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Utilizing Visual Attention and Inclination to Facilitate Brain-Computer Interface Design in an Amyotrophic Lateral Sclerosis Sample

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by

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ABSTRACT

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Individuals who suffer from amyotrophic lateral sclerosis (ALS) have a loss of motor control and possibly the loss of speech. A brain-computer interface (BCI) provides a means for communication through nonmuscular control. Visual BCIs have shown the highest potential when compared to other modalities; nonetheless, visual attention concepts are largely ignored during the development of BCI paradigms. Additionally, individual performance differences and personal preference are not considered in paradigm development. The traditional method to discover the best paradigm for the individual user is trial and error. Visual attention research and personal preference provide the building blocks and guidelines to develop a successful paradigm. This study is an examination of a BCI-based visual attention assessment in an ALS sample. This assessment takes into account the individual's visual attention characteristics, performance, and personal preference to select a paradigm. The resulting paradigm is optimized to the individual and then tested online against the traditional row-column paradigm. The optimal paradigm had superior performance and preference scores over row-column. These results show that the BCI needs to be calibrated to individual differences in order to obtain the best paradigm for an end-user.

DEDICATION

For my family.

Without their support this document or any of my research would not be possible.

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CHAPTER 1

INTRODUCTION

Previous research has shown that an event-related potential (ERP) based brain-computer interface (BCI) can successfully be used as means of communication for individuals who have amyotrophic lateral sclerosis (ALS) (Sellers & Donchin, 2006; Sellers et al., 2007) and individuals with a variety of other movement disabilities (Hoffmann, Vesin, Ebrahimi, & Diserens, 2008). Previous studies have included a sample of patients with ALS as a proof of concept for the novel paradigm examined in the study; however, past studies did not focus on improving an individual patient's BCI performance. The current practice is to find the best overall paradigm, not the best paradigm for each person. An individual's strengths and weaknesses should be assessed to obtain the information to customize a paradigm for that specific user. This study is intended to develop a BCI-based visual attention assessment to reveal an individual's paradigm that obtains optimal BCI performance.

Communication of feelings, ideas, and knowledge is the essence of what makes us human. This simple everyday act can be lost to those who suffer from a brain stem stroke, certain head trauma, or ALS. The result can leave a person with little to no muscle control, unable to reciprocate an essence of being human. Locked-in syndrome (LIS) is the condition of losing all voluntary muscle control except eye movement; nonetheless, eye movement and control can deteriorate as well. A person with LIS does not possess the means to convey a message of his or her own volition. A BCI offers an alternate avenue for communication, one that allows independent composition of a message and operates without muscle control (Wolpaw, Birbaumer, McFarland, Pfurtscheller, & Vaughan, 2002).

History of BCI

The first human brain waves, or electroencephalography (EEG), were recorded by Hans Berger (1929). Using a machine that was originally designed as an electrocardiograph (EKG); Berger recorded the brain's electrical activity and described frequency bands such as Alpha and Beta. Since Hans Berger's experiments, EEG based research has developed to study more than the brain wave's change in frequency to include the brain's responses to stimuli. One method takes samples of EEG that follow the repeated presentation of stimuli and average the EEG responses together, resulting in ERPs. ERPs have higher signal-to-noise and reveal ERP components (Fabiani, Gratton, Karis, & Donchin, 1987). One component in particular, the P300, was the keystone to an EEG based communication device described by Emanuel M. Donchin (1987). Less than a year later the first P300 based BCI was developed and tested (Farwell & Donchin, 1988). A history of the BCI is not complete without a brief description of the P300 component.

The P300 Component

The P300 ERP component was discovered almost 50 years ago (Sutton, Braren, Zubin, & John, 1965) and was thought to be associated with the participant's degree of uncertainty of the upcoming stimulus. Through the years this definition has been shaped towards the context updating of our environment (Donchin, 1981; Donchin & Isreal, 1980; Fabiani et al., 1987). The presence of a P300 in an ERP is confirmed by a positive deflection at 300ms to 700ms poststimulus. Simultaneous high density ERP and functional magnetic resonance imaging (fMRI) data suggest the generators of a P300 are located in the parietal and inferior temporal areas (Bledowski et al., 2004). The energy of the P300 recorded on the scalp has the highest amplitude along the midline, with the parietal electrode sites having the highest amplitude and attenuating as the recording sites move anterior (Fabiani et al., 1987).

The P300 is most commonly elicited through an “oddball” paradigm. The oddball paradigm can present stimuli in a few modalities (visual, auditory, & tactile); however, this work is focused on a visual oddball. In a simple visual oddball paradigm there are two stimuli, one is to be noticed and labeled the target (X) and the other stimulus is ignored and labeled the nontarget (O). Both stimuli are presented in a series at visual fixation. The target ‘X’ stimuli is presented at a lower probability (.20) than the nontarget ‘O’ stimuli (.80). The participant in an oddball paradigm is instructed to notice or count the target Xs and ignore the nontarget Os. Each time a target ‘X’ is noted by the participant a positive deflection 300ms postimulus presentation will occur in the EEG (i.e., P300), while the nontarget ‘O’ will not have the positive deflection.

Farwell and Donchin (1988) developed the first P300 BCI. Their idea was that a P300 could be elicited through a modified oddball paradigm. The target would be a particular letter of the alphabet and the rest of the letters of the alphabet would be nontargets. The authors used a 6x6 matrix (i.e., 36 items) that was populated with the English alphabet and a few computer commands. The matrix would flash individual rows and columns randomly. Thus, one sixth of the flashes contained the target letter. The 600ms of EEG data that followed the presentation of a stimulus was collected for analysis. The authors used a flash duration of 100ms and examined two inter-stimulus intervals (ISI), the time between a flash that has been turned off to the next flash turning on, of 25ms and 400ms. The 25ms ISI would test the effectiveness of overlapping stimuli and both ISIs use overlapping ERPs (i.e., the start of an ERP begins before the previous ERP is complete). Increasing the speed of the presentation rate is an inherent part of increasing the communication speed of the system; interestingly, increasing presentation rate could result in more system error. Four types of EEG data analysis were used to determine which letter the participant was focusing attention (i.e., P300 detection): 1) stepwise linear discriminant analysis (SLWDA), 2) peak picking (negative point to highest positive point), 3) area (sum of data points of P300 timeframe), and 4) covariance (P300 template was derived from a training set of ERP responses and applied to an analysis set of ERPs to find the highest covariance). The authors were testing multiple variables in this experiment (further testing of the variables mentioned here are still researched currently); nevertheless, the main objective of the study was to determine the minimum number of trials needed to detect a P300.

Using a bootstrapping technique, 1,000 iterations were used to test the two ISIs and four algorithms. Three of the four participants performed best using the SWLDA algorithm in the 25ms ISI condition and three of the four participants performed best using the peak picking method in the 400ms ISI condition. This study did not result in a system that could be applied as a means of communication; nonetheless, it did provide a proof of concept for a P300 BCI and laid the groundwork for BCI research.

Several researchers around the world have contributed to the advancement of BCI in different ways. BCI research areas include: stimulus presentation (matrix design, stimulus characteristics, and timing), signal acquisition (optimal electrode sites, electrode materials, and amplification design), signal processing (numerous classification algorithms, single trial classification, and dynamic stopping techniques), and cognitive variables (motivation, arousal, and disease progression). All of these research areas are important to understanding the user’s needs and developing an effective means of communication. The current study is focused on visual stimulus presentation and how visual attention concepts can enhance the stimulus presentation of a P300 BCI.

Amyotrophic Lateral Sclerosis and BCI

Amyotrophic lateral sclerosis (ALS), or Lou Gerig's disease, is a progressive motorneuron disease that causes irreversible loss of motor function. As the disease progresses, muscle movement deteriorates with reduced dexterity and agility. ALS has little to no influence on the affective neurons (sense of touch), cognitive, or emotional abilities. Eventually almost all muscle movement will be lost, including respiration. At this point only eye-movements are still intact and the person is considered to have LIS. If the person wants to continue living he or she must choose artificial ventilation. More than 90% do not choose artificial ventilation (Mitsumoto, 1994) due to an expected lower quality of life, mostly because of the loss of the ability to communicate (Albert et al., 2005).

Measuring Remaining Functionality in ALS

The most common measure of ALS progression is the ALS functional rating scale – revised (ALSFRS-R). The score is determined on the person's ability to perform nine common tasks (e.g., swallowing, climbing stairs, speaking, handling of food, etc.), and three questions regarding breathing ability on a scale of 0-4 (0=not at all, 4= normal). An updated scale, ALSFRS-extended (ALSFRS-EX), adds three more questions regarding finger movement, facial expression, and mobility in the home. The ALSFRS-EX does provide an easy to interpret score on the ability to perform daily tasks (i.e., 60=normal and 0= severely disabled). The instrument does not provide enough resolution on the disabled (i.e., low) end of the spectrum. That is, one person with a score of 0 might be able to communicate with eye blinks, eye gaze, or even subtle facial movements, and another person with the same score might be completely unable to communicate. The ALSFRS-EX only conveys the lack of motor ability; it does not clearly convey any avenues still intact for communication. Once the disease has progressed to advanced stages, these remaining pathways of communication become vital for the passage of messages regarding comfort and wishes. An additional revision of the ALSFRS-EX should be considered that measures the functionality of remaining avenues of communication (e.g., eye movement and fixation, eye blinks, and facial twitches) to provide the lacking resolution of the current scale.

In late stages of ALS augmentative and alternative communication (AAC) methods are required. These methods include a simple letterboard to more technologically advanced methods such as eye-tracking. The letterboard does require some motor control and the assistance of another person. Eye-tracking equipment can fail when the eyes' muscles become weak or unstable. On the other hand, with the person's cognitive skills still intact a BCI's information pathway is still open. Additionally, research has shown that the progression of ALS has minimal affect BCI performance (McCane et al., 2014; Silvoni et al., 2013). Moreover, once disease progression reaches a completely locked-in state, a BCI is the only means of communication (Murguialday et al., 2011).

Types of BCI

The first BCI was developed to use EEG collected at the surface of the scalp (Farwell & Donchin, 1988). Other techniques have developed to get the electrodes closer to the source. One such method places electrodes on the surface of the brain, called electrocorticography (ECoG). ECoG provides improved spatial resolution, signal-to-noise, and high frequency sensitivity that are all diminished when recording through the skull (Leuthardt, Schalk, Wolpaw, Ojemann, & Moran, 2004). These advantages have led ECoG researchers to develop a BCI that can be used to control a prosthetic limb (Hochberg et al., 2012; Hochberg et al., 2006). Recent research has shown that an ECoG based BCI is excellent at detecting the firing neurons associated with upper limb movement; nevertheless, it cannot distinguish specific movement types (Do et al., 2013). A similar study has shown 60%-79% accuracy in controlling a prosthetic hand to perform three actions (i.e., rest, grip, and extend two fingers) in real time (Yanagisawa et al., 2011). ECoG can also be used in P300 spellers, and often has high performance results (Brunner, Ritaccio, Emrich, Bischof, & Schalk, 2011; Speier, Fried, & Pouratian, 2013). The authors of these studies claim superior performance of ECoG over EEG-based systems; nevertheless, studies have extremely low number of participants (e.g., one or two). ECoG studies are lacking in participants due to recruiting methods. The majority of subdural electrode grids are implanted to localize seizure foci prior to surgical resection. Therefore, these participants are not true BCI candidates in that they are not at risk for losing the ability to communicate. The advantages of ECoG over EEG are clear in terms of detecting seizure foci; nonetheless, in the aspect of decoding neural signals as an input for a BCI the differences become much smaller. In P300 ECoG studies, the enhanced performance claim is mainly based on a measure called bit rate. This measure takes into account the number of items in a matrix, accuracy, and selections per minute. This measure and its flaws are explained further in Performance Metrics. An increase in accuracy is often highlighted as an advantage of invasive over noninvasive methods; nevertheless, a case study that examined P300 BCI performance between EEG and ECoG signals revealed slightly higher accuracy for EEG (Krusienski & Shih, 2010). Moreover, in a study that examined finger movement detection using both ECoG and EEG, the noninvasive EEG obtained 77% accuracy and the invasive ECoG obtained 91% accuracy (Liao, Xiao, Gonzalez, & Ding, 2014). Considering the complexity of implanting an ECoG electrode grid, which requires a procedure performed by a neurosurgeon, to the simplicity of placing an EEG cap on the scalp, which requires minimal training, and the arguable difference in signal classification, the noninvasive method of EEG is a more desirable method for signal recording. Moreover, when surveyed 16 of 17 patients with late stage ALS chose the slower, higher error, noninvasive method of BCI over an invasive method (Birbaumer, 2006).

