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A brain-computer interface for long-term independent home use

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Abstract

Our objective was to develop and validate a new brain-computer interface (BCI) system suitable for long-term independent home use by people with severe motor disabilities. The BCI was used by a 51-year-old male with ALS who could no longer use conventional assistive devices. Caregivers learned to place the electrode cap, add electrode gel, and turn on the BCI. After calibration, the system allowed the user to communicate via EEG. Re-calibration was performed remotely (via the internet), and BCI accuracy assessed in periodic tests. Reports of BCI usefulness by the user and the family were also recorded. Results showed that BCI accuracy remained at 83% ($r = -.07$, n.s.) for over 2.5 years (1.4% expected by chance). The BCI user and his family state that the BCI had restored his independence in social interactions and at work. He uses the BCI to run his NIH-funded research laboratory and to communicate via e-mail with family, friends, and colleagues. In addition to this first user, several other similarly disabled people are now using the BCI in their daily lives. In conclusion, long-term independent home use of this BCI system is practical for severely disabled people, and can contribute significantly to quality of life and productivity.

Keywords: *Amyotrophic lateral sclerosis, electroencephalogram, brain-computer interface, P300 event-related potential, assistive communication*

Introduction

Background and need

Brain-computer interface (BCI) research has emerged as one of the most exciting research areas of the day due largely to its potential for improving the lives of people with severe motor disabilities, such as those locked in by amyotrophic lateral sclerosis (ALS). A decade after Birbaumer et al. (1) reported that a paralyzed person used a BCI to type a paragraph in 16 h, more than 650 papers have been published on the topic. Nevertheless, the practical promise of BCI technology remains unfulfilled. BCIs remain confined to the laboratory or to limited home demonstrations that require close technical oversight (2,3).

This report describes a new BCI system that provides a variety of important functions (e.g. word processing, e-mail, environmental control, speech generation) and is suitable for independent home use. The system has proven to be life-changing for a person unable to communicate independently due to being locked in by ALS, a progressive motor neuron disease that causes inexorable loss of motor function. With home ventilators and other support equipment, people with ALS can lead long and fulfilling lives despite their extreme disability (4). Nevertheless, of nearly 6000 people diagnosed with ALS each year in the U.S. (4), more than 90% do not choose to prolong life by accepting ventilation, and as a result, only 10% live more than 10 years following diagnosis (5). The anticipated loss of the ability to communicate is a major factor in the decision to decline ventilation (6).

Conventional alternative and augmentative communication (AAC) devices require muscle control and they fail as the disease progresses to a point at which muscle function is lost. BCIs allow people to communicate with brain signals (such as scalp-recorded electroencephalogram or EEG) rather than muscles (7). Thus, a BCI can allow a person to communicate even after other AAC devices have failed. BCIs could markedly improve the lives of people with ALS and other similarly disabling disorders,

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and might positively influence the decision whether to accept ventilation. However, our experiences and those of others over the past decade (e.g. 8–10) indicate that four issues limit the long-term home use of BCIs: 1) they are not usable by non-technical personnel; 2) they do not provide basic communication capacities in a convenient and accessible format; 3) they are not easily configurable for the needs of each user; and, 4) they are not amenable to periodic long-distance technical oversight. As a result, BCIs suitable for long-term independent use by severely disabled people are not yet available despite the fact that many people need them.

System design and capabilities

Guided by initial studies in people severely disabled by ALS (2,8,11), we have developed an EEG-based BCI system that is suitable for independent home use. This unique system incorporates a modified version of the general-purpose BCI software platform BCI2000 (12), and overcomes the four principal limitations to long-term home use of BCI systems.

One, this new system can be easily managed by most caregivers after four to five 1-h practice sessions. The caregiver needs only to place the electrode cap properly on the user's head, insert gel into the electrodes, turn the system on, and click on the 'Calibration' or 'Run' icon. From then on, operation is automated and the user is in complete control through his or her EEG. This EEG based control includes the capacity to suspend or resume BCI operation as desired.

