Design and implementation of a P300-based brain-computer interface for controlling an internet browser

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Abstract—An electroencephalographic (EEG) brain-computer interface (BCI) internet browser was designed and evaluated with 10 healthy volunteers and 3 individuals with advanced amyotrophic lateral sclerosis (ALS), all of whom were given tasks to execute on the internet using the browser. Participants with ALS achieved an average accuracy of 73% and a subsequent information transfer rate (ITR) of 8.6 bits/minute and healthy participants with no prior BCI experience over 90% accuracy and an ITR of 14.4 bits/minute. We define additional criteria for unrestricted internet access for evaluation of the presented and future internet browsers, and we provide a review of the existing browsers in the literature. The P300-based browser provides unrestricted access and enables free web surfing for individuals with paralysis.

Index Terms—brain-computer interface, electroencephalography, rehabilitation

I. INTRODUCTION

The application of brain-computer interface (BCI) can enable communication for those who lose the ability to communicate due to neurodegenerative disease, traumatic brain injury, stroke, spinal cord injury, Guillain Barré syndrome, degenerative muscle disorders, and other diseases of the peripheral nervous system [1], [2]. In the most common non-invasive method of BCI, electroencephalographic (EEG) electrodes on the scalp record electric potentials, which can then be used to control devices. EEG BCI is typically controlled either via voluntary modulation of neural rhythms in specific frequency bands or via presentation of stimuli to elicit specific event-related potentials (ERP) which can indicate the user’s voluntary selection (see [3], [4] for reviews).

Individuals with amyotrophic lateral sclerosis (ALS), the most common motor neuron disease in adults, have stated that communication is important to their quality of life (QOL) [5], [6]. ALS can lead to complete motor paralysis and currently has no cure [7], [8]. Locked-in syndrome (LIS), a state in which only minimal voluntary movement is possible (e.g., vertical eye movements or blinking), occurs at advanced stages of the disease if people opt to undergo life sustaining treatment [9]. For people with ALS, BCI offers new possibilities for communication with their environment independent of voluntary movement [10] – [14].

The advent of the internet has dramatically increased the potential for rapid communication on a global scale. The paramount challenge to this development is to make the internet accessible for those whose ability to communicate is restricted by disease. Additionally, the recent surge in the amount of medical information available to people with disease on the internet and emergence of online support communities represent a growing need for people with disease to access the internet. As more aspects of daily life become accessible online (education, retail, personal finance or business), the potential benefit of connectivity also increases [15], [16]. Design of an internet browser that can accommodate the needs of those with locked-in syndrome is essential to connecting people with disease to the world beyond their immediate environment.

In this paper, we present an internet browser controlled by the P300 electroencephalographic event-related potential as well as the results from testing this browser with 10 healthy participants and 3 individuals in advanced stages of ALS. The browser was evaluated quantitatively by assessing accuracy of participants’ performance on assigned tasks using the browser and qualitatively with questionnaires. The P300 Browser not only satisfies the requirements proposed by Mankoff and colleagues (see following sections) but furthermore adheres to our additional guidelines to enable unrestricted access to the internet.

Previous attempts at creating a BCI browser have achieved significant successes toward enhancing internet accessibility for people with LIS, although each system has its disadvantages. In the following section, we detail the previous
attempts to accommodate internet browsing while also providing efficient and easy navigation.

Criteria for Assessment of BCI Internet Browser

In 2002, Mankoff and colleagues [15] described the requirements of a system that would “allow true web access”:

1) The currently selected link is visible.
2) The user can read and navigate text even when it contains no link.
3) The user can traverse the history list forward and backward.
4) The user can access [his or] her bookmarks and add to them.
5) The user can go quickly to a point of interest with a minimal number of [command] signals.
6) The user is given alternatives for entering text and dealing with form elements.
7) The user is given enough information about link targets to make informed decisions about whether to follow them.

Although these are suitable guidelines, these criteria are insufficient and lack specifications for free surfing of the internet, which we consider a part of “true web access”. The primary basis for a “web browser” is that a user can browse any internet site at will. We therefore presently define “free surfing” as the ability to navigate to any page on the internet that could be accessible by a standard browser, yielding unrestricted internet access, and we add this criterion to our evaluation of existing BCI browsers. The incorporation of physical address entry into an address bar satisfies this criterion.

Additionally, a rate of accuracy above 70% is necessary for satisfactory communication [17], [18]; we therefore apply this precept of satisfactory use to evaluation of the existing browsers.

Finally, clarification of the vague requirement for a “minimal number of command signals” is needed; this is not a quantitative guideline and therefore cannot be measured nor employed for comparative purposes. We state here that a system is considered superior to others if it takes fewer command signals to reach an intended target. In an ideal system, only one command signal (either logical, such as a keyboard shortcut, or physical, such as movement of a mouse (terms introduced by Mankoff [15]) would be needed to navigate to a targeted hyperlink. Although no such ideal system currently exists in the literature, we can evaluate this type of efficiency quantitatively based upon execution time and information transfer rate.

