate. However, we find this explanation highly unlikely, because the data from a third group that was trained (on Galvanic Skin Response) using the exact same procedure (Spronk, Arns, Kleinnijenhuis, Breteler, & van Luijtelaar, in preparation) did not show this SCP differentiation. If the experimental design would have caused consistent eye movements that affected the SCP at Cz and, moreover, would not have been corrected by the EOG correction procedure, we should have observed similar SCP differentiation in the SMR-trained participants and in this third group of Galvanic Skin Response–trained participants.

Similar to the physiological responses, the ability to improve the success percentage (above the 33% chance level) over sessions varied considerably across participants in our experiment. On average, the increase in the percentage of successful trials was only moderate, but individual participants showed considerable improvements in successful responses. Comparable results have been obtained by Neumann and Birbaumer (2003), who investigated correct response rates in a group of five patients with ALS who were trained on their SCPs. Their results indicated significant improvement in correct response rates in three patients, with only one patient exhibiting a very high and stable degree of control.

In other BCI research employing mu and beta rhythms, the correct response rate is generally higher than observed in this experiment. McFarland, Sarnacki, Vaughan, and Wolpaw (2005) reported accuracies ranging from 80% to 100% (with a chance level of 50%) after 10 sessions in 5 of 7 participants, whereas 2 participants were unable to achieve control over their mu or beta rhythm. Pfurtscheller and colleagues used a different approach to BCI. They classified imaginary movements of the users by detecting event-related desynchronization or event-related synchronization. In one of their initial BCI experiments, Pfurtscheller, Neuper, Flotzinger, and Pregenzer (1997) reported on 3 participants who showed large differences in EEG rhythms over sensorimotor cortex during left versus right hand movements that could be classified with an accuracy of 70 to 90% (chance level at 50%). However, 7 participants failed to show sufficient EEG differences.

The methodology that was used in these experiments was different from our own,

and this could explain the differences between the correct response rates. First, the trained EEG frequencies were different. We sought to investigate the possibility of operating a BCI with the 12 to 15 Hz rhythm, whereas McFarland et al. (2005) and Pfurtscheller et al. (1997) used a strategy of finding the exact frequency of mu or beta oscillation in individual participants and centering the bandpass filter around that frequency. Nevertheless, in experiments featuring this approach a number of participants also failed to respond to training, despite being trained on their exact mu or beta frequency. Moreover, a relatively large number of participants in other experiments did respond well to 12 to 15 Hz training without selection of the exact mu or beta frequency (Lantz & Sterman, 1988; Sterman, 1984). For example, Lubar and Lubar (1984) showed improvements in SMR acquisition with extended training in all six children that were included in their report. However, they did not specify the inclusion criteria. The selection of the mu or beta rhythm therefore is neither a requirement nor a guarantee for achieving control.

Second, only a single electrode was used in contrast to other studies. The electrode location for feedback used in this experiment was Cz. Whereas for SCP neurofeedback good results have been obtained with the Cz placement (Birbaumer et al., 1999; Hinterberger et al., 2004; Rockstroh et al., 1993) in sensorimotor neurofeedback lateralized electrodes over sensorimotor cortex are considered most suitable (Kropotov et al., 2005; Sterman & Friar, 1972). This is especially important in the procedure of Pfurtscheller et al., because the specific instruction of motor imagery of, for example, hand movements calls for the placement of electrodes over the hand areas of the motor cortex. Furthermore, Cz electrode placement can be problematic for measurement of the SMR, because of cancellation of non-phase-locked synchronized rhythmic activity from the left and right sensorimotor cortex on the sagittal midline (Storm van Leeuwen, & Versteeg, 1978; but see Egner and Gruzelier (2003) and Pfurtscheller, Brunner, Schlögl, and Lopes da Silva (2006) for examples of SMR/mu rhythm control over Cz). We selected the Cz electrodes for both the SCP and SMR-trained groups for standardization purposes between the groups, but this could have impeded learning in the SMR-trained participants.

