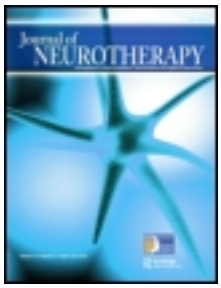

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Discrete-Trial SCP and GSR Training and the Interrelationship Between Central and Peripheral Arousal

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Discrete-Trial SCP and GSR Training and the Interrelationship Between Central and Peripheral Arousal

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ABSTRACT. *Introduction*. Slow Cortical Potential (SCP) neurofeedback and Galvanic Skin Response (GSR) biofeedback training were used to investigate self-regulatory control over central and peripheral arousal processes in two groups of healthy participants.

Method. One group completed the SCP neurofeedback training procedure; the other group performed the GSR biofeedback procedure. Both groups underwent treatment while the other variable was passively recorded. The participants were instructed to either increase (Up trials) or decrease (Down trials) arousal. Twenty sessions were completed by each of the 18 participants over an 8-week period.

Results. Participants in each group performed better on the variable they were trained on. In the GSR group, a significant increase in performance over blocks was obtained for both trial types (Up and Down). In the SCP group a better performance on the Down trials was obtained. When comparing performance of both trial types, the SCP-trained participants showed a marginal increase and the GSR-trained participants a significant increase over time preliminary-training.

Conclusion. Overall, the results showed that GSR regulation is easier to learn than SCP training with neurofeedback, that both variables can be trained in a bidirectional design, and that the SCP training subjects were predominantly able to learn performance at the Down trials. Preliminary results from the cross-correlations are inconsistent over trial types, trained parameters, and participants. However, the general trend shows a more positive correlation at the end of training compared to the start of training. Cross-correlation analysis suggests that this training encourages positive correlation between the SCP and GSR. Future research directions should be aimed at improving motivational conditions, implementing contingent reward principles, and controlling confounding variables.

KEYWORDS. EEG biofeedback, galvanic skin response, GSR biofeedback, neurofeedback, operant conditioning, slow cortical potential

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INTRODUCTION

Slow cortical potential (SCP) and galvanic skin response (GSR) biofeedback are techniques by which a person receives real-time feedback on their SCP or GSR measures, respectively. The primary purpose of these biofeedback techniques can be either clinical or in the field of Brain Computer Interfacing. Most work on GSR biofeedback was performed in the field of relaxation training (Collet, Cottraux, & Juenet, 1986; Parente & Parente, 2006), but it has also been proposed as a treatment modality for epilepsy (Nagai, Goldstein, Fenwick, & Trimblea, 2004), SCP neurofeedback has been applied mostly in the treatment of epilepsy (Kotchoubey et al., 2001; Rockstroh et al., 1993), ADHD (for an overview, see Arns, de Ridder, Strehl, Breteler, & Coenen, 2009), migraine (Kropp, Siniatchkin, & Gerber, 2002) and as a communication tool for ALS patients (Birbaumer et al., 2000; Hinterberger, Kubler, Kaiser, Neumann, & Birbaumer, 2003; Hinterberger et al., 2004; Kübler et al., 1999). Despite the investigation and performance of both techniques in a variety of applications, a better understanding of the underlying mechanisms and learning processes during both training protocols is necessary in order to offer better and more efficient clinical treatment.

SCPs are a reflection of potential changes in the cerebral cortex. The SCP can be regarded as a measure of *central* arousal, because changes in SCP amplitude reflect varying levels of excitability of cortical pyramidal neurons. SCPs are in the frequency range of 0.1–2 Hz and have a duration from 300 ms up to several seconds (Birbaumer, as cited in Elbert, 1993). Healthy volunteers performing a SCP protocol—which consists of discrete training or bidirectional control (training both negativity *and* positivity)—were able to successfully demonstrate amplitude differences between positivity-required and negativity-required SCP conditions (Elbert et al., 1980). Acquiring successful control over SCPs has been associated with reduction of symptoms in epilepsy, ADHD, and migraine patients (Arns et al., 2009; Kotchoubey et al., 2001; Kropp et al., 2002; Siniatchkin, Kropp, & Gerber, 2000; Strehl et al., 2006). Another application of SCP control is in brain-computer interfacing. Using this technique, patients with ALS (locked-in syndrome) are able to communicate by means of shifting their SCP in a positive or negative direction to choose, for instance, letters of the alphabet (Birbaumer et al., 2000, Hinterberger et al., 2003; Hinterberger et al., 2004; Kübler et al., 1999).

The GSR response is mediated by the autonomic nervous system (Wallis, 1981) and has been used to index arousal for a long time (Lykken & Venables, 1971). Most often in biofeedback applications, GSR training consists of subjects learning to lower their GSR, or arousal, to achieve relaxation (Alster, Oren, Wolmer, & Ron, 1997; Fehring, 1983). However, in a recent study by Nagai, Goldstein, Fenwick, et al. (2004a) it was shown that upregulating GSR/arousal led to a reduction in seizures in patients with epilepsy. The use of discrete—bidirectional—GSR training similar to the methods used in SCP training (voluntary increases *and* decreases of GSR) has not been performed to the authors' knowledge. Some older studies, however, have indicated that the naturally occurring decline of the phasic GSR response can be successfully inhibited (Volow, Erwin, & Cipolat, 1979) and that participants can acquire the skill to successfully decrease their GSR in relaxation studies (Collet et al., 1986; Fehring, 1983).

