Brain-Computer Communication and Slow Cortical Potentials

Thilo Hinterberger, Stefan Schmidt, Nicola Neumann, Jürgen Mellinger, Benjamin Blankertz, Gabriel Curio, and Niels Birbaumer

Abstract— **A Thought-Translation-Device (TTD) has been designed to enable direct brain-computer communication using self regulation of slow cortical potentials (SCPs). However, accuracy of SCP control reveals high inter-subject variability. To guarantee the highest possible communication speed, some important aspects of training SCPs are discussed. A baseline correction of SCPs can increase performance. Multi-channel recordings show that SCPs are of highest amplitude around the vertex electrode used for feedback but in some subjects more global distributions were observed. A new method for control of eye movement are presented. Sequential effects of trial-to-trial interaction may also cause difficulties to the user. Finally, psychophysiological factors determining SCP-communication are discussed.**

Index Terms—**Brain Computer Interface (BCI), Thought Translation Device (TTD), Slow Cortical Potentials (SCP).**

I. INTRODUCTION

THE Thought-Translation-Device (TTD) is an EEG-based brain computer communication system which has been developed to re-establish communication in severely paralyzed patients [1]-[3]. The device relies on the self-regulation of slow cortical potentials (SCPs), i.e. the voluntary production of negative and positive potential shifts. Other Brain Computer Interfaces (BCIs) utilize different components of the EEG such as the μ-rhythm [4];[5]. Healthy subjects [6], [7] as well as severely paralyzed patients [8] can learn to self-control their SCPs when they are provided with visual or auditory feedback of their brain potentials and when potential changes in the desired direction are positively reinforced. In the TTD the vertical position of a feedback cursor reflects the amplitude of an SCP shift. After a patient has achieved reliable control over his or her SCP shifts, the responses can be used to select items presented on a computer screen. A spelling program included in the TTD allows patients to select single letters by sequential selection of blocks of letters presented in a dichotomic structure with five levels [9]. To improve speed of communication, this program has been supplemented by a dictionary offering word completion after only a few letters have been selected. Several completely paralyzed patients diagnosed with amyotrophic lateral sclerosis (ALS) were able to write messages or letters of considerable length using their brain potentials and the TTD [1], [10]. A special internet browser has been developed for the TTD that allows patients to access the internet by selecting links with their brain responses and thus navigate through the world-wide web [11]. The applications are described in detail in section III.

Self regulation skills differ between subjects and not all reach the high performance level which is necessary to effectively operate a communication device. The present report is aimed to discuss some important aspects of training and strategies to enhance the individual performance. In particular, a method for individual baseline adaptation and evaluation of the influence of eye movements will be presented (IV B, C). The question of SCP sources and optimal recording sites is raised in IV D. Effects of different sequences of task presentation are demonstrated in IV E.

II. METHODS

Operant SCP feedback training was conducted at the patients' homes with the patients sitting in wheelchairs or lying in bed, and in the laboratory with healthy subjects. Fig. 1 illustrates the procedure of the TTD. The EEG is recorded with Ag/AgCl electrodes (8 mm diameter) from the vertex (position Cz of the international 10/20 system, Jasper 1958) referenced

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Manuscript received July 10th, 2003. This work was supported by the Deutsche Forschungsgemeinschaft (DFG) within the SFB 550 (B5) and the National Institute of Health (NIH). Stefan Schmidt's work is sponsored by the Samueli Institute for Information Biology, Corona del Mar, CA. Benjamin Blankertz and Gabriel Curio were partly supported by a grant of the BMBF, FKZ 01IBB02A/B.