The P300 is not the only signal that has been used as input for a BCI. For example, sensory motor rhythms (SMRs) called Mu (8-12Hz) and Beta (18-28Hz) rhythms are associated with actual or imagined muscle movement and can be recorded from electrodes placed above motor cortex (Cochin, Barthelemy, Roux, & Martineau, 1999) . Participants can learn to modulate the power spectra of these SMRs to move a computer cursor (Birbaumer et al., 1999; Birbaumer et al., 2000; McFarland, Sarnacki, & Wolpaw, 2010). The training required by the user can take several weeks to obtain an average of 80% accuracy (Wolpaw et al., 2002). The amount of time needed for training mu and beta rhythms is a stark contrast to the minimal training (i.e., 5 min) required for a P300 BCI (Guger et al., 2009; Wolpaw et al., 2002). There are multiple modalities used to elicit a P300 other than the traditional visual paradigm.

Tactile P300 BCI

An oddball paradigm is not limited to the visual modality. In some cases a visual paradigm is not a feasible option for a user who suffers from severe visual impairment. Several tactile P300 BCIs have been tested. Brouwer and van Erp (2010) used tactors (i.e., vibrating motors) placed inside a belt worn around the waist as an alternate input modality. The belt contained six tactors mounted at different locations that were turned on in groups of two, four, or six. This design resulted in low accuracy (65%) but did show proof of concept. Ortner et al. (2013) introduced a similar style of tactile stimulation that was tested in healthy and in a LIS sample. The results suggested that the device was feasible in both populations; however, the accuracy of the device was similar to that found by Brouwer and van Erp (2010). In a more comprehensive experiment, van der Waal, Severens, Geuze, and Desain (2012) compared the traditional visual matrix similar to Farwell and Donchin (1988) using overt and covert attention, a Hex-o-spell design (discussed further in Visual Paradigms) using covert attention similar to Treder and Blankertz (2010), and a new tactile design using a Braille stimulator in conjunction with a visual 6x6 matrix. The Braille stimulator tapped one of the six fingers from both hands (excluding the ring fingers and thumbs) instead of flashing each row. The user would count the number of times a finger was tapped for the target row of letters. Next the row of letters that was selected was presented as a column of six letters and each letter was associated with one of six fingers. The 6x6 matrix and the subsequent column of letters were only presented before the tapping began and not during. Therefore, the participant had to remember which row of letters or single letters corresponded to each finger. Requiring memorization could increase workload thus, reducing P300 amplitude (Fabiani et al., 1987) and classification probability. The tactile speller performance was similar to the previous tactile spellers mentioned here (67%), again presenting proof of concept albeit with low accuracy. Tactile stimulation is an important alternative for those with visual or auditory impairment, thus it needs further research.

Auditory P300 BCI

Another alternative to the visual paradigm is the auditory BCI. One type of auditory BCI does not use the P300, instead it uses two concurrent auditory stimuli sequences and the user attends to one stimulus and ignores the other (Hill, 2005; Kim, Cho, Hwang, Lim, & Im, 2011). The binary choice design of these paradigms limits the efficacy and has an inherent high risk of chance (i.e., 50%). A P300 auditory system can present more than two different tones and has a lower risk of chance. Therefore, the concurrent auditory stimuli should not be a main option when considering the application of an auditory system.

The auditory P300 is elicited with an oddball task similar to the visual oddball task. A series of target and nontarget auditory stimuli are presented and the presentation probability of the target sound is lower than the nontarget sound probability. A modified auditory oddball task is used in an auditory P300 BCI. Visual impairments that often occur in late stage ALS progression (Streshinsky et al., 2013) can hinder the visual BCI task performance where an auditory BCI task is not affected (Furdea et al., 2009; Sellers, Kubler, & Donchin, 2006). Several auditory BCIs use a visual matrix and present a sound, instead of a flash, for each row or column. Sellers and Donchin (2006) provided a proof of concept of a four-choice paradigm in a sample of patients with ALS. The authors examined three conditions using auditory, visual, and simultaneous auditory and visual stimuli. An offline analysis revealed simultaneous presentation of visual and auditory stimuli had a slight increase in performance over auditory or visual alone (68%, 65%, and 66%, respectively). Other experiments have varied in the type of auditory stimuli that were presented. A spoken number has been used to represent the presentation of each row and column of a 5x5 matrix resulting in a mean accuracy of 65% in nondisabled participants (Furdea et al., 2009) and 13% in patients with ALS (Kübler et al., 2009). Participants with ALS cited difficulty in maintaining attention to the auditory stimuli as a reason for poor performance. The poor performance could be caused by increased workload. The requirement of attentional resources to perform the task of remembering which number corresponded to each row and column may have resulted in too few resources to attend to the auditory stimuli. In an attempt to increase accuracy and decrease attentional demands environmental sounds were used for the presentation of each row and column, resulting in 48% accuracy (Klobassa et al., 2009). Sound direction (left, middle, right) and tone pitch (high, medium, low) via headphones have been used as stimuli for a 3x3 matrix in conjunction with a word prediction program (i.e., similar to T9 word prediction on cell phones) to increase performance (Gofrit et al., 2013). The participants were required to copy spell two sentences with the system resulting in an online accuracy of 89%, the highest performance of an auditory system to date. Another study examined a 5x5 matrix using five tones each paired with a direction to enhance discriminability (Streshinsky et al., 2013). This novel auditory speller was compared to a visual 5x5 speller that included measures of mood, motivation, P300 amplitude, system usability, and workload. The visual system had higher accuracy than the auditory (94% and 66%, respectively). The difference in accuracy could partially be explained by the increased workload reported in the auditory condition over the visual condition. Participants also reported higher usability for the visual system over the auditory. Workload and motivation had no correlation with performance in the visual condition. Conversely, in the auditory condition motivation had a positive correlation with P300 amplitude and workload was correlated with lower accuracy. A few participants who performed better in the auditory than visual condition reported to play an instrument or sing in a choir.

Auditory P300 BCIs provide a modality to those that have compromised visual capabilities. Interestingly, the auditory system has lower reported system usability than the visual P300 BCI (Streshinsky et al., 2013). The auditory paradigm requires the user to fully perceive each sound before discrimination of target or nontarget can take place. The visual P300 task can be performed with lower attentional resources because visual targets can be filtered out by location in the matrix and not every stimulus presentation has to be fully perceived. This allows for additional matrix items in a visual task without a substantial increase in workload. Increased speed in item selection is also possible due to the visual system's relatively efficient filtering process compared to the less efficient auditory system's filtering process. The authors found the visual BCI had no correlations between performance and mood, motivation, or P300 amplitude (Streshinsky et al., 2013). Conversely, in the auditory modality motivation had a positive correlation to P300 amplitude and a negative correlation of workload to BCI performance. Special training might be required to improve the auditory modality's performance, as suggested by better performance observed in participants who reported playing an instrument or singing in a choir. These results suggest that the visual modality has increased performance, lower workload, and increased usability compared to the auditory condition. The auditory condition does outperform the tactile modality; however, the visual modality has the best performance of all modalities.

Performance Measures

Traditionally BCI performance is measured by dividing the correct number of selections by the total number of selections resulting in the accuracy of item selection. Accuracy of 70% has been repeatedly cited as the minimal accuracy for an effective BCI system (Furdea et al., 2009; Kübler, Kotchoubey, Kaiser, Wolpaw, & Birbaumer, 2001; Nijboer et al., 2008; Streshinsky et al., 2013). At 70% accuracy there is a 30% chance that all correctional selections will also result in error, each requiring more correctional selections at the same error probability. To correct all errors of a 10 selection message with a system that had 70% accuracy, it would require 25 selections to present an error-free message. Some may argue that without correcting errors if 70% of a message is correct then it is very probable that the intended message can be understood; nonetheless, certain messages would need to be error free. A higher level of accuracy should be considered for meaningful communication. At 90% one in every 10 selections is an error and to create a 10-character sentence would require approximately 12 selections (Sellers, Krusienski, McFarland, Vaughan, & Wolpaw, 2006). Therefore, meaningful messages can be communicated with little interruption of error correction and frustration from incorrect selection feedback. Ninety percent accuracy should be the benchmark for a useful BCI system. Any system that performed below this threshold would not be considered useful by the general public and this same level of acceptability should apply to those who are locked-in.

The measure of percentage accuracy violates the assumptions of regression model statistics (e.g., t-test or ANOVA), particularly in regard to BCI performance. One assumption of regression is incremental consistency. A change from 50% to 51% has very little change in probability of an error; however, an increase from 98% to 99% reduces the probability of an error by half. Another assumption of regression is that the variable is reported on a continuum without a lower or upper boundary. Percentages are limited by 0% and 100%; thus regression models could make predictions outside these boundaries. To address these issues in analysis of percentages, a logit transformation should be implemented. The logit function (See Formula 1) results in a variable that has no boundaries and more importantly reflects an incremental consistency. In this formula, *p* represents proportion.

$$\text{logit}\ (p) = \log\ (p/1\text{-}p) \qquad \text{(Formula 1)}$$

Bit rate or information transfer rate (ITR) is a measure that takes into account the accuracy, selections per minute, and number of possible selections of a system resulting in a single measure (Wolpaw et al., 2002). Theoretical ITR is a measure that removes the time between selections in an effort to make comparisons across systems (Townsend et al., 2010). The comprehensive component of ITR makes it very appealing to researchers when reporting the performance results because it allows for an unbiased direct comparison between studies and methods. Nonetheless, there are several problems associated with using ITR as the only evaluation metric. A system can have a very high ITR and a very low accuracy, for example

(Kaper & Ritter, 2004). ITR should always be accompanied by the measure that it was calculated from (i.e., accuracy, selections per minute, and number of possible selections) and theoretical ITR should be accompanied by the amount of time removed to ensure proper comparison. Practical ITR takes into account the same measures as ITR with the addition of error correction measure called practical selections. That is, for every selection that results in an error two more selections must be made with the same probability of an error (i.e., one selection to erase the erroneous selection and another to attempt the correct selection). Practical ITR is a measure that provides a more realistic measure of how the system will perform with the end-user.

BCI performance metrics can be applied regardless of whether the data are collected in an offline- or online-mode (i.e., whether or not the participant receives feedback in real time). The online method requires the study to collect or utilize previously collected training data to build a classifier that is subsequently tested by requiring the participant to make selections in an additional session. The offline method requires the same collection of training data or utilization of previously collected training data to build a classifier. The subsequent test of the classifier is simulated offline with previously collected data in lieu of the participant making additional selections. Offline performance results make an assumption that the participant would perform in the same manner during the initial data collection. Offline results do not take into account the feedback of each selection that occurs during an online session. It has been shown that feedback may positively or negatively affect the motivation of the participant to use the BCI system (van der Waal et al., 2012). Online performance incorporates the variability of human performance with feedback, resulting in higher external validity.