GSR and SCPs are both measures of arousal, which at least partly share a common neurophysiological network. Imaging studies that have examined GSR-related brain activity, demonstrate activation of a distributed network of brain regions (Critchley, Melmed, Featherstone, Mathias, & Dolan, 2001, 2002; Fredrikson et al., 1998). Furthermore, peripheral and central arousal measures share common underlying reticulo-thalamo-hypothalamo-cortical networks suggesting a functional link between central and peripheral arousal measures (Lim et al., 1996). To our knowledge, only one study has addressed the relationship between the GSR and SCP arousal measures in which an inverse relationship was demonstrated. It was shown that the Contingent Negative Variation (a slow cortical potential) was greater in amplitude in a

state of lower peripheral arousal (Nagai, Goldstein, Critchley, & Fenwick, 2004). In a study by Barry, Clarke, Johnstone, McCarthy, and Selikowitz (2009), it was shown that the skin conductance level (also referred to as GSR) was correlated with alpha EEG power rather than theta/beta ratio. However, which EEG frequencies are the best reflection of arousal is still not clearly defined (Barry et al., 2004; Lim et al., 1996). The definition of arousal is also not unequivocally known, or used in the same manner among researchers. These studies show that there is still much uncertainty about the interrelationships between these arousal measures.

Although there is evidence that GSR biofeedback and SCP neurofeedback procedures are quite successful in a variety of applications, many questions regarding the actual learning processes remain. For the purpose of this study, a new SCP neurofeedback and GSR biofeedback design were developed (for technical details, see Kleinnijenhuis, Arns, Spronk, Breteler, & Duysens, 2008) and subsequently examined in healthy participants who completed either the GSR or SCP feedback procedure. From the studies just described, a significant learning rate was expected for both procedures, and therefore we expected a clear increase in performance over time for both training procedures. In addition, differences in performance on increases and decreases in arousal were specifically compared. To investigate the interrelationships between these two feedback modalities, both GSR and SCPs were recorded from all participants throughout the training in order to directly compare GSR biofeedback and SCP neurofeedback. The correlations between central (SCPs) and peripheral (GSR) arousal were explored by means of simultaneous recordings of both SCP and GSR, where one modality was trained and the effects in the other modality were investigated.

METHODS

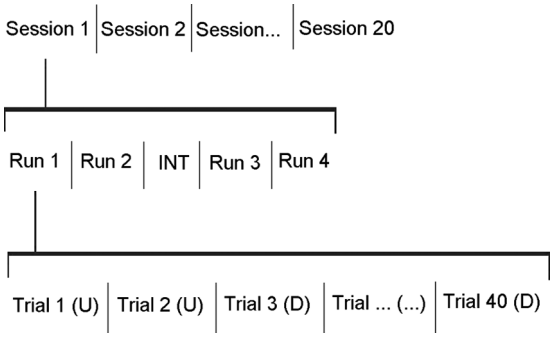
Participants

In this study 20 healthy individuals participated in a standardized biofeedback training program. There was one dropout after the qEEG pretest, and 1 participant did not complete 20 sessions and was therefore excluded from the analysis. The final group consisted of 8 men and 10 women. The mean age of the participants was 23.2 years (range = 18–40 years). Exclusion criteria were the presence of a psychiatric or neurological history, drug abuse or a history of drug usage, and/or use of psychoactive medication. Every participant gave informed consent prior to the study. The study was approved by the Institutional Review Board (METC Noord-Holland).

Design and Procedure

The participants were distributed over two groups: one group received feedback on their SCP and one received feedback on their GSR signal. Each group consisted of 9 participants and were matched with respect to gender and age. From each participant the EEG (SCP) and the GSR were recorded simultaneously, but feedback was provided on only one of the variables. Every participant completed 2 pretraining sessions and 20 training sessions, which were distributed over an 8-week period. Sessions were 30 min long. Each session was divided into four runs. Each run consisted of 40 trials, of which 16 trials were in the upward direction (U trials) and 24 trials were in the downward direction (D trials); see Figure 1. Each trial had a duration of 8 s and started

FIGURE 1. Construction of the SCP neurofeedback/GSR biofeedback training. U trials reflect an increase in arousal, D trials reflect a decrease in arousal.



with a tone. The baseline of the feedback signal was determined in the last 500 ms of the 1st s. After the baseline period, the trial entered the 7-s feedback phase. The order of the trials was randomized within a session.

The participant sat in front of the computer screen, whereupon he was connected to the EEG and the GSR devices. A couple of minutes were recorded to ensure SCP and GSR signals were stabilized. During the 1st s, the trial type was indicated, by lighting up either the upper squares (U trials) or lower squares in the feedback screen (D trials). During the feedback phase, feedback was provided to the real-time measured level of the signal as compared to the 500 ms pretrial phase. Feedback was reflected by the varying height of a vertical bar that moved according to the amplitude of the signal. When the participant was able to move the signal in the desired direction and pass a threshold for more than 2 s, this was rewarded by a smiley image and a tone.

For the SCP group, feedback was provided based upon the SCP signal, whereas for the GSR group feedback was based upon the GSR signal. In the SCP design a negative SCP shift was reflected by an upward movement (increase in central arousal) and a positive SCP shift was reflected by a downward movement (decrease in central arousal). A negative GSR shift (decrease in peripheral arousal) was represented by a downward movement and a positive GSR shift (increase in peripheral arousal) was represented by an upward movement of the bar. For a more elaborate description of the design and procedure, see Kleinnijenhuis et al. (2008).