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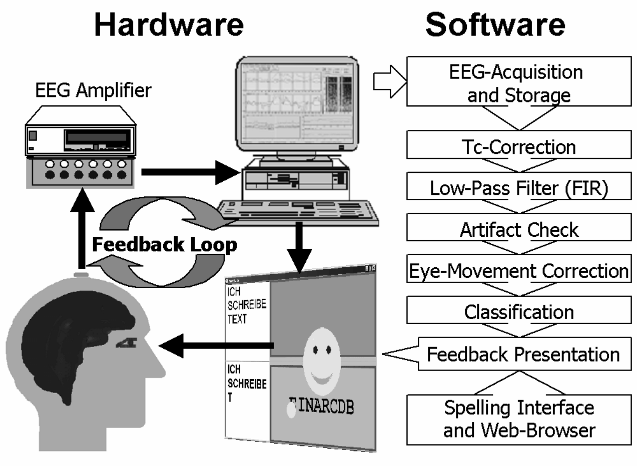

Figure 1: Experimental procedure of TTD as an SCP driven brain-computer communication system.

to both mastoids. The signals are amplified using an EEG amplifier (EEG 8, Contact Precision Instruments Inc.) and transmitted to a personal computer (PC). The TTD software performs data acquisition, storage, processing and presentation of feedback. It allows the experimenter to control the training session, set parameters, visually inspect the ongoing EEG and SCPs, including power spectrum and SCP averages across trials. The information the user needs to operate the device is presented visually on an additional monitor and/or auditorily.

The TTD operates on the basis of on-line single trial analysis. A trial typically consists of a 2-s preparatory phase in which the cursor remains stationary on the screen and an active feedback phase lasting between 2-3 s in which the cursor (yellow circle) moves horizontally with constant speed and vertically with the user's SCP amplitude shift. The onsets of these two phases are signaled by a high- and a low-pitched tone, respectively. For each trial, the user is required to produce either a negative or positive SCP shift. This task is indicated by a red area at the top or the bottom of the screen, prompting to move the cursor into the upper (by producing negative polarity) or lower (by producing positive polarity) half of the screen. The SCP amplitude shifts are referenced to the final SCP value of the 2-s preparatory phase immediately before the feedback starts. SCPs are calculated by a moving average over 500 ms of EEG activity that is updated every 62.5 ms and recorded with a time constant of 16 s and a 40-Hz low-pass filter. At the end of the feedback phase, the SCP shift is classified as a negativity or positivity response according to an algorithm that calculates the integral of the SCP shift across the feedback period. The classification methods for SCPs are described in [12]. A trial was judged as correct or incorrect by comparing the response with the task requirement to produce a negative or positive SCP shift. A trial is rejected (regarded as invalid) when a) SCP changes remain below 0.5 µV (no response), b) the SCP shift exceeds 200 µV (artifact, caused e.g. by involuntary movements such as swallowing that sometimes occur even in patients at advanced stages of paralysis), or c) excessive eye movements. The electrooculogram correction and rejection algorithm has been described in detail by Kotchoubey et al. [13], [6]. The task of a rejected trial is automatically repeated in the next trial. Because the task has only two possible response outcomes on each trial and both targets appear with equal probability, the chance accuracy is 50%. A correct SCP shift is reinforced by a "smiley" presented in the center of the screen at the end of the feedback phase. The final outcome has been indicated as percentage of correct responses after 70-100 single trials referred to as a session.

When patients have achieved stable response accuracy of more than 70% correct responses, they can start to use the TTD's applications [14], [15]. Patients often reach such levels of proficiency after 1-5 months of training with 1-3 training days per week. However, some patients are not able to reach this level after more than a year of training while others achieve an accuracy sufficient for communication after a few weeks. A training day comprises 7-12 sessions, and a session comprises between 70-100 trials.

III. APPLICATIONS

A. *Communication Training*

Using an application by the self-regulation of SCPs entails the problem of dual task interference: Different tasks that all need attentional resources interfere with each other, unless they are automated enough to be performed at the same time [16]. Thus any new application has to be introduced stepwise, because new task requirements, such as selecting letters, or preparing to write might disturb the self-regulation skill. A training protocol has been developed in order to prevent a drop of performance due to dual task interference [15]. Confronted with the TTD, users are not confronted with a specific task to perform, but are first told to watch the cursor on the screen and try to explore if its movement corresponds to any kind of mental activity (step 1, *habituation*). *Acquisition* (step 2) consists of moving the cursor in a top or bottom target on the screen according to the task requirement (see above). A spelling application is introduced in an *error ignoring mode* (step 3), so that errors are ignored and thus do not lead to wrong selections or rejections of letters. Letters are presented in the bottom target (see below). Their number is gradually increased, so that the user adapts to their sequence and position. Words are presented to the user to copy during *copy spelling* (step 4), the user has to perform the same task as before, but errors have consequences in such a way that the user has to correct them by using a back or delete option (see below). Finally if successful, users are transferred to *free spelling*, a mode in which they are free to select between 32 letters and symbols and to write their own text. A personal dictionary is also available. [14], [15].

