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Noninvasive brain-computer interface enables communication after brainstem stroke

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Abstract

Brain-computer interfaces (BCIs) provide communication that is independent of muscle control, and can be especially important for individuals with severe neuromuscular disease who cannot use standard communication pathways or other assistive technology. It has previously been shown that people with amyotrophic lateral sclerosis (ALS) can successfully use BCI after all other means of independent communication have failed. The BCI literature has asserted that brainstem stroke survivors can also benefit from BCI use. This study used a P300-based event-related potential spelling system. This case study demonstrates that an individual locked-in owing to brainstem stroke was able to use a noninvasive BCI to communicate volitional messages. Over a period of 13 months, the participant was able to successfully operate the system during 40 of 62 recording sessions. He was able to accurately spell words provided by the experimenter and to initiate dialogues with his family. The results broadly suggest that, regardless of the precipitating event, BCI use may be of benefit to those with locked-in syndrome.

INTRODUCTION

Brain-computer interfaces (BCIs) facilitate communication and environmental control for individuals whose motor and communicative abilities have been impaired by severe neuromuscular disease (1–3). A BCI operates by translating volitional modulation of brain signals into computer commands, which can be recorded from the scalp using electroencephalography (EEG) (4), from the dura mater or cortical surface using electrocorticography (ECoG) (5), or from cortical neurons (6). Most BCI research has involved participants without disabilities. Fewer studies have included individuals with neuromuscular disabilities, typically amyotrophic lateral sclerosis (ALS). Ultimately, ALS renders people physically incapacitated as they lose all voluntary muscle control, although

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SUPPLEMENTARY MATERIALS
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cognitive function can be spared. Similar to ALS, brainstem stroke may cause people to become locked-in. Locked-in syndrome (LIS) is a condition in which a person has lost all neuromuscular control except for eye movement or subtle muscle control that is not sufficient for independent communication (7). For the purposes of this study, independent communication is defined as the ability to produce information without the assistance of muscle control or another individual. In contrast, dependent communication relies on muscle control (for example, infrared forehead switch, button press) or interaction with another person (for example, moving the eyes right for "yes" and moving the eyes left for "no"). Studies show that individuals disabled by ALS can use noninvasive BCI to provide independent communication (8, 9).

The severe motor impairment of LIS renders individuals completely dependent on caregivers to attend to their every need. However, the use of a BCI can mitigate their isolation and dependence by providing a method of communication that is not contingent on neuromuscular activity. For example, by controlling a computer with a BCI, one individual regained and maintained a level of independence that allowed him to continue working (3). Although the literature has widely suggested that individuals with LIS due to brainstem stroke can also benefit from noninvasive BCI technology (2, 10, 11), no study to our knowledge has reported such a finding.

In the present case study, we now show that an individual locked-in by a brainstem stroke can use a noninvasive BCI to produce messages. In addition, the BCI provided a higher level of autonomy than a low-tech solution, such as requiring an assistant and the patient's residual muscle control. Research has also shown that individuals with other forms of stroke are able to use BCI technology, specifically sensorimotor rhythms, for rehabilitation purposes (12–14). This, too, is another important innovative function of BCIs that may prove useful in the future, expanding the number of people that can benefit from the technology.

RESULTS

Formulating a BCI technology

Averaging time-locked EEG responses—also referred to as event-related potentials (ERPs)—to stimuli is a common classification method for BCI. ERPs are manifestations of neural activity that are triggered by and involved in the processing of specific events. Thus, they can be reliably extracted from the ongoing EEG.

The P300 ERP is a positive deflection in the EEG occurring over the parietal cortex of the brain, and occurs at about 300 ms after stimulus identification. The P300 ERP is typically elicited using the oddball paradigm (15); an "oddball" is a relatively rare but meaningful stimulus presented within a series of frequently occurring stimuli. A modified oddball has become the foundation of all P300 BCIs (4). In the P300 BCI paradigm, an array of rapidly flashing items (letters and other symbols) is presented on a computer monitor. The participant focuses attention to one of the items and makes a mental acknowledgment of the attended item when it flashes—in other words, counts the number of times the item flashes and ignores all other stimuli. After all of the items in the array flash several times, the waveform corresponding to the attended item will reveal a P300 (fig. S1). Participants complete a calibration procedure, and the ERP data are used to derive classification coefficients using a predefined algorithm [for example, stepwise linear discriminant analysis (SWLDA)].

