PAPER

Predictors of successful self control during brain-computer communication

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Objectives: Direct brain-computer communication uses self regulation of brain potentials to select letters, words, or symbols from a computer menu to re-establish communication in severely paralysed patients. However, not all healthy subjects, or all paralysed patients acquire the skill to self regulate their brain potentials, and predictors of successful learning have not been found yet. Predictors are particularly important, because only successful self regulation will in the end lead to efficient brain-computer communication. This study investigates the question whether initial performance in the self regulation of slow cortical potentials of the brain (SCPs) may be positively correlated to later performance and could thus be used as a predictor.

Methods: Five severely paralysed patients diagnosed with amyotrophic lateral sclerosis were trained to produce SCP amplitudes of negative and positive polarity by means of visual feedback and operant conditioning strategies. Performance was measured as percentage of correct SCP amplitude shifts. To determine the relation between initial and later performance in SCP self regulation, Spearman's rank correlations were calculated between maximum and mean performance at the beginning of training (runs 1–30) and mean performance at two later time points (runs 64–93 and 162–191).

Results: Spearman's rank correlations revealed a significant relation between maximum and mean performance in runs 1–30 and mean performance in runs 64–93 (r= 0.9 and 1.0) and maximum and mean performance in runs 1–30 and mean performance in runs 162–191 (r=1.0 and 1.0).

Conclusions: Initial performance in the self regulation of SCP is positively correlated with later performance in severely paralysed patients, and thus represents a useful predictor for efficient brain-computer communication.

Brain-computer interfaces (BCIs) are devices that translate brain signals into operational commands for technical devices. That way paraplegic or completely paralysed ("locked in") patients can operate applications, such as switches, prostheses, and communication devices. Different brain signals and translation algorithms have been used to control a BCI (for a review see Kübler *et al*[1] and Wolpaw *et al*[2]). The currently most advanced BCIs make use of the fact that humans can acquire control over EEG parameters by means of neurofeedback—that is, real time visual or auditory feedback of a specific EEG parameter. Existing BCIs are based on the self regulation of the action potential firing rate,[3] the 8–12 Hz mu rhythm,[4 5] or slow cortical potentials (SCPs).[6 7]

The Tübingen BCI (Thought Translation Device, TTD) is based on the self regulation of SCPs.[8–11] SCPs reflect changes in cortical polarisation lasting from 300 ms up to several seconds. Functionally, SCPs represent a threshold regulation mechanism for local excitatory cortical mobilisation. Negative SCP shifts, such as the Bereitschaftspotential[12] or contingent negative variation,[13 14] indicate local excitatory preparation, whereas positive potential shifts indicate cortical disfacilitation. Neurophysiologically, negative surface SCPs result from a sink caused by synchronous slow excitatory postsynaptic potentials in the apical dendrites of cortical layers I and II with the source in cortical layers IV and V. The origin of positive SCPs is less clear, but may result from sinks in deeper layers or inhibitory activity in upper cortical layers I and II.[9] Paralysed patients were trained to communicate by means of SCP self regulation.[7 15] By voluntarily changing the polarity of the SCP amplitude, paralysed patients can move a cursor on a computer screen thereby selecting letters and writing messages. For patients with intractable neurological diseases, such as amyotrophic lateral sclerosis (ALS), communication is an important aspect of the will to live. Bach, for example, showed that establishing and maintaining effective communication greatly increased the quality of life in ALS patients.[16]

SCP self regulation is a skill that has to be acquired during an extended training period of several weeks or months.[15] There are no definite cognitive strategies how to self regulate SCPs: although it was found that providing patients with initial strategies may aid self regulation at the beginning of feedback training, it seems to impede learning later, perhaps by limiting subjects from trying other potentially successful strategies.[17–19]

For communication, it is important that patients obtain a high rate of correct potential shifts, because errors decelerate communication exponentially.[20 21] People, however, vary in their ability to self regulate SCPs: in a study by Rockstroh *et al*, for example, only 21 of 45 healthy subjects learned to produce a hemispheric asymmetry of SCP.[22] Patients with epilepsy differed from each other in their capability to self regulate their SCPs even after an extended training period.[23] Not all paralysed patients acquire SCP self regulation, either. The aim of this study is to investigate predictors of successful self control. From a practical point of view it is important to have predictors, because training patients requires substantial financial and staff resources, and it is preferable to train patients who are likely to succeed in achieving self regulation of their SCPs and will benefit from BCI training. From a theoretical point of view it is essential to know the neurophysiological and behavioural mechanisms and preconditions for success in SCP self regulation.