Bit-rate or information transfer rate (ITR) is commonly employed as a quantitative measure for evaluating the efficiency of BCI due to its intrinsic time and accuracy measurements [19]. A measure of mutual information, it is based on the amount of time it takes to execute a decision while also incorporating the accuracy of that execution. Using the formula established by Wolpaw and colleagues [19],

\[ B = \log_2 N + P \log_2 P + (1 - P) \log_2 \left[ \frac{1 - P}{N - 1} \right] \]  

in which B is the number of bits per trial, P is the probability of a specific outcome and N is the number of possible options, this standard measure of efficiency can be calculated for most BCI systems.

Although information transfer rate is a valuable method for calculating the efficiency of BCI, it provides a skewed method for evaluating the efficiency of a BCI web browser. Due to the high variability of the number of possible options presented for selection on any given web page, the effective N in the Wolpaw equation varies. For example, a web page could have zero or over one hundred hyperlinks as a user surfs from one page to the next, yet the number of concrete options presented to the user as part of the interface remains constant. Therefore ITR is an unreliable measure for BCI browsers, and a more pertinent quantitative measure is needed (see below). This is not to say that ITR is not meaningful unit of measure for BCI as a whole; we employ it here as a quantitative measure of performance for comparative purposes.

Although the amount of time it takes to execute a navigation decision is not the most important factor in evaluating BCI [20], we supply an additional quantitative assessment of BCI browsers by introducing evaluation of the minimal time to execute any randomly selected link on a page. For example, in calculating the minimal time it takes to execute navigation to any hyperlink on a page with 25, 50, and 100 links, we provide a practical quantitative measure for users that could be used in evaluation of all low-bandwidth browsers, not just those specific to BCI. This quantitative measure aids in comparison of BCI browser systems, yet it cannot be calculated for all browsers given the information provided in the literature. Ultimately, the satisfaction of the user is most important in determining whether the speed of the system is acceptable.

These additional criteria to allow “for true web access” can be summarized as:

1) The user is able to navigate to any page on the internet that could be accessible by a standard browser.
2) The user can achieve ≥ 70% navigational (or browsing) accuracy (derived from [13]).
3) The time to execute a navigation decision for any link on a page is not considered excessive by the user.

These new criteria provide both a quantitative and qualitative assessment of web access, which can be evaluated via experimental trials and user questionnaires. Using these criteria in addition to the Mankoff requirements, we can evaluate the efficacy of previous BCI internet browsers.

Assessment of Existing BCI Internet Browsers

Descartes, the first BCI browser, used slow cortical potential (SCP) regulation as a control mechanism [21]. SCP regulation, in which a subject can control the polarity of direct current potentials in upper cortical layers over time (seconds), requires training time employing operant conditioning principles before successful control of a BCI can occur [13]. Because electrical polarity is either positive or negative, the decisions are binary. Descartes therefore divided all options in
a tree diagram and listed links alphabetically, with each binary decision taking approximately 120 seconds. This system was tested with a trained individual with LIS in 2006 by Karim and colleagues [22], during which the subject achieved an average of 80% successful link selection. The individual, who was well trained with the SCP-BCI, enjoyed surfing the internet despite its slow speed; he regularly read his favorite newspaper and a magazine related to his career field. See Table 1 for full evaluation of Mankoff and colleagues introduced a web browser designed for low-bandwidth input and described a system in which amplitudes of a user’s two lowest-error “neural signals” could be set with a threshold to create four separate command signals for a browser [15]. Hyperlinks were organized linearly in a window below the browser, and selection of a link or an option was automatic if the user paused (executed no voluntary neural signal) for 2 seconds. However, no exact details of the system were described. BrainBrowser, an extended version of the Mankoff browser, was introduced by Tomori and Moore [23]. Documentation of testing with the BrainBrowser system was not present in the literature, and additional information is needed for further evaluation of these systems. For full evaluation of the BrainBrowser Mankoff browser, see Table 1.

The Neural Signal Surfing Interface, or “Nessi”, was developed in 2003 as a further development of the Descartes system and therefore used a similar binary decision tree paradigm [24], [25]. This system can use either SCP or sensory-motor rhythm (SMR) regulation. All links on the page are highlighted with one of two colors, and binary neural signal modulation to select the color associated with the targeted link was conducted in an adjacent window. Both predefined websites and e-mail links were presented for surfing selection. Nessi was tested with four people with ALS and two healthy participants (unpublished data), but there was no clear information on their performance accuracy. For further evaluation, see Table 1.

Based upon our aforementioned criteria, we can make a few generalizations for all existing browsers. For most browsers, navigation was simplified by reducing the internet to a series of selected pages, buttons or functions, thereby sacrificing truly free surfing. Additionally, important information needed for proper evaluation of preexisting browsers is not available in the publications; we present a comparative table based on the available information (Table 1). The most efficient system, based on the information of minimal number of commands available for each system, was the Nessi system, which nevertheless may be unsatisfactorily slow from the perspective of the system user. Finally, evaluation of these browsers would each be strengthened by experimental testing with people with disabilities in addition to healthy subject use; unfortunately, not all browsers have been tested with locked-in or otherwise impaired individuals.