Physiological Recordings and Materials

The participants' EEG was recorded at Cz and was referenced against linked mastoids using a wireless two-channel bipolar EEG device (Brainquiry PET-EEG). The SCPs were computed from the EEG by a moving average of 500 ms that was updated every sample of the EEG and was recorded with a rate of 200 samples per second. The second channel was used for recording of vertical eye movements. Electrodes were placed 1 cm above and below the middle of the right eye. Active silver-silver chloride electrodes were used for all recordings. All electrode sites were abraded with a preparation gel to reduce impedances. For more details, see Kleinnijenhuis et al. (2008). The GSR was recorded by a wireless GSR device (Brainquiry PET-GSR). The GSR was recorded from the third and fourth finger of the nondominant hand. Before application of the GSR electrodes, the recording sites were cleaned with an alcohol swab. The device has a range of 0–10 MΩ and has a sensitivity of 5–50 kΩ with a maximal deviation of 2%. The GSR signal was sampled at a rate of 10 Hz and was filtered with a high pass first-order Butterworth filter with a cut-off frequency of 0.5 Hz. The protocol designs were created in BioExplorer (CyberEvolution, Seattle, WA) and can be found at http://www.brainclinics-products.com.

Data Analyses

Each participant was provided with individually determined threshold settings for the D and U trials. Grand-average SCP and GSR amplitudes were obtained by averaging the recorded signal for each trial type separately in five blocks of four sessions. For details on the threshold procedure and computation of the integrals, see Kleinnijenhuis et al. (2008). In addition, we calculated a differentiation measure by subtracting the integrals of the D and U trials. This was done to investigate general performance levels, rather than specifically looking at the differences in performance for the two trial types.

Statistical analyses were conducted using the SPSS 17.0 software package. Integrals of the U and D trials over five blocks were analyzed by means of repeated measures analyses of variance (ANOVA). To compare the integrals of the U and D trials directly, for the SCP signal the U trials were multiplied with −1 and for the GSR signal the D trials were multiplied with −1. The differentiation measure was analyzed by a separate repeated measures ANOVA with five levels of block. In case of significant results

from the ANOVA, planned comparisons were performed to explore trends in learning over blocks.

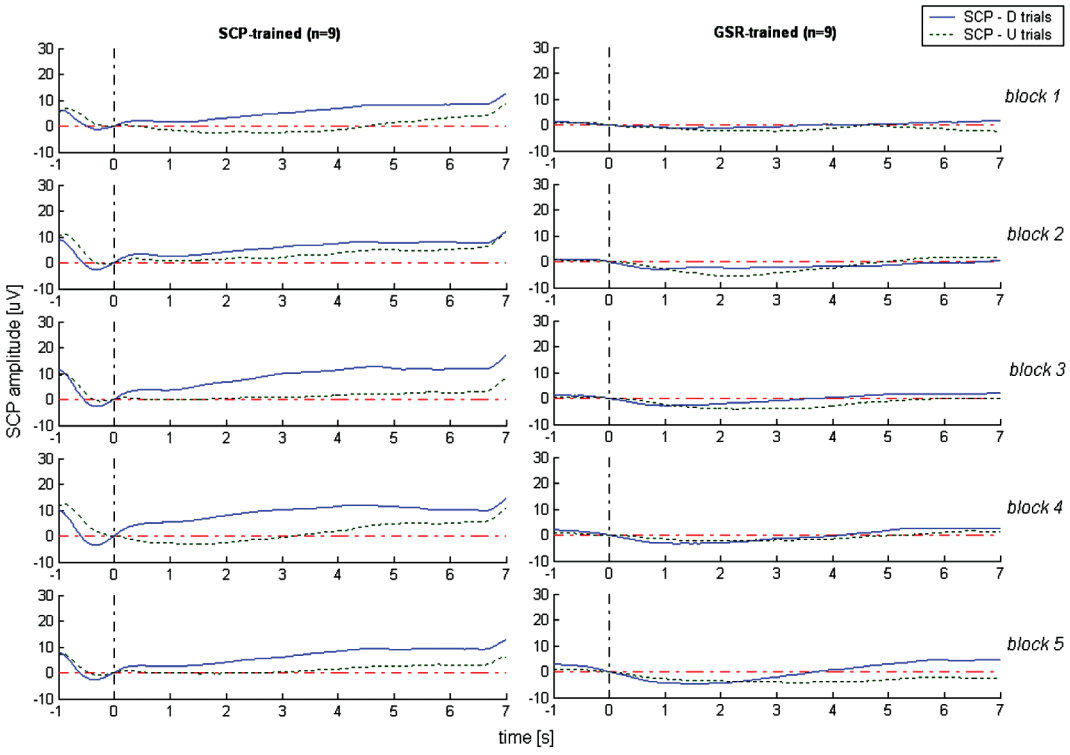
The relation between the SCP and the GSR was investigated by cross-correlating the SCP grand-averages with the GSR grand-averages of every participant for the D and U trials separately. To evaluate if any change in the relationship between SCP and GSR had occurred as a result of the training procedure, the cross-correlations were computed for the first and the last session. Furthermore, the cross-correlations were calculated at several lags. It is plausible that the lag with the highest correlation between SCP and GSR can be found in the positive range because the GSR is a relatively slow signal as compared to the SCP and therefore would lag behind the SCP. The cross-correlations are therefore evaluated at time lags 0, 1, 2, 3, and 4 s. Cross correlation-coefficients were averaged over the participants in each group. Comparisons between the first and the last session, as well as between the positive and negative trials, were made and discussed separately for the SCP-trained and the GSR-trained participants.