Different neuropsychological, demographical, and personality trait variables have already been tested as predictors for successful SCP self regulation. Measures of short-term memory and attention, such as block tapping span and digit

Abbreviations: SCP, slow cortical potential; BCI, brain-computer interface; ALS, amyotrophic lateral sclerosis; CRR, correct response rate

Table 1 Description of the patient sample

Patient	Sex	Age	Years since diagnosis	Years since artificial ventilation	Motor/speech functions	Months of feedback training
1	male	43	6	not ventilated, when feedback training started	Tetraplegic, head and eye movement	6
2	male	66	1	not ventilated	Paralysed legs, speech intact	1
3	male	63	3	2	Nearly completely paralysed, very weak horizontal eye movement	5
4	male	31	2	1	Tetraplegic, eye movement	6
5	male	40	2	1	Nearly completely paralysed, very weak horizontal eye movement	2

span, were found to correlate positively with SCP self regulation for the treatment of epilepsy,[24] but the results could not be replicated. Neuropsychological assessment in completely or nearly locked in patients is difficult, because standard tests require motor responses, speech, or both. There is evidence, however, that depending on the skill investigated performance variability remains constant with practice.[25] This study investigates the question whether initial performance in SCP self regulation may be correlated to later performance. Based on past research, our hypothesis is that the initial performance in SCP self regulation can predict successful self control.

METHODS

Patients

Five patients diagnosed with ALS participated in the study. ALS, also known as Lou Gehrig's disease, is a progressive neurodegenerative disease that causes widespread loss of both upper and lower motor neurons, leading to progressive physical impairment. In the end stage of the disease voluntary muscular movement is completely lost and the patients are locked into their paralysed bodies. Sensory and cognitive functions may be sometimes impaired additionally.[26–28] Table 1 describes the patient sample. At the time of data collection, all except one patient were in an advanced stage of ALS and three were artificially fed and ventilated. The patients communicated by speech (patient 2), signalled yes and no by head movement (patient 1), or spelled letters with the aid of a spelling board by eye blinking (patient 4), and weak, horizontal eye movement (patients 3 and 5), respectively. Patients gave informed consent to participate in the study, which was approved by the ethics committee of the Medical Faculty of the University of Tübingen. In the case of patient 3, eye movement seemed unreliable, so that the additional consent of his legal agent was requested.