Third, in principle it is possible that our evaluation of success was not optimally suited for learning to increase the success percentage. We adopted a procedure that started the participants at 33% (chance level) correct responses in the first experimental session, whereas in the aforementioned studies, chance level was at 50% correct responses. Related to this, the experiment featured an approach of fixed threshold levels based on two pretraining sessions. With this method, the thresholds may have been set too high. Because the participants were highly motivated at the start of the experiment, it is conceivable that learning has already taken place in the pretraining sessions. This would be in accordance with the results of Kotchoubey, Schleichert, Lutzenberger, and Birbaumer (1997), who found that healthy participants can learn to control their SCP in as few as two sessions. If the participants indeed learned to increase or decrease their SCP and SMR levels in the pretraining sessions to a near maximal performance, this would certainly have led to threshold settings that did not leave much room for improvement. For the SCP group, our data support this hypothesis, because already in the first block of the experiment a differentiation was found in the SCP response between D and U trials in some participants. Furthermore, the fixed threshold levels throughout the experiment could have diminished the performance. As was already argued by Skinner (1975), the shaping of the desired response is a very important element in operant conditioning. In neurofeedback, when the rewarding and discriminative value of the feedback decreases (e.g., in the case where a client responds adequately more than 90% of the time), the threshold for feedback is adapted to a lower level of reward. The client is informed about this change and socially rewarded by the therapist for the production

of the desired brain activity. Thus, a new, stricter criterion for successful responding is introduced in the context of improved performance. The inability of some participants to increase their success percentages and low degree of control over their physiological responses could have been because of the absence of a shaping procedure.

Fourth, the time window associated with the response criterion may be an important element. Our approach required the participants to sustain their SCP or SMR amplitude above threshold level for a period of time. The window for sustaining the threshold level was set at 0.5 sec for the SMR-trained participants. This criterion is very suitable for training patients with epilepsy to produce SMR, as they are rewarded only for extended burst of activity. For BCI, however, sustained activity is not necessary but could serve as a mechanism to reduce false positives. The SCP-trained participants had to hold their SCP above threshold for 2 sec. In the approach of Rockstroh et al. (1990) the SCP response is averaged over the active phase of the trial (3–5 sec) and considered correct if the average response is above a threshold level. Presumably, the correct response criterion of holding the SCP/SMR level above threshold for an extended period is more difficult, as only minor shifts in SCP/SMR amplitude can have a large impact on whether the criterion is met. This can possibly explain the difficulty of improving the correct response rate in our experiment. This can also explain why some participants seemed to improve their correct response rate to a lesser extent than their physiological performance.

Another consideration related to the trial setup that could have influenced our results negatively is the continuation of the trial after the delivery of the reward. In operant conditioning, a rewarded response is followed by a burst of dominant frequency activity called a postreinforcement synchronization (PRS) that indicates a strengthening of the associations between the response and the reward (Buchwald, Horvath, Wyers, & Wakefield, 1964; Clemente, Sterman, & Wyrwicka, 1964; Pfurtscheller, 1992; Sterman, 1996). The occurrence of a PRS is therefore an important element of learning in neurofeedback. In our experiment, the PRS may have been hampered by possible effects of not ending a trial immediately after the reward has been delivered. Instead, on reaching the reward criterion the feedback on the physiological parameter continued for the remainder of the trial. The ongoing feedback after the reward delivery could have encouraged the participants to unconsciously stay focused on the feedback and thereby hampered the PRS necessary for consolidation of the response–reward association. Furthermore, the continuation of the trial might have confused the participants in thinking that they had not reached the true goal yet.