Once calibration is complete and the classification coefficients are produced, the participant volitionally attends to the flash of a specific array item. The items contained in the array flash in pseudo-random order for a predetermined amount of time (37 s in this study). After the items stop flashing, classification coefficients are applied to each item of the array, and the item receiving the highest score is presented to the participant as feedback. If the feedback is correct, the participant will select the next appropriate item. If the feedback is incorrect, the participant will attempt to select "backspace" and correct the mistake, or continue without correcting the error.

The participant in this study previously attempted to use the MyTobii eye-tracking device for 2 months; however, he was unable to communicate using the system. No other high-tech assistive communication device, except for the BCI, was assessed in this study. Throughout the course of the study, his ability to use motor output pathways to communicate with caregivers and researchers remained variable. For example, he would use subtle vertical eye movements (up for "yes"; down for "no"), or a subtle head nod for "yes" and lack of movement for "no." Eye movements were preferred because they provide two responses; however, the participant was not always able to reliably move his eyes.

Magnetic resonance imaging of acute stroke

The participant in this study suffered a multifocal acute ischemic infarction predominantly within the distribution of the right posterior cerebral artery (PCA). Magnetic resonance imaging (MRI) is able to image stroke, especially diffusion-weighted imaging (DWI), which uses the principle of Brownian motion (16, 17). Normal diffusion-weighted images are of low signal intensity, indicating that there is free diffusion of water molecules along the axon. If there is restricted diffusion of water, as there is in an acute stroke, the areas of infarction will demonstrate increased (bright) signal. Figure S2 (A and B) shows axial diffusion-weighted images through the area of the pons and cerebellum, respectively. The arrows in fig. S2A show that the insult caused restricted diffusion in the pons and right occipital areas. The damage to the pons resulted in LIS. Part of his left visual field may have been compromised by the damage to his occipital areas, although no obvious hemifield-specific sensory deficit was observed. Imaging through the inferior cerebellum demonstrated broad restriction in the right hemisphere (fig. S2B).

In contrast to DWI, angiographic MRI shows high signal as bright and low signal intensity as darker. Normal blood flow was visible in the participant's left PCA (fig. S2C, arrowhead), and the absence of flow was evident in his right PCA (fig. S2C, arrow). Angiographic MRI through the upper cervical spine indicated loss of blood flow in the right vertebral artery (fig. S2D, arrow) and normal blood flow in the left vertebral artery (fig. S2D, arrowhead).

Neuropsychological testing

We administered cursory neuropsychological tests. However, these results must be interpreted with caution because the reliability of the participant's responses cannot be determined. Using vertical eye movements, the participant was able to answer correctly all 20 of the questions contained in the Auditory Verbal Comprehension portion of the Western Aphasia Battery (18). Thus, the participant was considered aware of his surroundings and retained basic semantic knowledge. The Judgment of Line Orientation Task (19) was also administered once to assess the extent of damage due to left or right hemisphere lesions by discriminating the differences in line angles. Scores range from 0 to 30; a score below 21 is commonly used as a cutoff to suggest cognitive impairment. Impaired performance has also been shown in patients with various dementias and Parkinson's disease. The participant received a score of 13 on the instrument. Unfortunately, we cannot determine whether the poor performance is due to brain damage or an inability to see clearly the cards.

In addition to the two neuropsychological tests, 12 questions from the Minnesota Multiphasic Personality Inventory (MMPI) were asked (Table 1). The questions were selected by the participant's wife because she had confidence that she knew how he would respond. The participant answered each of the 12 questions as expected by his wife, which indicated that he was able to understand the content of the questions. The questions are presented in Table 1. On the basis of the results of the above tests, we concluded that the participant was aware of his surroundings, had some type of visual impairment, and did not have a measureable change in his personality.