Apparatus

The feedback apparatus (Thought Translation Device, TTD) included amplifier, PC with monitor for online control of electroencephalogram (EEG) recording and feedback notebook. EEG was recorded from Fz, Cz, and Pz according to the international 10–20-system[29] referenced to both mastoids using 8 mm Ag/AgCl electrodes and Elefix electrode cream. Feedback was provided from the Cz electrode, whereas recordings from Fz and Pz were used for offline analysis. Electrode impedances were kept below 5 kOhm. The signals were amplified with an EEG amplifier (EEG 8, Contact Precision Instruments) set to a low pass filter of 40 Hz and a time constant of 16 seconds and then digitised with a sampling rate of 256 Hz. To record vertical electrooculogram (vEOG), electrodes were placed above and below the right eye. EEG was corrected on line for vEOG artefacts as described in detail elsewhere.[7 30] EEG and vEOG were displayed online for surveillance of signal quality by the trainer. Patients were seated in front of the notebook that provided feedback of their current SCP amplitude by means of a cursor moving in correspondence with SCP amplitude shifts. Two targets at the top and the bottom of the feedback display indicated the directions in which the cursor had to be moved. Negative SCP amplitude shifts moved the cursor upward; positive SCP amplitude shifts moved it downward. Feedback was not provided continuously but in discrete trials. Each trial, permitting a binary yes-no answer, consisted of two phases, a one second to four second preparatory passive phase and a three second to five second active phase, respectively, in which the cursor could be moved by SCP amplitude shifts (fig 1). Phase and trial durations were adapted to individual patients. At the beginning of the passive phase the highlighting of a target either at the top or the bottom of the feedback screen indicated the task requirement—that is, in which direction the cursor had to be moved during the active phase. The average amplitude of the last 500 ms of the passive phase served as a baseline and reference value for SCP amplitude shifts during the active phase. In the active phase, the cursor started to move in correspondence with SCP amplitude shifts. To filter SCPs online during the active phase, the EEG was averaged across a sliding time window of 500 ms and subtracted from the baseline. The result was fed back every 62.5 ms. At the end of the active phase, the average SCP amplitude during the active phase was classified as negative or positive: if the average SCP amplitude was negative, the trial was regarded as "negativity performed", and if it was positive, the trial was regarded as "positivity performed". The trial was invalid when the average SCP amplitude was in the range of –0.5 to 0.5 µV. A trial was judged as correct or incorrect by comparing the SCP amplitude with the task requirement to produce a negative or positive amplitude shift. Correct responses were reinforced by a smiling face at the end of trial and a running count of correct responses was increased by one. The final score and the achieved percentage of correct responses (correct response rate, CRR) were presented after a sequence of 50–70 single trials referred to as a *run*.

Training

Patients were trained at home two to four times a week on overall 32 (patient 1), 8 (patient 2), and 28 (patient 5) training days. When the patient's home was located more than two hours from the research institute, he was trained irregularly in blocks of several days, with breaks of some weeks between blocks on overall 23 (patient 4), and 34 (patient 3) training days. The patients have not been instructed to use any specific cognitive strategy, but were rather told to produce two different brain states to move the cursor in either direction. Training steps to use the BCI device for communication included basic training to learn SCP self regulation as described above (a), the copying of presented words (copy spelling) (b), and free spelling (c). During copy spelling and free spelling letters were presented in the bottom target and patients had to select them by producing positive SCP amplitude shifts or to reject them by producing negative SCP amplitude shifts, respectively (for detailed information see Kübler *et al*[15]). However, only patients 1 and 4 reached the criterion level of a CRR above 70 with a few runs above 75% to proceed to copy spelling (training step b) after 86 and 121 runs, respectively. Finally, they were transferred to free

Table 2 Minimums, maximums, means, and standard deviations (SD) of percentages of correct responses in SCP self regulation in runs 1–30, 64–93, and 162–191, respectively

	Runs 1–30				Runs 64–93				Runs 162–191			
Patient	Min	Max	Mean	SD	Min	Max	Mean	SD	Min	Max	Mean	SD
1	40.0	88.7	65.5	13.3	49.0	94.1	77.6	13.7	81.7	100.0	94.3	4.3
2	37.0	62.0	51.4	6.4	40.9	69.0	56.5	7.7	–	–	–	–
3	31.0	68.0	50.5	8.1	36.0	82.0	48.8	8.4	32.0	60.0	47.6	7.4
4	49.2	80.4	63.3	9.3	49.2	86.2	67.0	9.8	39.0	77.6	63.6	10.0
5	43.5	72.1	59.1	8.1	46.4	75.5	61.5	7.8	45.3	78.7	59.2	8.3

spelling (training step c) after 191 runs (patient 1), and 264 runs (patient 4). The other patients continued with basic training (training step a), until training was stopped at the request of the patient or because of limited resources on the part of the research institute. Patient 2 conducted 93 runs, patient 3 226 runs, and patient 5 233 runs of basic training.

Data analysis

Performance was measured as CRR in each run as described above. To determine the association between initial performance and later performance in SCP self regulation, Spearman's rank correlations were calculated. The maximum and mean CRRs of runs 1–30 served as outcome measures for initial performance and were correlated with the mean CRRs in runs 64–93 and runs 162–191 as measures for later performance. Outcome measures and interval borders were chosen according to the following considerations: As a measure for initial performance both the mean and the maximum CRR of runs 1–30 were selected, because 30 runs correspond to three or four training days, a training period after which all technical adjustments have been made. Interval borders have been chosen with respect to the patients' individual training duration: runs 64–93 represented the last training runs of patient 2, before he stopped training, and runs 162–191 represented the last training runs of patient 1, before he was transferred to free spelling. Thus Spearman's rank correlations were calculated between the maximum and mean CRRs in runs 1–30 and the mean CRR in runs 64–93 across five patients, and between the maximum and mean CRRs in runs 1–30 and the mean CRR in runs 162–191 across four patients.