RESULTS

SCP Performance

The SCP performances on D and U trials for SCP-trained and GSR-trained participants are displayed in Figure 2. A repeated measures ANOVA with the factors trial-type, group, and block revealed a significant effect of group, $F(1, 16) = 5.21$, $p = .036$. As expected, SCP-trained participants (who were trained to control this variable) showed a larger effect on the SCP than GSR-trained participants (from whom the SCP was only passively recorded).

FIGURE 2. Mean SCP grand average amplitudes for SCP-trained and GSR-trained participants over all blocks for Down and Up trials. Please note that the figures on the left shows the 'learning effect' and the figures on the right the potential interrelations (subjects were trained on GSR and the SCP amplitude is shown for those trials).

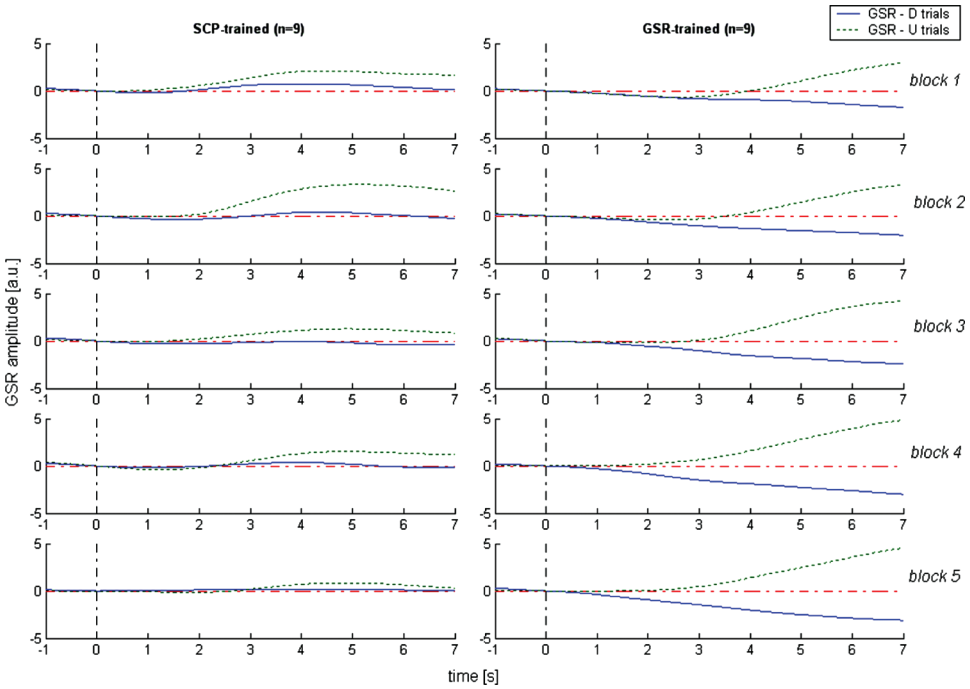


Changes in SCP performance were also calculated with a repeated measures ANOVA for the SCP-trained group separately. There were no significant effects of block, $F(1, 8) = 1.70$, $p = .175$, nor was there a significant Block × Trial-Type interaction effect, $F(4, 32) = 1.42$, $p = .249$. This means that the SCP performance of the SCP-trained participants did not change over the course of the training for both of the trial types. There was a significant effect for trial-type, $F(1, 8) = 19.43$, $p = .002$, with better performance for the D trials as compared to the U trials (see Figure 2). The differentiation measure (i.e., the net area between the curves of the D and U trials) that looks at an integrated measure of learning, rather than for each of the trials separately, showed a marginally significant effect of block, $F(4, 32) = 2.23$, $p = .088$. The effect showed an increase in learning over blocks; however, the planned comparison on trend did not yield a significant effect ($p > .05$).

GSR Performance

A repeated measures ANOVA was conducted to explore the effect of between-subject factor group (SCP-trained and GSR-trained) and within-subject factors block (five levels) and trial-type (D and U) for the GSR performance (see Figure 3). There was a statistically significant main effect of group, $F(1, 16) = 5.00$, $p = .040$. In a similar fashion as for the SCP-trained group, the GSR-trained participants—who were trained to control their GSR—showed a larger effect on the GSR signal than the SCP-trained (in whom the GSR was only passively recorded). Follow-up repeated measures ANOVA within the GSR-trained group showed that there were no differences in performance for trial-type, $F(1, 8) = .759$, $p = .409$, indicating equal performance for both trial-types. However, there was a significant effect of performance over blocks, $F(4, 32) = 4.41$, $p = .006$. Planned contrasts

FIGURE 3. Mean GSR grand average amplitudes for GSR-trained and SCP-trained participants over all blocks for Down and Up trials. Please note that the figures on the right shows the 'learning effect' and the figures on the left the potential interrelations (subjects were trained on SCP's and the GSR amplitude is shown for those trials).



showed that there was a significant linear trend over blocks, $F(1, 8) = 8.79$, $p = .018$, indicating a linear improvement over time in both trial-types. Investigation of the "differentiation" measures (by taking the performance of both trials together as a single measure of learning) showed a significant effect of block, $F(4, 32) = 4.41$, $p = .006$. Planned comparisons showed a significant linear trend over block, $F(1, 8) = 8.80$, $p = .016$, associated with an overall improvement in self-control over time.