Four-choice, seven-choice, and copy-spelling BCI protocols

Six months after stroke, we began testing the BCI. A total of 62 sessions were conducted on 34 different days (that is, visits) during the 56-week duration of the study. On 22 of the visits, multiple sessions were conducted (two sessions were conducted in 19 visits; three sessions were conducted in five of the visits). Testing began with a typical spelling display shown in Fig. 1A. The 6 × 6 version of the speller was tested in seven sessions and yielded a mean accuracy of 32.3% correct in copy-spelling mode (that is, the participant is instructed to attend to specific characters).

On the basis of these results, we tested several different paradigms. First, we used a four-choice P300 BCI task (Fig. 1B) modeled from (20) where each letter of the display flashed randomly. To answer questions, the participant focused attention on the appropriate choice: Y (yes), N (no), P (pass), or E (end). Using the four-choice BCI task, accuracy over a 5-week period (seven visits) averaged 94.7%. Table 2 provides a sample of the communicated dialogue using the four-choice system during an experimental session conducted during week 12 of testing. The participant answered a series of questions leading to the conclusion that he desired more information regarding his prognosis and likelihood of recovery. Twenty-four yes/no questions were required for his intent to be conveyed. As demonstrated by the questions, it is necessary to make assumptions regarding the message that the participant wants to convey. This can be problematic because, by definition, the paradigm is limited to four choices. Thus, the user does not have the ability to express his/her wishes directly.

We next visited variations of the spelling display. Building on the success with the four-choice paradigm, we designed a seven-choice toggle-display. Figure 1C (left) shows the home menu providing groups of letters and symbols. Once a group of letters was selected from the menu, the array toggled to the second array that provides the individual letters contained within the group. The participant was then able to select the desired letter, backspace, or return to the main menu (Fig. 1C, right). The seven-choice requires several selections to navigate the six sub-menus; therefore, to further extend the efficiency of the system, larger displays with one sub-menu were created (3 × 5 and 3 × 6). Despite adequate performance (77.8% correct; one session), the 3 × 5 array did not provide the necessary items to compose sentences with only one sub-menu. The 3 × 6 array (Fig. 1D) provided more selections than the 3 × 5 without crowding the items (cf. the 6 × 6 array) and only required one sub-menu for all necessary items to compose sentences. Accuracy using the 3 × 6 was sufficient for communication (81.5% over 11 successful sessions). The process of iterating through the different paradigms took about 12 weeks. A complete list of all of the paradigms is shown in Table 3. The table does not show free-spelling accuracy because it is not possible to provide an accurate measure for at least two reasons: first, the participant may not correct all errors; second, the participant may choose to alter the content of the message depending on the feedback provided by the BCI.

Volitional BCI messages

Testing sessions beyond 12 weeks typically focused on allowing the participant to produce volitional messages. At the beginning of each visit, accuracy was assessed with copy-spelling. For sessions in which copy-spelling accuracy was above 70%, the current coefficients were used and no additional calibration data were collected. When copy-spelling accuracy was below 70%, calibration data would be collected and tested in copy-spelling mode before free-spelling would be conducted. Examples of the messages produced are shown in Table 4. The number of flashes used and the stimulus onset asynchrony were varied across visits and sessions in an effort to optimize performance (table S1). As an example (3 × 6 speller condition), the letters would randomly flash in groups of four and five until each letter had been flashed 16 times. The process would take 37.0 s, and then the classifier would select a character and present it to the participant as feedback. After the feedback was presented, 8 s elapsed before flashing resumed. (Time between each selection is necessary to provide time for the participant to evaluate the feedback and focus attention to the location of the next character to be selected.)

On three of the visits, the participant continued to communicate thoughts or themes that began on a previous visit; for example, a conversation beginning on week 26 was continued on week 30. At other times, the participant showed perseveration—a common result of stroke (21, 22)—during character selections. For example, the participant would select three characters, backspace the characters, and select the same three characters again.

