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Critical Review: Can brain-computer interface (BCI) systems facilitate communication in persons with Amyotrophic Lateral Sclerosis (ALS)?

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This critical review evaluates studies about brain-computer interface (BCI) systems and their potential in facilitating communication for persons with Amyotrophic Lateral Sclerosis (ALS). Of the five studies examined, designs included: two quasi-experimental designs and three comparative designs. Altogether, the evidence supports the potential for these systems to be used by people with ALS to communicate. Further development is needed to make BCI communication systems more feasible for everyday use by patients with ALS. Further research is indicated involving larger samples, randomization of participants, blinding of researchers and participants, inclusion of participants with advanced ALS, and investigation into the role of psychological variables within the ALS population. Some clinical implications for speech-language pathologists are discussed.

Introduction

ALS is the most frequent cause of degenerative neuromuscular disease (Kübler, Kotchoubey, Kraiser, & Wolpaw, 2001). It involves the steady, progressive degeneration of central and peripheral motoneurons. Ultimately, ALS leads to paralysis and death. Persons with ALS, or persons with other neuromuscular diseases like brainstem stroke, cerebral palsy, or muscular dystrophies, who are unable to use their muscles but are conscious and alert are said to be "locked-in" and cannot communicate vocally or in writing. Since they have no remaining muscle movement to use for communicating, current communication devices which operate with motor input are not feasible for many of these people. Instead they need an alternative that does not rely on muscular channels – such as a brain-computer interface (BCI) (Wolpaw, Birbaumer, McFarland, Pfurtscheller, Vaughn, 2002).

The development of BCI has been the focus of nearly 25 years of research to present day (Wolpaw et al., 2002). The primary goal of research has been to provide users who are locked-in with basic means of expressing their needs and wants and controlling their environment. This has enormous potential for people with advanced ALS. They are one of the primary clinical populations for BCI and would be most likely to use BCI systems long-term (Sellers, Krusienski, McFarland, Vaughn, & Wolpaw, 2006; Birbaumer, Mirguialday, & Cohen, 2008). Present-day BCIs are able to determine the intent of the user based on the information from electrophysiological responses recorded from the brain, such as electroencephalogram (EEG) or event-related potential (ERP). To evoke a response, users are presented with either visual or auditory-based stimuli. Visual BCI devices are commonly employed in most studies, while auditory-based ones are still being developed and investigated. Auditory BCI devices would benefit patients with ALS who have lost muscular control of eye movement. The auditory or visual stimuli presented evoke the EEG response and the brain recordings are taken. Recordings are done either invasively or non-invasively and monitored with methods like slow cortical potentials, sensorimotor rhythms (SMR), P300 ERP, mu or beta rhythms from the scalp, or implanted electrodes that record cortical neuronal activity. Real-time translation of these signals enables the user to select a communication symbol or produce a command in order to relay a message or control an external device, such as a computer screen. (Kübler et al., 2001; Wolpaw et al. 2002).

Research studies and reviews have examined various noninvasive and invasive BCI methods in helping people with locked-in syndrome communicate messages and send controls (Wolpaw et al., 2002; Birbaumer, McFarland, Pfurtscheller, Vaughn, 2002; Birbaumer, 2006; Birbaumer & Cohen, 2007; Birbaumer et al., 2008; Daly & Wolpaw, 2008). However, there are a limited number of studies that focus specifically on BCIs that operate using EEG signals and their effectiveness at facilitating communication using participants who have ALS. Further, there are a limited number of studies that explicitly outline implications for the profession of speech-language pathology (SLP). This is important because speech-language pathologists (SLPs) are the professionals who are dedicated to facilitating communication for individuals suffering from diseases such as ALS. Since there are no effective therapeutic strategies directly for ALS (Kübler, Kotchoubey, Kraiser, & Wolpaw, 2001), facilitating communication in a person with ALS is paramount. In fact, communication is vital to the will to live and to quality of life for individuals suffering from such severe diseases.

Objectives

The primary objective of this critical review was to outline and evaluate selected studies that pertain to non-invasive BCI devices and their potential in facilitating communication for persons with ALS. The BCI systems focused on were those that give visual stimuli to evoke P300 or SMR signals – both are based on the EEG signal which is the method of choice in BCI devices developed for persons with ALS (Brain, 2005). A second objective is to discuss the potential implications for SLPs who may be considering BCI systems as an augmentative communication method with clients who have ALS.

