in the previous section. The robust Kalman filter was trained using red and yellow light averages from the maximal electrode site for obtaining the P3 for each subject. We used the whole trial epoch for recognition because it yielded better recognition than just the time area around a potential P3. In order to look at the reliability of the robust Kalman filter two of the Subjects (S4 and S5) returned for another VR driving session. The results of this session using the robust Kalman Filter trained on the first session are shown in the last column of Table II. The recognition numbers for red and yellow lights between the two sessions were compared using correlation. Red light scores between the sessions correlated fairly highly: 0.82 for S4 and 0.69 for S5. The yellow light scores between sessions correlated poorly with both S4 and S5 at around -0.1. This indicates that the yellow light epochs tend to correlate poorly with each other due to the lack of a large component such as the P3 to tie them together.

IV. Future Work

The recognition rates presented make it practical to use the P3 EP as an interface to devices such as TV's, radios, and other appliances. The ease of swapping user interfaces in this BCI system facilitates such environmental control work. We expect that the most useful BCI will rely on a variety of brain signals. For example, if a patient can develop μ-rhythm control, they might want to use it to control the volume on a TV with a P3 being used to control the on–off functions. Contextual information, when available, should also be used. Environmental control provides many ready opportunities for this because of the different physical locations of items.

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The Thought Translation Device (TTD) for Completely Paralyzed Patients

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***Abstract*—The thought translation device trains locked-in patients to self-regulate slow cortical potentials (SCP's) of their electroencephalogram (EEG). After operant learning of SCP self-control, patients select letters, words or pictograms in a computerized language support program. Results of five respirated, locked-in-patients are described, demonstrating the usefulness of the thought translation device as an alternative communication channel in motivated totally paralyzed patients with amyotrophic lateral sclerosis.**

***Index Terms*—Electroencephalogram (EEG), language support program, locked-in, operant learning, slow cortical potentials (SCP's).**

I. Introduction

A communication device for the completely paralyzed was developed using an operant learning approach for the self-regulation of EEG signals. The procedure was tested in locked-in patients with amyotrophic lateral sclerosis (ALS) [1]–[4]. The thought translation device (TTD) uses slow cortical potentials (SCP's) to select letters or words from a language support program. SCP's are shifts in the depolarization level of the upper cortical dendrites which are caused by intracortical and thalamocortical afferent inflow to neocortical layers I and II. Negative SCP's are the sum of synchronized ultraslow excitatory postsynaptic potentials from the apical dendrites. Positive SCP's result from a reduction of synchronized inflow to the apical dendrites or may be caused by inhibitory activity or by excitatory outflow from the cell bodies in layers IV and V. Positive SCP's lasting from 300 ms to several seconds or minutes are correlated with a disfascilitation of the involved cortical networks. Behavioral and cognitive performance is improved after subjects or patients have learned to increase the negativity of the SCP, while cognitive and

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behavioral performance is reduced during positive cortical potentials [5].

Operant conditioning of SCP's is possible and leads to improved behavioral and cognitive performance involving the respective brain region if negativity is trained, and reduced performance if positivity is achieved (for a review see [4]). SCP's are used for the thought translation device because their neurophysiological basis is well understood and the learning rules of the acquisition of SCP self-control are well known. Because SCP's indicate the overall preparatory excitation level of a cortical network, they are universally present in the human brain. In patients with extensive lesions or atrophy of the brain, such as in ALS, SCP's can be recorded from most cortical areas without serious pathological deviations. The same is true for other candidates for brain-computer-communication, such as people with stroke, muscular dystrophies, autistic and schizophrenic disorders. A series of studies examined the pathophysiology and mechanisms or several therapeutic applications of self-regulation of SCP's with neurological and psychiatric disorders, for example, untreatable chronic epilepsy [6], [7].

