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Neural Internet: Web Surfing with Brain Potentials for the Completely Paralyzed

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Neural Internet is a new technological advancement in brain-computer interface research, which enables locked-in patients to operate a Web browser directly with their brain potentials. Neural Internet was successfully tested with a locked-in patient diagnosed with amyotrophic lateral sclerosis rendering him the first paralyzed person to surf the Internet solely by regulating his electrical brain activity. The functioning of Neural Internet and its clinical implications for motor-impaired patients are highlighted.

Key Words: *Brain-computer interface (BCI)—Neuroprosthesis—Slow cortical potentials (SCP)—Neurofeedback—Amyotrophic lateral sclerosis (ALS)—Locked-in syndrome (LIS).*

"Cogito, ergo sum – I think, therefore I am!" This famous quotation from the rationalistic philosopher Descartes may bear a new meaning for completely paralyzed patients. Neurological diseases such as amyotrophic lateral sclerosis (ALS), Guillain-Barré syndrome, or brainstem stroke can lead to severe or total motor paralysis, often referred to as locked-in syndrome, where the intact intellect is locked into a paralyzed body. Locked-in syndrome (LIS), a term coined by Plum and Posner,[1] denotes a neurological condition consisting of tetraplegia and paralysis of all cranial nerves except vertical eye movements and blinking.[1-3] Consciousness is fully preserved and can be demonstrated by voluntary blinking.[2]

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Bauer and others[4] classified LIS into 3 categories: the "classical" LIS, as described by Plum and Posner; the "incomplete" LIS, which resembles classical LIS, but with additional remnant voluntary movements; and the "total" LIS, which includes patients who are completely motionless and unable to communicate. In ALS, patients can use rudimentary muscle control or eye movements to operate augmentative devices before entering the total locked-in state. However, in the course of the disease, such rudimentary muscle control becomes increasingly weaker or even lapses, leaving the patient without any (reliable) communication possibility. Although ALS patients may experience a loss of all motor functions including speech, their sensory and cognitive functions often remain largely unimpaired.[5,6] For such patients, thinking is the only activity over which they still have control, and thus the last manifestation of their conscious mind (see ref. 7 for a patient's perspective on living without the ability to move). However, ALS patients in LIS are rarely seen, because patients succumb to breathing insufficiency unless they choose artificial ventilation. Healthy individuals and medical professionals commonly assume that quality of life in such patients, especially if they depend on artificial life-sustaining treatment,[8] is poor. Anticipated poor quality of life and biased or fragmental information about the late stage of ALS and the possible care and treatment options (such as augmentative communication devices) are crucial reasons that can cause patients to wish for a hastened death with the aid of physician-assisted suicide or euthanasia.[9] Remarkably, a recent study by Kübler and others[10] has shown that the majority of patients suffering from ALS rated their quality of life as satisfactory or good and that ventilated patients did not differ from nonventilated patients in severity of depressive symptoms and experienced quality of life. Studies investigating factors that contribute to a good quality of life have pointed out that the maintenance of communication ability is an essential factor.[10,11] However, conventional augmentative communication devices, which depend on some muscle control, may not be feasible for patients in the end stage of ALS if they have no remaining reliable muscle control. Thus, the final option for restoring communication to those patients is to provide the brain with a new, nonmuscular communication and control channel, a direct brain-computer interface (BCI) for conveying messages and commands to the external world. Several studies have successfully applied slow cortical potentials (SCPs),[12,13] sensory-motor rhythms (SMRs),[14] P300 evoked potentials,[15] and neuronal action potentials16-18 for different BCI systems.