The bottom two rows of Table 4 show messages recorded during the same visit in week 54 of testing. The first sentence was completed using the BCI with the 6 × 3 matrices shown in Fig. 1D. The second sentence was completed using a letter board. The BCI was more efficient than the letter board. Total time to complete the BCI sentence was 24 min, and the time to complete the letter board sentence was 29 min. The BCI sentence included 18 correct selections and yielded a correct selection every 1.33 min. The letter board sentence included nine correct selections and yielded a correct selection every 3.22 min. The experimenters who implemented the letter board task were experienced in using letter boards in general and had used the letter board with the participant on several occasions. The BCI/letter board comparison was only performed once because the main focus of the study was to optimize BCI performance; therefore, generalizability of the result cannot be determined.

DISCUSSION

In this case study, BCI technology provided an additional means of volitional communication for an individual locked-in by a brainstem stroke. Letter board communication was dependent on constant interaction between two or more individuals. In contrast, once the BCI was set up by another person, it provided the participant with his only method of unassisted communication. It is possible that the BCI helped the participant to regain a sense of autonomy from an otherwise dependent situation. In addition, while the BCI is in use by a participant, caregivers could be provided with an opportunity to perform other tasks.

This study confirms a long-standing assertion in the literature that individuals with LIS resulting from brainstem stroke can benefit from a noninvasive BCI (2, 10, 11). Producing self-initiated messages with the BCI allows the user to compose any message about any topic; however, in this study, we facilitated his communication by anticipating and confirming the context of the words being communicated. For example, one of the dialogues shown in Table 4 is with regard to a jacket for his son. The participant's wife was able to surmise that he was asking to purchase a sport coat for one of his sons because he was starting a new job. Once it was determined that he wished to purchase a sport coat for his son, his wife asked, "Do you want to buy [your son] a new sport coat because he is starting a new job?" to which he responded with a subtle nod indicating "yes." Moreover, such dialogues are aided by the fact that the most common 100 words in the English language account for 50% of the words in every sentence (23). Therefore, common words can be surmised by other people. Context must be provided by the BCI user, and this requires autonomy.

Twenty-two of the 62 sessions (33%) in this study were unsuccessful. There are several limitations to studies with individuals who have LIS. An amalgamation of reasons could be responsible for poor BCI accuracy. The participant may not have been able to focus his vision and/or attention on the display; he may not have been able to remain cognitively aware throughout the task; he may have been experiencing pain that distracted him from the task; he may have become frustrated and stopped participating. Unfortunately, during testing, it would be very difficult for the participant to alert the researcher of a problem. Moreover, on unsuccessful visits, non-BCI communication was difficult and very few interactions provided consistent and/or useful information. Thus, to make conclusions regarding why the BCI did not work properly during these visits with one participant would be speculation. However, it is not likely that his verbal comprehension and/or reading ability would have contributed to poor performance considering his education level (Ph.D.).

A further limitation is the extent to which we can draw conclusions regarding our attempts to measure cognitive impairment. The participant's ability to answer questions was severely compromised; therefore, it would not be possible to administer, or for him to complete, neuropsychological exams. Moreover, even if a nonstandard administration of the instrument was implemented, there would not be norms for the nonstandard administration, thereby bringing the validity of the results into question.

It is also difficult to interpret the perseveration that we observed. Perseveration does suggest some specific cognitive impairment. However, the extent to which individuals with LIS are cognitively intact cannot be adequately ascertained. It has been suggested that individuals that deteriorate beyond LIS to complete LIS (that is, eyes become paralyzed) lose the ability to associate the contingency between a voluntary response and appropriate feedback (12); this has been referred to as "extinction of goal-directed thinking" (9). Moreover, the cognitive processes that occur during times of nonstimulation (that is, when caregivers are not interacting with the person) are unknown.

In summary, this study demonstrates that an individual locked-in by a brainstem stroke can use a BCI for independent communication. The BCI provided a level of autonomy (that is, volitional and direct interaction with others) to the participant that otherwise could not be achieved owing to the muscle control required for augmentative and alternative communication methods. These results show proof of principle and successful BCI use of a visual, noninvasive P300 Speller in a patient with LIS caused by a brainstem stroke. The results broadly suggest that, regardless of the precipitating event, BCI use may be of benefit to those with LIS.