Methods

Search Strategy

The computerized databases searched included SCOPUS, CINAHL, PubMed, PsychInfo, Medline-OVID, and the Google Scholar search engine. The search strategy used was: (Brain-computer interface) AND (Amyotrophic Lateral Sclerosis) AND (Communication) AND (Rehabilitation) AND (Electroencephalogram) AND (P300) OR (SMR) AND (Visual Stimulation). The search was limited to journal articles written in English and published between 2006 to present.

Selection Criteria

To be selected for this critical review, studies were required to examine the use of P300 or SMR visually-based BCI devices intended for facilitating communication for persons with ALS. Study subjects included persons with ALS and those without ALS. Selection criteria did not include any demographic variables or specific stages of ALS. Studies were based out of various institutions in the USA, UK, Italy, and Germany. Studies were taken from a variety of disciplines, including clinical neuroscience, biological psychology, psychophysiology, and clinical neurophysiology.

Data Collection

Based on the selection criteria, the literature search generated five experimental group studies. Two studies used a quasi-experimental design, and three were comparative designs.

Results

Study #1 Furdea, Halder, Krusienski, Bross, Nijboer, Birbaumer, and Kübler (2009) explored whether P300-based BCI users would be able to spell with an auditory-based ERP spelling system, versus a visual equivalent. The study involved comparing the performances of 15 healthy participants. A single experimental session took place and consisted of three experimental runs. In each run, the participant had to spell the word 'brainpower' letter by letter using a 5x5 matrix. Target stimuli were presented in a random series of either visual or auditory stimuli. The auditory ERP speller used a visual support matrix. This consisted of an oddball paradigm, in that rare events were presented in the context of other "irrelevant" stimuli to elicit a P300-like ERP. The BCI2000 software program controlled stimulus presentation and data collection. The EEG was recorded using a 16-channel tin electrode cap. Analysis of the comparison between the visual ERP speller and the auditory ERP speller was based on the performances of 13 participants (two of original 15 were excluded). The results analyzed classification accuracy (the number of sequences per user in the auditory and visual spelling mode), bit rate (amount of information conveyed per time unit), and written symbol rate (accounts for bit rate and correction of wrongly selected letters) in order to provide a realistic measure of the speed of written communication. Results indicated that the visual modality led to the highest possible accuracy in fewer sequences, versus the auditory modality. The ERP waveforms were also analysed. For the auditory speller, 8 of 13 participants had typical waveforms and 9 of 13 achieved accuracy above 70%. For the visual speller, all participants exhibited typical P300 waveforms.

The data analysis in this study involved the stepwise linear discrimination analysis (SWLDA) for classification and weight generation of the visually evoked P300. This method is an extension of Fisher's Linear Discriminant (FLD) used for classifying EEG data and recently for BCI data. The study was thorough in analyzing this EEG data and determining the statistically most significant single feature using p-value >.15. However, given the study's design, the authors failed to employ the appropriate statistical test for within-group factors - the repeated measures ANOVA – to determine any significant differences or main effects for either of the two conditions. Overall, results with the visual speller were better than those for the auditory speller. However, the auditory speller was said to hold potential for further development for the ALS population. The findings must be taken cautiously for several reasons. The results are based on a single session. The reliability is somewhat poor due to lack of clear descriptions and sufficient details for replication. The construct validity of the results is questionable because there were no participants with ALS involved. The statistical conclusion validity is also problematic because there was no statistical testing to show any significant differences between the two conditions. Also, there was no descriptive statistics reported (e.g. mean), and the power and effect size was small due to the small sample size.

Further studies need to take place over multiple sessions with a larger sample and/or with participants directly from the ALS population. The validity, clinical importance, and applicability equivocally support the use of visual BCI spelling systems for individuals with ALS. Research is needed into auditory BCI systems.

Study #2 Nijboer, Sellers, Mellinger, Jordan, Matuz, Furdea, Halder, Mochty, Krusienski, Vaughn, Wolpaw, Birbaumer, & Kübler (2008) evaluated the efficacy of a visual-based P300 BCI communication device. The BCI device was a 6x6 or 7x7 matrix speller. The study involved six individuals (originally eight, but two did not complete it). All participants in the study had ALS. The study was completed in two phases. The purpose of phase 1 were to reliably detect P300 response to a desired character in individuals with ALS with a minimum of 70% accuracy, to assess stability of accuracy over time, and to assess changes in P300 amplitude and latency over time. Phase 1 involved copy-spelling sessions over 6-14 weeks. Here, the participants were prompted by a computer program with text to copy letter by letter. The purpose of phase 2 was to determine if a BCI can be useful for individuals with severe disabilities who need to communicate independently. Phase 2 involved free-spelling sessions over 17-40 weeks. In this phase, the participants chose whichever letters they desired to spell spontaneous utterances. The BCI200 software was used to collect the data and control the experimental design. EEG recordings were taken in a 16-channel cap. The classification of EEG/ERP signals was done online and offline using SWLDA. Classification accuracy was the number of characters that the SWLDA accurately classified online and offline. Online condition reflected the actual performance, while offline condition reflected expected performance based on methods suggested by a previous study (Krusienski, Sellers, Cabestaing, Bayoudh, McFarland, Vaughn, et al., 2006)