The goal of this study was to investigate the feasibility of a Web browser based on self-regulation of brain potentials for completely paralyzed patients. This technology, which we call Neural Internet, could enable such patients to regain autonomy by using the unique communication and interaction possibilities of the World Wide Web independently of any voluntary muscle control. We define Neural Internet as a system that uses neuronal signals from the brain and transforms them to binary or multidimensional computer commands enabling the patient to surf the Internet and read and send e-mails. The following brain signals might provide quite conceivable approaches for Neural Internet:

- Electroencephalographically (EEG)-controlled Web browser using SCPs,[12,13] SMR/beta EEG-rhythms,[14] or P300 evoked potentials[15]
- Invasive methods using electrocorticographic activity (ECoG),[19,20] local field potentials,[21-23] or neuronal action potentials[16-18]
- Metabolic brain activity measured by hemodynamic methods such as near infrared spectroscopy[24,25]

Here, we introduce a prototype of an EEG-controlled Web browser, which can be operated by SCP self-regulation. This system was called *Descartes* as an homage to the French philosopher. Figure 1 illustrates the setup of *Descartes.*

PATIENT AND METHODS

Patient HPS

Descartes has been developed and tested since 1999 with a nearly locked-in patient (HPS), rendering him the first paralyzed patient to surf the Internet only with his electrical brain activity. HPS worked as a lawyer for the state government when he was diagnosed with ALS in 1989. The first symptom was a weakness of the right arm after an accident in a volley ball game. Since 1993, he has been artificially ventilated and fed. His motor abilities were then already reduced to 2 small facial muscle movements (M. levator labii superioris alaeque nasi and M. depressor anguli oris) and weak eye movements. Although almost completely paralyzed, HPS is still interested in law and current affairs. Following sports and political news on TV and surfing the Internet with *Descartes* keeps him in touch with his former interests. He lives in an apartment on his own but needs 24-h care. HPS was intubated in an emergency against his previously declared will but now rates his quality of life and his desire to live highly. Questioned why he demanded hastened death at that time, he jokingly answered: “Anyone can make a mistake.” Since 1993, HPS has been using eyeblink spelling for communication. However, because of increasing fatigue of eye movements and the lack of reliable voluntary muscle movement, he has not been able to operate conventional augmentative communication devices, which depend on rudimental muscle control.

Data Acquisition

The EEG was recorded from Cz, Fz, and Pz according to the international 10-20 system. One electrode at the patient’s forehead served as reference. Ag/AgCl electrodes were applied with Elefix electrode cream. Electrode impedance was kept below 5 kOhms. The EEG was amplified using an EEG8 amplifier system (Contact Precision Instruments Inc., London, UK) and acquired with a sampling rate of 256 S/s. The low-pass filter was set to 40 Hz and the high-pass filter to 0.1 Hz. Although the EEG was recorded with a bandwidth of 40 Hz, the software applied a low-pass filter at 1 Hz to detect the SCP signal. This low-pass filter was achieved by using a moving average window of 500 ms, updated 16 times a second.

Feedback of Slow Cortical Potentials

In previous studies, we have shown that self-regulation of SCPs can be acquired according to operant learning principles.[8,9] EEG data acquisition, online signal processing, and classification were performed using the Thought Translation Device (TTD) Software.[26] *Descartes* was designed as a program module providing a Web browser that could be controlled by the signals from the TTD. *Descartes* provided feedback of SCP amplitude shifts at the vertex (Cz) in a rhythmic, time-locked manner. After the presentation of a discriminative stimulus (highlighting of a target on a computer screen), the correct behavior (production of SCP shifts in the required direction) was reinforced with a rewarding stimulus (a smiling face appearing at the center of the screen). One training day consisted of 10 to 20 runs. Each run comprised 100 trials with no intertrial intervals. Each trial was divided into a 2-s preparation phase, in which the required task was indicated but no feedback was provided, and a 2-s active phase, in which the patient was required to regulate his SCP amplitude. The beginning of the preparation phase was indicated by a