Interrelationship Between SCP and GSR

To investigate a possible relationship between central and peripheral arousal measures, the group-averaged cross-correlation between the SCP and the GSR were compared on positive and negative trials at different time lags.

SCP trained. As can be seen in Figures 4-1, the cross-correlation in the D trials for the SCP-trained participants in Session 1 is largest at time lag 0 s. The SCP and GSR are negatively correlated. That indicates that the SCP and GSR time courses show a tendency of opposite behavior, that is, increases in SCP are associated with decreases in GSR and vice versa. In the last session, however, the largest correlation is positive and occurs with a lag of 1 or 2 s. Therefore, the supposed SCP–GSR relation changed from an opposite pattern in Session 1 to more similar time courses in Session 20 with the GSR lagging 1 to 2 s behind the SCP.

In the U trials, the highest correlation in Session 1 is positive and observed at time lag 0 (see Figures 4-2). In Session 20 the highest correlation is positive as well and is found in case of no time lag between the SCP and GSR signals. The cross-correlation in Session 20, however, is considerably larger as compared to Session 1. Similarly, in the U trials the SCP and GSR signals are more similar at the end of training.

GSR trained. Similar to the SCP-trained participants in the first session, the GSR-trained participants showed a negative correlation between SCP and GSR in the D trials, which is largest at time lags of 2 to 3 s (see Figures 5-1). Different from the SCP-trained participants, however, is the fact that in Session 20 the correlation is also negative. The largest coefficient is now found at time lag 0 s, whereas the SCP-trained participants showed a lag of 1 to 2 s in Session 20. Although only moderate, the trend that was observed in the SCP-trained group was more positively correlated at the end of the training.

Evaluating the cross-correlations of the U trials in Figures 5-2, the SCP and GSR are

FIGURE 4. Cross-correlations between the SCP and GSR in Down trials (left panel) and Up (right panel) trials averaged over the nine SCP-trained participants at time lags 0, 1, 2, 3, and 4 seconds for the first and last session.

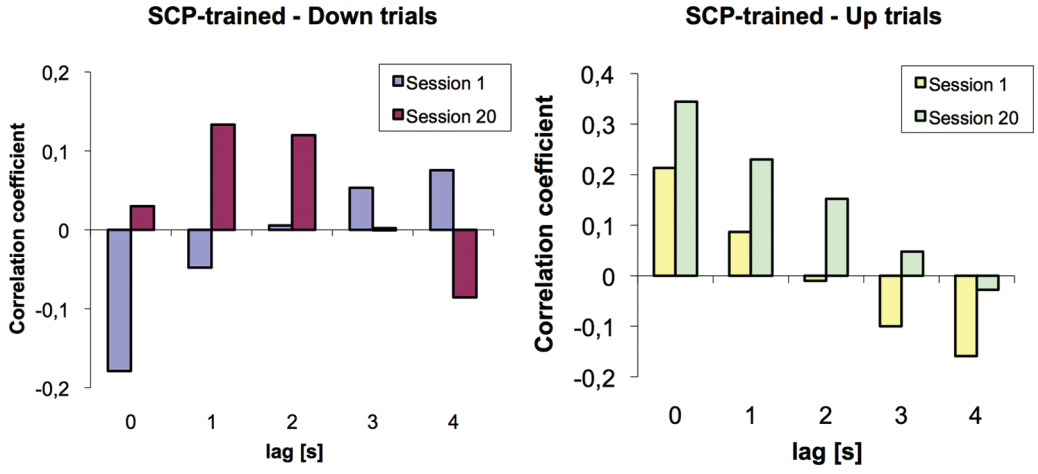
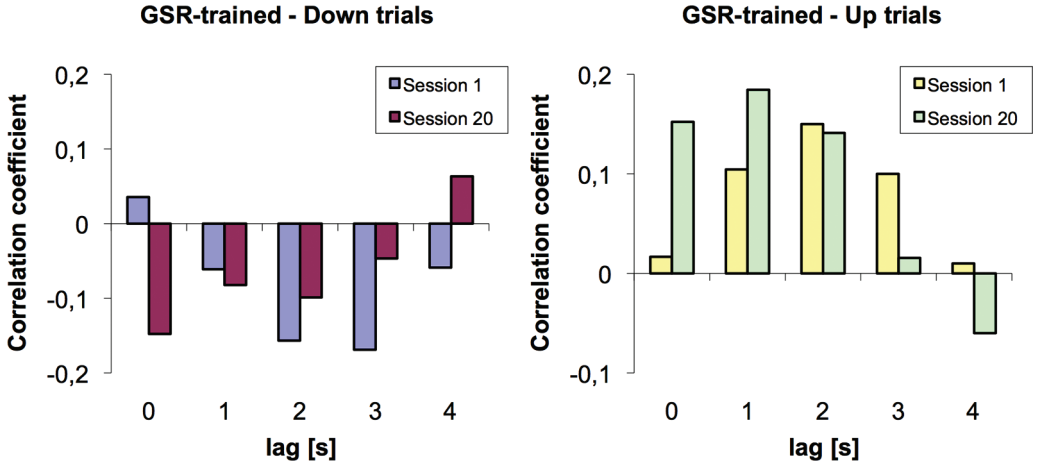


FIGURE 5. Cross-correlations between the SCP and GSR in Up (right panel) and Down (left panel) trials averaged over the nine GSR-trained participants at time lags 0, 1, 2, 3, and 4 seconds for the first and last session.



maximally (positively) correlated at a time lag of 2 s in Session 1. Comparable to the D trials of the GSR-trained participants, the time lag of maximal correlation decreases in Session 20 and occurs with the GSR lagging 1 s behind the SCP. The positive correlation is similar to the U trials of the SCP-trained participants, larger in Session 20 as compared to Session 1.