II. METHODS

A. Patients

The present report describes the results of five patients. Three patients acquired reliable self-control of SCP and two patients have been using the thought-translation-device for communication for several months. Both patients have been artificially ventilated and artificially fed for more than four years; one has rudimentary control of a small face muscle, the other has some rudimentary control of eye movements, but only for a short period of time. The third patient has partial control of eye movement and is intermittently on respiration. One patient did not continue training for motivational reasons. Another patient, who still had rudimentary muscular abilities, discontinued training for personal reasons after several months of successful learning of SCP.

III. APPARATUS AND RECORDING

All experiments take place in the patients' homes with portable training devices that remain with the patients. The patients are lying in bed or sitting in wheelchairs. Conventional eight-channel EEG-amplifiers with a high time constant ranging from 3 to 16 s (depending on the patient's response) are used. EEG is recorded from the vertex relative to mastoids at a sampling rate of 256 Hz. During the first and subsequently every 30th training session a multielectrode recording session is performed using C3 and C4 (left and right central) and P_z (parietal) and F_z (frontal) electrodes in addition to C_z (vertex). Vertical eye movements are simultaneously recorded with standard online removal of eye movement artifacts [5]. Ag/AgCl-electrodes (8 mm) are fixed with elefix electrode cream at an impedance of less than 5 kΩ. Electrodes are attached with collodium and remain on the patient's head for several days before they are cleaned and reattached. Therefore, patients have 24-h access to the thought-translation-device. SCP's are extracted online from the regular electroencephalogram, filtered, corrected for eye movement artifacts and fed back to the patient with visual, auditory or tactile feedback. Visual feedback of the SCP consists of an EEG signal that is updated every 63 ms and is converted to the shape of a ball-like light that moves toward or away from a target box that is located in the upper part of the monitor and is highlighted when the patient has to produce an SCP negativity and flashes in the lower part of the monitor when the patient has to produce a positivity. After a 2-s baseline, the SCP's are fed back for 2–4 s. In order to avoid erratic movements of the feedback-curser the EEG is averaged over a sliding window of 500 ms moving in steps of 63 ms. With a sampling rate of 256 Hz the EEG is digitized with a rate of 4 ms. If the patient achieves the required amplitude change, as assessed by an online classification system, reinforcement is provided by presenting a smiling face and a new trial begins. A training day usually consists of 6–12 sessions each of which lasts about 5–10 min and comprises 70–100 trials. Patients are trained several times per week. Initiation of the baseline period is indicated by a high-pitched tone, initiation of the 2–4-s feedback period is initiated by a low-pitched tone. The training procedure follows a shaping program in which progressively more demanding SCP amplitude changes are reinforced. The response criterion is gradually increased from 5 to 8 μV. If stable performance of at least 75% correct trials is achieved, the patient begins to work with the first level of the language support program. With the exception of patient 003, who achieved 75% self-control after only a few weeks of training, all other patients had to be trained for several months before they reached the criterion of 75% correct.

For the language support program (spelling device), the alphabet is first (level 1) split into halves (letter-banks) which are presented successively at the bottom of the screen for several seconds. If the subject selects the letter-bank being shown by generating an SCP shift, the letter bank is then split into two new halves and so on, until each of the two letter-banks has only one letter in it. When one of the two final letters is selected, it is displayed in the top text field of the screen and a new selection begins at level 1. A "return function," which appears as an option after rejecting two successive letter-banks, allows the patient to erase the last symbol written in the text field. Most training sessions are video-documented.

IV. RESULTS

Fig. 1 presents the results of three patients who successfully learned to spell with the TTD. Patient 001 has been trained for more than 260 sessions and has progressed to free spelling [see Fig. 1(a)]. The patient reached the free spelling stage after about 100 sessions (with a session consisting of 70 to 100 trials) of "copy spelling" (i.e., selection of letters that are presented on the screen) and has maintained a high level of correct responses since then.

Both patients can write their own letters by using the TTD. Patient 002 [see Fig. 1(b)] has been trained for 220 sessions and he also maintains a high level of correct responses. The patients' average number of trials for the selection of a letter varied from 8 to 80 with a median number of 28. This means that they needed about 2 min for the selection of one letter (based on a trial-length of 4.5 s). Fig. 2 shows averaged SCP's over 700 representative trials for each of the three patients of Fig. 1 separated for trials where selection of a character was required with cortical positivity and for trials where rejection without cortical positivity was required.