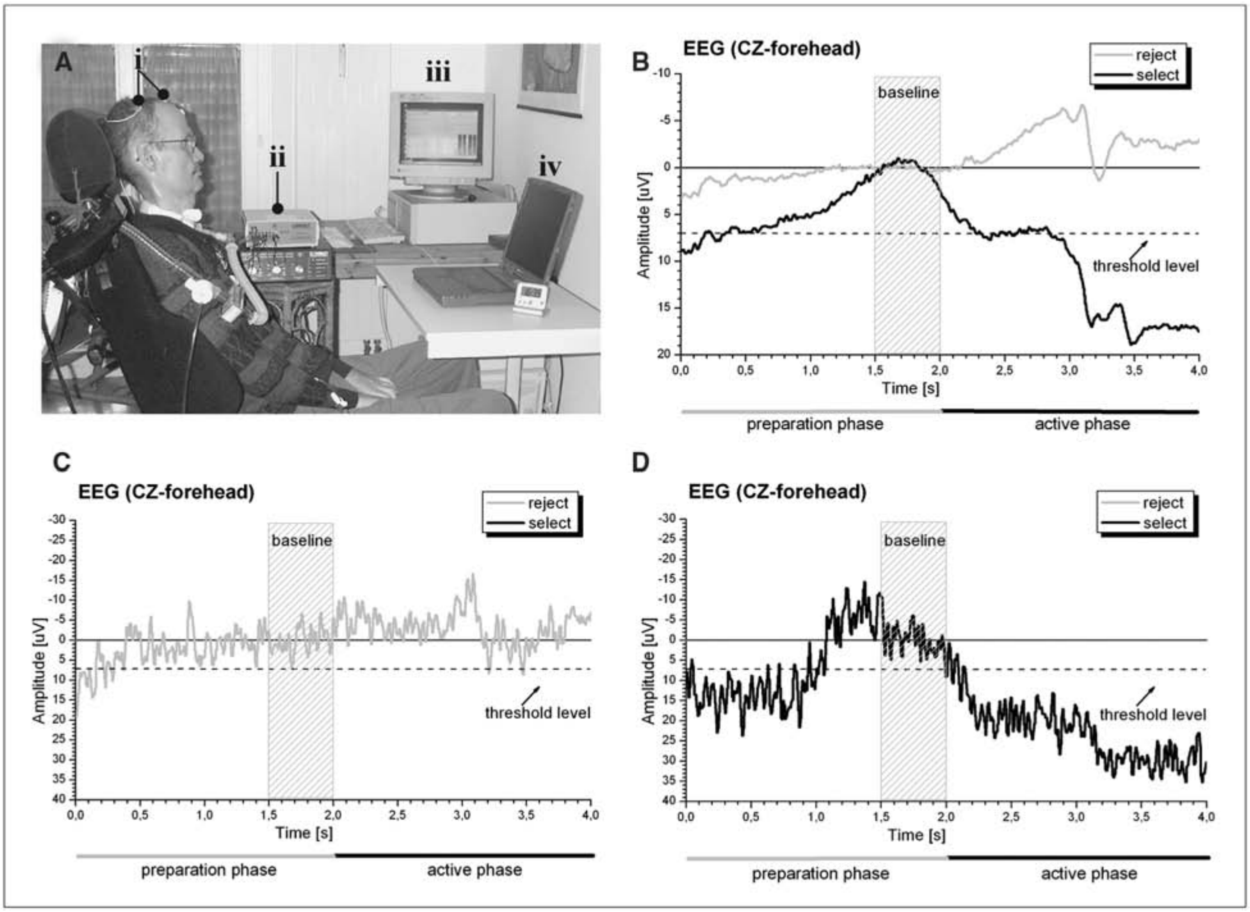

Figure 1. Setup of the electroencephalogram (EEG)-controlled Web browser *Descartes*. A, The EEG is recorded with Ag-AgCl electrodes from the patient's scalp (i). The signals are amplified using an EEG amplifier (ii) and transmitted to a PC with an analog-digital card (iii) for online supervision for the training assistant. Slow cortical potentials (SCPs) are extracted by appropriate filtering, corrected for electrooculographic (EOG) activity, and fed back to the patient as a cursor movement on a laptop screen (iv). B, Averaged SCP curves over 3200 trials. A trial consists of a 2-s preparation phase, where the system measures the user's initial baseline voltage level, and a 2-s active phase, where the user can move the cursor upward (*reject* a command) by producing negative SCP shifts or move the cursor downward (*select* a command) by producing positive SCP shifts above a predefined threshold of 7 µV. C, SCP shift in a single trial during a "reject" task. D, SCP shift in a single trial during a "select" task. The pictures are published with permission from the patient.

short high-pitched tone of 1200 Hz, whereas the active phase was introduced by a clearly distinguishable low-pitched tone of 500 Hz. Feedback of SCP amplitude shifts was provided for the patient with a yellow ball on the computer screen referred to as a cursor. The position of the cursor during the feedback period was determined by the current SCP amplitude compared to a baseline recorded 500 ms prior to the low-pitched tone. Negative cortical potential shifts moved the cursor upward; positive shifts moved the cursor downward.