MATERIALS AND METHODS

Study design

This case study focused on one patient locked-in as a result of brainstem stroke. The goals of the study were to systematically collect experimental data to optimize a P300 BCI, and to provide the participant with a mode of communication that yielded higher speed and accuracy than other methods. On the basis of our previous work with locked-in participants, the starting point of the study was to begin with the standard 6 × 6 speller paradigm, and then test additional paradigms to select a paradigm that provides a high rate of character selection while keeping accuracy above 70%. The endpoint of the study was defined as failure on four consecutive visits, or withdrawal from the study (in this case, death).

Each visit followed a general protocol. At the beginning of the visit, we collected data using a copy-spelling task (that is, the participant is provided the items to select). The copy-spelling task was determined by the performance of the previous visit. If accuracy during the copy-spelling task was 70% or greater, an online free-spelling session would be conducted without further data collection. The online session could last for up to 2 hours depending on the accuracy of the system and apparent motivation of the participant. In the event that the initial protocol yielded accuracy less than 70%, an additional copy-spelling session would be conducted to recalibrate the system. In all cases, SWLDA was used for calibration (24–26). The ultimate goal of each visit was to provide volitional communication. Thus, the exact data used to calibrate the system were, at times, aggregated across many different sessions.

Participant information

The study was approved by the East Tennessee State University Institutional Review Board. Informed consent was provided by a family member having power of attorney over the participant. The participant provided assent to participate in the study using eye movements. The participant was a 68-year-old male who suffered a multifocal acute ischemic infarction predominantly within the distribution of the right PCA. Before the insult to his brain, the participant used computers on a daily basis and his highest level of education was a Ph.D. He was given a very poor prognosis and was described as having LIS. The participant could intermittently track movement but was unable to adequately control blinking. His ability to process information was questioned and his eye control was described by his neurologist as "worse than that typically observed in locked-in syndrome." Auditory brainstem evoked potentials were normal. Middle latency evoked potentials were normal in the left ear and absent during right-ear stimulation. Comorbidities included aplastic anemia (bone marrow does not produce enough blood cells) and paroxysmal nocturnal hemoglobinuria (a rare disease in which red blood cells break down earlier than normal). The participant was hospitalized for 30 days and had a percutaneous endoscopic gastrostomy tube placed for feeding. He was then released to a nursing home. BCI use was initiated 6 months later, and 62 sessions of data were collected over the next 13 months.

BCI calibration and testing

During BCI use, the participant was in the prone position with the head slightly elevated. His head leaned slightly up and to the left. The computer display was placed on a bedside tray about 1 m from the participant's head. EEG was recorded with a 16-channel electrode cap (tin electrodes; Electro-Cap International Inc.). All channels were referenced to the right mastoid and ground to the left mastoid; impedance was reduced to below 10.0 kilohms before recording started. BCI2000 controlled stimulus presentation, data collection, and online processing. Data acquisition and processing was identical for each session with the exception that the stepwise linear discriminant coefficients were changed to maximize online performance.

Signal acquisition and preprocessing

The signals were amplified and digitized by a g.tec (Guger Technologies) 16-channel USB biosignal amplifier (amplification to ±2 V before ADC; high-pass and low-pass filters of 0.5 and 30 Hz, respectively; digitization rate of 256 Hz). Preprocessing and channel selection were based on the results of (26), which showed that the optimal electrode set included the following electrodes: Fz, Cz, P3, Pz, P4, PO7, PO8, and Oz. These electrodes were used for BCI operation. Data were referenced to the right mastoid, decimated to 20 Hz, and segmented into 800-ms epochs.

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Classification algorithm and procedure

SWLDA was used to create the classification coefficients. SWLDA was selected on the basis of the results of (25) where the authors showed that SWLDA performed as well as one other classification algorithm and statistically better than three other classification methods. Before data were submitted to the SWLDA analysis, they were down-sampled to 20 Hz. The SWLDA algorithm uses a combination of forward and backward stepwise regression. The model first selects the feature that accounts for the most unique variance at a P value of <0.1. After each additional feature is added to the model, a backward stepwise regression removes any features that have P values >0.15. The process of forward and backward steps continues until the model includes a predetermined number of feature values, or until no additional features satisfy the criteria for entry and removal. Here, the maximum number of variables was set to 60.