CHAPTER 2

VISUAL ATTENTION

Using vision, people can identify and locate objects quickly in their environment faster and more accurately than any other modality. Moreover, vision also allows people to accurately identify their own location within an environment better than any other modality. These feats are accomplished by a visual system that allows attentional focus to switch at will through a constant stream of information. The visual interface of any system is extremely important to the interdependent performance of user and system. The speed at which target information in the system can be found has a great effect on how quickly and accurately a user can navigate a system's information. Poorly organized information can lead to a user becoming lost or frustrated. Distracting information can slow down the speed of the interface between the user and the system and can lead to errors in feedback information. Human visual perception happens extremely fast (i.e., 10-200ms) depending on the complexity of the object or environment being perceived (Niedermeyer & Da Silva, 1999). At these speeds errors in focused attention can occur of which the perceiver might not be completely aware. Visual attention researchers examine the process of how humans perceive the visual world and how this information goes from photons activating the photoreceptors in the retina to an understanding of an environment or the familiar smile of a friend. Visual attention concepts can be used as a guide to develop a BCI system that facilitates attention, results in less fatigue, and can be used for an extended period of time. Enhancing attention and limiting distraction should also result in consistent ERP responses to targets and nontargets, improving classification of target selection.

Our environment consists of a wide range of visual stimuli; selective attention is the mechanism through which our attention is focused on certain stimuli while ignoring irrelevant stimuli (Egly, Driver, & Rafal, 1994). Two concepts that attempt to explain selective attention are; 1) object-based attention proposes that selective attention perceives objects dictated by grouping principals and attention is limited by the borders of these objects, and 2) spatial attention proposes that selective attention is similar to a spotlight that moves freely throughout our visual field. The following sections provide a portion of the research of object and spatial attention.

Object-Based Attention

Object-based attention explains that selective attention is focused on and limited within the borders of an object (Egly et al., 1994). How borders, or groups, are defined creating the perception of objects was first explained when Wertheimer discovered Gestalt psychology (Rock & Palmer, 1990). Gestalt operates on the theory that the whole perception of an object is greater than its summed parts. That is, whatever an object is perceived as has more meaning that the simple identification and summation of the components that comprise the object (e.g., the "whole" is more than the sum of its parts). Gestalt principles explain how a presentation of a series of images (e.g., cartoon animation) can be perceived as motion, or apparent motion. Motion is not perceived when each frame is examined, only when multiple images are rapidly presented in a series. There are several Gestalt principles. The current study focuses on three: 1) proximity, what is close together will be grouped, 2) similarity, common properties define a group, and 3) synchrony, stimuli presented together will be grouped. The process of Gestalt grouping occurs very rapidly and is a part of visual perception.

An extensive amount of information is present in our visual field. It has also been suggested that we visually "see" more than we can remember from a complex visual stimulus. This suggestion implies that there is a memory limit and the memory of information decays in a brief time after presentation (Abe, 2004; Sperling, 1960). This brief visual memory or iconic memory momentarily holds information, an estimated 100-200ms, until attention transfers the selected information to working memory while the unattended information decays (Long, 1980). To isolate and compare the information available in iconic memory and short-term memory, Sperling (1960) developed a paradigm that consisted presenting a matrix of letters for a short duration (50ms). In the whole report condition the participants were instructed to write down all the letters they could remember, this resulted in an average of 4.3 letters out of 12. In the partial report condition the participants were presented with a tone (e.g., high, medium, or low) immediately after the stimulus that correspond with one of the three rows of letters as instruction for which row of letters to report, this resulted in an average of 9.1 letters out of 12. As the poststimulus latency of the tone increased, accuracy decreased to that of the whole report (36%) when tone latency was delayed by 1s. The results of these experiments reveal an iconic memory and its large amounts of information that decay rapidly without attention. Once attention is applied the information is very rapidly organized and grouped based on properties. Gestalt theories attempt to define the grouping principles that happen during this early stage.

Iconic memory and the preattentive stage, as describe by Neisser (1967), have similar properties; that is, information in the preattentive stage requires attention to be applied to a specific stimulus, or object, thus moving the information to the focal attention stage. To this point, Neisser (1967) adds the application of Gestalt principles; in the preattentive stage visual field information is processed in parallel and group characteristics of stimuli according to Gestalt principles occurs to create the perception of objects. Attention is then applied to these objects allowing the information to move into the focal attention stage. In the focal attention stage attention is applied in a serial manner to the objects, this limiting process allows for more attention to detail for attended objects while restricting the amount of detail processed by unattended objects. Neisser's (1967) work influenced visual attention research toward the object-based theory.

Object-based attention was also used to explain how the report of stimulus characteristics could be facilitated or hindered. Duncan (1984) used the simple stimuli of a rectangle with either an open or closed segment on the left or right side of the rectangle and a dashed or dotted line that crossed over the rectangle at varying angles. The overlapping line and rectangle were presented simultaneously for 1 second. Two conditions were implemented that both required two pieces of information be reported: a) one object report, describe the line's tilt and texture, and b) two object report, describe the line's texture and the location of the open segment of the rectangle. Object-based attention suggests that attention would be limited by the boundaries of each object; thus when reporting one characteristic of two objects, accuracy would decrease as compared to higher accuracy when reporting two characteristics of the same object. Conversely, spatial attention suggests that the two objects occupy the same space and attention is not limited by the boundaries of the object therefore, accuracy would be the same across the two conditions. The results of the study revealed higher accuracy for reporting two characteristics of one object than one characteristic for two objects. A similar study found that increasing the number of features of an object did not affect accuracy; however, increasing the number of objects did affect recall accuracy and resulted in features being assigned to the wrong object (Luck & Vogel, 1997). Another study found that items grouped using Gestalt cues had higher recall accuracy than items grouped without Gestalt cues (Woodman, Vecera, & Luck, 2003). These results suggest at the preattentive stage stimuli were organized into objects before full attention could be applied at the focal attention stage when attention was applied in a serial manner. This method results in detailed memory of one object and limited memory of multiple objects, supporting Neisser's theory of object-based attention at the preattentive stage.

Several studies support the theory of object-based attention; however, this theory does not fully explain visual attention. The next section examines the main properties of spatial attention.

Spatial Attention

Similar to object-based attention, spatial attention breaks down visual attention into stages. First, the eyes move and are fixated on the stimulus and then attention is engaged allowing stimulus detection, and finally disengagement of attention (Posner, Walker, Friedrich, & Rafal, 1987). As a caveat, the first stage of eye movement and fixation is categorized as overt orienting and is not required to engage attention. Covert attentional orienting allows attention to shift to a position other than the point of eye fixation (Posner, 1980), as when reading a book but momentarily shifting attentional focus from the book to passerby while keeping fixation on the text. Posner, Nissen, and Ogden (1978) examined how cueing could influence reaction time to detecting a stimulus with covert attention. The participants' task was to keep their eyes fixated on a crosshair and identify the location of a target through a button press. Above the crosshair a directional cue (left or right arrow) would be presented prior to the presentation of the target stimuli. The target stimuli would appear at either the right or left of the crosshair. Eighty percent of the cues matched the target location and 20% of the cues did not match the target location. Invalid cues resulted in longer latencies in reaction time than valid cue reaction times. These results suggest that attention can move to spatial regions independent of fixation, similar to a spotlight, that when cued to the correct location facilitated target identification. Further research was needed to reveal the features of the attentional spotlight.

Eriksen and Yeh (1985) proposed that the attentional spotlight operated on a continuum from a large area of the visual field to a focused area. In the task the participant was presented with a circle of eight letters centered on a fixation point. Of the eight locations, four locations (i.e., main compass points) could contain one of two target letters (S or Y). The other four positions (nonmain compass points) were assigned nontarget letters. Three different conditions were implemented: 1) the target would only be in one of two locations; thus the cue would be valid or the target would be in the secondary location or, 2) the target location could be in one of the three possible locations other than the cued position, and 3) provided no cues as control. Results showed that the valid cue had the shortest latency. The control condition latency was significantly longer than the primary location (i.e., valid cue). When the target was in the secondary location (i.e., invalid cue), the latency was longer than control. The latency was longest when the target was in one of three uncued locations. The authors suggest that these results reveal the zoom in and zoom out feature of spatial attention. In the uncued condition the attention zoom lens is expanded to cover all possible target locations. When the target was in the cued location reaction time was very short, reflecting zoomed in spatial attention. As the target moved further away from the cue it would take longer to identify, as seen with the secondary target location. This additional time reflects the attentional spotlight shifting to the secondary location. Once the participant searched the secondary location unsuccessfully, the attention zoom lens is expanded to search the other two possible locations. These additional steps are reflected in the longest reaction times. The authors propose that the attentional zoom lens can either be expanded to cover a large area with less detail and then zoom in to provide more detail trading off the amount of visual field covered.

Reviewing these studies reveals the different schools of thought regarding the process of visual attention. Through the evolution of visual attention research, spatial or object-based theories presented empirical evidence; however, neither could completely rule the other one out. In an effort to unify the two models of visual attention, Egly et al. (1994) argued that components of both spatial and object-based attention were necessary. To examine both theories a paradigm was comprised that included aspects of spatial and object-based attention. The paradigm included the outline of two rectangles, either above and below fixation or to the left and right of fixation. The task was to identify the target location, a filled in area within one end of a single rectangle. A cue (e.g., valid or invalid) highlighted the outside of one end of a single rectangle prior to the target presentation. The ends of the rectangles (i.e., possible target locations) were equidistant to account for spatial attention. Therefore, an invalid cue was always the same distance from all other possible target locations. Results showed that invalid cues that directed attention away from the rectangle containing the target had longer reaction times than invalid cues within the same rectangle to the target. Invalid cues within the rectangle had longer reaction times than valid cues. The authors concluded that object-based attention is used to orient attention in our visual field and spatial attention is used within the boundaries of an object.

Visual Attention Principles and BCI Performance

Visual attention research has developed certain principles that reveal the limits of visual attention. There are two concepts that apply specifically to BCI performance: flanker effect and attentional blink. If a BCI paradigm does not account for these principles, they will cause attentional interference resulting in lower performance because the target flash may not elicit a P300, or the P300 amplitude may be reduced (Fabiani et al., 1987). Without the P300 response, or a low amplitude response, the classifier has limited discriminatory (i.e., target verses nontarget) information. Conversely, if a BCI paradigm avoids these attention limiting effects, a robust P300 response is more likely to be elicited. Brief descriptions and their influences on BCI performance are provided below.

The flanker effect was discovered by Eriksen and Eriksen (1974). The flanker task was designed to find the baseline effect of noise in a target identification task. The task description is simplified here to remain within the scope of BCI performance. One of two possible target letters (H or S) was presented at fixation flanked on either side by three distractor letters that were either congruent (HHHHHHH) or incongruent (SSSHSSS). The distractor letters varied in spacing by three separate degrees of visual angle (0.06, 0.50, and 1.00). The task was to identify the target letter through a motor response. When the distractor letters were incongruent reaction time increased as spacing decreased. Congruent letters had shorter latencies than the incongruent letters and congruent letter spacing had little influence on reaction time. Longer reaction times to incongruent stimuli suggest the influence of spatial attention and Gestalt grouping interfering with target identification. In a BCI speller matrix the characters are arranged in rows and columns, very similar to the presentation of the characters in the flanker task. The results of this study show the importance of character spacing in an attention based paradigm. In a BCI paradigm the flash of an adjacent character can mistakenly be categorized as a target flash that could result in an error in item selection. Errors can also result from attentional resources being depleted, as seen with attentional blink.

Attentional blink describes a temporary reduction of attentional resources subsequent to the identification of a target stimulus (Raymond, Shapiro, & Arnell, 1992). This reduction of attentional resources can be observed through a rapid serial visual presentation (RSVP) of stimuli (e.g., letters or numbers). Raymond et al. (1992) used the RSVP in a paradigm in which each letter was presented in a serial fashion with a duration of 15ms and 75ms between each stimuli, at fixation. The participant's task was to report the target letter (a white letter) among 10 nontarget letters (black letters). A secondary task was to report if the probe letter "X" was present and its placement in the series. The probe letter was not present in all blocks of letters and placement was random. Trials that did not contain a target letter had a minimum of 90% accuracy when reporting the probe letter, regardless of position. Report accuracy of the probe dropped to 55% in the trials that contained the probe letter in the second, third, or fourth position subsequent to the target letter. This reduction in report accuracy suggests a reduction in attention resources, or attention blink, 180-450ms subsequent to the identification of a target. Attentional blink is important to the design of BCI paradigms when considering the target-to-target interval. If a target letter has a subsequent flash 180-450ms after the previous flash, the participant may not have the attentional resources available to categorize the subsequent flash as a target. Without this categorization the P300 will have reduced amplitude or be absent, reducing the probability of classifying the target flash as the intended letter.