Before the patient could surf the Internet using *Descartes*, he was trained in a stepwise procedure.[27,28] The first stage was the SCP feedback training as described above, by rewarding the patient for producing cortical shifts in the requested direction. After 4 weeks of training (2 to 3 times per week), HPS was able to produce negative and positive SCP amplitudes according to the task requirement. After 2 months, he was able to select letters in a language support program. Within the following year, he succeeded in writing his first message with the BCI.[12] Recently, HPS wrote a detailed description of the mental imagery he uses to control cursor movement.[29] HPS produced negative SCP shifts with images of preparation such as an arrow being drawn on a bow. To produce a positive potential shift, he imagined the arrow shooting up from the bow. This mental strategy is in line with the notion that SCPs reflect a threshold regulation mechanism for local excitatory mobilization. Negative SCP shifts indicate local excitatory mobilization, whereas positive potential shifts indicate disfacilitation.[29,30] SCP shifts from single trials are exemplary shown in Figure 1b and c. To produce cortical positivity, a preceding negative SCP shift can be seen during the preparation phase. This negative preparatory potential helped to establish a more negative baseline level at the end of the preparation phase. In other words, by producing a negative SCP shift during baseline, the patient can promote his ability to produce a positive SCP shift in the active phase.

Compared to other ALS patients who tried SCP-based BCI, he is one of the best performing patients in self-regulation of SCP (for prior BCI data from this patient, see refs. 12 and 27).

Web Surfing with *Descartes*

In *Descartes*, the commands are arranged in a dichotomous decision tree based on a modified Huffman's algorithm.[31] For *selecting* a command, the patient produces positive SCP shifts (above a predefined threshold of 7 μV), which move the cursor downward. For *rejecting* a command, the patient produces negative SCP shifts, which move a cursor on a computer screen upward. A threshold level for rejection was not implemented, meaning that "reject" is the default option, if the criterion for "select" is not met. Previous EEG classification analyses revealed that this threshold method leads to the highest correct response rate for this patient.[26,32] However, for different patients, the optimal EEG classification for the select and reject options has to be individually assessed.

At the first level of the decision tree, the patient can choose whether to write an e-mail or to surf the Internet. If the patient decides to write an e-mail, the e-mail address and the text body have to be spelled out using the BCI spelling device.[12] If the patient decides to surf the Internet, he or she first receives a number of predefined links arranged in the dichotomous decision tree (see Fig. 2). Each Web page is offered successively for selection at the bottom of the monitor. The patient can select a Web site by producing a positive SCP shift, or reject it by producing a negative SCP shift. Once the patient has selected a Web page, it will be automatically loaded and shown for a predefined time until the SCP feedback mode will start again offering the patient to choose a link from the selected Web page, to go 1 page back, or to start from the initial list again. In the SCP feedback mode, a dichotomous decision tree is dynamically produced, containing all links from the viewed Web page in alphabetical order. For example, the patient is offered links beginning with A–K, which he or she can select or reject by altering his or her SCP amplitude. If the patient rejects this option, links beginning with L–Z are offered. If both options are rejected, the patient receives a CANCEL option for returning to the previous level. The lowest level of the decision tree contains the name of a single link, which is loaded after selection. To test HPS, 2 or 3 test runs (each consisting of 100 trials) were conducted at the beginning of each Web-surfing session. The patient was asked which e-mail message he wanted to write or which Web site he wanted to view. Using eye-blink spelling, the patient dictated this information. The target state was then entered into *Descartes*, so that the system could evaluate how many trials the patient needed to achieve his aim and in which trials the patient performed correct SCP modulation and in which trials the patient failed. Furthermore, to compare the frequency of correct response, which occurs under voluntary SCP control with the frequency of correct response by chance alone, we conducted 300 trials with contingent SCP feedback (test condition) and 300 trials without SCP feedback (control condition). Both conditions were performed within the same training session. In the control condition, the feedback screen was turned off, so that the patient could not voluntarily modulate his SCP amplitude in accordance with the task (required negativity versus required positivity). Instead of providing the patient with contingent SCP feedback, the patient saw a video tape of the feedback screen, which was recorded during the 300 trials with SCP feedback. The reason for this substitution was, first, to avoid monotony during the control condition and, second, to provide the patient with similar visual stimuli as in the test condition but without contingent SCP feedback. The frequency of correct and incorrect SCP shifts in the 2 conditions was compared using a chi-square test.