### JUSTIFICATION FOR CREATION OF A NEW BCI INTERNET BROWSER

BCIs incorporating the “P300” event-related potential (ERP) have been shown to succeed without previous training at a high success rate in healthy subjects as well as people with motor impairment [11], [26]. Additionally, ERPs occur quickly and could lead to increased web surfing speed. For these reasons, and with the goal of creating a more efficient internet surfing system, a browser which utilizes the P300 ERP was created.

The P300 ERP has most commonly been used in BCI as part of the P300 Speller paradigm. The P300 ERP is elicited approximately 300 milliseconds after presentation of rarely-occurring or “oddball” stimuli in a sequence of standard stimuli [27], [28]. The P300 Speller paradigm, pioneered by Farwell and Donchin in 1988, utilizes this response by displaying characters in a matrix and briefly highlighting every row and column in the matrix [29]. The event of highlighting the target letter therefore becomes the less common, or “oddball” stimulus, and a P300 response is generated when the row or column containing the target character is highlighted. The selection of the desired or targeted character occurs through the intersection of the selected row and column. In this manner, the target character in the matrix can be discerned by evaluating which stimuli elicited the P300 response.

A BCI browser controlled via the P300 ERP has the potential to be much more efficient than previous browsers. The duration of character selection by the BCI2000 module [30] is derived from the number of required iterative, highlighting sequences of stimuli as well as stimulus duration and inter-stimulus interval.

In the specific case for determining the ITR of a P300-letter matrix interface, the formula derived by Nykopp is more appropriate than the Wolpaw formula [31], as it accounts for unequal probability of selection of erroneous selections, which is not included in the Wolpaw formula [19]. The Nykopp formula accounts for this unequal probability, notably those that exist due to a “flanker” effect with the P300 matrix, in which an undesired item has a higher incidence of being selected if it neighbors the target character [32]. The mutual information is defined by Nykopp as:

\[
I(X;Y) = \sum_{x \in X} \sum_{y \in Y} p(x,y) \cdot \log \left( \frac{p(x,y)}{p(x)p(y)} \right)
\]

### Table 1. Evaluation of browsers using the Mankoff and supplemental criteria

<table>
<thead>
<tr>
<th>Browser</th>
<th>Descartes</th>
<th>Mankoff Browser</th>
<th>BrainBrowser</th>
<th>Nessi</th>
<th>P300 Browser</th>
</tr>
</thead>
<tbody>
<tr>
<td>Link is visible</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>User is able to read &amp; navigate text</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>User can use navigation function</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Bookmarks are accessible</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>“Minimal command signals”</td>
<td>Not Enough Information Provided</td>
<td>Not Enough Information Provided</td>
<td>Not Enough Information Provided</td>
<td>Not Enough Information Provided</td>
<td>Yes – maximum two command signals per action</td>
</tr>
<tr>
<td>User can type</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>User can access elements</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Capability of informed navigation</td>
<td>Not Provided</td>
<td>Not Provided</td>
<td>Not Provided</td>
<td>Not Provided</td>
<td>Not Provided</td>
</tr>
<tr>
<td>Published text with patient use</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>Not Unpublished</td>
<td>Yes</td>
</tr>
<tr>
<td>User can navigate to any page accessible by a standard browser</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>Not Reported</td>
<td>Yes</td>
</tr>
<tr>
<td>User can achieve 70% navigational or browsing accuracy</td>
<td>Yes</td>
<td>Not Reported</td>
<td>Not Reported</td>
<td>Not Reported</td>
<td>Yes</td>
</tr>
<tr>
<td>The time to execute a navigation decision for any link on a page is not considered exceeded by the user</td>
<td>Not Reported</td>
<td>Not Reported</td>
<td>Not Reported</td>
<td>Not Reported</td>
<td>Yes</td>
</tr>
</tbody>
</table>

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where \( I(X;Y) \) is the mutual information, \( p(x_i) \) is the a priori probability for class \( x_i \), and \( p(y_j \mid x_i) \) is the probability of selecting \( y_j \) for target character \( x_i \).

Schlögl and colleagues and Kronegg and colleagues note that although Nykopp’s definition is more precise, it is not frequently used in the literature due to the need for a priori probabilities for selections [33], [34]. For this reason, both formulae are considered in our work, the Wolpaw values for comparing ITR with other values in BCI literature and the Nykopp values for calculating ITR more accurately.

II. METHODS

Description of the P300 Browser

The browser was designed using the open-source technology of Mozilla’s Firefox (Version 2.0), which allows for supplementary “add-on” code to be implemented. The pre-existing add-ons that comprise the browser include “Hit-a-Hint”, which enables the links on a page to be selected with simple keystrokes, and GreaseMonkey script “Send-Keys”, which simulates typical browser commands by reassigning standard shortcuts. Hit-a-Hint assigns all links on a page a tag with a numeric or alphabetic code, from top to bottom and left to right. Any link displayed in the browser window can then be selected by entering of the corresponding code. By combining these pre-existing elements in Firefox, the browser can be controlled with commands sent from the P3Speller paradigm (via BCI2000 and BCIK Keyboard, a tool of BCI2000).