It is important to avoid attention blink and flanker effects in order to develop a successful BCI paradigm. These concepts should be considered when reviewing and designing a visual paradigm to prevent unnecessary errors. Additionally, individual differences are present in the influence of attention blink and the flanker effect. To obtain an individual's peak BCI performance, the parameters of these attentional concepts should be found and optimal ranges implemented into his or her own personal BCI paradigm.

Visual Attention ERP Components

ERPs are comprised of several positive and negative peaks known as components. The components are labeled by their polarity (N, negative and P, positive) and average latency in milliseconds. Thus, the P300 is a positive response, typically 300ms poststimulus. Alternatively, the component name can be shorted to the polarity and first digit of latency (e.g., P3). ERP components can be categorized into exogenous (10-100ms postimulus), associated with visual processing of stimuli, and endogenous (100ms and later), associated with the internal cognition regarding the stimuli (Niedermeyer & Da Silva, 1999). This section provides a brief review of visual ERP components and how visual attention modifies these components.

The P1 is usually elicited through simple light flash paradigms, increases when attention is applied to the stimulus, and is associated with noise suppression (Key, Dove, & Maguire, 2005). The N1 is also associated with orienting to a stimulus and can increase in amplitude to a novel stimulus, with subsequent habituation (Niedermeyer & Da Silva, 1999). Similar to the N1 and P1, the P2 has higher amplitude associated with attended stimuli as well as increased stimulus complexity (Key et al., 2005). The N2 has been associated with orienting response, stimulus discrimination, target selection, and decreases in amplitude with shorter latency when ISIs are shortened (Key et al., 2005). Additionally, the N2 amplitude increases with motion detection, when judging the speed of an object, and amplitude increases with the processing of faces (N170) (Hillyard & Anllo-Vento, 1998). The recognition of familiar faces is associated with two latter components, the N400f and the P600f (Eimer, 2000). Mismatch negativity (MMN) occurs in the same time frame as a N2 (100-250ms) and is similar to the P300 in that MMN is elicited through an oddball paradigm. The key difference between MMN and the P300 is that the P300 requires attention to the deviant stimuli and to categorize the stimuli as a target; however, the MMN is elicited passively to the deviant stimuli (Duncan et al., 2009).

The P300 can be separated into two components, P3a and P3b. This distinction depends upon the novelty of a less probable distractor stimulus in a three-stimulus oddball paradigm. A typical three-stimulus oddball paradigm has target, nontarget, and distractor stimuli. When a distractor stimulus is presented a slightly different P300 will occur, known as a P3a. The P3a has a slightly shorter latency than the classic P300 and has higher amplitude distribution over the frontal and central areas of the scalp (Comerchero & Polich, 1998). This component habituates quickly to repeated stimuli and is associated with frontal lobe attentional task processing (Polich, 2007). The P3b does not differ greatly from the classic P300 description. P3b has peak latency around 300ms, a temporal and parietal peak amplitude scalp distribution and is associated with temporal-parietal memory activity (Polich, 2007). Given that the majority of stimuli used by BCI paradigms do not vary greatly (e.g., flashing alphanumeric characters) and classification requires multiple responses from the target character, the P3b is more robust in BCI paradigms.

Another factor that has shown to impact component characteristics is mental workload. Mental workload is defined as the ratio of the participant's task demands and the participant's capacity to carry out said demands (Gopher & Donchin, 1986). High workload would place task demands close to the limit of capacity. As task demands increase (e.g., memory load, multiple tasks, and task difficulty), P300 amplitude decreases and latency increases (Allison & Polich, 2008; Isreal, Chesney, Wickens, & Donchin, 1980; Isreal, Wickens, Chesney, & Donchin, 1980). These effects on component characteristics have been shown to affect BCI performance as task demands increase (Brouwer et al., 2012; Kleih et al., 2011; Ryan et al., 2011; Streshinsky et al., 2013). To help reduce the effects of workload, Brouwer et al. (2012) have suggested the coimplementation of a passive workload monitoring system with traditional BCI software. The passive system would reduce task demands when EEG markers of high workload were present, facilitating classification accuracy. The implementation of this passive monitoring system is outside the scope of this work; nevertheless, it should be considered for a BCI end-user.

CHAPTER 3

BCI VISUAL PARADIGMS, PERFORMANCE, AND ERPS

Since its inception, BCIs have been manipulated in numerous ways with the goal of improving performance and expanding utility. These methods include the different modalities to the user (e.g., visual, auditory, and tactile), different brain signals to the computer (e.g., ERP based, sensory motor rhythms, and frequency desynchronization), signal processing, and almost any command a computer can execute (Kleih et al., 2011; Wolpaw et al., 2002). The focus of this work covers paradigm development, another area of BCI research. BCI paradigms have received a fraction of the total research attention, as the majority of research lies with signal processing. This section covers a number of paradigms, starting with the first BCI's paradigm row/column.

Row and Column

The row and column (RC) paradigm, mentioned above in the section *The P300 Component,* was introduced by Farwell and Donchin (1988). Entire rows and columns of a matrix would flash in a random order. This paradigm was easy to implement and effectively flashed all items in the matrix quickly. Despite RC's early success, there were performance issues that some researchers tried to address through paradigm manipulation. One method was to increase the number of items in the matrix to reduce the probability of a target flash (Allison & Pineda, 2003), based on knowledge that lower target probability increases P300 amplitude (Fabiani et al., 1987). An examination of different visual properties of the matrix (i.e., black background, white back ground, large symbol size, and small symbol size) revealed no difference in accuracy (Salvaris & Sepulveda, 2007); nonetheless, this study had limitations (i.e., few participants, n=3, and was conducted as an offline analysis). Another study examined the effects of matrix size (i.e., 6x6 and 3x3) and ISI (i.e., 175ms and 350ms) on BCI performance (Sellers, Krusienski, et al., 2006). The 3x3 matrix had a higher accuracy but a lower bitrate than the 6x6, suggesting that fewer stimuli caused less distraction. Several researchers tried to address the issues of the RC paradigm; nonetheless, it took 19 years from RC's introduction to properly identify these issues. Fazel-Rezai (2007) defined two problems: adjacency error and double flash. Adjacency error is reflected by the majority of errors occurring in the same row or column as the target (Fazel-Rezai, 2007; Townsend et al., 2010). This error is a result of attention being drawn away from the target. The flanker effect has already shown that attention is given to items around a target (Eriksen & Eriksen, 1974). Additionally, Gestalt and Neisser's (1967) theories on the preattentive stage of perception suggest the flash of an entire row or column could result in the entire flash group being perceived as an object (Figure 1, yellow boxes). Therefore, when an adjacent item flashes attention is drawn to that nontarget item, resulting in a classification error. This same error can be explained by spatial attention. If the spotlight of attention includes items around the target or wanders free from fixation (Figure 1, highlighted circle), attention could be given to the adjacent items resulting in the adjacency error. The second error described by Fazel-Rezai (2007) was a double flash, defined as single item's subsequent flash occurring within 500ms (i.e., target-to-target interval less than 500ms), reducing the probability of the participant perceiving the subsequent flash. The double flash error is explained by the attentional blink that follows a target presentation (Raymond et al., 1992), resulting in a lack of attentional resources resulting in lower ERP component amplitude (Hillyard & Anllo-Vento, 1998; Martinez, Ramanathan, Foxe, Javitt, & Hillyard, 2007). Despite these issues, the RC paradigm is still the benchmark for visual BCIs, due to its ease of use, practicality, and efficacy. The following sections provide a brief review of different paradigms attempting to improve on the benchmark RC performance.

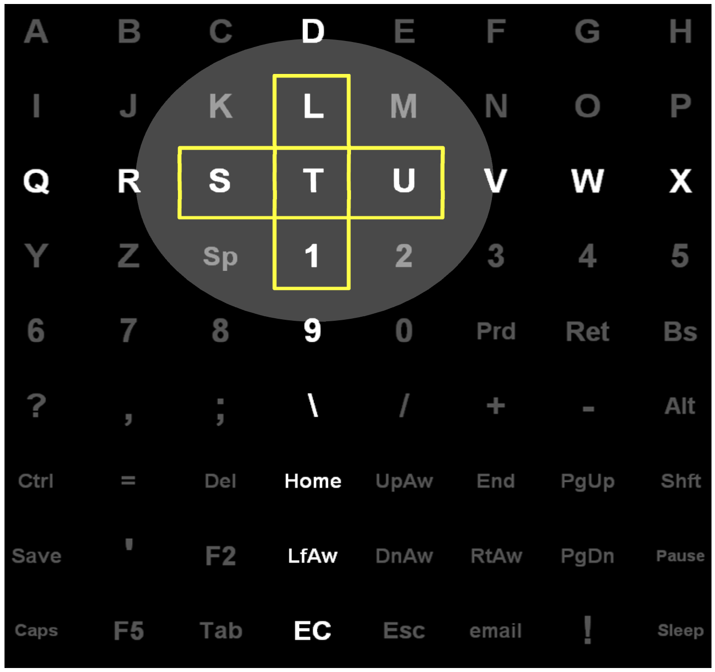

Figure 1. The R/C paradigm with “T” as the target. Spatial attention is given to items around the target, as suggested by the highlighted circle. Items that flash with the target in the same row and column can be grouped with the target and given attention, depicted by the yellow boxes. Results from flanker tasks suggest that items adjacent to the target are given attention.

Motion Onset and Face Stimuli

In an effort to utilize ERP components in addition to the P300 for classification, Hong, Guo, Liu, Gao, and Gao (2009) developed a paradigm to elicit a N200 by motion onset. The stimuli were presented in a RC fashion; however, the paradigm did not flash any characters. Instead it moved colored vertical bars from left to right below each item. This paradigm did succeed at eliciting both a P300 and a N200, which resulted in minor improvements over the RC paradigm (i.e., 91% and 88% offline accuracy, respectively). Even with two large components for classification, this paradigm did not show a significant increase in performance. The motion onset paradigm still used the RC method of presentation and carried over RC's attentional issues, thus limiting the paradigm's performance capability. In another attempt to utilize additional ERP components, Kaufmann, Schulz, Grunzinger, and Kubler (2011) developed a paradigm that presented famous faces (i.e., Albert Einstein or 'Che' Guevara) instead of flashing items (i.e., the letter switched to a famous face instead of flashing). Famous faces were selected with the idea of eliciting an N170 for facial processing and an N400f and P600f for familiar (i.e., famous) faces. An offline analysis revealed significantly higher accuracy for the faces than for the traditional item flash. Waveforms also showed higher component amplitude for the faces than for the item flash. In a similar study conducted with participants who had neurodegenerative diseases face stimuli resulted in higher online and offline accuracy than traditional item flash, as well as higher component amplitude (Kaufmann et al., 2013).

After observing the effect of motion and faces in BCI paradigms, a study was carried out to tease apart the effects of combining different stimuli. Jin et al. (2012) examined six conditions: item flash, item motion onset, neutral face, smiling face, neutral face motion onset, and smiling face motion onset. The RC presentation was replaced with an alternate flash pattern that was shown to outperform RC in an offline analysis (Jin et al., 2010). A set of k combinations (k~2) from a set (n=12) resulted in four to seven characters flashing each stimulus presentation. Results revealed that each face condition had better online performance than the item flash or the item motion onset conditions. No performance differences were found between the face stimuli conditions. Despite the better performance of the face stimuli, no participant preferences to any of the conditions were found. Similar to the previous studies above in this section, the presence of a face instead of a flash has increased the ERP component amplitude and classification accuracy. It has not been established that these enhancements are resistant to habituation or excessively tax attentional resources.