RESULTS

Slow cortical potential curves of patient HPS averaged over 3200 trials are presented in Figure 1b. These trials are from 7 training sessions (days) chosen randomly from the year 2005. HPS has achieved a mean accuracy of 80% (± *SD* 6.2%), which varies on different days from 68% to 95%. The false-positive rate averages 8.6% (± *SD* 4.1%). To test the patient's ability to use 2 different brain responses (positive vs. negative SCP shifts) for operating *Descartes*, a point-biserial correlation between the required SCP shift (negativity vs. positivity) and the achieved SCP amplitude was computed over these data revealing a significant differentiation between the 2 brain responses ($r_{pbis} = 0.56$, $P < 0.001$). Furthermore, to compare the frequency of correct response that occurs under voluntary SCP control with the frequency of correct response that occurs merely by chance alone, 300 trials with contingent SCP feedback (test condition) were compared with 300 trials without SCP feedback (control condition). As depicted in Figure 3, the ratio between correct and incorrect responses was significantly better in the test

Figure 2. Web surfing with *Descartes.* The left panels depict the patient's computer screen during different stages of Web surfing. The right panels explain the procedure in more detail. A, The patient views a list of predefined Web pages. Each Web page is offered successively for selection at the bottom of the monitor. The patient can select this link by producing a positive slow cortical potential (SCP) shift, or reject it by producing a negative SCP shift. B, Once the patient has selected a Web page (here his favorite German newspaper), it will be automatically loaded and shown for a predefined time until the SCP feedback mode will start again, offering the patient further commands. C, The patient has chosen to read one of the links that were shown on the previous Web page. The links are offered alphabetically in a dichotomous decision tree, in which he can select or reject each item by regulating his brain potentials.

condition than in the control condition ($x^2 = 62.30$; $P < 0.001$), confirming the patient's ability to voluntarily modulate his SCP amplitude to operate *Descartes.*

In a Web-surfing session of usually one and a half hours, the patient views 5 to 9 Web pages, and when he writes an e-mail, he needs on average 1 min for 2 characters (for a video of HPS operating *Descartes,* see Supplementary Online Information). HPS is now using *Descartes* regularly 1 to 2 times a week, for example, to read his favorite German newspaper online, to search

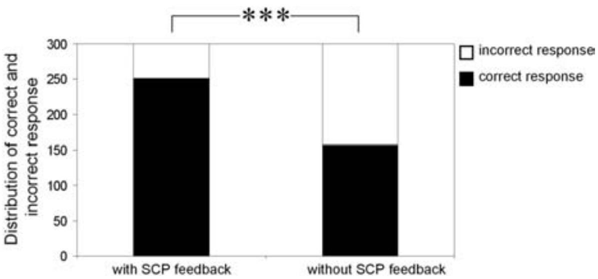

Figure 3. Frequency distribution of correct and incorrect slow cortical potential (SCP) shifts with contingent SCP feedback (test condition) and without SCP feedback (control condition). Correct SCP shifts occurred in the control condition in 52% and incorrect SCP shifts in 48% of the 300 trials, which resembles a random distribution. However, in the test condition, correct SCP shifts occurred in 84% and incorrect SCP shifts in 16% of the 300 trials. ***$P < 0.001$.

and order recently published law books, especially those of his former colleagues, or to read and write e-mails to friends and relatives.