The results of the cross-correlation analysis thus indicate that the cross-correlation coefficients are generally more positive and more stable over groups and trial types at the end of training as compared to the start of training. The time lag of maximal correlation is relatively small (0–1 s) in Session 20.

DISCUSSION

In the present study the effects of a SCP neurofeedback and GSR biofeedback training were evaluated and compared. A new training paradigm was developed, and this was the first application of a bidirectional design (increase and decrease of arousal) in a GSR biofeedback paradigm (this approach being identical to what is done in SCP training). Moreover, preliminary analyses were carried out to examine the relation between central (SCP) and peripheral (GSR) arousal.

Analyses of variance on SCP and GSR performance demonstrated a group effect. SCP-trained participants performed better with respect to the SCP data than the GSR-trained participants, whereas the GSR-trained participants performed better with respect to the GSR data, which is what would be expected. To summarize the physiological findings, it can be concluded that in terms of the bidirectional design, GSR biofeedback was the easiest to learn. Also, it was confirmed that the primary learning effect can be found in the variable being trained, that is, if participants are trained with SCP, then the differentiation of the SCP is also largest. A significant increase in performance over blocks could be demonstrated for the GSR-trained group. A marginal significant effect for the SCP-trained participants for the differentiation measure was observed, indicating a small improvement in the learning course over time. The SCP-trained participants showed overall a better performance for D trials, whereas no differences in performance for both trial-types were observed in the GSR-trained group. This suggests that learning to decrease one's central arousal is easier to obtain. This finding has potential implications for the development of Brain Computer Interfacing (see also Kleinnijenhuis et al., 2008).

With regard to SCP training in healthy participants, it has been previously reported that the results were not as good as in

patients (Schneider, Heimann, Mattes, Lutzenberger, & Birbaumer, 1992). Kübler (in Hinterberger et al., 2004) argued that healthy participants may have low subjective attributions of self-efficacy. It can also be concluded that learning of skills without any external or internal perceptual feedback such as brain activity or some autonomic changes such as skin conductance or blood pressure is more difficult as compared with somatomuscular or easy to perceive bodily responses such as heart rate (Brener, as cited in Hinterberger et al., 2004). With regard to GSR biofeedback, not much research has been performed into bidirectional control (increase vs. decrease in arousal). It has been argued by Volow et al. (1979), for example, that the level of skin conductance is controllable only to the extent of facilitating or arresting spontaneous declines.

The cross-correlation analysis between the SCP signal and the GSR signal did not show a very consistent pattern for the SCP and the GSR group. The high correlation coefficients suggest a functional relation, but the degree and time lag of the association vary considerably over trial types and trained parameter. Furthermore, the correlations were found to be inconsistent within the groups and are therefore likely to be highly individual. Still, some interesting observations were made. First, the correlation coefficients were more positive at the end of the training as compared to the start of the training. This provides evidence that if a SCP–GSR relation indeed exists, the correlation is positive in nature and that training stabilizes the association between them. Second, a shift in time lag of maximal correlation (2–3 s in Session 1 to 0–1 s in Session 20) was observed in the GSR participants. The shift probably reflects that the GSR-trained participants were able to exert control earlier in the trial in the last session, whereas the SCP signal developed comparably to the first session. Third, in both the SCP- and GSR-trained group the cross-correlation profile of the positive trials mirrored the profile of the negative trials in Session 1. In Session 20, on the other hand, the profiles were more alike. This suggests that in Session 1 the trained signal developed in opposite directions, whereas the passively recorded signal was the same for both trial types. Together, the data provide some indication that SCP and GSR are positively correlated with a minor time lag for the GSR of 0 to 1 s. This might mean that volitional up-regulation of central arousal (negative SCP shift) is accompanied with a delayed decrease of peripheral arousal. On the other hand, volitional up-regulation of peripheral arousal would invoke a positive SCP shift that still precedes the GSR because, irrespective of instantaneous changes in peripheral arousal, the GSR is still expressed with a delay. However, it has to be stressed that the variability over participants was large, and therefore no strong conclusions can be drawn on the basis of these data.

The relation between central and peripheral arousal measures has never been clearly investigated and has always been hard to define. Nagai, Goldstein, Critchley, et al. (2004) found that a low level of peripheral arousal (low GSR) was associated with a high central arousal, whereas at high levels of peripheral arousal central arousal was low. Lacey (1958), on the other hand, proposed that different types of arousal exist, suggesting that central and peripheral arousal might not be as closely linked as is often assumed. Hughdahl (1995) argued that activation (central arousal) and arousal (peripheral arousal) are strongly interrelated and that they are both generated by the same mechanism. Moreover, studies have demonstrated correlations between the GSR and frequency band in the EEG (Barry et al., 2004; Lim et al., 1996) and imaging studies have associated the occurrence of the GSR with a largely distributed network of areas in the brain (Critchley et al., 2001, 2002; Patterson, Underleider, & Bandettini, 2002; Raine, Reynolds, & Sheard, 1991; Williams et al., 2000).

Implications

Improvements to this study design, such as the retaining of the participants' motivation, should be considered. The duration of our study (8 weeks) was likely too long.