Fig. 3 presents a self-generated letter of patient 002. Patient 003 has been trained for 190 sessions and has so-far only used copy spelling. He has quickly obtained a very high level of accuracy and will soon be switched to pictograms since his reading and writing skills would not permit the use of self-selected letters and words. Of the two remaining patients, patient 004 achieved 65% control after several months of training but then stopped training because he lost self-control of SCP after he changed his cognitive strategy; despite of several days of new training he never regained control. Patient 005 who had less advanced ALS stopped training because the patient inadvertently received false feedback and the patient's will to live and to change from mask respiration to respiration through a tracheotomic device was low. He later refused to continue to live.

Communication speed could be considerably improved by presenting entire words, word prediction after spelling the first letters, and pictograms in the language support program. Despite the improved

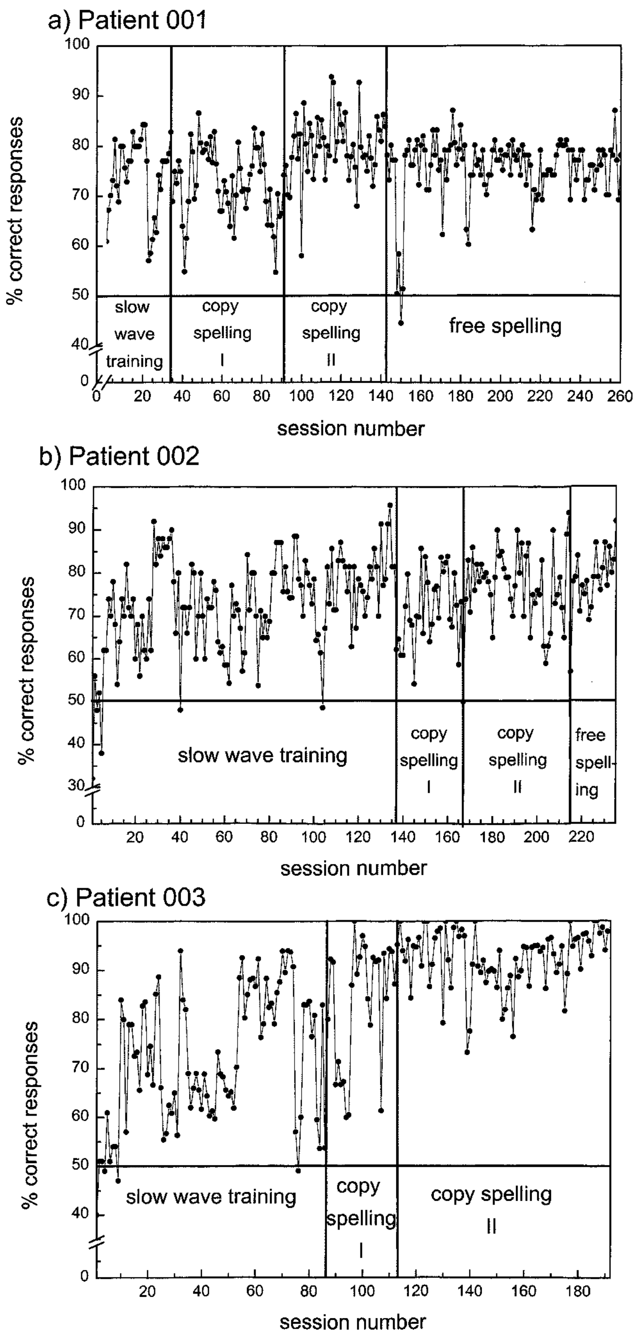

Fig. 1. Learning rates of patients 001–003 using SCP feedback. After an initial training phase that required positivity or negativity of the SCP, the patients used their preferred SCP response (positivity or negativity) to copy letters. Copy spelling I refers to a phase where the selection of wrong letters resulted in the repeated presentation of the letter that was to be selected. Copy spelling II refers to a phase where the patients were presented with the letter they had selected even if the selection was wrong. They subsequently had to erase the letter if they had made a mistake. Free spelling refers to a phase where the patients selected letters and words according to their own wishes. Error rates of this phase are deduced from the words the patients completed. Fig. 1(a) shows only the last 40 sessions of the SCP training of patient 001 who received overall more than 200 SCP training sessions. (Patient 001 and 002 Fig. 1 from *Nature*, vol. 398, pp. 297–298, Mar. 25, 1999; N. Birbaumer, N. Ghanayim, T. Hinterberger, I. Iversen, B. Kotchoubey, A. Kübler, J. Perelmouter, E. Taub, and H. Flor, A spelling device for the paralyzed, with permission.)