Browser functions that can be executed with the P300 Browser are: navigation (forward, back, reload, and home), data form entry, address bar entry, and scroll up and scroll down. These functional options are all presented as icons in an expanded 8-by-8 form of the traditional 6-by-6 P3Speller matrix in BCI2000 (Figure 1). By employing alphabetic code for link tags, each link on the page can be executed by entering either a one- or two-letter command. For example, the two-letter link tag BA can be executed by first selecting a command with an asterisk (“B*”) and then the following letter (“A”). Therefore, for sites with over 26 links on a page (up to 338 links on a page), any link can be selected by execution of at most two commands, far less than the amount of commands necessary if the link selection method were binary. Characters in the matrix can not only be used to select links in the browser window, but they can also be used in typographical fashion to write emails or fill out form elements (after the user selects the form element’s tag). Visual feedback of the selected command is displayed to the user after every selection.

Web browsing is an asynchronous process; the user controls the pace of the activity. However, the P3Speller is a synchronous process, reliant on specific timing to detect a decision made by the user. Because of the difference between asynchronous and synchronous processes, timing between the two monitors was coordinated so the users were not overloaded with information (Figure 2). To allow for variable loading time for each web page (more page content can lead to longer loading times) and also to allow the user to fully assess the page before deciding on a navigational action, pauses of modifiable length are inserted before presentation of link tags (default: 5 seconds after page load) and onset of P3speller sequences (default: 16 seconds after previous command execution). The time duration needed for selection of a P3Speller command depends on the amount of sequences needed to determine the user’s target character. One sequence comprised 16 flashes (once for each row and column) of 0.0625 s length with an interstimulus interval of 0.125 s. Although one test subject could reliably select the target character in as little as 3 sequences, for testing purposes, the minimum number of sequences was set to 5. This resulted in a minimal time for all subjects of 15 seconds (using an 8x8 matrix) for one selection \((6 \times 5 \times 0.0625 + 0.125)\). Some subjects required more sequences, resulting in increased browser execution times.

Because the P3Speller process continually repeats to detect user decisions, selection of a “Read” option will void other commands of the P3speller and hide hyperlink tags, which can be useful when reading web pages with lots of text or when the user would like to pause. The “Read” mode nullifies all

![Fig. 1. Character matrix for P300 Browser. In this frame, the second column is highlighted.](image)

![Fig. 2. An overview of the P300 Browser’s algorithm (including approximate duration of actions) and the corresponding user action sequence.](image)
commands except for scroll commands (page up and page down) and the “Tags” command, which redisplay plays over the links, thereby returning the system to active navigation. The “Tags” command therefore ends the “Read” mode.

Additionally, an option for correction of typed or navigation error is available. If a command is executed incorrectly by the user, the error can be corrected with selection of “back” (if the wrong link was executed), “reload” (if a starred letter was incorrectly selected, to prevent the system from looking for an additional letter entry), or delete with “Bs” (backspace; if a typographical error resulted). Further description of the browser, as well as preliminary evaluation of the P300 Browser with one healthy test person, was published by Mugler and colleagues [35].

Data Acquisition

All sessions for this study were recorded using a 16-electrode EEG cap (Sn, 8 mm, Electro-Cap International, Inc.) according to the International 10-20 System [36], with impedance held under 5 kOhm with the application of electrode gel. Electrodes were connected to a 16-channel amplifier (g.USBamp from g.tec, Linz, Austria) with a sampling frequency of 256 Hz and a gain of 20,000 (bandpass: 0.1 Hz to 30 Hz, notch: 40-60 Hz). BCI2000 software was used to control presentation of stimuli, record and save data and for online-classification, on an IBM ThinkPad Laptop (screen: 15”). The P300 Browser window was presented on the laptop, and an additional monitor (screen: 17”), on which the BCI2000 P3Speller paradigm (with the added navigational options in an 8x8 matrix, as seen in Figure 1) was displayed, was placed directly adjacent to the laptop.

Subject Pools and Procedure

The 10 healthy participants (5 male, 5 female) had no previous experience with a BCI and attended testing sessions with the browser on two consecutive days at the same time of day to avoid circadian influence on P300 response [37]. Participants’ age ranged from 20 to 29 years (M = 24.5, SD ± 2.72). All participants were right-handed and either spoke German as a first language or spoke it fluently as a second language. No participants exhibited neurological or psychiatric symptoms. Three potential participants were not included in the subject pool due to technical difficulties in the first session (excessive blinking, technical errors); resulting data from these participants is not included in this study.

During screening, healthy participants spelled 3 words (18 letters total) in sets of 15 sequences for the selection of one character, in which a sequence is defined as the highlighting of each row and each column of the matrix once. The words were provided before the trial, and during spelling, the target letter was displayed on the screen (in “copy-spelling mode”) [10]. Visual feedback of selection to the subject was suppressed during screening. After the screening (< 14 minutes), there was a short break in which step-wise linear discriminant analysis (SWLDA) was performed in Matlab to determine the coefficients to apply to each EEG electrode to adequately detect each individual’s P300. Accurate selection for each subject determined the number of sequences necessary to correctly classify the signal. Although this quantity was variable for each individual, a lower limit of 5 sequences was set to maintain consistency in the individual result [38], [10].