Checkerboard and Other Matrix Paradigms

To address the errors in the RC paradigm brought on by attentional issues (Fazel-Rezai, 2007) a new paradigm was needed. Townsend et al. (2010) attempted to correct the attentional blink and adjacent error effects by implementing constraints on which items could be presented in each flash group called the checkerboard paradigm (CB). Organizing the matrix with checkerboard pattern allowed each item to be assigned one of two colors. Thus, the matrix would be split into two virtual matrices by common color, from which flash groups were generated. This prevented any flash group from presenting an adjacent item simultaneously, limiting the distraction of adjacent items. Gestalt grouping and the influences of flanker effects are restricted when adjacent items do not flash simultaneously (Eriksen & Eriksen, 1974; Rock & Palmer, 1990). Additionally, after a group of matrix items had flashed, the sequencing required that six groups of other items were presented before any item in the first group could be presented again. Given the study's SOA of 125ms (i.e., 62.5 stimulus on, 62.5 stimulus off), there would be a minimum target-to-target time of 750ms thus, controlling errors caused by attentional blink. Furthermore, CB's target-to-target time limited ERP epoch overlap; when target epochs overlap, P300 amplitude reduces or changes ERP morphology (Martens, Hill, Farquhar, & Scholkopf, 2009; Woldorff, 1993). The results of the Townsend et al. (2010) study showed that the CB had significantly higher accuracy and bitrate than the RC paradigm. Moreover, the CB paradigm elicited higher component amplitude than the RC paradigm at Cz and Pz electrodes, suggesting better classification performance. The CB paradigm is an example of how enhancing attention by limiting distraction facilitates performance when using an attention-based response (i.e., P300).

Building upon the success of the CB paradigm, the five flash (FF) paradigm was developed to use the constraints of the CB paradigm with improved speed and accuracy (Townsend, Shanahan, Ryan, & Sellers, 2012). The authors hypothesized that an improvement over CB paradigm could be achieved by increasing the number of times an item flashed and increasing the number of items that could be flashed simultaneously. Thus, all the items could be presented more rapidly in randomized flash groups without flashing entire rows and columns. Results showed that the FF paradigm had a significantly higher bitrate than the CB paradigm without a significant loss in accuracy.

Nonetheless, the CB and the FF paradigms did have attentional issues. The CB paradigm did not control for the simultaneous flash of diagonally adjacent items that could still be grouped with the target (Figure 2, yellow boxes) and were still in the attentional spotlight (Figure 2, highlighted circle). Moreover, the FF paradigm did not control for adjacent simultaneous flashes in any direction. Attempts to address the adjacent flash issue are covered in the following section.

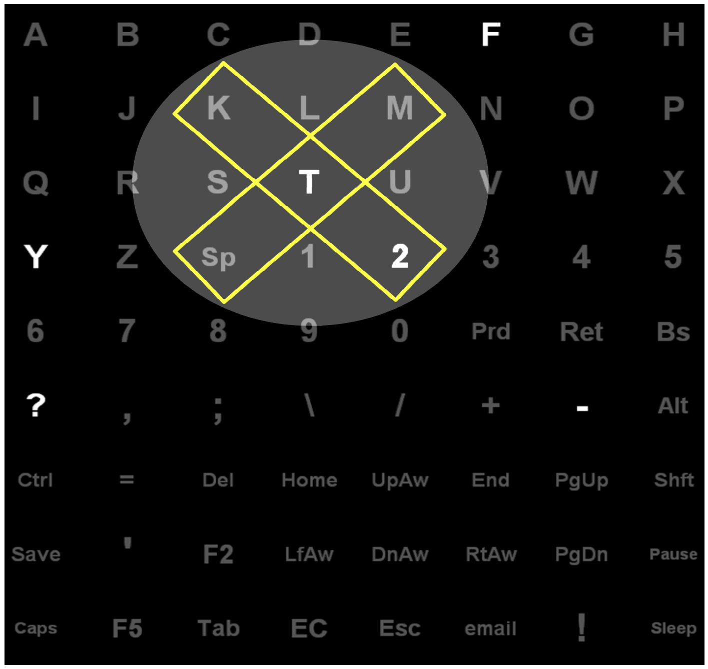

Figure 2. The checkerboard paradigm with “T” as the target. Spatial attention is given to items around the target, as suggested by the highlighted circle. Diagonal items that flash with the target can be grouped with the target and given attention, depicted by the yellow boxes.

Color Paradigms

The first color paradigm used a RC presentation of two colors (e.g., blue and green) least associated with inducing a seizure (Takano, Komatsu, Hata, Nakajima, & Kansaku, 2009). Matrix items would remain blue (stimulus off) until they flashed green (stimulus on). The color stimulus resulted in a significant increase in performance; nonetheless, the paradigm did still use the RC presentation with its attentional issues of double flash and adjacent flash. In order to improve the performance of the blue and green paradigm and the CB paradigm, Ryan et al. (2011) combined the two paradigms. Moreover, nine unique colors were assigned to items in the matrix so that no one item had the same color as any adjacent item. The study examined three conditions: (1) a standard gray-to-white flash (WT); (2) a gray-to-color condition (CL); and (3) a color-to-intensified-color condition (CI). The CI condition consisted of each item was presented with its assigned color (stimulus off) and would then flash (stimulus on) the same color intensified (e.g., an item would be dark red and then flash bright red). The addition of a color stimulus allows the participant another feature to distinguish the target flash from adjacent nontarget flashes. The unique color limits Gestalt grouping of similarity and synchrony while enhancing ERP components associated with color processing (Hillyard & Anllo-Vento, 1998; Rock & Palmer, 1990). The CL condition had higher bitrate and user preference over the CI and WT (i.e., 23/28 preferred CL; 24.29, 21.84, and 21.61 bit/m, respectively). The CL also had higher ERP amplitude temporally associated with color-processing components. The CL increase in bitrate reflects the fewer flashes needed by the classifier. The classification performance can be attributed to the increase in amplitude and consistency of the color processing component.

Covert Attention Paradigms

Covert attention is used when visual attention is directed away from fixation. This is an important concept considering that late stage ALS can result in the loss or limited control of eye movement (Esteban, De Andres, & Gimenez-Roldan, 1978). To overcome this oculomotor problem, researchers designed a covert attention paradigm. There are several problems with a covert paradigm. Peripheral vision is subject to a decline in spatial acuity with increasing visual eccentricity (Treder & Blankertz, 2010). Additionally, as stimuli are presented further in distance from fixation early ERP components (i.e., < 200 ms) see a reduction in amplitude, known as sensory gating (Hillyard & Mangun, 1987). This reduction in amplitude decreases signal-to-noise ratio and lowers the probability of correct classification. Furthermore, the crowding effect (i.e., unable to resolve items if surrounded by similar objects) results in misbinding of features belonging to different objects and is positively correlated with distance from fixation. The traditional 6x6 matrix is subject to these issues of peripheral vision due to the row and column design. Brunner et al. (2010) examined using covert and overt attention with a 6x6 matrix in an online analysis with nondisabled participants. In the covert attention condition participants kept their eyes fixated at the center of the matrix, and in the overt condition they were allowed to fixate their eyes on the target letter. Their results revealed poor performance of the 6x6 matrix using covert attention; nonetheless, performance was improved when 64 channels, as compared to 8, were included in classification. The authors did note that the covert attention condition had a higher workload due to additional task of inhibiting eye fixation on the target. Further analysis revealed that classification accuracy was lower for items that were further away from fixation. Additionally, when the epoch window excluded time prior to 200 ms, the accuracy of the overt condition dropped significantly and the covert condition showed no change. These results support the issues (i.e., sensory gating and crowding) of a row and column matrix in a covert condition. Therefore, Treder and Blankertz (2010) designed a speller that arranged the selectable items into a circle around a fixation point. The hex-o-spell paradigm is a two-stage speller, that provides the full matrix but with only six selections available at one time. Six discs arranged in a circle (i.e., at the six points of a hexagon) contained five characters each. Once a disc was selected the five letters that populated that disc were presented individually on five of the six discs, the sixth disc was used to go back to the first stage menu. Instead of flashing items, which could easily be misbinded, each disc increased in size for 100 ms. Treder and Blankertz (2010) compared the hex-o-spell paradigm to the traditional 6x6 matrix offline with 13 nondisabled participants. Each paradigm was tested in an overt (i.e., fixation on item) and covert (i.e., fixation at center) condition. In the covert condition the hex-o-spell paradigm outperformed the 6x6 matrix (40% and 15% accuracy, respectively). The overt condition had higher ERP amplitudes than the covert condition; nonetheless, the larger stimuli in the hex-o-spell paradigm had higher amplitudes than the 6x6 matrix. The larger stimuli elicit an increase in amplitude (Covington & Polich, 1996); however, the accuracy of the hex-o-spell paradigm was still too low to be a useful means of communication. Noting the lack of early component amplitude in covert attention BCIs and its importance to classification algorithms, Treder, Schmidt, and Blankertz (2011) hypothesized that the integration of visual processing features could increase early component amplitude. A unique color was added to each of the six discs of the hex-o-spell paradigm. The authors then compared the new hex-o-spell paradigm to two other covert attention paradigms. The first paradigm was the cake speller, which used the same hexagon pattern as the hex-o-speller but instead of circles for the background of each item the whole hexagon was divided into six “slices” that extended to the center fixation point. Each slice was assigned a unique color flash. The second paradigm was the center speller that presented at fixation one of three unique shapes (i.e., triangle, circle, and hourglass) assigned one of six unique colors. Each colored shape was presented with five letters. The participant would attend to the target letter group with the colored shape. Similar to presenting the letters that populate the rows and columns of a matrix, each letter would be presented twice in two different letter groups. Therefore, the center speller requires no second menu in contrast to the hex-o-speller and cake speller. After a calibration session with each paradigm, the participants were to copy-spell one sentence and then compose their own sentence (i.e., 20 selections) as an online test. The center speller and hex-o-speller had higher accuracy than the cake speller (97%, 91%, and 88%, respectively). P300 amplitude was higher in the center condition than the hex-o-spell and cake speller conditions. The authors claim that the center speller did best because all items were presented at fixation and did not require the workload of attending away from fixation; however, the P3 latency was longer than the hex-o-speller and cake paradigms. The longer latency suggests that the categorization task was more difficult in the center speller paradigm because all stimuli, target and nontarget, were presented at fixation; thus, every stimulus needed to be evaluated. Conversely, in the hex-o-speller and cake speller five of the six stimuli could be ignored based on spatial location. Liu, Zhou, and Hu (2011) developed a similar paradigm to the center speller with similar results.

At their theoretical best these spellers would require 15s of continuous attention to make one selection. Considering the possibility of deteriorated attentional resources in a person with locked-in syndrome, it is unknown if the person is able to attend away from fixation for any significant amount of time. Presenting items around at or around a fixated point does not simulate the condition of poor oculomotor control. It is also unknown if people with LIS can focus their eyes on a computer monitor. These covert attention models should be revisited to take into account unpredictable eye shifts to better simulate loss of oculomotor control.

CHAPTER 4

CURRENT STUDY

Visual attention research has shown that the characteristics of visual stimuli affect reaction time, accuracy of categorization, and ERP component amplitude. A BCI task requires fast reaction time to target flashes, the correct categorization of target and nontarget flashes, and high amplitude ERP components for optimal classification. Moreover, visual attention research has shown a variation in individual's task performance and ERP characteristics. One aim of BCI paradigm development is to design the "best" overall paradigm; however, in practice a BCI paradigm should be adapted to an individual's needs and capabilities. It is the common practice to calibrate the BCI system to an individual's ERPs to enhance performance; the same individual calibration should be applied to the visual presentation. Currently, there is not an optimization procedure to determine the ideal paradigm for each individual, just trial and error. Using the trial and error method, many users are only presented with the original RC paradigm. If the user's performance is above 70%, accuracy is considered to be adequate and further optimization is not explored. As stated above (see Performance Measures), 70% is far too low for effective communication. In some cases initial BCI sessions using the RC paradigm are not successful, the user could be considered unable to use any visual BCI system. To reveal a person's full performance potential, a BCI-based visual attention assessment needs to be implemented. This assessment would exhibit the visual attention characteristics of the individual through BCI paradigm manipulations; thus providing objective information to develop the paradigm with the highest potential for that individual. Additionally, the trial and error method does not take into account personal preference. Considering the capabilities of people with locked-in syndrome, a BCI might be their only means of independent communication, and the individuals should have the option of picking the paradigm they prefer. The current methods aim to capture visual attention characteristics and personal preference information to develop a BCI paradigm that matches the ability and highest potential of an individual. It is hypothesized that the resulting paradigm will have higher performance metrics and higher user preference than the RC control paradigm.