Oral and written reports indicated that their motivation decreased during the progress of the training. Neurofeedback on SCPs is highly motivationally dependent (Hinterberger et al., 2003) and participants' lack of motivation negatively affects their ability to self-regulate their SCPs. Moreover, it is clear that healthy participants do not expect to have a high gain from biofeedback trainings, contrary to epilepsy patients, for example, who expect beneficial effects and possibly symptom reduction. Beneficial measures to be taken are to shorten the number of sessions as well as the number of trials within a session. In addition, possibly adding a secondary gain for healthy volunteers in the form of an extra bonus when there is high improvement in percentages may be useful. Elbert, Rockstroh, Lutzenberger, and Birbaumer (1980) successfully applied this in their neurofeedback study by paying their participants in relation to their degree of learning. Optimal strengthening of this response–reward association could have been confounded by not immediately ending the feedback after successful completion of the criterion (Kleinnijenhuis et al., 2008). This might have encouraged participants to stay focused on the feedback rather than allow the response–reward association to consolidate. Each time a participant directed his feedback signal in the desired direction, he was reinforced with a high-pitched tone and a smiley image. The response to improvement in GSR is highly dependent on the novelty characteristic of the stimuli (Berlyne et al., 1963). The incidence of a GSR response weakens after repetitions of the same stimulus. It is therefore desirable to introduce a variable reinforcer within and across sessions, as well as introducing more effective reinforcement.

The measurements and analyses of the signals should also be reconsidered. Our analysis of the SCP signal differs from other groups. Also other groups differ on their measurement and statistical analyses of SCPs (Hinterberger et al., 2003; Rockstroh et al., 1993; Siniatchkin et al., 2000; Strehl et al., 2006). It could be useful to develop a standardized protocol for analyzing SCP shifts. It might also be useful to develop such a protocol for GSR biofeedback studies. These measures may lead to better comparability of the results between studies. It was noticed that the SCP and GSR signals are susceptible to confounding environmental and physiological factors. Breathing patterns, eye movements, and muscle activity could have confounded the GSR and SCP. Edelman (1970) suggested that when performing a GSR conditioning study, respiration and EMG variables should always be passively recorded. By means of modulating respiratory patterns and muscle activity interferences with the recordings of the GSR signal could be made. In the present study the participants' efforts to try to modulate the GSR signal by means of muscle contraction or by unusual breathing patterns was noticed by experimenters' observations and was found in the written self-reports after a session. As soon as this was detected, participants were reinstructed not to alter their normal breathing pattern and sit quietly without using their muscles. Nevertheless, modulation by means of other physiological variables may be too subtle to notice and the participants may be unaware of this, which could have contaminated the data. The SCP signal is sensitive to vertical eye movements. This effect was minimized by online and offline corrections using the corecorded vEOG. It is recommended to obtain simultaneous recordings of respiratory patterns and EMG in SCP and GSR biofeedback trainings as well.

In addition to the potential improvements to be made, it can also be suggested to use both trainings complementary. To optimize a SCP neurofeedback training it can be suggested to start with a biofeedback relaxation session. People will be more relaxed and comfortable and can enhance their skills for the SCP neurofeedback.

CONCLUSIONS

In summary, in this study we demonstrated that healthy participants were able to learn self-regulation of their SCPs to a moderate degree and self-regulation of GSR to a medium degree. Participants in

each group performed better on the variable they were trained on. In the GSR-trained group, a significant increase in performance over blocks was obtained for both trial-types. In the SCP-trained group a better performance on the D trials was obtained. When taking into account performance on both trials, the SCP-trained participants showed a marginal and the GSR-trained participants a significant increase, indicating improved performance over time. Overall, the results show that GSR biofeedback control is easier to learn than SCP neurofeedback control, that both variables can be trained in a bidirectional design, but that for the SCP training control over the D trials was easiest to learn. Preliminary results from the cross-correlations seem inconsistent over trial types, trained parameters, and participants. However; the general trend shows a more positive correlation at the end of training compared to the start of training.

REFERENCES

Alster, J., Oren, H., Wolmer, L., & Ron, S. (1997). Multicomponent biofeedback for achieving lower arousal in insomnia. *Sleep Research*, *26*, 539.

Arns, M., de Ridder, S., Strehl, U., Breteler, M., & Coenen, A. (2009). Efficacy of neurofeedback treatment in ADHD: The effects on inattention, impulsivity and hyperactivity: A meta-analysis. *Clinical EEG and Neuroscience*, *40*, 180–189.

Barry, R. J., Clarke, A. R., Johnstone, S. J., McCarthy, R., & Selikowitz, M. (2009). Electroencephalogram theta/beta ratio and arousal in attention-deficit/hyperactivity disorder: Evidence of independent processes. *Biological Psychiatry*, *66*, 398–401.

Barry, R. J., Clarke, A. R., McCarthy, R., Selikowitz, M., Rushby, J. A., & Ploskova, E. (2004). EEG differences in children as a function of resting-state arousal level. *Clinical Neurophysiology*, *115*, 402–408.

Berlyne, D. E., Craw, M. A., Salapatek, P. H., & Lewis, J. L. (1963). Novelty, complexity, incongruity, extrinsic motivation, and the GSR. *Journal of Experimental Psychology*, *66*, 560–567.

Birbaumer, N., Kübler, A., Ghanayim, N., Hinterberger, T., Perelmouter, J., Kaiser, J., et al. (2000). The thought translation device (TTD) for completely paralyzed patients. *IEEE Transactions on Rehabilitation Engineering*, *8*, 190–193.