DISCUSSION

We have shown here for the first time that an EEG-controlled Web browser based on self-regulation of SCPs can be reliably operated by a nearly locked-in patient. Neural Internet seems to be a very promising approach for connecting motor-impaired users such as HPS to the World Wide Web and offering them unique communication and interaction possibilities with the outside world—possibilities which they would not otherwise be able to use due to their motor disability, such as shopping, receiving information, or even running a business. Moreover, using options like e-mail with a BCI Web browser may offer completely paralyzed patients the only possibility to read, write, and send confidential letters to relatives or friends without an intermediator (a caregiver or a nurse). Thus, Neural Internet can help motor-impaired patients to regain *autonomy* in the interaction with the outside world and thereby enhance their quality of life. However, to enable severely paralyzed patients to use Neural Internet more efficiently, the following constraints have to be addressed in future BCI research:

Access to the Whole World Wide Web

Our goal is to offer paralyzed patients access to the whole World Wide Web and its options and not only to a preselected list of Web pages. One of the problems is, for example, selecting an icon or a picture as a link on a Web page. Because graphical links are often not defined comprehensively in the HTML code, the user will not be able to identify the textual label of this link in the SCP feedback mode. A further problem in selecting from an alphabetically sorted decision tree is when several links have the same name. Imagine, for example, that the user views a Web page that contains a list of items from a Web shop. For each item, the user may, by clicking a symbol associated with the item, execute some action, for example, buy. If the links do have a textual description, it will say "buy" for all items, so that the user will not know which item he or she buys when choosing a link. To overcome these problems, we are currently testing the usability of graphical "in-place" markers instead of textual labeling, whereas different brain responses (cortical positivity vs. cortical negativity) correspond to 2 different frame colors placed around selectable items.[33]

The Optimal Input Signal for a BCI Web Browser in Different Patients

Future studies will have to investigate under which conditions Neural Internet can be offered to a wide range of severely paralyzed patients, suffering from significant communication impairment. In general, it can be assumed that if a patient can achieve reliable control of any brain signal, which can be used as a binary or even as a multidimensional input signal for a BCI system, Neural Internet can be implemented based on this signal. Thus, SCPs are not necessarily the optimal input signal for all patients, but rather one possible option as demonstrated in this case study. The main challenge is therefore first to find for each patient the optimal input signal for a BCI system, which can considerably vary interindividually. In cooperation with the Wadsworth group,[34] we are conducting an international study comparing different brain signals for BCI control in ALS patients. Preliminary results show that a P300-based BCI may offer for some patients with intact eye fixation the highest accuracy (90%–100%) and communication speed (up to 12 letters per minute), if a P300 response can be detected.[35] The special advantage of a P300-based BCI is that neurofeedback learning is not required. On the other hand, if pronounced P300 responses are not available, the patient cannot be trained to generate them. A further very promising alternative may consist of the implementation of a BCI Web browser based on self-regulation of SMR/beta EEG-rhythm. Wolpaw and McFarland[14] recently demonstrated that combining SMR and beta-rhythm with an adaptive algorithm can provide users with multidimensional cursor control. Such an approach could clearly facilitate the speed of operating an EEG-controlled Web browser. Conceivable are also invasive BCI Web browsers using ECoG activity[19,20] recorded from the cortical surface as well as local field potentials[21,23] or neuronal action potentials[16-18] recorded within the brain. These approaches could provide motor-impaired patients with real-time multidimensional control of a computer cursor or even a robotic arm. However, future studies will have to evaluate the clinical risks these techniques may entail and the conditions for stable long-term recording.

If future BCI research can overcome the mentioned constraints of the current brain-computer communication systems, then the following scenario could be reality in the not too distant future: The patient is sitting paralyzed in his wheelchair but can chat with a relative in another city, play chess with a friend in another country, search the World Wide Web for information, and even buy or sell articles. And all that without any voluntary muscle control, solely by the power of his thoughts. Cogito ergo sum.

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SUPPLEMENTARY ONLINE INFORMATION

Video 1. Patient HPS uses the electroencephalogram-controlled Web browser *Descartes*. HPS initializes connecting his laptop with the Internet. HPS selects the Web site of his favorite German newspaper. The patient was instructed to open the link of the headline news from this page, which he chooses from an alphabetically sorted dichotomous decision tree. Finally the patient opens a Web site of recently published law books.

Video 2. HPS writes a message for an amyotrophic lateral sclerosis patient in another country, who is starting to train with the brain-computer interface. HPS wants to motivate the other patient, therefore the message says “U CAN DO IT”.

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