CHAPTER 5

METHODS

Six participants diagnosed with ALS were recruited from previous BCI studies. All participants provided informed consent, by power of attorney if necessary. The informed consent document has been approved by East Tennessee State University's Institutional Review Board. The ALSFRS-EX was administered at the beginning of the first session. Despite its flaws in resolution, the ALSFRS-EX is the only standardized measure of ALS progression. Demographic information including ALSFRS-EX, age, and gender were collected (see Table 1). Additionally, their current method of communication and its selections per minute was also recorded.

Table 1.

Demographics of Participants in the Current Study

Participant	ALSFRS-EX	Age	Gender
1	33	44	F
2	6	63	M
3	8	38	M
4	2	44	M
5	2	64	F
6	37	56	M
Means	14.67	51.5	

Data collection was conducted in the participants' homes. They were in a comfortable position, most typically their preferred position, and a computer monitor was placed approximately 1m away from their heads. A 6x6 matrix that includes alphanumeric items and keyboard commands was shown on the computer monitor. A 16-channel EEG cap (Elecro-Cap) was placed on the participant's head and impedances were reduced below 40KΩ (Kappenman & Luck, 2010). A 16-channel amplifier (g.tec) digitized the EEG signals recorded from the scalp.

BCI2000 software was used to control stimulus presentation, perform signal processing, and classify EEG data (Schalk, McFarland, Hinterberger, Birbaumer, & Wolpaw, 2004). The protocol consisted of a BCI-based visual attention assessment that resulted in a customized paradigm. The assessment itself took 95 minutes and was split into two sessions. In a third session, the customized paradigm and RC the paradigm (i.e., RC as control) were tested online copy-spelling 18 selections. Online classification included a Bayesian approach to dynamically controlling data collection called dynamic stopping (Throckmorton, Colwell, Ryan, Sellers, & Collins, 2013). Dynamic stopping classifies the ERP response from each flash in real time (i.e., as the matrix items are flashing) and then stops the flash presentation once a confidence threshold of .90 probability is reached by an item. Therefore, higher classification accuracy results in faster item selection with few item flashes and poor classification accuracy requires more flashes. The performance measures used were: accuracy, ITR, practical ITR and ERP waveform analysis. Accuracy percentages were transformed by a logit function prior to statistical analysis.

BCI-based Visual Attention Assessment

The BCI-based visual attention assessment consists of three different types of manipulation and each manipulation consists of three variations, resulting in 27 unique conditions. The three manipulations include: (1) flash type (i.e., gray-to-white (WT), gray-to-color (CL), and gray-to-black (BL), all on a black background, see Figure 3), (2) item size and spacing (i.e., visual angle increased by 25% increments: small 0.34 x 0.43, medium 0.46 x 0.57, and large 0.57 x 0.72), and (3) flash duration (i.e., short 62.5ms, medium 125ms, and long 187.5ms, ISI were held constant at 62.5ms). The order of the conditions was randomized for each participant. Due to previous success, all paradigms used the CB style of item presentation

(Townsend et al., 2010). Each condition consisted of one word (i.e., six characters) randomly selected that was copy-spelled by the participant using the BCI. Due to the large amount of time required to collect a small amount of data (i.e., one condition yields 84 target responses and 672 nontarget responses), an offline bootstrapping with cross-validation analysis was used to reveal the classification performance of each condition. Bootstrapping was used to derive a more robust estimate (i.e., more resolution and less variability) of the small sample's characteristics than a cross-validation alone. The bootstrapping (i.e., resampling 5,000 times) with cross-validation technique was used to test a classifier within each condition's six selections. Each condition yielded six character responses (i.e., target and nontarget). A classifier was derived from five of the six character responses. The sixth character responses were used as an offline test for the classifier. This process was repeated for each character; resulting in six different classifiers and a pool of scores for each condition. SWLDA was used to derive classification coefficients (Krusienski et al., 2006) from eight channels shown to have adequate BCI performance: Fz, Cz, P3, Pz, P4, PO7, PO8, and Oz (Krusienski, Sellers, McFarland, Vaughan, & Wolpaw, 2008).

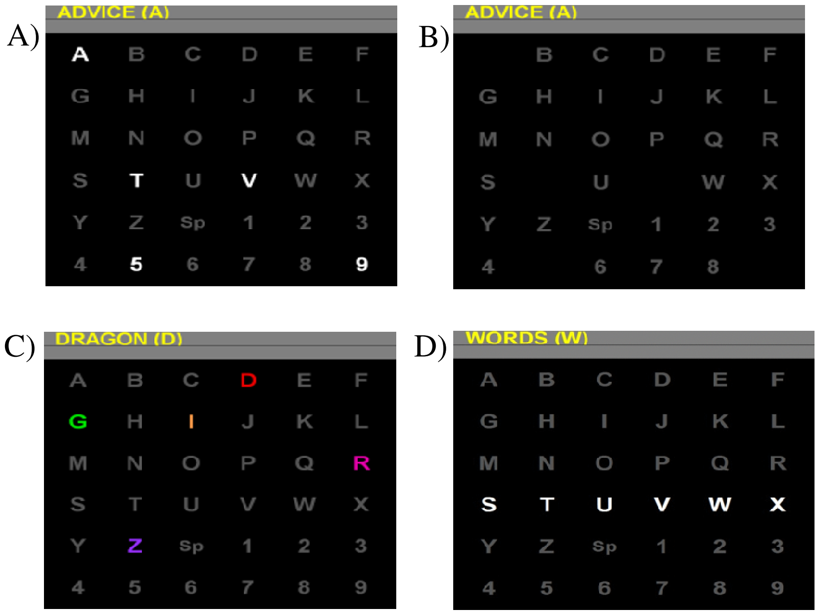

Figure 3. The three flash types of the BCI-based visual attention assessment and the control paradigm. A) is the gray-to-white (WT) flash, B) is the gray-to-black (BL) flash, C) is the gray-to-color (CL) flash, and D) is the row-column (RC) style flash presentation. WT, BL, and CL all use the checkerboard (CB) style of flash presentation.

The RC paradigm has been the standard paradigm since the first BCI and is still the standard implementation. For this reason the RC paradigm is presented as the control in this study. There have been some documented performance advantages to the CB (Townsend et al., 2010); nonetheless, there are some advantages to the RC paradigm as well. The sequence time (i.e., time it takes to present all the items in the matrix) is shorter for the control paradigm, RC, than the CB paradigm. The RC paradigm flashes entire rows and columns that contain six characters per flash presentation and the CB paradigm flashes either four or five items per flash presentation. This results in the RC paradigm requiring only 12 flashes per sequence (i.e., present every item in the matrix twice) and the CB paradigm requiring 18 flashes per sequence. In this study the RC paradigm presents each sequence 1.5 seconds faster than the CB paradigm.

Therefore, the RC paradigm has an inherent advantage in the measures of selections per minute and ITR. For example, the RC paradigm can make 10 selections 1 minute and 15 seconds faster than the CB paradigm (i.e., at five sequences for each paradigm). A CB paradigm could be used as control; however, this is generally not the paradigm presented to the end user.

There are several variables that can influence performance, this includes visual angle (i.e., distance from screen to eyes).Visual angle can vary with the participant's preferred position and limitations of equipment mobility. To control for variable distance between the participant and the screen, item size was adjusted to maintain a consistent visual angle. Each participant who was unable to speak was video recorded to capture his or her remaining muscle control and current methods of communication.

A personal preference survey was administered after each condition. It was comprised of five statements to be answered on a seven-point Likert scale (i.e., Strongly Agree-Strongly Disagree); the statements are shown in Table 2. The five scores were transformed into one score. The first question was reversed scored and questions four and five were averaged because both were related to speed and would have biased the importance of speed in the final score. The four scores were then summed, which resulted in a range from 4 to 28; thus, the lower the score the better the rating. Combining the personal preference survey and the classification performance results provided the necessary information to select the optimal paradigm, as well as baseline information from the RC (i.e., control) condition.

Given the large number of paradigms, a method was developed to select the optimal paradigm. Of the three variables, only flash type provided categorical differences, whereas size and flash duration were incremental differences. Moreover, participants expressed strong opinions about flash type. Therefore, participant preference, not accuracy, was used to select the flash type. Then within the preferred flash type, the combination of item size and flash duration resulting in the highest accuracy was selected.

Table 2.

The Personal Preference Survey. After the Completion of Each Condition, Participants' Responses Were Recorded For Each Question.

Please answer each question regarding the last paradigm.	Strongly Disagree-Strongly Agree
1) I was able to focus on the target item	1 2 3 4 5 6 7
2) Nontarget items were distracting	1 2 3 4 5 6 7
3) It was difficult to see all the target flashes	1 2 3 4 5 6 7
4) This paradigm was too slow	1 2 3 4 5 6 7
5) This paradigm was too fast	1 2 3 4 5 6 7

Measures and Statistical Analysis

To compare the performance of the customized paradigm and control paradigm, a hierarchical linear model (HLM) was used to reveal the differences in performance measures: accuracy (i.e., number correct divided by total number of selections), selections per minute, ITR, and practical ITR. Due to the exponential effect of accuracy on performance (see Performance Measures), a logit transform of accuracy percentages was carried out prior to statistical analysis. Additionally, ERP component latency and amplitude were also analyzed. ERP analysis was limited to the eight channels used for BCI classification (Krusienski et al., 2008). To limit statistical tests and limit chances of a Type I error, the eight EEG channels were organized into two groups then averaged. The Midline group was comprised of Fz, Cz, and Pz. The Parietal and Occipital group was comprised of P3, P4, PO7, PO8, and Oz. Component peak latency and amplitude was tested in two preset time windows of 180-350ms for positive peaks and 400-700 for negative peaks. The paradigm preference survey and demographic measures (i.e., age, gender, and ALSFRS-EX scores) were entered as covariates.

CHAPTER 6

RESULTS

Prior to analysis the difference between the survey scores was calculated (i.e., control survey score subtracted from optimal survey score), the differences were averaged, and then centered on the mean difference (i.e. -9.66). The mixed model for the logit accuracy transform revealed marginal significance of main effects for condition (B = 5.17, SE = 1.89, $p = 0.052$, CI = -0.077, 10.417) of the optimal condition (M = 6.89, SD = 5.09) over the control condition (M= 1.71, SD = 1.01). The model for ITR did reveal significance for main effect of condition (B = 6.58, SE = 2.23, $p = 0.042$, CI = 0.389, 12.77). There were no significant effects for selections per minute. The mixed model revealed a significant main effect of condition for practical ITR (B = 6.73, SE = 2.22, $p = 0.039$, CI = 0.566, 12.894) of the optimal condition (M = 24.99, SD = 8.22) over the control condition (M= 18.26, SD = 11.55). Centered survey scores only had a moderately significant interaction with ITR (B = -0.84, SE = 0.31, $p = 0.054$, CI = -1.701, 0.021, See Figure 4b) and practical ITR (B = -0.86, SE = 0.31, $p = 0.052$, CI = -1.717, 0.005, See Figure 4c). Statistical results are located in Table 5. The interaction shows that optimal condition ITR and Practical ITR performance increases over control condition as preference for the optimal condition increases. The mixed model revealed a main effect of condition for the survey (B = -9.66, SE = 3.17, $p = 0.029$, CI = -18.471, -0.869) with the optimal survey (M = 6.58, SD = 1.50) lower (i.e., better) than the control survey score (M = 16.25, SD = 7.74). Waveform analysis did not reveal any significant differences for positive peaks (i.e., 180ms-350ms) or negative peaks (i.e., 400ms-700ms) in the Midline and Parietal and Occipital groups.