B. *Spelling*

Spelling allows the user to select letters from a natural language alphabet, including punctuation marks, and to combine letters into words and sentences. Because the number of letters in an alphabet (typically about 30) exceeds the number of brain response classes the user can produce (two), the selection of a letter must be broken down into a sequence of binary selections. This leads to the concept of presenting the alphabet's letters in a dichotomous decision tree which the user navigates by giving brain responses [9]. Letters are associated with leaves of this tree such that, whenever the user visits a leaf, the associated letter is entered into a text field which holds the text written up to that point. If one wants to allow for the correction of errors, the user needs an option to revoke a decision already detected by the system, i.e. to go towards the root of the tree rather than towards its leaves. Thus, the concept of a tree is generalized into a graph structure that, like a tree, has a unique root node but, unlike a tree, may contain loops (closed paths between its nodes). The nodes of a speller tree are defined in a configuration file that specifies, for each possible brain response at each node, (1) a label to appear in the target box associated with the response, (2) a portion of text to be entered into the text field, (3) the node to visit next. For "non-leaf" nodes, the text field (2) is left blank, for "leaf" nodes, it usually contains a single letter, and a leaf's "next node" field (3) points to the root node.

For training purposes, a "copy spelling" mode is available in which the system guides the user towards spelling a text specified by the operator. While entering letters, at each point in the selection sequence the system indicates which brain answer to give next in order to spell the current letter, or to correct any error made up to that point.

Within this general implementation, a speller design introduced by Perelmouter et al. [9] is applied in which only one of the two brain responses actually navigates towards the leaves of the quasi-tree ("select"), whilst the other one acts as a do-nothing-option ("reject"). At the first level, the alphabet is subdivided into two sets of letters. The letters are arranged in a way that facilitates the selection of the more frequent letters, whereas the less frequent letters require more steps to select. In the first trial, one half of the alphabet is presented as the first set of letters. If the patient wants to select one of the letters in this set, he has to generate a positive SCP shift which is coded as a "select" response. In the case of a successful select response (i.e. positive SCP shift, lower target, cf Fig 1), during the next trial the first half of the previous letter set is presented. In the case of a reject response (i.e. negative SCP shift, upper target), the second half of the alphabet is presented. A subsequent select response would then result in the presentation of the first half of this letter set. At the top level, a second rejection would lead to the option for a deletion of the previously spelled letter, after which the program would re-start with the presentation of the first letter set. At subsequent levels, a rejection of the second letter set results in the presentation of a box offering a "go back" option. If the patient selects this box, the program will move up by one level. This is a useful option in the case of unintended selections. If the "go back" option is rejected, the program will again present the first letter set at this level and continue that procedure until a selection is made. At the final level, when the bottom of the decision tree is reached, selection of a single letter will result in this letter being written into the text field. Texts are thus generated by adding further letters to the previously written ones.

In this system, writing the most conveniently situated letter, the "E", takes five trials, i.e. 20-25 s depending on the duration of the active phase, whereas writing the most remote sign the period takes nine trials, i.e. 36-40 s. In an attempt to make free spelling less time-consuming, a simple dictionary has been introduced in which the experimenter may enter words that are frequently used by the patients. With the dictionary option, a complete word is suggested after at least two letters have been written and a corresponding word is available. This word can then be chosen with a single select response. Initial attempts proved that it was important to keep the number of words in the dictionary small to avoid too many suggestions, therefore we stored only about 500 commonly used words. This language support program including the dictionary option has been used by several patients.