Two, a wide range of basic communication functions (e.g. e-mail) and environmental control (e.g. TV) are accessible using a simple matrix-based menu format (see Figure 1, (13)). The matrix format is highly flexible and can be readily adapted to a wide variety of different applications. For example, the system includes speech generation – an important component of AAC systems that allows people to interact with others and to meet their daily communication needs (14). Since people severely disabled by ALS have very limited mobility, word processing, e-mail, and environmental control can significantly increase their independence and quality of life. E-mail particularly can restore the ability to interact with family, friends, coworkers, and social networks. Matrix items also include function keys and shortcuts that allow the user to operate any Windows-based program that can be operated with a keyboard. Thus, the matrix is equivalent to an on-screen keyboard. The user can readily switch from matrix to matrix, accessing a different application in each one. For example, one matrix contains an alphanumeric set of characters for word processing, and includes a predictive speller that allows the user to write more rapidly. Another matrix includes environmental control commands such as those controlling the television or the lights. The system can also be modified to present icons or pictures as stimuli instead of alphanumeric characters, allowing more flexibility and making it accessible to illiterate users.

Three, the system can be adapted to each user's needs: the matrix size, shape, and content are readily changed. Matrix items can represent a range of content including single alphanumeric characters, keyboard hotkeys, shortcuts to alternative matrices, and entire words or phrases. Selections can also generate specific requests (e.g. selecting a cell containing the word 'suction' could result in the system speaking "I need suction, please."). For those with compromised vision, the matrix items can be presented in an auditory format (presented via speaker

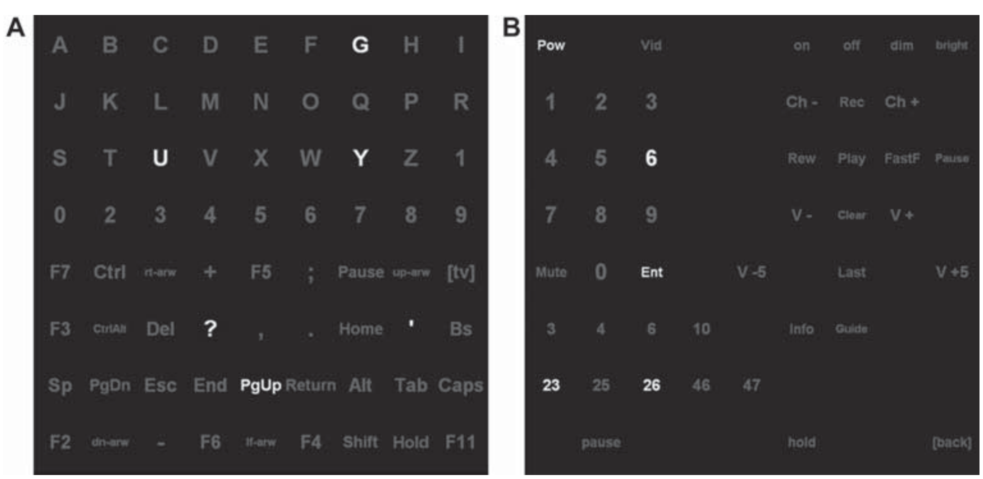

Figure 1. (A) The basic 9 × 8 72-item matrix of letters, numbers, and functions that emulates the keyboard and allows the BCI user to operate a wide variety of Windows-based programs (e.g. word processing, e-mail, environmental control). The user wears an EEG cap and faces a monitor that displays the matrix. Every 125 ms (i.e. 8 times/s) a different group of six matrix items flashes (as shown). Each flash lasts 62.5 ms and then 62.5 ms intervenes before the next flash. The user attends to the item desired and counts how many times it flashes. The computer calculates the EEG response to each group from each of eight scalp electrodes (referenced to mastoid), and uses a multiple-regression algorithm derived by a stepwise linear discriminant analysis (SWLDA) to determine from these responses which item the user desires (see (18,19) for details of methods). (B) The BCI user's environmental control menu.

or through headphones), or in a combined visual and auditory format. For example, each row and column in the matrix can be represented by a specific sound (15).

Four, the BCI home system needs very little on-site technical support. The system can be monitored remotely using a high-speed internet connection and a virtual desktop (e.g. GoToMyPC). Thus, once the caregiver and user are trained, most problems related to system parameters, EEG recording quality, or equipment can be resolved quickly without necessitating a home visit. If system hardware fails, it can be replaced rapidly via express mail. Each one of these features is important in moving the system from the laboratory to the home. Together, they provide a system that should be practical for long-term independent home use.