For phase 1, a two-way Analysis of Variance (ANOVA) included the factors of analysis mode using online vs. offline conditions on sessions 1-10. A main effect was found for analysis mode, but not for session or interaction. Mean classification rates were reported and showed that offline accuracy was higher. To evaluate stability of performances (i.e. the amplitude or latency or both of the P300 ERP), a one-way ANOVA was done on the amplitude and latency of each participant's P300 response at a specific electrode for sessions 1-10. No significant differences were found for either the amplitude or latency ANOVA across the sessions, thus performance was said to remain stable for up to 40 weeks. For phase 2, online accuracy increased because of improvements to the classification methods from phase 1. Nearly twice as many selections were made per minute. All participants were able to produce novel spontaneous messages. No statistical testing was done for the results in phase 2. Altogether, the design was well-formulated and the study is easily replicated because it had sufficient details and descriptions of measures. Strong efforts were made to employ appropriate statistical tests, and descriptive statistics were reported. The small sample size yielded small power and effect size. However, by involving persons with ALS, the study is more clinically important and applicable and results in higher construct validity. The numerous sessions and lengthy time periods used strengthen the study's findings.

Overall, the validity and importance are both strongly suggestive of the efficacy of P300-based BCI systems that provide visual stimulation. Indeed, they have potential to be used as communication devices for individuals with ALS.

Study #3 Nijboer, Furdea, Gunst, Mellinger, McFarland, Birbaumer, and Kübler (2008) studied the performance of a two-choice BCI device that used auditory or visual stimuli to evoke SMR. The intention was to determine if an auditory SMR-based BCI communication device could be feasible for persons with ALS. To study this, they were interested in whether participants had similar performance in visual versus auditory modalities, and whether there are differences in learning as a function of feedback modality. Additionally, they were interested in the influence of psychological factors, such as mood and motivation, on performance. Participants included 16 healthy volunteer students with no history of neurological or psychological disorder. They were divided into two groups – auditory feedback group (AFG) and visual feedback group (VFG). In both, they learned how to decrease or increase the amplitude of SMR of the EEG. Their task was to control the movement of a cursor in a predefined direction towards a target. This was completed over three training sessions. EEG recordings were done using a 16 channel tin cap. Psychological parameters were assessed at the beginning of each session with questionnaires.

Accuracy was defined as the percentage of hit targets (visual feedback) or achieved sounds (auditory feedback). Data analysis compared BCI performance as a function of modality using a 9 x 2 repeated measures ANOVA. The VFG performed better than the auditory, on average. Pairwise comparisons of blocks between the groups revealed that the VFG performed significantly better initially. Ultimately there was no difference though, as performance of the AFG increased from the first to last block but did not do so for the VFG. Analysis of individual data was completed using linear trends to investigate learning in each group. Analysis of the psychological data used multiple regression analysis ($p < .05$) with the VFG and AFG. Main effects for variables, such as mood, were found. The authors conclude that a two-choice BCI based on auditory feedback is as feasible for communication as a BCI based on visual feedback, as long as there is sufficient training time allotted. In sum, the findings of this study are based on appropriate use of statistical measures. In fact, a significant effort is made to ensure statistical conclusions are valid. Moreover, the details provided make it easily replicated. One drawback is that the sample only included healthy participants, limiting generalization of results to the ALS population. Additionally, the design did not directly address BCI use for persons with ALS. At time of publication, the authors were investigating BCI performance in patients with ALS who are severely paralyzed. They state that previous studies show that patients with ALS can learn to use auditory feedback BCI, albeit with slower learning. Future studies should focus more on the feasibility of auditory-based BCI communication devices for patients who have ALS, and determine if there is a causal relationship between psychological variables and performance.

Overall, the validity and clinical utility of these findings are suggestive of the potential in visually-based BCI for use in the ALS population. Further development is needed for BCI communication devices that are auditory-based, ensuring adequate training time and sufficient accuracy for users.