After parameters were calculated and loaded for each subject, they spelled 3 additional words (31 letters total) in copy-spelling mode to verify sufficient performance (>70%) using these weights and to compare the performance of copy-spelling and browser execution. If sufficient performance was not achieved during screening, subjects were removed from the testing pool for the browser; this only occurred with one healthy individual.

The second subject pool, consisting of 3 people with ALS (UBA, KR, and LEK; all female; ages: 52, 40, 50; all with spinal-progression ALS; time since diagnosis: 5, 6, and 12 years, respectively), had four sessions with the browser – one screening session and three test sessions – each exactly one week apart, approximately 2.5 hours in duration. All participants had late-stage ALS and had regular BCI training (P300, SCP, SMR) prior to this study (average experience: 3.33 years). UBA and LEK were artificially ventilated and fed; all needed wheelchairs or power-wheelchairs. ALS progression was categorized with the ALS-Functional Rating Scale (ALS-FRS) which assessed the extent of physical capabilities (walking, stair climbing, writing), in which perfect functioning would result in 40 points (maximum) and the locked-in state would result in 0 points [39]. Quality of life of people with ALS was assessed with the “Schedule for the Evaluation of Individualized Quality of Life” – Direct Weighting (SEIQoL-DW) [40], [41] and the “Anamnestic Comparative Self Assessment (ACSA)” [42]. Two could only communicate with a communicator device or blinking as a binary response to an alphabet key; speech of the third individual declined dramatically over the course of the study. Because of communication issues with people with ALS, responses to surveys were standardized; all surveys were completed by binary response (blinking, nodding, or other form of communication) to questions from the experimenter. Additionally, a screening process similar to that of healthy test participants was performed (differences between screening processes included selected words, length of test words, and individuals with ALS had a single session for screening instead of two due to their familiarity with the P300-BCI system). For UBA, who could not move her head, the two screens were positioned as far away as possible and font size was increased.

Because the selection algorithm for the P300 can be adversely influenced by subject depression or poor motivation [43], [44], all participants completed questionnaires on depression, mood and motivation. Depression was screened using the “General Depression Scale Short Form” (“GERMAN VERSION” ASD-K) for healthy participants [45] and the ALS-Depression Inventory (ADI-12) for people with ALS [46]. All participants completed these at the beginning of the
experiment. Mood was assessed with the SEL-S, a subscale of the SEL questionnaire (“Skalen zur Lebensqualität” quality of life [47]), motivation was assessed with the FAM-BCI2000, a modification of the FAM (“Fragebogen zur aktuellen Arbeitsmotivation”) for the use with BCI participants [43]. The SEL and the FAM were completed before each session for each subject.

Initially-acquired weights (calculated from copy-spelling of 21 characters) were used for every session with the individuals with ALS. To evaluate performance and to verify correct parameters, one-word copy-spelling was performed at the beginning of every session with the individuals with ALS. For each session with healthy participants, new weights were calculated because of training effects and possible change of selection procedure in the second session by untrained users.

The study was approved by the Ethical Review Board of the Medical Faculty University of Tübingen. After having been informed about the purpose of the study, healthy subjects signed informed consent; individuals with ALS consented via eye blinking, or their communication system.

**Quantitative Testing**

In each session with all participants, after a brief copy-spelling test for online accuracy comparison, various internet tasks were presented to the participants for execution using the browser to standardize the browsing procedure and to determine whether an individual with ALS had selected the link they intended. The number of steps or decisions needed to accomplish a task was recorded and the time needed to execute these tasks was assessed (Digital Appendix: Table 5). Representative tasks for each session included searching for specific information on the local university’s homepage, ordering a specific book online, searching for “BCI” and finding information on the human brain on the Wikipedia. Task design was based on typical introductory surfing behavior and tasks people with ALS might find useful or interesting; task assignments were consistent for subject pools.

Sessions with the ALS participants were momentarily interrupted when an obvious distraction occurred, e.g. breathing problems, excessive salivation. In the final session with participant LEK, the EEG signal was noisy and could not be improved; the session was repeated 14 days later.

**Qualitative Testing**

Qualitative testing was performed with the goal of acquiring a more accurate evaluation of the P300 Browser based on the criteria established in the introduction. Additionally, qualitative analysis served the purpose of providing user feedback for development of this and future browsers. A “post-study evaluation” was provided for all participants at the conclusion of the final session to assess experience with the browser, personal recommendations and interest in further use of the browser. Consisting of 10 items to be ranked from 1 to 7, the survey attempted to ascertain general opinion of the P300 Browser. Open-ended questions allowed for expression of observations and criticism. (Participants in the ALS group had an additional question: “My expectations were fulfilled”). The goal of these questions was to amass opinions on methods to further improve browsing for everyday life (Table 2).

### III. RESULTS

We present the results of the browser in terms of quantitative and qualitative analysis and further analyze the potential influence of psychological variables on these results.