The present study

This study presents the results of the first substantial test of the hypothesis that this new BCI system is practical for long-term independent home use. The study asks whether a severely disabled person, assisted by his caregiver, can use the system independently at home, whether it provides important communication functions, and whether it will continue to be used extensively over months and years. The principal outcome measures are: 1) the intensity and long-term continuation of BCI use; 2) periodic objective measurements of communication accuracy; and, 3) subjective reports about the usefulness and impact of the system on quality of life from the user, his family members, and his caregivers.

Materials and methods

Subject

The subject was a 51-year-old ventilator dependent man with advanced ALS (i.e. ALSFRS-R score 1) (16). Before receiving the BCI, he was using an eye-gaze device to interact with family and friends and to run his NIH-funded research laboratory. However, as his eye movements weakened, the device became unreliable, and he and his family despaired of his being able to continue the independent communication essential to his quality of life and to his professional productivity. The study was reviewed and approved by the Institutional Review Board of the New York State Department of Health, and the user gave informed consent.

BCI system set-up, format, and maintenance

In several initial training sessions, the user's caregivers learned to place the eight-electrode EEG cap properly on the user's head (electrode locations shown in Figure 2), to add gel, to ensure good electrical contact, and to start the BCI2000 software (12). Once learned, this procedure takes 5–10 min. Ensuring EEG recordings with impedance values less than 5 kΩ requires parting the hair beneath each electrode and inserting in each one a small amount of water-based conductive gel. To assist the caregiver, the system automatically measures electrode impedances and provides results for each electrode. Once satisfactory impedances are present, they typically remain stable and the BCI functions effectively for at least 8 h.

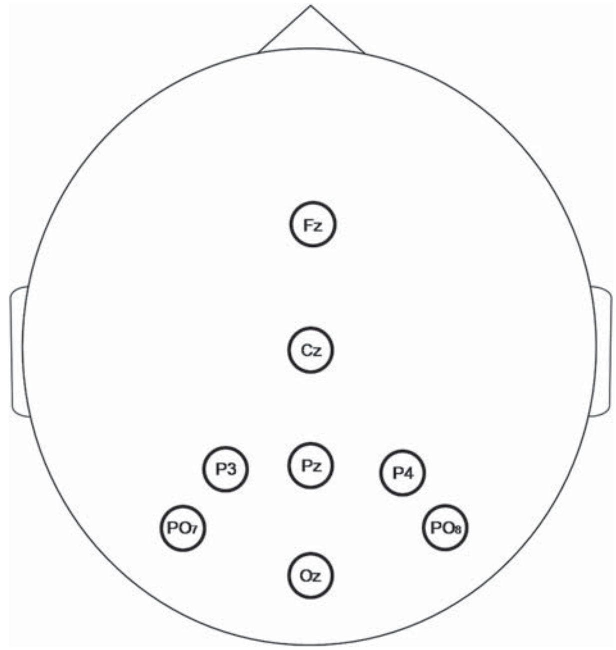

Figure 2. The eight electrode locations used by the SWLDA algorithm to determine which item the user wants to select (18,20).

To communicate using the BCI, the user faces a monitor displaying a matrix of letters, numbers, and functions (Figure 1A) while EEG is recorded. The software analyzes the EEG and measures the P300 event-related potential (ERP). P300 is a positive peak that occurs in the EEG about 300 ms after a stimulus that has special significance (13,17). As the user watches, different groups of matrix items flash in rapid succession. To make a selection, the user attends to the desired item as the groups flash. Only the group containing the desired item produces a P300 ERP. The computer evaluates the EEG responses to each group, applies a multiple-regression algorithm derived by a stepwise linear discriminant analysis (SWLDA) to determine which item produces a P300 ERP, and then selects that item (see (18) for details of the analysis.)

The caregivers make notes regarding system usage and any changes in its performance. Each day, these notes are sent automatically via the Internet to the Wadsworth server, along with complete data on BCI system use. When questions or problems arise concerning BCI operation, Wadsworth personnel are available to both the caregiver and the user by e-mail, and to the caregiver by phone. BCI accuracy is assessed periodically by a brief copy-spelling test. Updates in system parameters and minor software changes are installed remotely via the Internet. New electrode caps and other system supplies are provided by mail as needed and major hardware or software updates by occasional home visits. The user alternates between two electrode caps on successive days, and caps are replaced after about 600 h of use.