Group Study #4 Sellers, Krusienski, McFarland, Vaughan, and Wolpaw (2006) assessed the properties of a visual-based P300 BCI. The BCI is the P300 Speller which uses a 6 x 6 matrix to present characters (letters, numbers) to the user. The study involved manipulating the size of the matrix (3 x 3 or 6 x 6) and crossing this with the duration of inter stimulus interval (ISI) between classifications (175ms or 350ms) to create four experimental conditions. In doing so, the authors examined if stimulus properties and stimulus presentation rates impact classification accuracy in the selection of target items. They also examined the consistency of a user's performance over time. Five participants participated in five sessions over three weeks. EEG recordings were done with a 64-channel cap. The task was to focus attention to one letter of the matrix and count how many times that letter intensified. Each session consisted of copy-spelling a four-letter word. SWLDA determined the coefficients for online and offline classification.

Numerous analyses using ANOVA were completed to determine the presence of significant effects. Different analyses were done for factors that examined presentation time, training data, number of sequences (needed to select characters), general versus user specific coefficients, bit rate comparison, and waveforms and classification coefficients. The results are quite detailed so reference to the article is recommended. Overall, the results showed different significant effects. The 3 x 3 matrix condition and the 175ms ISI condition resulted in higher accuracy. The larger matrix (6 x 6) produced larger P300 amplitudes for the target stimuli. The relationship between speed, bit rate, and accuracy was somewhat complex. However, authors stated that accuracy was said to be crucial for determining the effectiveness of a practical BCI. Additionally, it was noted that individual differences for user specific EEG responses play a role in classification performance. All five users were able to use a P300-BCI spelling system and their performance appeared consistent across all five sessions. Altogether, this study should be applauded for the extensive use of statistical testing in order to ensure their conclusions were statistically valid. Confounding variables were accounted for in the analyses. The study design is well-formulated as it maximized the number of experimental conditions in order to gather more data. Future studies of its kind should involve participants who have ALS. Further, a larger sample would yield higher power and effect size.

In sum, the validity, clinical importance, and applicability of the results are strongly suggestive of the feasibility of providing visual BCI communication devices for persons with ALS. Moreover, the specifics around matrix sizes, ISI, accuracy, and consistency of performance, have important implications for making BCI devices personalized for individual clients.

Group Study #5 Sellers and Donchin (2006) evaluated the effectiveness of a P300-based BCI system four-choice paradigm. It randomly presented four choices to provide users with the ability to answer simple questions. Additionally, the study examined the effect of BCI across three different stimulation modes: auditory (AM), visual (VM), and auditory + visual (A+VM). The study notes that patients with ALS are most likely to benefit from a BCI. Participants included two groups: three patients with ALS (of varying severity) in group 1, and three participants without ALS in group 2. Ten experimental sessions took place over six weeks. The stimuli presented in the three modes were: YES, NO, PASS, END. The task was to attend to one stimulus and ignore the other three in order to either focus on a predefined target stimulus, or to correctly answer a simple unambiguous question (e.g. Is today Monday?). This design involved random feedback and a constant number of trials run, admittedly not something expected in a clinic setting and something the authors acknowledged. EEG recordings were done with a 16 channel cap.

The authors applied the SWLDA in their classification analysis to define the P300 waveforms. Results of waveform analysis showed that ALS participants' responses were more variable across mode and session, versus participants without ALS. A mixed design factorial ANOVA using two between-groups variables and four within-groups variables was performed to analyze classification accuracy. Several effects and interactions were found to be significant: method, number of stimuli, group x method, group x stimuli, session x number, and mode of presentation x number of stimuli. In practice, the authors noted that individual users will differ in their preferences for speed versus accuracy when using the BCI to communicate. Descriptive statistics were reported for mean accuracy for different variables across all sessions. The authors examined the practical, theoretical, and methodological issues within their design framework. The study acknowledged that the two groups were not age-matched, which may be a limitation as it could have affected differences between the waveforms for the two groups, as mentioned in other studies. Results of the different mode of presentations favored the VM and A+VM over the AM. However, the AM results appeared high enough that people who have visual limitations could still use an auditory-based BCI. Findings showed the differences in performance across sessions were not large enough to cause the BCI system to be inefficient. In practical application, users may experience a mild habituation effect on P300 amplitude and latency. The information transfer rate, or bit rate, was poorer in this study. However authors cautioned that bit rate can be misleading and may not be valuable in the assessment of a BCI and in the context of a person with ALS who needs to communicate. In sum, the study design was superb in formulation and measurement. The statistical conclusions are valid given the extensive statistical tests performed. The details provided make the study easily replicated. The multiple sessions were beneficial as they provided a large enough sample of data to increase strength of the findings, despite the small sample size. The use of two groups, one including participants with ALS, strengthened the validity of the findings.