#### A. Quantitative Analysis

The results for browsing and copy-spelling averaged over all sessions for each individual with ALS, along with the averaged values of healthy participants, are presented in Tables 3 and 4. Due to the length of the pauses between two selections of hyperlinks, the bit rate is calculated also without these pauses to give a more interpretable value and for comparison purposes to other browsers.

Task execution across subjects was consistent; however, due to the dynamic nature of the internet, the number of links on a page or the number of characters in a tag often varied without significantly changing execution of the task. The number of steps included incorrect selections and the steps taken to correct mistakes in browser execution; the time needed for
these corrections is therefore within the accuracy data.

Healthy participants, on average, controlled the browser with over 90% accuracy with an ITR of 13.4 bits/minute (Wolpaw) and 14.4 bits/minute (Nykopp) without the pre- and post-set pauses for browser loading. With the pauses, the average ITR across healthy participants was 8.8 bits/minute (Wolpaw) and 7.1 bits/minute (Nykopp). The total number of mistakes across all healthy participants in both sessions was 36 out of 601 browsing selections, for an overall 94% accuracy. Accuracy ranged from 89 to 100% in browsing tasks; notably, one healthy subject (IZH) had perfect performance for both sessions in both copy-spelling and browsing. Comparing copy-spelling results with results from browsing activity, healthy participants who could learn to use the speller within the first session could also learn to use the browser, suggesting that naïve users of the P300 Browser could successfully use it to browse.

Participants with ALS achieved an average ITR with the P300 Browser of 4.7 (Wolpaw) and 5.3 (Nykopp) bits/minute (inclusive of pauses), or 5.7 (Wolpaw) and 8.6 (Nykopp) bits/minute (without pauses), with an average accuracy of 72%. Further quantitative assessment for each participant with ALS is detailed in Table 3. Notably, both groups had a satisfactory (≥70%) average performance on tasks by the end of the first session with the browser.

The assessment of the physical status of the ALS-FRS depicts a very low functional level of the participants with ALS (ALS functional rating scores: 0, 0, 8). In reference to the categorization of Kübler and Birbaumer (2008), two participants were in the locked-in state and one was majorly impaired [1]. ITRs results are presented according to their formula in Table 4. This table illuminates the discrepancies between the formulae. This is theorized, in part, to stem from the influence of the flanker effect included in the Nykopp approach.

Additionally, all results for ITR and accuracy in browsing inherently include the corrective steps in browsing that a user must perform after an erroneous selection is made. This necessary error-correction, which does not exist during copy-spelling sessions, leads to a comparative increase in the Nykopp ITR value, as at least one correct selection must be made for each incorrect selection.

Table 3. Average accuracy, number of sequences and ITR of participants with ALS while browsing with the P300 Browser. HP: healthy participants.

<table>
<thead>
<tr>
<th>Patient</th>
<th>Session</th>
<th>Accuracy</th>
<th>Number of sequences</th>
<th>Bits/Minute with pauses (Wolpaw)</th>
<th>Bits/Minute without pauses (Wolpaw)</th>
</tr>
</thead>
<tbody>
<tr>
<td>UBA</td>
<td>1</td>
<td>69.57%</td>
<td>10</td>
<td>4.21</td>
<td>4.94</td>
</tr>
<tr>
<td></td>
<td>2</td>
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<td>5.20</td>
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<tr>
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<td>8</td>
<td>4.79</td>
<td>6.13</td>
</tr>
<tr>
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<tr>
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<tr>
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<tr>
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<td>8.66 (±2.4)</td>
<td>13.70 (±6.8)</td>
</tr>
<tr>
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<td>2</td>
<td>95.25%</td>
<td>6.7 (±3.0)</td>
<td>9.00 (±1.7)</td>
<td>13.61 (±5.3)</td>
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<td>Avg</td>
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<td>93.80%</td>
<td>6.85</td>
<td>8.85</td>
<td>13.44</td>
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Table 4. Information Transfer Rate formula comparisons. All data is averaged over all sessions for each subject. Healthy Participants (HP) averaged across all subjects. All units are bits/minute.

B. Qualitative Analysis

A follow-up questionnaire of both subject pools revealed that the sessions with the browser were found to be interesting (Table 2). All three participants with ALS stated a preference to train further with the browser and to use it in their daily lives. The participants all agreed in their responses that working with the BCI-Browser was interesting (all ranked it 7 out of 7) and that they were not at all bored during training.

Participant LEK had the lowest score for “my expectations for the browser were fulfilled” (3 out of 7), which may correlate with the participant’s response to “it takes much too long to surf on the internet with the BCI-Browser”. Although all participants with ALS found the duration for the selection of a link in the browser to be too long, participant LEK felt the strongest on the matter.

Participant KR was the only participant that took the opportunity to answer open-ended questions. The participant had reportedly high expectations for the browser (“My expectations were very high (Hope!)”). When asked her opinion of the program, responses were positive (KR: “It’s super!”). This participant also noted that the “@” symbol was left out of the matrix selection, and requested that it be added to the options for the browser, as well as a selection for a 20 second pause to briefly read a webpage. These factors suggest a great desire to work with the browser and a satisfaction with its use.