BCI calibration procedure

To calibrate the BCI, data were collected in copy-spelling mode. During copy-spelling, the participant was provided with strings of items to select. The string is displayed at the top of the monitor with the item-to-spell (the target item) indicated in parentheses at the end of the string. For example, if the assigned string was “JUMP,” it would appear at the beginning of the run as JUMP (J). The participant’s task was to find the target letter in the array and attend to (or count) the number of times the item in parentheses flashed within the array. After the flashing stopped, the next target item appeared in parentheses [for example, JUMP (U)]. This process was repeated until the string of items was complete (one run). Data from 16 characters were used for input to the SWLDA. The duration of each flash was 187.2 ms, followed by a 62.5-ms inter-stimulus interval. These values were varied throughout the course of the study (table S1).

A BCI accuracy of 70% is commonly accepted for the minimum level of accuracy needed for communication. Therefore, when initial accuracy was 70% or higher, the participant began to free-spell without further calibration. If accuracy was lower than 70%, additional copy-spelling data were collected. New classification coefficients were then derived from the copy-spelling data collected from the current and previous sessions. This was done in an effort to identify classification coefficients that were optimal in terms of speed and accuracy. Once the classifier was 70% correct, the free-spelling session began. [The 70% criterion was relaxed in two sessions (62 and 58%) to provide the participant with every possible opportunity to communicate.] Each session concluded when the participant no longer produced interpretable output.

Statistical analyses

Only measures of central tendency were used in the study. No statistical analyses were conducted in this case study. In the copy-spelling sessions, selection accuracy was measured. In the free-spelling sessions, subjective interpretation of whether or not a coherent message had been produced was evaluated as a binary choice, as determined by the researcher(s) conducting the session (that is, E.W.S., D.B.R., and/or C.K.H.).

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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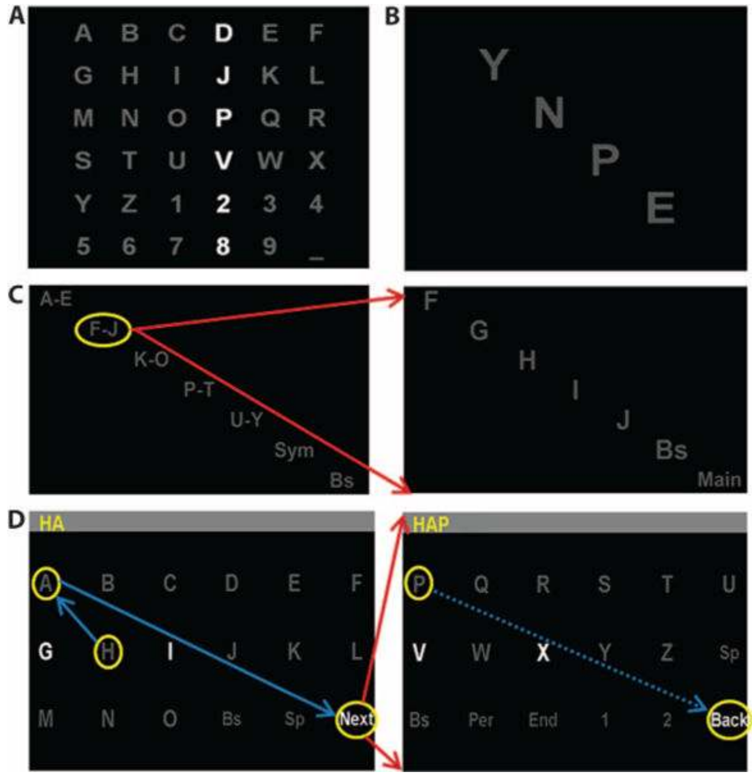

Fig. 1. Displays used for spelling

(**A**) The 6 × 6 display used to select letters. Entire rows and columns flashed and the participant focused on the desired letter. Rows and columns flash at random. (**B**) For the four-choice display, the four letters flash and the participant attends to the letter corresponding to the answer to the question: "Y" (yes), "N" (no), "P" (pass), or "E" (end). (**C**) Seven-choice toggle speller [see (D) for toggle description]. (**D**) The 3 × 6 toggle display. The items selected are labeled with yellow circles. The blue arrows indicate the order of selection. Items selected by the BCI are located in the top left of the gray output bar. The left panel shows the first display of items. In this example, the word to be spelled is HAPPY. "H" is selected and placed in the output bar, and then "A" is selected. After the selection of "A," it was necessary to switch to the second display by selecting "Next." The red lines indicate that selecting "Next" spawns the second display. The participant could then select "PPY." Selecting "Back" (dashed blue line) returned to the initial display.