CONCLUSIONS

Using this approach, 10 of 19 participants trained on their SCPs or SMR were able to achieve control over their brain activity. The group of SCP-trained participants showed more improvement in the positivity-required condition as compared to the negativity-required condition. The group of SMR-trained participants performed better on SMR enhancement as compared to SMR suppression. For SMR, most participants did not achieve bidirectional control. The answer to the question which EEG characteristic, SCP or SMR, could be controlled best is inconclusive. A larger percentage of participants were able to gain unidirectional control over SMR, but the responding SCP-trained participants showed bidirectional differentiation. Our findings indicate that for BCI research future studies should acknowledge interindividual differences. For example, by finding whether someone is better in up or downtraining SCP or SMR, one could focus the training only on that aspect rather than focusing on bidirectional control. Our results also stress the need for personalizing training procedures for clients in order to achieve reliable responses with BCIs. Of interest, changes in the passively recorded parameter occurred in the SMR but not in the SCP-trained group, that is, the SMR-trained group

showed SCP differentiation, but the SCP-trained group did not show equivalent effects in SMR response. This suggests that excitability thresholds in the striatal-thalamocortical motor loop are modulated by SMR training, whereas shifts in the excitability thresholds in this loop induced by SCP training do not affect the thalamic bursting that underlies the SMR.

REFERENCES

Arns, M. W., & van Dorsten, J. W. A. (2005). *System is for recording electrical signals occurring in living body and has at least two electrodes for obtaining first analogue signal corresponding with electrical signal occurring in living body* (Patent NL1024860C).

Bazhenov, M., Timofeev, I., Steriade, M., & Sejnovski, T. J. (1999). Self-sustained rhythmic activity in the thalamic reticular nucleus mediated by depolarizing GABA-A receptor potentials. *Nature Neuroscience*, *2*(2), 168–174.

Beauregard, M., & Lévasque, J. (2006). 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. *Applied Psychophysiology and Biofeedback*, *31*(1), 3–20.

Birbaumer, N. (2006). Breaking the silence: Brain–computer interfaces (BCI) for communication and motor control. *Psychophysiology*, *43*, 517–532.

Birbaumer, N., Elbert, T., Canavan, A. G. M., & Rockstroh, B. (1990). Slow potentials of the cerebral cortex and behavior. *Physiological Reviews*, *70*(1), 3–41.

Birbaumer, N., Flor, H., Ghanayim, N., Hinterberger, T., Iverson, I., Taub, E., et al. (1999). A spelling device for the paralyzed. *Nature*, *398*, 297–298.

Breteler, R., de Ridder, S., Monsuwe, A., & Arns, M. (2006). *The usability of tele-neurofeedback: Procedures and results.* Presented at the 2006 Society for Applied Neuroscience Inaugural Abstracts, paper session, Swansea, Sept. 2006.

Buchwald, N. A., Horvath, F. E., Wyers, E. J., & Wakefield, C. (1964). Electroencephalogram rhythms correlated with milk reinforcements in cats. *Nature*, *201*, 830–831.

Clemente, C. D., Sterman, M. B., & Wyrwicka, W. (1964). Post-reinforcement EEG synchronization during alimentary behaviour. *Electroencephalography and Clinical Neurophysiology*, *16*, 355–365.

Egner, T., & Gruzelier, J. H. (2003). EEG biofeedback of low beta band components: frequency-specific effects on variables of attention and event-related brain potentials. *Clinical Neurophysiology*, *115*, 131–139.

Elbert, T., Rockstroh, B., Lutzenberger, W., & Birbaumer, N. (1980). Biofeedback of slow cortical potentials. *Electroencephalography and Clinical Neurophysiology*, *48*, 293–301.

Ferster, C. B., & Skinner, B. F. (1957). *Schedules of reinforcement*. New York: Appleton-Century-Crofts.

Gordon, E. (2003). Integrative neuroscience and psychiatry. *Neuropsychopharmacology*, *28*, 2–8.

Gratton, G., Coles, M. G. H., & Donchin, E. (1983). A new method for off-line removal of ocular artifact. *Electroencephalography and Clinical Neurophysiology*, *55*, 468–484.

Hinterberger, T., Neumann, N., Pham, M., Kübler, A., Grether, A., Hofmayer, N., et al. (2004). A multimodal brain-based feedback and communication system. *Experimental Brain Research. Experimentelle Hirnforschung. Experimentation Cerebrale*, *154*(4), 521–526.