BCI system operation

The BCI user sits in a wheelchair facing a video monitor at a distance of approximately 1.5 m. EEG is recorded from eight electrode locations (Figure 2; i.e. Fz, Cz, P3, Pz, P4, PO7, PO8, Oz), each referenced to the right mastoid with the left mastoid serving as a ground. Previous P300-based BCI studies using many more electrodes showed that the eight channels used in this study consistently provide the best (i.e. most accurate) performance (18). The data are digitized at a rate of 256 Hz, bandpass filtered at 0.5–30 Hz, processed online to make selections from the matrix, and then stored. To make a selection from the 72-item matrix, the user attends to the desired item in the matrix and counts how many times it flashes. (For this first home user, the system presents purely visual stimuli.) For each selection, when the system is being used for communication, all matrix items flash 12 times in quasi-random groups of six (i.e. 12 six-item groups $\times$ 12 per item = 144 flashes per selection; Figure 1A) (19). After the 72 items have flashed, the flash sequence is re-randomized.

Applications of the BCI system

The user employs the BCI system both at home and at work. With it, he writes manuscripts and grant proposals, sends e-mail, and reads scientific articles. In these tasks, the BCI controls standard software programs including Microsoft Office, Eudora, and Acrobat Reader. He also uses the BCI for environmental control and entertainment, such as controlling the room lighting and the television (Figure 1B).

Remote calibration of the BCI system

During a brief (8-min) automated calibration run, usually performed 1–2 times/week, the system prompts the user to select specific items. Data are sent to our laboratory over the Internet. An automated stepwise linear discriminant analysis (SWLDA; based on the Matlab stepwisefit function) uses the calibration data to identify the best EEG features and their coefficients for the multiple regression algorithm used during online BCI operation (20). SWLDA has been shown to be more effective and computationally simpler than other methods (21).

After each new calibration run, the EEG data from that run are aggregated for analysis with the data from at least the previous 10 calibration runs. Each calibration run includes 20 selections. Therefore, the data from at least 250 selections are typically used as input to SWLDA. For each selection, during calibration, all 72 matrix items flash 16 times in groups of six (i.e. 12 six-item groups $\times$ 16 per item = 192 flashes). Thus, the resulting data include responses from each of the eight electrodes to 48,000 flashes of six-item groups. Of these 48,000 flashes, 4000 include the target item (i.e. the item the system asked the user to select).

Prior to the SWLDA procedure, the responses elicited by flashes of groups that included the target item and flashes of groups that did not contain the target item are separated and coded as 1 or 0, respectively. The data epochs begin with the onset of each flash (i.e. time 0 ms) and include 800 ms of data (or 205 samples at the sample rate of 256 Hz). These data are moving-average filtered at 20 Hz and decimated by 20 Hz to produce one voltage value for every 50-ms period of the 800-ms epoch. The result is 16 voltage values, or 'features' from each of the eight electrodes, and 128 features from all eight electrodes. Thus, the 48,000 flashes (4,000 targets and 44,000 non-targets) produce $128 \times 48{,}000 = 6.1 \times 10^6$ feature values. From this data set, the SWLDA algorithm determines a set of features and feature coefficients that best discriminate between the target item and the non-target items. In the final analysis step, this set is compared to the set currently in use by the online system. If the new set provides higher selection accuracy, it is incorporated into the ongoing operation of the BCI in the user's home via the Internet. Aside from the 8 min needed to collect the calibration data, this automated recalibration procedure does not involve the user or the caregiver; it is entirely transparent to them. In our experience, the optimum set of features and feature coefficients changes very little over time. For the user described here, the optimum set remained the same and performed well for as long as 16 months. Similar stability has been found in our laboratory studies of able-bodied subjects, where the same set performed well in two sessions 11 months apart (18).