Table 1

Questions from the Minnesota Multiphasic Personality Inventory asked of the participant

The table shows the 12 MMPI questions selected by the participant's wife. The questions were selected because she felt confident that she knew the correct answer.

Question	Wife's expected response	Participant's response
I like mechanics magazines.	N	N
I am easily awakened by noise.	Y	Y
My hands and feet are usually warm enough.	Y	Y
A person should try to understand his dreams and be guided by or take warning from them.	N	N
I enjoy detective and/or mystery stories.	Y	Y
My father was a good man.	Y	Y
When someone does me wrong, I feel I should pay him back if I can, just for the principle of the thing.	Y	Y
I find it hard to keep my mind on a task or job.	N	N
During one period when I was a youngster, I engaged in petty thievery.	Y	Y
I do not always tell the truth.	Y	Y
My judgment now is better that it has ever been.	N	N
Sometimes my soul leaves my body.	N	N

Table 2

Four-choice paradigm dialogue

Experimenters and the participant's wife asked questions and the participant responded using the four-choice BCI shown in Fig. 1B. The most relevant questions of the dialogue are listed below.

Question no.	Question	Response
1	Do you have a question about your health?	Y
5	Is it about mental health?	N
6	Is it about physical health?	Y
11	Is it regarding your recovery?	Y
17	Is it something to do with rehabilitation?	Y
18	Do you want additional rehabilitation?	N
20	Do you want another opinion?	N
24	Do you want more information regarding your prognosis and recovery?	Y

Table 3

Paradigms tested for copy- and free-spelling

The six paradigms tested are shown in the left column. Copy-spelling shows the number of unsuccessful sessions (defined as <70%) by paradigm, and the number of successful sessions by paradigm. For the successful sessions, mean accuracy is also shown. Free-spelling shows the number of sessions that resulted in undecipherable (incomplete messages) and decipherable messages (complete messages). Twenty-five of 40 copy-spelling sessions were successful, and 15 of 23 free-spelling sessions resulted in decipherable messages.

Paradigm	Copy-spelling			Free-spelling	
	Sessions below 70%	Sessions above 70%	Accuracy (%)	Incomplete messages	Complete messages
6 × 6 speller	5	2	72.0	NA	NA
4 × 4 speller	2	0	NA	NA	NA
Four-choice	0	7	94.7	0	3
Seven-choice	0	4	84.6	0	1
3 × 5 speller	0	1	77.8	NA	NA
3 × 6 speller	8	11	81.5	7	11
Total	15	25		7	15

Table 4

Examples of BCI communication

The final message (after corrections) is shown in the right column for a given week of testing (56 total weeks). Time to complete included the time between each run, periodic calibration (which may or may not have been conducted), and other stimulus parameter adjustments. A letter board was tested in week 54, and is compared to BCI that same week.

Week	Total selections	Number of selections in message	Time to complete (min)	Message
16	100	41	60	[WIFE] THANK YOU FOR ALL OF YOUR HARD WORK
19	122	28	90	I LOVE MY KIDS: DOC S WHERE IS
26	141	30	79	BUY A SPORT JACKET FOR [SON] AND [SON]
30	76	26	28	SHOULD COST APP SIXTY DOLR
31	73	32	45	[WIFE] WILL U HELP WITH AHMEN DIN.
36	52	22	32	BUY YOURSELF A PRESENT
47	60	42	45	DR S FASTER ON E PAGE WHERE IS PUNCTUATION
Week 54 comparison between the BCI and letter board				
BCI	32	18	24	CAN ANY ONE DO BCI
Letter board	9	9	29	YOUVE SHAV