Hinterberger, T., Veit, R., Strehl, U., Trevorrow, T., Erb, M., Kotchoubey, B., et al. (2003). Brain areas activated in fMRI during self-regulation of slow cortical potentials (SCPs). *Experimental Brain Research. Experimentelle Hirnforschung. Experimentation Cerebrale*, *152*, 113–122.

Kleinman, K. M. (1981). The role of reinforcement and motivation in biofeedback performance. *Physiology & Behavior*, *26*(5), 921–925.

Kotchoubey, B., Busch, S., Strehl, U., & Birbaumer, N. (1999). Changes in EEG power spectra during biofeedback of slow cortical potentials in epilepsy. *Applied Psychophysiology and Biofeedback*, *24*(4), 213–233.

Kotchoubey, B., Schleichert, H., Lutzenberger, W., & Birbaumer, N. (1997). A new method for self-regulation of slow cortical potentials in a timed paradigm. *Applied Psychophysiology and Biofeedback*, *22*(2), 77–93.

Kotchoubey, B., Strehl, U., Uhlmann, C., Holzapfel, S., König, M., Fröscher, W., et al. (2001). Modification of slow cortical potentials in patients with refractory epilepsy: A controlled outcome study. *Epilepsia*, *42*(3), 406–416.

Kropotov, J. D., Grin-Yatsenko, V. A., Ponomarev, V. A., Chutko, L. S., Yakovenko, E. A., & Nikishena, I. S. (2005). ERPs correlates of EEG relative beta training in ADHD children. *International Journal of Psychophysiology*, *55*, 23–34.

Kübler, A., Kotchoubey, B., Hinterberger, T., Ghanayim, N., Perelmouter, J., Schauer, M., et al. (1999). The thought translation device: a neurophysiological approach to communication in total motor paralysis. *Experimental Brain Research. Experimentelle Hirnforschung. Experimentation Cerebrale*, *124*, 223–232.

Kübler, A., Nijboer, F., Mellinger, J., Vaughan, T. M., Pawelzik, H., Schalk, G., et al. (2005). Patients with ALS can use sensorimotor rhythms to operate a brain-computer interface. *Neurology*, *64*, 1775–1777.

Lantz, D. L., & Sterman, M. B. (1988). Neuropsychological assessment of subjects with uncontrolled epilepsy: Effects of EEG feedback training. *Epilepsia*, *29*, 163–171.

Lubar, J. O., & Lubar, J. F. (1984). Electroencephalographic biofeedback of SMR and beta for treatment of attention deficit disorders in a clinical setting. *Biofeedback and Self-Regulation*, *9*(1), 1–23.

McFarland, D. J., Sarnacki, W. A., Vaughan, T. M., & Wolpaw, J. R. (2005). Brain-computer interface (BCI) operation: Signal and noise during early training sessions. *Clinical Neurophysiology*, *116*, 56–62.

Nagai, Y., Goldstein, L. H., Critchley, H. D., & Fenwick, P. B. C. (2004). Influence of sympathetic autonomic arousal on cortical arousal: Implications for a therapeutic behavioral intervention in epilepsy. *Epilepsy Research*, *58*(3), 185–193.

Neumann, N., & Birbaumer, N. (2003). Predictors of successful self control during brain-computer communication. *Journal of Neurology, Neurosurgery, and Psychiatry*, *74*(8), 1117–1121.

Neumann, N., Hinterberger, T., Kaiser, J., Leins, U., Birbaumer, N., & Kübler, A. (2004). Automatic processing of self-regulation of slow cortical potentials: Evidence from brain-computer communication in paralyzed patients. *Clinical Neurophysiology*, *115*, 628–635.

Parente, A., & Parente, R. (2006). Mind-operated devices: mental control of a computer using biofeedback. *Cyberpsychology & Behavior*, *9*(1), 1–4.

Pfurtscheller, G. (1992). Event-related synchronization (ERS): An electrophysiological correlate of cortical areas at rest. *Electroencephalography and Clinical Neurophysiology*, *83*, 62–69.