C. *WWW Browsing*

The spelling concept has been carried over for use of a hypertext (web) browser. Instead of selecting letters from a natural language alphabet, sequences of brain responses are used to select hyperlinks from web pages. In a previous attempt described in [14] links were extracted and presented on the feedback targets. The current approach [11] uses graphical markers 'in-place', i.e. on the browser's web page display. Colored frames are placed around user selectable items, circumventing any need to maintain a separate presentation of choices. The frame colors are assigned to the possible brain responses. By default, red frames are selected by producing cortical negativity and green frames are selected by the production of cortical positivity. As an aid, feedback is displayed at the left rim of the screen by depicting the vertical movement of a cursor that can be moved upwards into a red area or downwards into a green area. The user only has to watch the current color of the desired link’s frame that indicates the brain responses which has to be produced for its selection. By presenting a series of brain responses as indicated by the changing color of the frame around that link, it can be chosen with binary decisions neglecting any knowledge about its position in a selection-tree. The computer is asking a sequence of questions, i.e. “What color does 'your' link have right now?” which the user answers by producing the brain response associated with the color in question. Besides links, other interactive elements on web pages are accessible to the user, particularly text fields for which a virtual keyboard is provided, opening up a wide range of hypertext based applications. Similarly to the spelling task, the user has to manage a dual task situation: Figuring out the task and performing the corresponding brain response. First tests with this system showed difficulties only when a web page contains too many links. One of our almost completely locked-in patients managed to navigate to sites of his favorite soccer team in the first sessions with the system.

IV. FACTORS FOR SUCCESSFUL BRAIN-COMMUNICATION

Several important aspects have to be considered for a successful SCP self-regulation training concerning both psychological factors and technical aspects. Basically, the training of slow cortical potentials depends upon a persons learning ability to produce a predefined brain response. However, inter-individual psycho-physiological characteristics have revealed substantial differences in training success and the brain response does not necessarily match with the predefinition and thus the standard paradigm may be sub-optimal. Several factors seem to be responsible and will be discussed by presenting new investigations on SCP training data and reporting experiences in the training of patients.

A. Psycho-physiological Factors

Success in self-regulation training depends not only on the correct selection of technical parameters, but also on the patient’s psychological and physical state, motivation, social context, and the trainer-patient-relationship. Recent data demonstrated that self-regulation and communication skills of severely paralyzed patients could be predicted from the results of the initial training period: Patients who later acquired the self-regulation skill well enough to communicate (i.e., > 75% correct responses), had already showed a high performance (>80%) in the first 30 training sessions (about three training days) [16]. Attentional capacities and motivational factors might be responsible for these performance differences between patients. Commencing self-regulation training when a patient is still in an early stage of disease (e.g., in ALS) is advisable, because the patient is still able to communicate and to signal his desires. Besides, the progression of the disease might affect the patient’s cognitive status, particularly his learning abilities [17], and thus render successful self-regulation training impossible. As far as performance fluctuations of patients are concerned, different factors, such as sleep quality, pain, and mood, were found to influence self-regulation performance [18]. However, these factors were neither identical for all patients, nor did they always affect self-regulation in an intelligible way (e.g., better performance, when the patient suffered from physical ailments). Further investigations are certainly necessary.

Crucial for successful training is a high motivation and endurance on the part of the patient. Like all skills, self-regulation has to be practiced on a regular basis to become more automatic and less interference-prone. Schedules of reinforcement may affect performance, but no systematic data with BCIs are available. A good patient-trainer relationship is a necessary condition for training motivation [19].

Another important issue for communication is the patient’s social context. It has to be ensured that there are people present who can operate the communication system in the absence of skilled trainers. Moreover there have to be valued communication partners available, otherwise the patient might not be motivated to use the system. For more information concerning these and related topics see [20].

B. Baseline Adaptation

Due to differences in the flexibility of individual brains’ learning abilities the learning process may stagnate at a sub-optimal level. Improvement can be reached by a careful quantitative analysis of the brain response followed by an adaptation. We analyzed a data set of 20 healthy people (8 male and 12 female, mean age=28, sd=9) who where trained over three sessions with the paradigm described above. The third session provided the data basis for the statistical analysis in which two thirds of the sample showed significant voluntary SCP control with a performance of greater than 55 % correct responses. One third exceeded 70 % of correct responses.