Overall, the validity, clinical importance, and applicability of these results are compelling. The evidence supports the use of a P300-BCI visual-based system for individuals with ALS, and outlines the potential for auditory BCI. It provides insight into the variables to consider in accelerating the move of these devices from laboratory to clinic to home.

Discussion

In summary, the evidence from the five studies demonstrates the potential for BCI devices in facilitating communication for people with ALS. That being said, the studies were limited in a number of ways. Firstly, all five studies involved relatively small sample sizes, ranging from 5-16; future studies would benefit from larger sample sizes. Second, only two of the five studies involved participants with ALS. Involving participants with varying degrees of ALS would aid in determining any effect of ALS disease progression on one's ability to use a BCI device. One of the studies involved student volunteers and this population did not seem suitable for ensuring relevancy to the ALS population in question. Another study involved two groups however the groups were not age-matched or balanced at all. Third, none of the studies involved randomization of participants or blinding procedures. Fourth, the duration of the study period and the number of sessions within each period varied widely, from one day to 40 weeks. This lack of consistency is a concern because, for one reason, authors noted that training time is a necessary part of learning to effectively use a BCI device. Moreover, there are concerns such as habituation that could arise from prolonged use of a BCI device. Time, therefore, is an important factor that should be more systematically determined. Fifth, although all five studies were selected because of use P300 or SMR signals with a visually-based BCI device, there were two different systems used. Three of the studies used a spelling system and two used a choice-making system. There are benefits and drawbacks to each system, and these needed to be more clearly compared within the studies. The two types of systems essentially engage different components of language for communication, making it difficult to compare results across studies. Sixth, even within a specific type of device (e.g. the P300 Speller), there were a number of features (e.g. matrix size, screen size, duration of stimulus presentation, time interval); only one study accounted for these features. Such features should be investigated in order to develop optimal BCI devices. Classifying and analyzing the

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communication success of the participants was done somewhat similarly across studies using a statistical analysis. Speed, accuracy, and bit rate were the measurements for successful communication with use of a BCI device. Lastly, however, only one study cautioned against relying on bit rate in assessment and in real-life contexts.

With regards to communication performance, there was both inter-subject and intra-subject variability. There are several sources of variability that could be attributed to each study. Only one study systematically assessed the role of psychological variables on participants' performance. None of the studies discussed the role of age of onset, literacy level, medications, effect of previous speech and language therapy, effects of previous computer or BCI use, or other co-morbidities. Clearly, there are numerous limitations and factors to be considered within these studies and with the BCI devices. Despite these, there are important findings across the studies. All of the studies showed that people – including those with ALS – can indeed use BCI devices to communicate by spelling or making simple choices. Notably, accuracy of communication was said to be most vital in measuring success, while bit rate was said to not be as useful a measure. Nearly all of the studies found that BCI devices based on visual stimuli were better than those based on auditory, although auditory-based devices hold some potential.

Clinical Implications

The move of BCI devices from laboratory to clinic to home holds several implications for SLPs. It is likely that introducing the use of a BCI device to a client will occur within a team setting. As with more conventional augmentative alternative communication devices, the BCI device may be introduced, demonstrated, and implemented by a team of professionals. The role of the SLP would need to be discussed and decided. For the SLP, a strong knowledge base and keen awareness is needed to be able to explain the psychological and cognitive communication patterns of ALS to others as they relate to the progression of the disease. Further, the SLP may need to be able to outline the different language components that are accessed by the brain when a person spells versus makes a set choice so that appropriate recommendations can be made.

In assessing the client, the SLP would need to extensively involve family and loved ones because of the client's condition. It would be important to gather information about the client's previous interests, technological savvy, literacy level, personality and general mood and motivation. Further, it is imperative to confirm what type of information the client will need to be communicating – whether it be requesting for needs to be met or engaging in a simple conversation. Also, SLPs may be responsible for assessing and determining the contexts or activities in which the BCI device could be integrated. Reassessing the client's needs will need to be done on a regular basis to ensure that their communication needs are being met and quality-of-life is being upheld.

Practical considerations surround implementing the device and measuring its communication success. Implementing the device will require initial training which the SLP may assist with. Cognition and consciousness may be a factor to consider here. According to authors in this review, measuring communication success by accuracy is said to be most important. The SLP may have a role in calculating and confirming accuracy of communication, in addition to speed and bit rate. The naturalness and quality of communication, the client's ability to independently operate it, and client satisfaction are also vital measures of communication success with the BCI device.

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