Pfurtscheller, G., Brunner, C., Schlögl, A., & Lopes da Silva, F. H. (2006). Mu rhythm (de)synchronization and EEG single-trial classification of different motor imagery tasks. *NeuroImage*, *31*, 153–159.

Pfurtscheller, G., Flotzinger, D., Pregenzer, W., Wolpaw, J. R., & McFarland, D. J. (1996). EEG-based brain–computer interface (BCI): search for optimal electrode positions and frequency components. *Medical Progress Through Technology*, *21*, 111–121.

Pfurtscheller, G., Neuper, Ch., Flotzinger, D., & Pregenzer, M. (1997). EEG-based discrimination between imagination of right and left hand movement. *Electroencephalography and Clinical Neurophysiology*, *103*, 642–651.

Rockstroh, B., Elbert, T., Birbaumer, N., & Lutzenberger, W. (1990). Biofeedback-produced hemispheric asymmetry of slow cortical potentials and its behavioral effects. *International Journal of Psychophysiology*, *9*, 151–165.

Rockstroh, B., Elbert, T., Birbaumer, N., Wolf, P., Duchting-Roth, A., Reker, M., et al. (1993). Cortical self-regulation in patients with epilepsies. *Epilepsy Research*, *14*(1), 63–72.

Skinner, B. F. (1975). The shaping of phylogenic behaviour. *Journal of the Experimental Analysis of Behavior*, *24*(1), 117–120.

Spronk, D. B., Arns, M. W., Kleinnijenhuis, M., Breteler, M. H. M., & van Luijtelaar, G. (in preparation). Manuscript in preparation.

Sterman, M. B. (1982). EEG biofeedback in the treatment of epilepsy: An overview circa 1980. In L. White & B. Tursky (Eds.), *Clinical biofeedback: Efficacy and mechanisms* (pp. 311–330). New York: Guilford.

Sterman, M. B. (1984). The role of the sensorimotor EEG activity in the etiology and treatment of generalized motor seizures. In T. Elbert, B. Rockstroh, W. Lutzenberger, & N. Birbaumer (Eds.), *Self-regulation of the brain and behavior* (pp. 95–106). Berlin: Springer.

Sterman, M. B. (1996). Physiological origins and functional correlates of EEG rhythmic activities: Implications for self-regulation. *Biofeedback and Self-Regulation, 21*(1), 3–33.

Sterman, M. B. (2000). Basic concepts and clinical findings in the treatment of seizure disorders with EEG operant conditioning. *Clinical EEG (Electroencephalography), 31*(1), 45–55.

Sterman, M. B., & Friar, L. (1972). Suppression of seizures in an epileptic following sensorimotor EEG feedback training. *Electroencephalography and Clinical Neurophysiology*, *1*, 57–86.

Sterman, M. B., & Shouse, M. N. (1980). Quantitative analysis of training, sleep EEG, and clinical response to EEG operant conditioning in epileptics. *Electroencephalography Clinical Neurophysiology, 49*(5), 558–576.

Storm van Leeuwen, W., Wieneke, G., Spoelstra, P., & Versteeg, H. (1978). Lack of bilateral coherence of mu rhythm. *Electroencephalography and Clinical Neurophysiology*, *44*, 140–146.

Strehl, U., Trevorrow, T., Veit, R., Hinterberger, T., Kotchoubey, B., Erb, M., et al. (2006). Deactivation of brain areas during self-regulation of slow cortical potentials in seizure patients. *Applied Psychophysiology and Biofeedback, 31*(1), 85–94.

Tozzo, C. A., Elfner, L. F., & May, J. G. (1988). EEG Biofeedback and relaxation training in the control of epileptic seizures. *International Journal of Psychophysiology*, *6*, 185–194.

Wolpaw, J. R., Birbaumer, N., McFarland, D. J., Pfurtscheller, G., & Vaughan, T. M. (2002). Brain–computer interfaces for communication and control. *Clinical Neurophysiology*, *113*, 767–791.