Averaging the mean SCP amplitudes during feedback of the same task over all trials of a session (about 250 trials per task), shows that the ranges between the positivity and negativity task were not centered around zero and vary over subjects Fig. 2a) indicating that self regulated potential shifts were not produced in both polarities with an equal reliability. This unequal performance also reduced the overall performance. The percentage of correct responses is a common performance measure but to obtain a more realistic measure of performance we calculated the information rate in bit per trial according to the information theorem by Shannon & Weaver [21]. The information rate I is calculated according to

$$I = ld(k) + Pld(P) + (1-P)ld\left(\frac{1-P}{k-1}\right) \qquad (1)$$

where k is the number of classes (here k=2) and P denotes the probability for a correct response. With a perfect hit rate of 100% a maximum of one bit per trial can be transmitted. If the hit rate drops below 100% noise is introduced that requires more than one trial to transmit one bit of information. At the chance level (50%) the information bit rate is zero. For all hit rates <50% I is set to zero.

The performance can be increased off-line by an adjustment of the baseline amplitude. Therefore, a data set containing all trials (about 500) of a session was used. Each trial provided one value defined by the average SCP during feedback referenced to the baseline for each trial. For all 20 subjects, such a set of all trials was then used for classification of those values. By default, each value was tested for being >0µV or <0µV, which was the on-line condition. Statistical methods of discriminant analysis could be used to find a deviant value for improvement of performance [12]. Here, as a non-statistical method free of assumptions about distribution an iterative process was applied on the data set determining an offset to

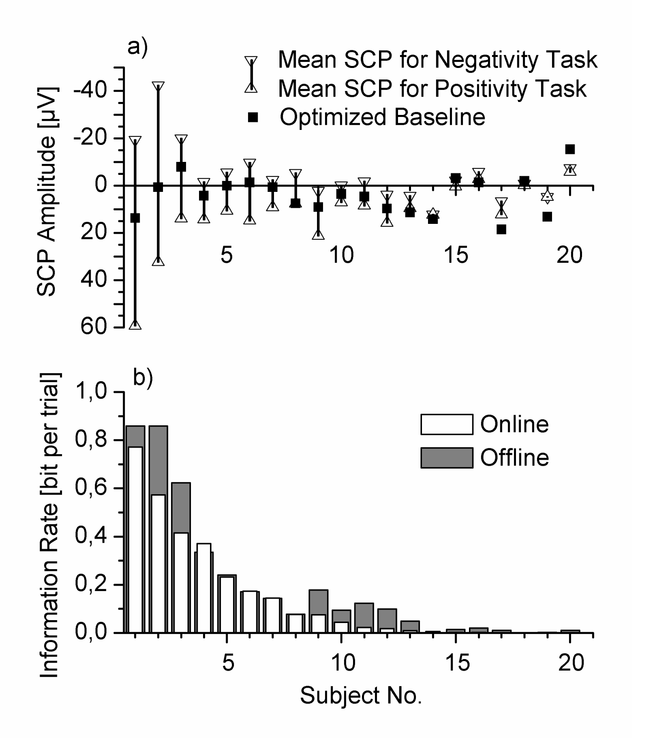

Figure 2: Performance measures of 20 healthy participants sorted by their on-line performance are displayed. In 2a) zero µV constitutes the on-line baseline level. The vertical lines indicate the difference of the mean SCP amplitude during feedback between the positivity task (lower triangle) and the negativity task (upper triangle). The squares show the offline applied baseline shift to obtain maximum performance. 2b) shows the percentage of correct responses in the on-line condition and the results of the off-line maximization procedure which is significantly better (4.7µV at average).

these values that maximized the information rate. The squares in Fig. 2a) show this optimal offset value for each subject and the dark bars in Fig. 2b) indicate the corresponding information rate. The difference in bit rate between the online condition and the adapted optimized baseline condition is significant (t(19)= 2.8, p<.01). At average, the information rate could be increased from 0.15 to 0.20. Further improvement can be reached by statistical classification algorithms as described in [12].

C. *Eye Movement Artifacts*

The major source of artifacts are glossokinetic artifacts, respiration effects and, in particular, eye-blinks and eye-movements. Therefore, the vertical EOG is recorded and used for on-line artifact control and correction. The on-line correction algorithm distinguishes between three cases. 1) When the slow wave filtered EOG signal has an opposite sign to the actual SCP shift the SCPs are not corrected as the eye movements do not support the feedback. 2) In case the EOG shift multiplied by a correction factor (usually about 0.12) is smaller than the SCP shift the SCPs are corrected by this factor. 3) In case the SCP shift is larger and in the same polarity feedback is suppressed [6], [13].