Practical Measures

The practical measures, found on Table 4, provide the performance measures based on the extra selections needed for error correction. The practical selections measure shows how many selections needed to error correct the 18 selection online task. Each participant, similar to the accuracy measure, performed better or the same in the optimal condition. Participant 2 had 50% in the RC condition; this resulted in 9,000 selections to complete the task, 9,000 selections to create an 18 selection message is an unrealistic expectation. With participant 2's practical selections removed from both conditions, a new mean is revealed of 24.55 practical selections for RC and 18.98 practical selections for optimal. The optimal condition saved 5.57 selections in an 18-selection task.

The main effect for the survey and bootstrapping accuracy for each of the 27 conditions can be found in Table 6. This provides an example of how personal preference and accuracy could conflict. Participant 1 had a preference for the WT flash; nonetheless, accuracy was higher in the other two flash types. The mean accuracy and survey score were the best for CL. The mean accuracy for item size varied by only 1% and the survey showed a preference for smaller items. The most consistent conflict was in flash duration. Most participants preferred the shortest flash and their accuracy was generally higher in the longest flash. Fortunately, in the online session a dynamic classifier, with a confidence threshold of .90, was used to make the online selections. In this case, three flashes from a longer flash that classified with higher accuracy would result in item selection faster than four flashes in a shorter flash duration.

Table 3.

Results From the Online Portion Grouped by Participant (P #), Condition (Control (CR), Optimal (OP)), Percent Correct, Logit Transform Of Accuracy, Sets Per Sequence, Time to Complete, Selections Per Minute, Theoretical Selections Per Min (I.E., Three Seconds of Time Between Each Selection Was Removed), ITR, and Theoretical ITR.

P #	Condition	Percent	Logit	Sets / Seq	Time	Sel/Min	Theo Sel/Min	ITR	Theo ITR
1	CR	83	1.59	3.31	3.66	4.91	6.4	17.89	23.29
1	Op	100	11.51	2	3.4	5.29	7.06	27.37	36.49
2	CR	50	0	6.76	6.6	2.73	3.13	4.38	5.03
2	Op	78	1.27	4	5.95	3.03	3.53	9.93	11.58
3	CR	94	2.75	1.5	2.13	8.47	14.12	38.41	64.02
3	Op	94	2.75	2.06	2.82	6.38	9.14	28.95	41.44
4	CR	83	1.59	5.86	5.83	3.09	3.61	11.24	13.15
4	Op	100	11.51	2.56	4.11	4.38	5.51	22.62	28.51
5	CR	94	2.75	3.28	3.64	4.95	6.46	22.44	29.28
5	Op	94	2.75	1.67	2.45	7.36	11.27	33.36	51.11
6	CR	83	1.59	3.6	3.91	4.6	5.88	16.76	21.41
6	Op	100	11.51	2.54	3.28	5.49	7.41	28.38	38.31
MEAN	CR	81.17	1.71	4.05	4.29	4.79	6.60	18.52	26.03
	Op	94.33	6.88	2.47	3.67	5.32	7.32	25.10	34.57
SD by Condition	CR	16.19	1.01	1.92	1.63	2.04	3.95	11.55	20.44
	Op	8.52	5.1	0.82	1.25	1.51	2.71	8.19	13.44
SE by Condition	CR	7.24	0.45	0.86	0.73	0.91	1.77	5.17	9.14
	Op	3.81	2.28	0.37	0.56	0.68	1.21	3.66	6.01

Table 4.

Results From the Online Portion Grouped by Participant (P #), Percent Correct, Practical Selections Required to Complete the Task (I.E., 18 Selections In The Online Task) With Error Correction, Practical Selections Per Minute, Practical ITR, Practical Theoretical ITR, Survey Score of Paradigm, and the Paradigm Tested (I.E., Flash Type, Item Size, Flash Duration).

P #	Condition	Percent	Prac Sel	Prac SelMin	Prac ITR	Prac Theo ITR	Survey	Optimal Paradigm
1	CR	83	27.27	4.82	17.54	20.63	19	RC Med L
1	Op	100	18	5.29	27.37	36.49	8	WT Sm L
2	CR	50	9000	2.58	4.15	4.15	8	RC Med L
2	Op	78	32.14	2.95	9.68	10.49	6	BL Lg L
3	CR	94	20.45	8.41	38.14	58.64	6	RC Med L
3	Op	94	20.45	6.34	28.74	39.02	6.5	BL Med M
4	CR	83	27.27	3.03	11.02	12.16	19	RC Med L
4	Op	100	18	4.38	22.62	28.51	8	CL Lg L
5	CR	94	20.45	4.91	22.28	28	21	RC Med L
5	Op	94	20.45	7.3	33.12	47.56	7	CL Sm M
6	CR	83	27.27	4.51	16.43	19.12	24.5	RC Med L
6	Op	100	18	5.49	28.38	38.31	4	BL Sm M
MEAN	CR	81.17	1520.45	4.71	18.26	23.78	16.25	
	Op	94.33	21.18	5.29	24.99	33.40	6.58	
SD by Condition	CR	16.19	3664.22	2.06	11.55	18.89	7.47	
	Op	8.52	5.51	1.52	8.22	12.76	1.5	
SE by Condition	CR	7.24	1638.69	0.92	5.16	8.45	3.34	
	Op	3.81	2.46	0.68	3.67	5.71	0.67	

Table 5.

Results of the Mixed Model for Logit, ITR, and Practical ITR With Survey as a Moderator.

	Logit accuracy			*ITR*			*Practical ITR*		
	B (SE)	*p*	*95% CI*	*B (SE)*	*p*	*95% CI*	*B (SE)*	*p*	*95% CI*
Intercept	1.71 (1.29)	0.25	[-1.872, 5.292]	18.52 (4.31)	0.01	[6.554, 30.486]	18.26 (4.3)	0.013	[6.321, 30.199]
Condition	5.17 (1.89)	0.052	[-0.077, 10.417]	6.58 (2.23)	0.042	[0.389, 12.771]	6.73 (2.22)	0.039	[0.566, 12.894]
Survey	-0.02 (0.18)	0.927	[-0.51, 0.49]	0.35 (0.60)	0.59	[-1.316, 2.016]	0.35 (0.61)	0.59	[-1.344, 2.044]
*Survey * Condition*	-0.42 (0.27)	0.2	[-1.17, 0.33]	-0.84 (0.31)	0.054	[-1.701, 0.021]	-0.856 (0.31)	0.052	[-1.717, 0.005]

Table 6.

Mean Bootstrap Accuracy and Summed Survey Score for Each Level of the Paradigm Characteristic.

		WT	CL	BL	Item Sm	Item Med	Item Large	Flash Short	Flash Med	Flash Long
1	Accuracy	87%	91%	96%	92%	86%	95%	86%	92%	96%
	Survey	59.5	86.5	88	76	79.5	78.5	72	80	82
2	Accuracy	18%	26%	30%	14%	23%	38%	13%	24%	38%
	Survey	51	46	42.5	38	53	48.5	42	39	58.5
3	Accuracy	82%	87%	92%	87%	91%	83%	74%	91%	96%
	Survey	43	43.5	44	41	45	44.5	35.5	44.5	50.5
4	Accuracy	43%	78%	87%	77%	57%	75%	51%	72%	86%
	Survey	60	57.5	86	55	55.5	55	60.5	39	66
5	Accuracy	75%	79%	39%	70%	69%	53%	48%	72%	73%
	Survey	81	47.5	110	68.5	77	93	61	78.5	99
6	Accuracy	77%	87%	93%	84%	91%	83%	83%	88%	86%
	Survey	59.5	48	40.5	50	50.5	47.5	37	49	62
Mean	Accuracy	64%	75%	73%	71%	70%	71%	59%	73%	79%
	SE	12.11	11.00	13.33	12.95	11.87	9.59	12.37	11.65	9.84
Mean	Survey	59	55	69	55	60	61	51	55	70
	SE	5.68	7.26	13.37	6.73	6.49	8.89	6.78	8.57	7.94

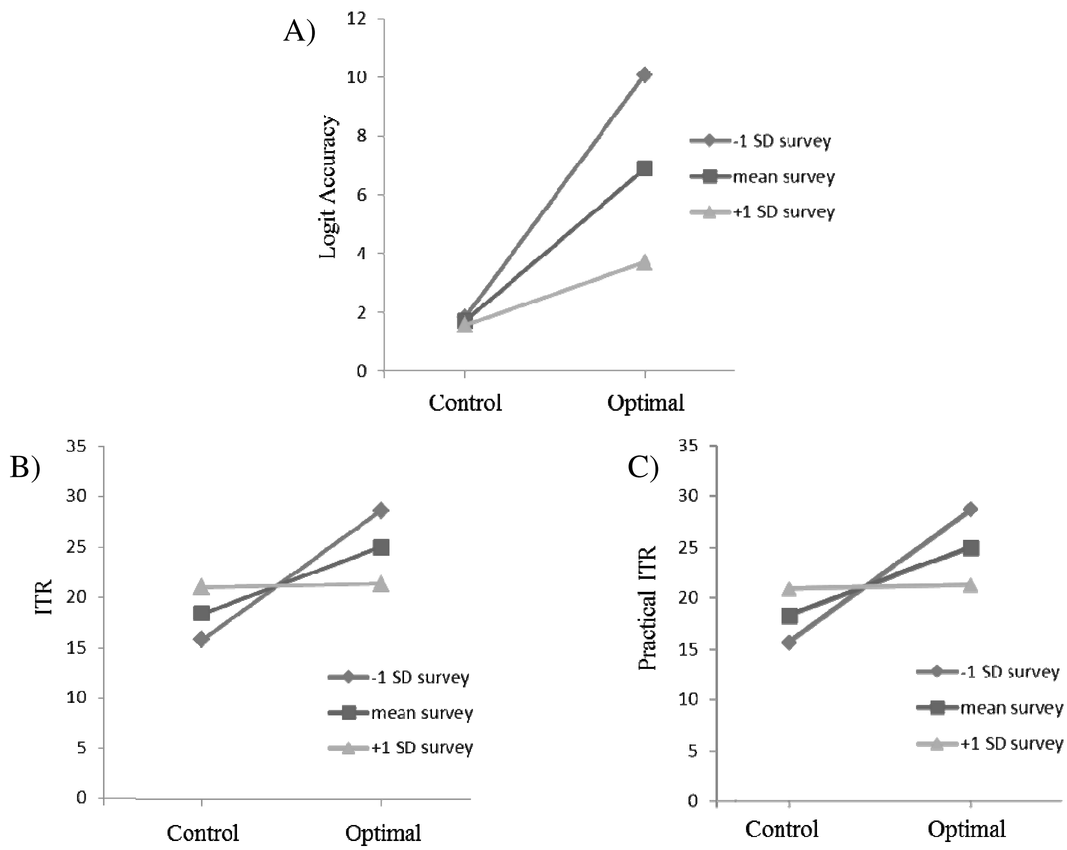

Figure 4. Interaction plots of performance measures and Survey difference (i.e., control survey score subtracted from optimal survey score, centered on the mean difference). A) Logit accuracy as a function of Condition and Survey difference, this interaction was not significant. B) ITR as a function of Condition and Survey difference, this interaction was moderately significant (B = -0.84, SE = 0.31, p = 0.054, CI = -1.701, 0.021). C) Practical ITR as a function of Condition and Survey difference, this interaction was moderately significant (B = -0.86, SE = 0.31, p = 0.052, CI = -1.717, 0.005).

Discussion

This study demonstrates a novel method to systematically expose a large number of paradigm possibilities and analyze the classification accuracy with personal preference of each paradigm. The online results support the hypothesis that the optimal paradigm will have higher performance measures (i.e., logit transform accuracy, ITR, and practical ITR) and better preference scores than the traditional (i.e., control) paradigm. This study has shown the importance of individual differences on paradigm development and subsequent BCI performance.