Healthy participants’ responses varied more in comparison with the data from the participants with ALS. Overall, there were trends toward not being bored (2.40 average out of 7) or impatient (3.10) during training. Other questions elicited an averaged “neither agree nor disagree” response.

The healthy subject pool responded to open-ended questions with many notations for improvement. They expressed a wish for quicker selection of letters (Subject HJH), a desire for more time to read the webpage before commencement of the...
P3Speller sequence (Subject FEH), and an overall wish for better control of the timing sequences (Subjects FEH, HJH, IZH, MFS). Subject MFS also noted that the second session was easier, as they had already become familiar with the browser during the first session. MMS noted that it was easier to select the symbols on the edges of the matrix; this confirms the existence of the flanker effect.

In reference to the new criteria established in the introduction section of this paper, as well as the Mankoff criteria, we also evaluated the degree to which the P300 browser fits the criteria based upon the user data (Table 1). Although the link is always visible during selection, some of the users of the P300 Browser could not always look at the corresponding tags during the P3Speller sequences, which might bring into question the degree to which the link is visible. The user can use all navigation functions of a standard browser, which satisfies the criteria, but a request for two extra functions, namely a 20 second pause option and the “@” symbol, demonstrates that the P300 Browser can be further improved. Although one participant with ALS reported that the browser took “too long” to surf the internet, most reported that there was not a strong opinion one way or the other; because all subjects found it interesting and were not bored or tired, we can conclude that the time to execute a navigation decision is not excessive. Additionally, because of the number of actions necessary to execute a navigation decision, the P300 Browser may have fewer command signals required than all other browsers. Further analysis of evaluation criteria is continued in the discussion.

C. Psychological Variables

Using the established scales introduced in the methods section, we can analyze potential influencing factors based upon mood, motivation, and depression. We also present the results of quality of life testing.

Mood and Motivation

Throughout all sessions, no participants demonstrated scores indicative of a negative mood or low motivation that might negatively influence their performance. All mood scores for healthy subjects on the SEL-S scale were between 3.1 to 4.3 (on a scale from 1 to 5), and motivation, measured by the FAM-Scale, did not significantly change from one session to the next (t-test for dependent samples).

Depression

No participants from either study pool exhibited symptoms of depression. In the ADI-12 test, participants with ALS had scores of 13 (UBA), 17.5 (KR) and 15 (LEK), all under the depression cut-off of 23 points. Similarly, the mean score for healthy subjects for the ADS-K test (on a scale from 0 to 45, depression cut-off of 18 points) was a 7.90 (SD ± 4.99), with scores ranging from 1 to 16.

Quality of Life

The subjective quality of life (sQL) of the individuals with ALS was measured with the SEIQoL-DW and the ACSA.

The sQL, determined through the SEIQoL-DW, is stated as a percentage (between 0 and 100%). The three participants with ALS achieved index values of 81.67% (UBA), 43.33% (KR), and 69.17% (LEK). All categories, weights, and scores are presented according to the participant in Figure 3. Note that the high importance and low score for “communication” for participant KR lowers the SEIQoL-DW index value.

The ACSA uses a numeric analog scale to indicate the subjective quality of life. Subjects are asked to think of a time or situation in which they had the worst and the best quality of life. To the worst quality of life a value of -5 is assigned and to the best a value of +5. Subjects are asked to allocate their current quality of life on this individual continuum. The participants achieved scores of 3.5 (UBA), 2 (KR) and 3 (LEK). It is worth noting that these scores are above the average for healthy subjects [48].

IV. DISCUSSION

The data verify that it is possible to freely surf the internet with the P300 Browser and that most of the functions of a manual “normal” browser can be successfully executed. To evaluate the P300 Browser, we used the criteria from Mankoff and colleagues in addition to the criteria presented in the introduction.

Most of the Mankoff criteria were immediately satisfied: selected links were visible to the user, although the user could not stare at the link, instead focusing on the character matrix; the user could read and navigate text even when it contained no link; the user could traverse the history list forward and backward; and the user was given enough information about link targets to make informed decisions about whether to follow them. Additionally, the remaining Mankoff criteria were satisfied indirectly: the user was not given alternatives for entering text and dealing with form elements, but these options were possible directly in our interface without the need for additional programs or alternatives; and the user could go quickly to a point of interest with a minimal number of commands, and thus, fewer commands than are needed for comparable browsers. The only Mankoff criterion that was not completely accomplished with the P300 Browser was the requirement that “the user can access her bookmarks and add
to them”; using the P300 Browser, a home page could be set, but bookmarks were not included. However, the number of commands to navigate to a given destination was greatly reduced and therefore the need for bookmarks was also diminished.

Additional criteria for browser evaluation stated in the introduction were also assessed. The browser could navigate to any page on the internet that could be accessible by standard browser. Most importantly, an average rate of accuracy above 70% was achieved for healthy subjects and participants in the locked-in state alike. With such a synchronous browsing paradigm, accuracy below 66%, which was the case in UBA’s 3rd session, may in fact work against the user, as decisions to correct for mistakes then outnumber the intended browsing actions. In a real world setting, the BCI session should be terminated when encountering such low accuracy; if the problem persists, a new screening is necessary to redefine the weights.