Even with on-line EOG correction, some people show high differentiation in the EOG signal between the two tasks. The data set of the previous paragraph B was therefore used for a detailed inspection of EOG effect sizes. The effect size is defined by the difference of the means of the average amplitude values during the feedback interval over trials between the two tasks divided by the overall standard deviation served as a measure for the discriminative abilities. This effect size was calculated for both the SCP shifts and the vertical EOG shifts. In case the absolute value of the effect size of the EOG is smaller than the effect size of the SCP, it can be assumed that SCP regulation is not solely of ocular origin. This criterion is important for the training of ALS patients, who loose their eye-movements in the final stage of their disease. The criterion was fulfilled in 12 of the 20 healthy subjects. The subjects' positions in the performance ranking of the 8 subjects who did not fulfill the criterion were 7, 9, 14, 15 and 17-20. This shows, that mainly bad performers who already show low effect sizes in the SCP reveal problematic EOG differentiations. The covariance between SCP and EOG is not an appropriate measure for artifacts as the vertical arrangement of the targets inevitably leads to vertical eye movements however of opposite sign and thus not supporting the SCP control. Thus, the sign of the effect size of the EOG could serve as an additional measure for EOG artifact control.

D. *SCP Localization*

15 healthy subjects participated in a training session with a 64-channel recording: The BrainAmp system (MES, Munich) was connected to the TTD software to provide on-line feedback in a paradigm identical to the one described above. Feedback was derived from Cz referenced to both mastoids. The session comprised 5 to 10 runs with 70 trials each. In an off-line analysis, the SCP courses of all trials were averaged separately for the two tasks (to produce cortical negativity or positivity), for each electrode, and for each subject. As a performance measure that expresses the specific information of a certain SCP differentiation obtained from a certain electrode the bi-serial correlation coefficient *r* was calculated as follows:

$$r = \frac{m_{pos} - m_{neg}}{sd} \frac{\sqrt{n_{pos} n_{neg}}}{(n_{pos} + n_{neg})} \tag{2}$$

m_{pos} and m_{neg} are the mean SCP amplitudes over n_{pos} trials with the positivity task resp. n_{neg} trials with the negativity task and *sd* is the standard deviation of all amplitude values. As SCPs develop slowly, their value in the middle of the feedback interval at 2.0 s after feedback onset was analyzed here.

A visual screening of the resulting r-mappings of the 15 participants allows to subdivide the group into three classes: 4/15 participants, referred to as 'non-regulators', did not show SCP differentiations or even produced SCP shifts of opposite polarity. Their maximum correlation values r_{max} of all cortical electrodes (without prefrontal, mastoid and EOG electrodes) stayed at $r<0.1$. 9/15 participants exhibited localized cortical activations during feedback with $r_{max}>0.1$. A quantitative measure to classify localized activity was defined by

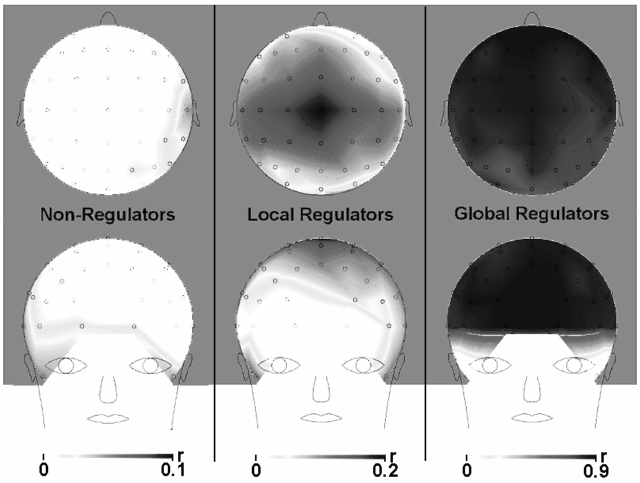

Figure 3: 64-channel recordings during SCP self-regulation training were performed with 15 subjects to map the correlation between the two tasks (to produce cortical negativity vs. positivity) and the SCP differentiation during the feedback interval. The mastoids served as reference.
Qualitatively, the subjects could be divided into three groups: a) Non-regulators (4 subjects) showing only small differentiations or differentiation of opposite polarity. b) Local regulators (9 subjects) showing localized activations focused at average around the central Cz electrode which was used for calculation of the feedback signal. A third group (2 subjects) showed high correlations almost homogeneously distributed on the whole scalp. Possibly, activity of opposite polarity was detected at the mastoid reference positions. The mapping data show that the Cz-mastoid derivation used for SCP feedback could be used by a majority of subjects for an effective focal SCP differentiation.