To evaluate learning progress in each patient, linear regressions have been calculated with the number of runs as predictor and the CRR as criterion. To check normal distribution of CRRs, Kolmogorov-Smirnov tests have been conducted for CRRs of each patient.

RESULTS

Minimum and maximum CRRs, as well as means and standard deviations for each patient are depicted in table 2.

The maximum CRR in runs 1–30 was significantly correlated with the mean CRR in runs 64-93 (r=0.9, p=0.04), and in runs 162–191 (r=1.0, p<0.01). There were highly significant correlations between the mean CRR in runs 1–30 and 64–93 (r=1.0, p<0.01), and between the mean CRR in runs 1–30 and 162–191 (r=1.0, p<0.01) (fig 2).

Kolmogorov-Smirnov tests revealed normal distributions of CRRs in all patients, except in patient 1 (Z=1.99, p<0.01). Therefore, a Spearman's rank correlation was performed to measure the learning progress of patient 1. The correlation between the number of runs and CRRs was highly significant in patient 1 (r=1.0, p<0.01). Linear regressions with the number of runs as predictor and the CRR as criterion were significant in patient 2 (F(1,91)=4.88, p=0.03) and highly significant in patient 4 (F(1,262)=7.53, p<0.01), but not significant in patients 3 and 5. Therefore, three of five patients showed significant or highly significant learning progress.

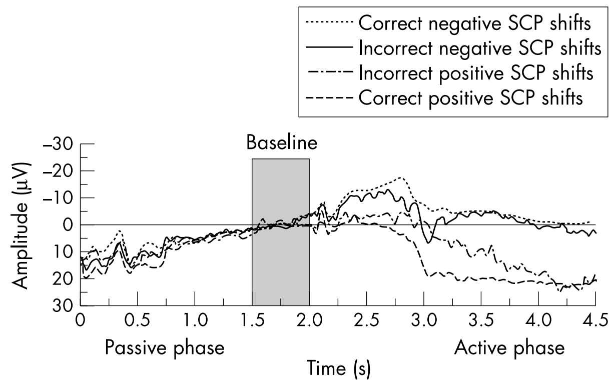

Figure 1 Grand average of 240 trials (patient 4) separated into correct and incorrect negative and positive SCP shifts.

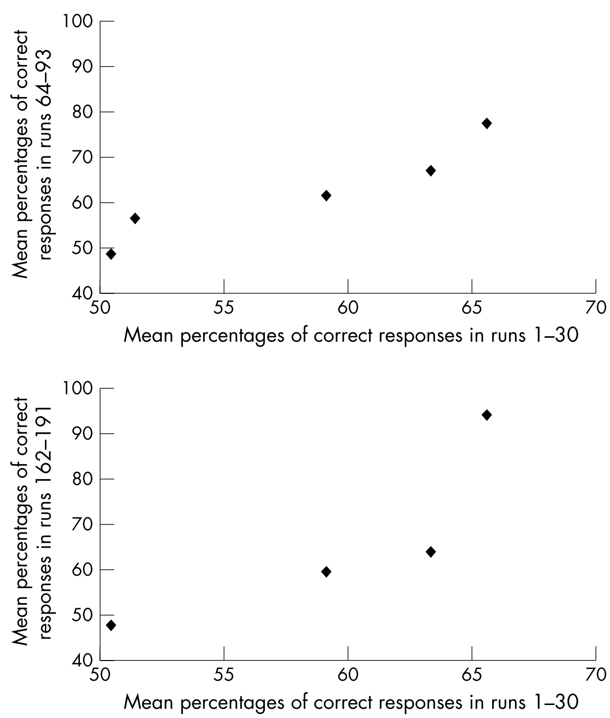

Figure 2 Spearman rank's correlations between the mean percentages of correct responses in runs 1–30 and 64–93 across five patients, and between the mean percentages of correct responses in runs 1–30 and 162–191 across four patients.