Collet, L., Cottraux, J., & Juenet, C. (1986). GSR feedback and Schultz relaxation in tension. Headaches: A comparative study. *Pain*, *25*, 205–213.

Critchley, H. D., Melmed, R. N., Featherstone, E., Mathias, C. J., & Dolan, R. J. (2001). Brain activity during biofeedback relaxation: a functional neuroimaging investigation. *Brain*, *124*, 1003–1012.

Critchley, H. D., Melmed, R. N., Featherstone, E., Mathias, C. J., & Dolan, R. J. (2002). Volitional control of autonomic arousal: A functional magnetic resonance study. *Neuroimage*, *16*, 909–919.

Edelman, R. I. (1970). Effects of differential afferent feedback on instrumental GSR conditioning. *Journal of Psychology*, *74*, 3–14.

Elbert, T. (1993). Slow cortical potentials reflect the regulation of cortical excitability. In W. C. McCallum & S. H. Curry (Eds.), *Slow potential changes in the human brain*, (pp. 235–251). New York, NY: Plenum.

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

Fehring, R. J. (1983). Effects of biofeedback-aided relaxation on the psychological stress symptoms of college students. *Nursery Research*, *32*, 362–366.

Fredrikson, M., Furmark, T., Olsson, M. T., Fischer, H., Andersson, J., & Långström, B. (1998). Functional neuroanatomical correlates of electrodermal activity: A positron emission tomographic study. *Psychophysiology*, *35*, 179–185.

Hinterberger, T., Kübler, A., Kaiser, J., Neumann, N., & Birbaumer, N. (2003). A brain-computer interface (BCI) for the locked-in: Comparison of different EEG classifications for the thought translation device. *Clinical Neurophysiology*, *114*, 416–425.

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*, *154*, 521–526.

Hughdahl, K. (1995). *Psychophysiology: The mind-body perspective*. Cambridge, MA: Harvard University Press.

Kleinnijenhuis, M., Arns, M., Spronk, D., Breteler, R., & Duysens, J. (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.

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*, 406–416.

Kropp, P., Siniatchkin, M., & Gerber, W. D. (2002). On the pathophysiology of migraine—links for ''Empirically Based Treatment'' with neurofeedback. *Applied Psychophysiology and Biofeedback*, *27*, 203–213.

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*, *124*, 223–232.

Lacey, J. I. (1958). Psychophysiological approaches to the evaluation of psychotherapeutic process and outcome. In E. A. Rubinstein & M. B. Parloff (Eds.), *Research in psychotherapy* (pp. 160–208). Washington, DC: APA Press.

Lim, C. L., Barry, R. J., Gorden, E., Sawant, A., Rennie, C., & Yiannikan, C. (1996). The relationship between quantified EEG and skin conductance level. *International Journal of Psychophysiology*, *21*, 151–162.

Lykken, D. T., & Venables, P. H. (1971). Direct measurement of skin conductance: A proposal for standardization. *Psychophysiology*, *8*, 656–672.

Nagai, Y., Goldstein, L. H., Fenwick, P. B. C., & Trimblea, M. R. (2004a). Clinical efficacy of galvanic skin response biofeedback training in reducing seizures in adult epilepsy: A preliminary randomized controlled study. *Epilepsy & Behavior*, *5*, 216–223.

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

Nagai, Y., Critchley, H. D., Featherstone, E., Fenwick, P. B., Trimble, M. R., & Dolan, R. J. (2004c). Brain activity relating to the contingent negative variation: An fMRI investigation. *Neuroimage*, *21*, 1232–1241.

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

Patterson, J. C., II, Ungerleider, L. G., & Bandettini, P. A. (2002). Task-independent functional brain activity correlation with skin conductance changes: An fMRI study. *Neuroimage*, *17*, 1797–1806.

Raine, A., Reynolds, G. P., & Sheard, C. (1991). Neuroanatomical correlates of skin conductance orienting in normal humans: A magnetic resonance imaging study. *Psychophysiology*, *28*, 548–558.

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*, 63–72.

Schneider, F., Heimann, H., Mattes, R., Lutzenberger, W., & Birbaumer, N. (1992). Self-regulation of slow cortical potnetials in psychiatric patients: Depression. *Biofeedback Self-Regulation*, *17*, 203–214.

Siniatchkin, M., Kropp, P., & Gerber, W. D. (2000). Neurofeedback: The significance of reinforcement and the search for an appropriate strategy for the success of self-regulation. *Applied Psychophysiology and Biofeedback*, *25*, 168–175.

Strehl, U., Leins, U., Goth, G., Klinger, C., Hinterberger, T., & Birbaumer, N. (2006). Self-regulation of slow cortical potentials: A new treatment for children with attention-deficit/hyperactivity disorder. *Pediatrics*, *118*, 1530–1540.

Volow, M. R., Erwin, C., & Cipolat, A. L. (1979). Biofeedback control of skin potential level. *Applied Psychophysiology and Biofeedback*, *4*, 113–143.

Wallis, B. G. (1981). Sympathetic nerve activity underlying electrodermal and cardiovascular reactions in man. *Psychophysiology 18*, 470–476.

Williams, L. M., Brammer, M. J., Skerrett, D., Lagopolous, J., Rennie, C., Kozek, K., et al. (2000). The neural correlates of orienting: An integration of fMRI and skin conductance orienting. *Neuroreport*, *11*, 3011–3015.