Results

After receiving the BCI system, the user's caregivers quickly mastered the brief set-up procedure. The user immediately abandoned the eye-gaze device and began using the BCI up to 6–8 h/day at home and at work. Over 2.5 years, his P300 responses have remained stable in magnitude and form, with P300 amplitude at about 4 μV and latency of 200 ms (Figure 3). His accuracy on periodic copy-spelling tests (1–2/week) has also been stable. Median performance on these tests has stayed at 83% ($r = -.07$, n.s.), with only 1.4% correct expected by chance. During system use, the time per selection averages 26.0 s. This time includes a 9-s pause that he prefers to have after each selection. With the standard 8×9 matrix and 72 possible selections (and without the

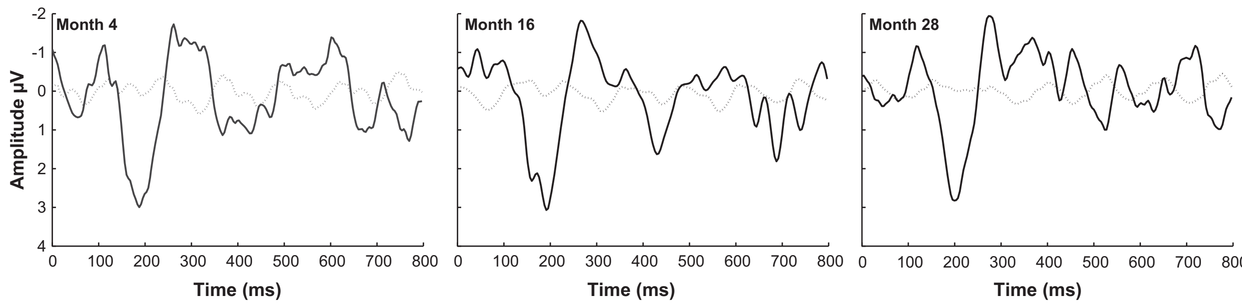

Figure 3. The BCI user's average ERP responses (at EEG electrode Cz) in months 4, 16, and 28 to the desired item (solid lines) and the other items (dotted lines). The responses remain stable over several years. In this user, a positive peak at 200 ms is the most prominent distinguishing feature of the response to the desired item.

9-s pause), his communication rate averages 18.5 bits/min.

The user and his family state that the BCI has restored his independence in social interactions and in scientific research. With it, he corresponds via e-mail with his children, other family members, and friends. He also uses it in supervising his research group, and recently used it to help him write a successful competitive renewal application for his NIH research grant. It provides him with environmental control as well (e.g. lights, television). Asked to describe the BCI's impact on his life, he sent a succinct and eloquent e-mail with BCI (Figure 4). More recently, in addition to this first user, a total of five other similarly disabled people have used the BCI home system independently in their daily lives for a variety of purposes, and with similar success.

Discussion

This study tested the hypothesis that BCI technology can restore useful communication to a person with ALS who is otherwise unable to control a computer. To do this, we provided an appropriate user with a BCI system with functions that emulated those of his previous (and no longer effective) AAC device. We used three outcome measures: the intensity and long-term continuation of BCI usage; periodic objective measurement of accuracy (i.e. the calibration runs); and self-reports from the user, his family members, and caregivers as to the usefulness and impact of the system. Each of these measures assesses an important aspect of the hypothesis. BCI use, no matter how simple and easy, does require time and effort on the parts of both the user and the caregiver. Thus, the fact that they continue to use it for hours per day over several years indicates that it is worthwhile to them. The periodic objective measurement of accuracy assesses the BCI's success in satisfying its primary purpose – communication. Finally, the reports from the user, caregivers, and family members assess the impact of the BCI on the lives of the user and those around him.

All three outcome measures indicated that the BCI system performed well. Over 2.5 years, the BCI continued to be used daily and extensively, accuracy was stable, and reports from the user and others were very positive. These results show that long-term