writing speed, the patients seem to dislike to use pre-selected word sequences or word predictions because they feel less free in selecting

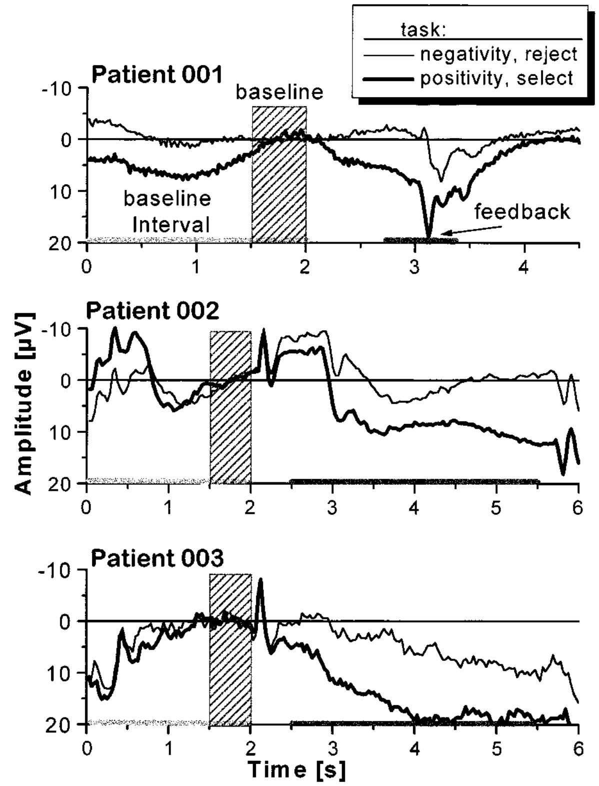

Fig. 2. Averaged SCP's of the patients of Fig. 1. Representative averages over 700 trials each during baseline, baseline interval and feedback interval separated for trials where selection of a letter was required with a cortical positivity (solid line) and trials where rejection of a letter was required with no positivity or negativity (thin line). Appearance and disappearance of the light-ball feedback is indicated by the bottom dark line during the feedback interval. Different waveforms develop during training which remain highly stable within each individual patient.

LIEBER-HERR-DAMBMANN-DAS-IST-MEIN-DRITTER-BRIEF-
DEN-ICH-NUR-MIT-MEINEN-GEDANKEN-GESCHRIEBEN-HABE.-
WELTWEIT-GIBT-ZWEI-MENSCHEN-DIE-DAS-KÖNNEN.-DAFÜR-
WERDE-ICH-VON-UNI-TÜBINGEN-DREIMAL-PRO-WOCHE-
TRAINIERT.-DAS-TRAINING-IST-HART-MACHT-ABER-
SPASS.-ICH-FREUE-MICH-ÜBER-IHREN-BESUCH.-
HERZLICHE-GRÜßE-AN-IHRE-FRAU.-IHR-JÜRGEN-BOROWICZ-

Fig. 3. One of the letters written by patient 002.

and presenting their own intentions and thoughts. All patients with the exception of the nonnative speaker (patient 003) select characters at a rather slow speed. Completely paralyzed patients may feel less time pressure and may therefore be satisfied with the achieved communication speed, which is a substantial improvement compared to the inability of communication before they used the Language Support Program. However, for verbal communication with healthy people the achieved spelling speed needs to be improved, i.e., by more extensive use of word prediction and abbreviation expansion already available in the language support program.