The significant results for practical ITR are particularly interesting due to this measure's estimate of how a system would perform with error correction. The translational importance of this measure is evident when considering the task of composing a message. For example, using the mean accuracy and sets per sequence of the control paradigm (i.e., 81% and 4 sets per sequence), it would require 258 selections and take 64 minutes 16 seconds to compose a sentence of 160 characters including spaces and punctuation. Using the optimal paradigm accuracy mean and sets per sequence (i.e., 94% and 2.7 sets per sequence), it would require 182 selections and take 45 minutes 4 seconds to compose the same sentence, a difference of 76 selections or 19 minutes 12 seconds. This difference is very important considering how much time and effort are required to use a system as slow and attentionally demanding as a BCI.

The influence of personal preference on BCI performance is not fully understood; nevertheless, it should not be ignored. For example, the current study had no significant differences in the waveforms between the optimal and control paradigms; nonetheless, performance and personal preference were significantly higher for the optimal paradigms.

Moreover, the interaction of practical ITR and preference was moderately significant. These results show that personal preference does have an impact on performance, even if a direct link is not clear.

The RC paradigm has been the standard presentation paradigm. Nonetheless, it has limitations. A growing body of research has shown that visual attention concepts explain classification errors caused by stimulus adjacency and consecutive flashes of the same stimulus (Fazel-Rezai, 2007). Additionally, visual attention research has been useful in limiting errors inherent to the RC paradigm by imposing constraints on how stimuli are presented limiting Gestalt grouping, flanker effects, and attentional blink (Townsend et al., 2010; Townsend et al., 2012). The results of previous research and those of this study show that the faster presentation of the RC paradigm does not result in faster communication. Other styles of stimulus presentation, such as the CB paradigm, may take more time; however, a flash presentation that follows visual attention concepts elicits ERPs that are more amenable to accurate classification.

The traditional method of trial and error paradigm development relies on the skill, experience, and knowledge of the researcher to find the correct parameters and this process can take many experimental sessions before the BCI is optimized. Yet, this method could still result in a suboptimal paradigm or an erroneous conclusion that the individual is unable to use a BCI. The method used in this study was guided by visual attention, personal preference, and data driven. It utilized a large systematic exposure to several paradigm characteristics. By analyzing the data from a BCI-based visual attention assessment, researchers can determine the characteristics to develop an individual's optimal BCI paradigm. Moreover, utilizing the participants' preferences, the resulting paradigm will match their abilities and inclination. This method also educates the users as to the presentation flexibility of the system, affording them the knowledge to request optional formats for further customization. For example, one participant inquired about combining two flash types, color items that flashed black. This request would be very unlikely if the participant has not seen both paradigms. Furthermore, this method can be used repeatedly as a check-up every few months or when performance declines to match the individual's changing abilities. A calibration process that uses these methods, results in a BCI system that can restore a level of independent communication to those who need it most.

Participants' Current State and BCI Applicability

This section provides information on each participant's remaining abilities, his or her current method used for communication, and the appropriateness of using a BCI on a daily basis. Only two of the participants in this study were not on ventilators and could still speak, 1 and 6. Both of these participants enjoy using the system but have no immediate need for a BCI. The remaining four participants required artificial respiration and were dependent on some form of AAC.

Participant 1 had an ALSFRS-EX of 33 and could speak with some difficulty. She had enough control of her right hand to operate a joystick input for her electric wheelchair. In this study she had much higher performance measures in her optimal condition (i.e., gray-to-white flash, small item, long flash duration) than in the control condition. The optimal condition's enhanced ERPs afforded better classification; thus, faster item selection was possible. Additionally, she had a better survey rating for the optimal paradigm than for the control paradigm. Fortunately, she still had her speech, making a BCI system unnecessary.

Participant 2 had an ALSFRX-EX of six. He could mouth the words Yes and No, had many facial expressions, and had unsteady eye movement. He used a letterboard as his primary method of communication and could spell about eight characters a minute with accuracy higher than 90%. The letterboard requires the full attention of the caregiver to call out the letters, watch his eye blinks (e.g., letter selection), and track his progress throughout the message. The participant also had an eye-tracker, but it had recently become too unreliable to use at an acceptable level of accuracy. In the current study he had higher performance measures in the optimal condition (i.e., gray-to-black flash, large item, long flash duration). The control condition only achieved 50% accuracy; at this level an infinite loop of error correction would occur and no meaningful message could be created. The optimal condition reached 78%, high enough to avoid an error correction cycle. Interestingly, he had the same survey rating for the control and optimal paradigms. This participant had shown an interest in obtaining a BCI system even with his performance in this study averaging three selections a minute (five selections a minute slower than his letterboard). A BCI would afford him more independence than the letterboard and better accuracy than the eye-tracker.

Participant 3 had an ALSFRS-EX of 10, full control of facial expressions, very little neck and head control, and excellent eye movement. At the time of the study he used a head tracker to interact with a computer and with the use of a predictive speller could generate 33 characters per minute. Despite the high output of this device, it was becoming unreliable because he was beginning to lose control of his head and neck muscles. He had attempted to use an eye-tracker; nonetheless, it had poor accuracy and therefore he did not use it often. He primarily communicated by mouthing words and used his eye gaze to direct attention to specific objects and locations. For the caregiver, this method requires a great deal of experience reading lips and having a good amount of contextual knowledge about the message. Participant 3 had been in several BCI studies and continues to do well regardless of the task condition. In the current study, his performance measures and survey scores were the same, or nearly, for both conditions (i.e., optimal condition was gray-to-black flash, medium item, medium flash duration). He had shown interest in obtaining a BCI system due to his excellent performance, as his current methods for communication are beginning to fail.

Participant 4 had an ALSFRS-EX of two, only had control of the corners of his mouth (i.e., moves the corner of his mouth once for Yes and twice for No), and had slow and unsteady eye movement. He did use a letterboard; nonetheless, his main method of communication was responding to the caregiver's Yes and No questions. Communication with him was difficult for people other than family members and caregivers because it is necessary to have experience understanding the subtle movements of the corner of his mouth, and the movements also occur at random. He was limited in communicating a message of his own volition and it was necessary for the caregiver to ask many questions before his intent could be realized. He did have an eye-tracker but it was difficult to calibrate; therefore, he did not use it due to very low accuracy. In the current study, he performed better in the optimal condition (i.e., gray-to-color flash, large item, long flash duration) than control condition by all measures and rated the optimal better than the control condition. He was interested in having a BCI system for daily use. For participant 4, a BCI is the most accurate communication option and offers him the most independence in his current state.

Participant 5 had an ALSFRS-EX of two, smiled often, had full eye movement, but did not have control of her jaw. She used a double eye-blink for Yes and single blink for No. An eye-tracker was her main method of communication and it performed well. The eye-tracker averaged 31.2 selections per minute and combined with a predictive speller could present 60 characters per minute. The eye-tracker also allowed her to email, browse the internet, and shop online (e.g., her husband said there was always another package being delivered). She was also proficient with a see through letterboard called an "eye-link" (i.e., the caregiver observes the user's eye gaze through the eye-link while the user fixes his or her gaze on a character and the caregiver moves the eye-link until both persons' gaze meet on the desired character). Using the eye-link she could produce 32 selections per minute and with the additional interpretation of her selections the caregiver could produce a total of 71 output characters per minute. This exceptional performance was a result of the user and the caregiver working well together. She indicated that another caregiver could not use the eye-link with her even after 4 years of practice. Similar to participant 3, participant 5 has performed well in multiple BCI studies. In the current study she had the same accuracy for both conditions; nonetheless, she had a much higher selections per minute, ITR, and practical ITR for the optimal condition (i.e., gray-to-color flash, small item, medium flash duration). The difference in speed reflects how the enhanced ERPs in the optimal condition could be correctly classified with fewer flash presentations than the control condition. Her survey results rated the optimal condition better than the control condition. Participant 5 was interested in continuing BCI research; nonetheless, her current methods of communication outperformed any BCI available.

Participant 6 had and ALSFRS-EX of 37, could speak clearly, could stand on his own, and had enough control of his right hand to operate a joystick input for his electric wheelchair. In the current study his optimal condition (i.e., gray-to-black flash, small item, medium flash duration) performance was higher by all measures than the control condition and his survey rating of the optimal condition was higher than the control condition. Again, these results reflect how enhancing ERPs improves accuracy and speed of the BCI. Participant 6 had always enjoyed participating in BCI research; however, due to his clear speech a BCI system would not provide any benefits.

The most appropriate application of the BCI system would be when an eye-tracker is beginning to fail. Once motor control of the eye begins to deteriorate, eye-trackers become increasingly difficult to calibrate. A BCI does not require the eyes to be stable, only that attention is applied to the intended selection. Other AAC methods such as the letterboard do offer a simple low-tech solution for communication; nonetheless, it requires the caregiver's full attention. The additional requirement of the caregiver's time could have an impact on how often the letterboard is used. In the case of participant 4, he was completely dependent on the caregiver to ask him the appropriate Yes and No question. The only way he could convey context of a question was to direct his gaze on the intended object, greatly limiting his communication. This reveals the importance of independent communication. A BCI is not a fully independent method; it does require an initial setup for each session. Once setup is complete, a BCI does provide a means for volitional messages to be composed without the assistance of the caregiver. This level of independence increases quality of life of the end-user and his or her family.

ALSFRS-EX and Communication

The ALSFRS-EX is an improvement over previous versions and does translate the remaining motor functionality to a comprehensive score; however, the score does not correlate with the performance of eye gaze based forms of AAC. Moreover, the ALSFRS-EX has a weak correlation with BCI performance (McCane et al., 2014). The motor control problems pertaining to the eye, such as nystagmus, diplopia, and ptosis (i.e., rapid uncontrollable eye-movements, double vision, and drooping eyelids, respectively) have been found to correlate with a decrease in BCI performance (McCane et al., 2014) and would present problems with an eye gaze based form of AAC. As an example, participant 5 has an ALSFRS-EX of two and could communicate very well with the BCI and multiple forms of AAC (e.g., eye-tracker, eye-link). The only other participant who had a score as low as participant 5 was participant 4. The key difference between the two participants was the eye movement control. Participant 5's eyes were steady and could respond quickly; conversely, participant 4's eyes were slow and unstable. This small difference could be the reason that the eye-tracker and letterboard performance were notably different between the two participants. An additional question or set of questions that address the speed of eye movement and the control of eye gaze would add more resolution to the low score end of the ALSFRS-EX scale. This increased resolution would provide more information to the caregivers, doctors, and researchers to the level of remaining ability, thus helping them find appropriate communication methods.

Future Directions

The methods used in this study are not inclusive to all possible BCI paradigms. Future studies should include addition stimuli and alternate presentation methods. The large amount of data resulting from this method could be interpreted many ways resulting in different optimal paradigms; future studies should examine alternate methods of paradigm selection. Future studies should also address the time required to administer the assessment. This process could be shortened when the user shows a distinct enjoyment or dislike for a certain paradigm characteristic. For example, if the user does not like the grey-to-white flash after seeing all of the flash types, the experimenter could omit the remaining conditions that contain the grey-to-white flash. In the current study the online analysis was based on 18 selections, resulting in limited accuracy resolution (e.g., one selection was worth 5.5%). Future studies should examine increasing the amount online selections to increase accuracy resolution and reliability.

CHAPTER 8

CONCLUSION

BCI research has made several advancements allowing those who are locked-in to communicate. Traditionally, the only part of the BCI system that was calibrated to the individual was the classification coefficients. Now that research has provided different types of visual presentation methods, these methods should be matched to the individual's abilities and inclination to fully calibrate the system to the user. Visual attention concepts can be used as a guide in this process of developing a BCI system that facilitates attention, results in less fatigue, and that can be used for an extended period of time. Moreover, enhancing attention and limiting distraction results in consistent ERP responses to targets and nontargets, improving classification of target selection. The BCI-based visual attention assessment has shown that it can provide a paradigm that allows independent communication when other forms of communication begin to fail.

The traditional method of trial and error paradigm assignment for an end-user results in a suboptimal system and does not address user preference. A paradigm that conforms to individual differences will have better performance than the paradigm that is considered best overall. The methods used in this study are the first steps to systematically finding the best paradigm for an individual, thus resulting in optimal BCI communication.

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