People with ALS who can already communicate with the P3Speller can also surf with the P300 Browser and demonstrate that after a brief weight calibration process they can achieve comparable performance to the P3Speller. Healthy participants without previous experience with the BCI can also control the P300 Browser after a brief training session with the P3speller copy spelling program and demonstrate similar performance in both programs (over 90% accuracy).

For a more quantitative evaluation of the “minimal number of commands”, we recorded the number of command signals to reach an intended target and the information transfer rate of the system as a whole. The information transfer rate was high during copy-spelling, confirming the general capability of the P300 BCI. The ITR of the P300 Browser closely approximated the copy-spelling results. Participants with ALS, however, had lower ITR than healthy subjects which may be due to the neurodegenerative nature of the disease. Neurodegeneration in motor cortical and other brain areas may lead to shorter attention span and impaired and decelerated eye movement. Both factors would be expected to increase the error rate and thus, the necessity for correction. But it has to be stressed that the performance of participants with ALS was still above the criterion level of 70% accuracy and that the people with ALS – despite lower ITR – enjoyed using the browser and were interested to continue using it.

As stated in the introduction, it is important to note that the information transfer rate of a system that allows dynamic and free web surfing is likely not the optimal measure of the success of that system. Any system that allows the user to visually search for information or to read a webpage with long pauses, such as the P300 Browser, will have an ITR that is disproportionately low. By using an 8 by 8 selection matrix, in one “decision” process, 1 out of 64 options can be selected. Comparably, surfing can occur much more quickly in browsers that must execute multiple binary decisions to select a link on a page. Because these synchronous systems must allow for cognitive processes, such as navigation decisions and reading, the standard ITR lacks applicability as an accurate measure of system efficiency. However, we employ it throughout this report as a quantitative measure based on its common use in BCI literature.

To give a more complete picture of satisfaction with the P300 Browser – a construct for which we consider a reasonable ITR necessary but by no means sufficient – we also asked subjects to rate different aspects of the browser on a 7-point Likert scale. This rating nicely demonstrated that results obtained from healthy subjects must not be transferred to people in the locked-in state. Notwithstanding some similarities in responses between the average response of healthy subjects and individuals with ALS (Table 2), participants with ALS were much more interested, less bored, found the browser more entertaining, and were less happy that the training was over. On a descriptive level we can also state that the participants with ALS were in a better mood, felt more challenged and had more interest in the task as compared to healthy subjects.

For use in a home setting, fine-tuning and adjustment must be made for the individual; by increasing the font size on participant UBA’s computer, the amount of information presented on a webpage is influenced (fewer hyperlinks and tags). Although it is not possible to control for accuracy, copy-spelling and browsing for UBA was comparable, so the two-screen conception likely did not influence the accuracy.

Our system fulfills the criteria (Table 1) and provides many functions via keyboard web browsing, and each of these options is possible within, at most, two selections with the P3Speller window. Pop-ups or new windows pose a problem, but most pop-ups are prevented by using Firefox, and settings can be changed in the browser for opening new windows. An additional icon in the character matrix that could close these windows could provide a solution. However, internet options which cannot be easily navigated via keyboard options, such as Flash animation, are complicated to access with the P300 Browser.

There is substantial room for improvement and future development of the P300 browser, incorporation of patient-specific functions in the program and implementation of their personal suggestions and preferences is encouraged. An ideal browser should also provide easy-access bookmarks or enable non-serial navigation through the history; both options which are not available in our P300 browser. Because there are two monitors currently used to present both the browser window and the P300 Speller paradigm to the user, eye movement and some head movement is required. Ideally, no eye movement would be necessary, so that the P300 Browser would be fully independent of motor control.

Although any improvements in the ITR of a BCI system or P300 selection paradigm would also increase the ITR of the browser, there may be an upper bound to ITR in browsers due to cognitive processing in accessing a page, the speed of the browser or Internet connection, and the time needed to read and log the tags. This maximum individual speed with which a
person can browse the internet on a standard browser should be the ultimate goal for future BCI browsers. Great potential lies in incorporating additional physiologically-controlled signals including eye movement or other muscular movement if available. However, the addition of other physiological signals increases cognitive load on the user; it is therefore an empirical question whether such additional input options could increase the ITR. Asynchronous signals, or signals that can be voluntarily controlled in time by the user, could enable a cursor and give more control to the user, but this may not be the best option for free surfing with BCI; some browser users prefer to use shortcut and keyboard options, and typing form elements with a cursor could be challenging and time-consuming. The frequent use of shortcuts in current standard browsers suggests that the P300 signal would remain relevant and serve as a strong basis for future browsers.

In conclusion, the P300 Browser has been demonstrated to be a useful tool for freely surfing the web with healthy volunteers and people with ALS alike. Although people with ALS reported high expectations for the browser (KR: “My expectations were very high”), when asked what they thought about the program, they were largely positive, confirming the results from the experiment and validating the P300 Browser as a useful brain-computer interface application and browser. A version of the P300 Browser updated to work with FF3.0 is available at http://nessi.mozdev.org/.

APPENDIX

A digital appendix (Table 5) is available online.

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REFERENCES


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