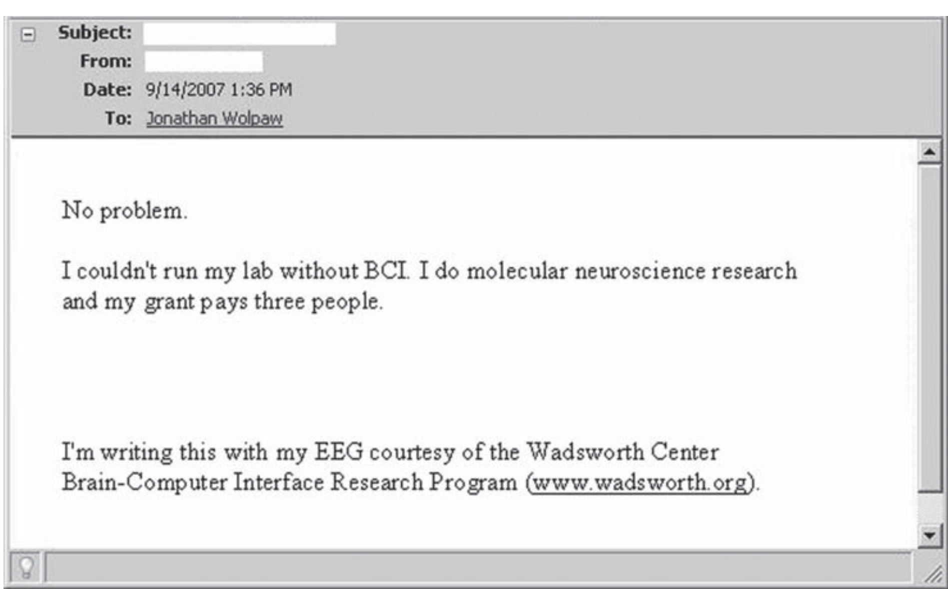

Figure 4. Asked to describe the impact of the BCI on his life, the user sent this message using the BCI. The statement at the bottom is included in all of his e-mails.

independent BCI use is practical for severely disabled people and their caregivers, and that it can have major sustained impact on quality of life and productivity. With continued refinement and wider dissemination, the present system and related BCI technology could substantially improve the lives of people with ALS and other devastating motor disorders, and might positively influence the decision whether to accept artificial ventilation when it becomes necessary.

Throughout the course of this study, we addressed the four main issues limiting the long-term home use of BCIs. The caregivers reported that the interface was easy to use. The software modifications include an impedance check that is performed after a single mouse click once the software boots, facilitating acquisition of high quality EEG signals. A second mouse click starts the calibration procedure or gives the user complete control of the computer through the BCI. We provided basic communication including speech generation, e-mail, and word processing in a convenient and accessible format. The system was configurable to the practical needs of the user by making the matrix layout flexible and allowing the user to determine which items and functionality the matrix provides (e.g. environmental control menus for specific devices). We have also been able to provide long distance oversight for 2.5 years. Moreover, we identified additional areas where the system could be improved. For example, new software has been created to increase access and ease of use for the BCI user by adding specific commands that combine several keystrokes into a single selection. Not only has the user benefited from the system, he has also suggested improvements to the BCI. His requests include improved speed and electrodes that do not require gel. Both of these advances are the focus of ongoing work by us and others (19,22,23).

In future studies with a larger cohort, we will incorporate formal measures of quality of life (QoL) and satisfaction with BCI use. The ALS QoL literature indicates that subjective QoL for ALS patients is similar to that of control subjects, that physical impairment and QoL do not usually correlate, and that depression is not related to physical impairment (24–27). At the same time, the people with ALS who need BCIs for primary communication are, on average, significantly more disabled than the populations included in these earlier studies. Thus, it may be more difficult to measure QoL formally in this group. We are evaluating a number of promising instruments (e.g. McGill QoL, a Visual Analog Scale for 'health state today', SEIQoL-DW) to perform these measurements.

In addition to further increasing the practicality and capabilities of long-term BCI home use, we are seeking to address a problem created by the initial success of the home system. Although the system is suitable for long-term independent home use and can improve the lives of people with severe disabilities, it is not yet clear how it will be widely disseminated to those who need it. Although many people cannot use conventional AAC devices and therefore need the BCI system, they are not numerous enough to provide the commercial incentive necessary to induce companies to produce, market, and support the system. Thus, while this new BCI home system is effective and needed, it has no ready avenue for widespread dissemination and is essentially an orphan technology. We are now exploring a new approach to this difficult problem with the goal of developing a self-sustaining non-profit organization that disseminates and supports the BCI home system for those who need it (see www.braincommunication.org). This effort has just begun and its ultimate success remains uncertain.

Conclusion

A 2.5-year study investigated independent home use of a newly developed non-invasive EEG-based BCI system by a person with ALS who could no longer use conventional assistive communication technology. The BCI system continued to be used extensively at home and at work, and performance remained acceptable. The system has made it possible for the user to continue to interact with family and friends and to continue his successful career in scientific research. He, his family, and his friends are extremely positive with regard to its impact on their quality of life. Other similarly disabled people have also begun using the system. These first results indicate that this new BCI system is suitable for independent home use and can substantially improve the lives of people with severe motor disabilities.

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