V. Discussion

The data presented here demonstrate that locked-in patients can regain communication ability by using their SCP's to select letters. Although still slow, the TTD satisfies the requirements for a successful brain-computer interface [8]–[10]. The TTD could connect online to the worldwide web with a program which is using a windows surface now under construction. This internet version of the thought-translation-device should allow patients to communicate worldwide using their brain activity. We hope that ALS patients who have to decide whether they will switch to artificial ventilation or die due to respiratory failure will decide to continue their lives when they have access to a communication device. The quality of life of these patients would heavily depend on the possibility to communicate with the social environment. Depression indices and quality of life scores need not necessarily be different from healthy subjects after a period of several months of adaptation to artificial respiration [11]. Data on life expectancy in respirated ALS patients should be interpreted with caution because the health and life expectancy of these patients depend more on psychological variables influencing the immunological condition than on the course of the illness. With appropriate physical care, patients with the TTD may remain psychologically healthy and can therefore continue to live with an acceptable quality of life over extended periods of time.

At this time we see no need for an invasive procedure such as implanting electrodes in the brain or under the skin because 24-h self-control of SCP's and sufficient communication speed can be achieved with the noninvasive thought translation device. A minority of our patients do not show sufficient learning speed and success. Therefore, the main future task will be to improve the ability to communicate by the combination of the SCP thought-translation-device and other brain–computer interfaces such as those developed by Wolpaw, Vaughan, and McFarland [9] and Farwell and Donchin [8].

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Brain–Computer Interface Research at the Neil Squire Foundation

Gary E. Birch and Steve G. Mason

***Abstract*—The ultimate goal of our research is to utilize voluntary motor-related potentials recorded from the scalp in a direct Brain Computer Interface for asynchronous control applications. This type of interface will allow an individual with a high-level impairment to have effective and sophisticated control of devices such as wheelchairs, robotic assistive appliances, computers, and neural prostheses.**

***Index Terms*—Assistive technology, brain–computer interface (BCI), electroencephalograph (EEG) signal processing.**

I. INTRODUCTION

The Neil Squire Foundation is a Canadian nonprofit organization whose purpose is to create opportunities for independence for individuals who have significant physical disabilities. Through direct interaction with these individuals the Foundation researches, develops and delivers appropriate innovative services and technology to meet their needs. Part of the Research and Development activities of the Foundation, in partnership with the Electrical and Computer Engineering Department at the University of British Columbia, has been to explore methods to realize a direct brain–computer interface (BCI) for individuals with severe motor-related impairments. The ultimate goal of this research is to create an advanced communication interface that will allow an individual with a high-level impairment to have effective and sophisticated control of devices such as wheelchairs, robotic assistive appliances, computers, and neural prostheses. This type of interface would increase an individual's independence, leading to a dramatically improved quality of life and reduced social costs.

The main focus of our work has been the development of advanced signal processing methods for single trial electroencephalograph (EEG) signals to explore new potential feature sets for a BCI. The techniques developed to date, the outlier processing method (OPM) and the low-frequency asynchronous signal detector (LF-ASD), have been designed to automatically recognize single-trial, voluntary motor-related potentials (VMRP's) [1] from scalp-recorded EEG signals with reasonable accuracy. Our data has been recorded in an asynchronous control paradigm in which our subjects switch from an idle state to a state of active (motor) control.

II. OVERVIEW OF WORK TO DATE

A. Outlier Processing Method

Our initial research effort was focused on developing, evaluating and improving the outlier processing method (OPM) [2] [3] [4] designed to extract single-trial VMRP from EEG. The OPM uses robust, statistical signal processing methods to estimate the spontaneous (background) EEG from the one-dimensional observed EEG signal. The single-trial VMRP is then calculated as the difference between the observed EEG

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