$$g = r_{\max} / r_{mean} \tag{3}$$

with r_{mean} being the mean r over all cortical electrodes. This localization parameter g was larger than 2.0 for the nine subjects. The averaged mappings of the ‘local regulators’ showed localized activations around a spot at the center electrode position Cz which had been used for the feedback (Fig. 3). A third group of 2/15 subjects featured almost spatially homogeneous activations spread out over the whole scalp with $g<1.5$. In addition, these ‘global regulators’ produced extraordinary large SCP differentiations of 30 to 50 µV (with $r_{max}>0.7$) enabling a reliability of 97 and 85 % of correct responses. As in the present setup all electrodes were referenced to the mastoids, the topographic origin of this huge and homogeneous SCP differentiation could also be the mastoid reference itself; this will be subject to future studies.

The mappings obtained in the middle of the feedback phase averaged for each of the three groups are shown in Fig. 3. Evidently, the Cz-mastoid derivation employed for SCP feedback learning led to an effective SCP differentiation at Cz in the across-subject map average (middle panel) in the majority of subjects. Interestingly, a post-hoc analysis for these local regulators revealed a significant increase of the r-value from 0.17 at Cz to 0.32 at the intraindividual r_{max} channel (t(8)=3.9, p<0.01). Thus, while feedback was derived in the present study from Cz, many subjects generated a maximal SCP differentiation at other, often neighboring electrodes. Accordingly, an individually tailored selection of the feedback channel could possibly boost TTD performance.

These initial findings from multi-channel SCP mappings motivate further studies which will focus to clarify the mechanisms underlying successful SCP training, e.g., by correlating reported strategies with the mappings. Sources of possible huge non-cerebral artifacts, such as glossokinetic or respiration effects, in the ‘global regulators’ can now also be investigated through source analysis.

E. Sequence Effects

Within a run a fixed number of trials are presented in a seamless mode, i.e. without inter-trial intervals. The new baseline value at the end of the preparation phase may be still influenced by the amplitude level that was achieved at the end of the previous trial. These carry-over effects might be of importance, e.g., if a negativity task after successful negativity cannot be achieved because saturation prevents a further increase of negativity. Two different types of sequence effects are possible: (i) *Improved performance with identical tasks*: The subject shifts the SCP in the intended direction and if the succeeding trial asks for the same polarity it might be easier than to change polarity. The subject just has to continue with his or her cognitive efforts, no change of strategy or intention is needed. (ii) *Improved performance with changing task*: Shifting the SCP towards one polarity may result in saturation and lower reactivity (law of initial value, [22]). Thus sequences of trials with the same task may result in a lower performance while a change of the conditions may enhance the performance. Both sequence effects might be relevant and we tried to find an empirical answer to solve this question.

We reanalyzed the data set of 20 healthy subjects already described in Section B according to a target sequence criterion and grouped the trials of the data set as follows. (i) Positivity trial preceded by a positivity trial (N=1598) (ii) negativity trial preceded by a negativity trial (N=1616) (iii) negativity trial preceded by positivity trial (N=3320) and (iv) positivity trial preceded by a negativity trial (N=3324). Thereby groups (i) and (ii) represent *identical task* condition and (iii) and (iv) the *changing task* condition.

The results for each of the 20 subjects are depicted in Fig. 4a).