DISCUSSION

In accord with our hypothesis, this study has demonstrated that in a sample of five ALS patients future performance in SCP self regulation could be predicted from initial performance. Only patients who showed a percentage of correct responses of at least 80% within the first 30 runs, succeeded in later training and communication. In other words, those patients who learned SCP self regulation to a high degree learned it quickly. These findings have practical implications, such as the possibility to make extended communication training dependent upon the results of short test training. It is unclear, however, why some patients did not acquire self regulation even after hundreds of runs.

Ackerman suggested a model of interindividual differences during skill acquisition.[31 32] According to this model, skill acquisition can be segmented into three phases, whereby interindividual differences are induced by different factors in each stage. The first stage is characterised by slow and error prone performance and individual differences are determined to some degree by task-appropriate abilities and moderately to highly by cognitive-intellectual general ability, involving a strong demand on the cognitive-attentional system. During the second stage the stimulus-response connections of the skill are refined and strengthened. Interindividual differences in this phase result from differences in perceptual speed ability. The final stage of performance is best characterised as automatic and corresponds to predominantly non-cognitive psychomotor abilities. In this study, two of five patients made no progress in SCP self regulation. According to Ackerman, failure in this acquisition stage is expected to be attributable to cognitive variables. These patients (patients 3 and 5) were in a very advanced stage of ALS when they started self regulation training. In ALS, lesions are not only confined to the voluntary motor system, but can be also observed in frontal and temporal cortical areas,[27 33 34] as well as in subcortical regions, such as the thalamus, striatum, and globus pallidus.[35] Pilot results obtained with functional magnetic resonance imaging demonstrated that the production of negative SCP is associated with metabolic activity in the prefrontal cortex, insula, anterior cingulum, medial thalamus, premotor, and central regions, whereas the production of positive SCP is associated with activations in putamen and pallidum, and a deactivation of the supplementary motor area. Thus, brain areas necessary for SCP self regulation may be lesioned in ALS patients preventing them from the acquisition of the self regulation skill. Cognitive deficits that have been demonstrated in some ALS patients include executive and working memory dysfunction.[36] It may be speculated that these two patients lacked the necessary attentional resources to acquire SCP self regulation. Practical implications are that self regulation training should be started, before the disease is too advanced. Whether successful SCP self regulation can be maintained during the progression of ALS remains to be investigated.

The third patient (patient 2) who showed only little learning in the SCP training and could not be transferred to copy spelling had been only trained for four weeks, before he refused to further participate in the study. A lack of motivation resulting from consistent failure might have been contributed to his decision. Although patient 2 was still in an earlier stage of ALS, he was the oldest of our patients (66 years), an age where multiple neurological defects are more likely. Rockstroh *et al* mentioned that age seemed to be an important mediating variable in their study being detrimental for SCP self regulation.[23]

Whether interindividual differences disappear with increasing practice in a task, depends according to Ackerman[31 32] on the consistency of the task information processing demands: when the task is consistent, variability declines as the general ability declines in influence. When the task has a substantial degree of inconsistent information processing demands, however, variability is predicted to remain stable. Whether this model can be applied to patients with brain damage, is unclear. In this study we found that individual differences remained stable, although the task to produce negative or positive SCP amplitude shifts was consistent. It may be concluded that SCP self regulation is a complex task requiring cognitive resources that not all ALS patients possessed. Apart from attention, as described above, variables contributing to success in SCP self regulation are velocity of perception[37–39] and self efficacy (Uhlmann, doctoral thesis). Self efficacy, the belief in one's capabilities to manage future events,[40] may be especially important to maintain motivation for time consuming self regulation training. However, locked in patients are completely committed and may suffer from a lack of self efficacy and learned helplessness.

To summarise, this study has demonstrated that in a sample of five ALS patients later performance in SCP self regulation could be predicted from initial performance. Assumptive mediating variables are attentional capacities and motivation.

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