The difference in performance between identical tasks and changing task is displayed as a gray or black part of the bar dependent on the polarity of the improvement. The white part reflects the performance that is obtained independent of the task order. Obviously both effects, improvement with identical and improvement with changing tasks, are possible. Variations can be seen between subjects but also within subjects dependent on the type of task (negativity or positivity). E.g. subject 2 performs better with changing tasks independent of the type of task. This can also be seen in detail in the averaged SCP curve that is displayed in Fig. 4b). On the other hand subject 7 shows either better or poorer performance with identical tasks dependent on the type of task (positivity or negativity).

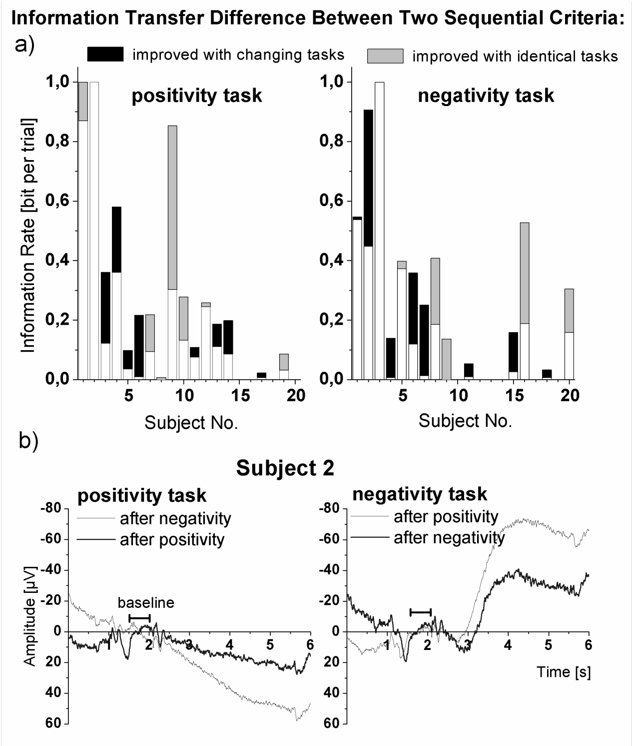

Figure 4: Performance in an SCP-feedback trial evaluated in relation to the preceding trial. a) displays the information transfer in a trial that was either preceded by a trial with an identical task or with a different task. Results are separated for positivity trials (left) and negativity trials (right). The lower white part of each bar reflects the performance independent of any sequencing. The upper part of the bar reflects the improvement of performance in trials preceded by either an identical task (gray) or by a changing task (black). Subjects characterized by white bars only show no difference dependent on the task sequence. Subjects are displayed in order of their overall performance with subject 2 showing the best results. b) displays the mean shift of the SCP during a 6 s trial obtained by averaging all trials in relation to the task sequence for subject 2. The SCPs are clamped to zero according to the mean of all data points between 1.5-2.0 s. This is marked as baseline in the graph. For the positivity task (left side) a more positive endpoint is reached if the preceding trial was the negativity task. Therefore the performance is better for changing tasks (This improvement with changing task is not visible in the above Fig. 4a because subject 2 has already a perfect information transfer of one bit per trial.) On the right side (negativity) also a change in condition (i.e. negativity after positivity) results in a better performance.

Overall, no clear cut sequence effects emerge from our data. The obtained intra- and inter-individual differences may be a reflection of subject specific strategies applied to manipulate SCP. Those strategies may vary with the task and certainly differ between subjects. Thus any application that aims at improving the performance by taking sequence effects into account has to be based on an individual and task specific approach. If these sequence effects prove to be robust we could apply baseline corrections for each of the four possible target sequences. These adjusted baselines may facilitate the task execution and thus lead to an improved information transfer.

V. CONCLUSION

The data presented demonstrate that the SCP learning paradigm allows acquisition of SCP self regulation in many healthy people. After three one-hour sessions two thirds of the sample show significant voluntary brain control of SCP. After a stable performance level and robust voluntary brain control has been achieved, performance can be further improved by individual adaptation of certain parameters of the physiological signal (i.e. avoiding sequence effects with flexible amplitude offset of SCPs). Most subjects regulate their SCP locally under the electrode used for feedback. Sequence effects of trials with identical or different task requirements may have a strong effect in some individuals but do not effect mean performance of the population.

ACKNOWLEDGMENT

We thank Barbara Wilhelm, Slavica von Hartlieb and Florian Losch for their contributions to the multi channel measurements.

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