ASSISTIVE TECHNOLOGIES USING BRAIN-COMPUTER INTERFACES: THE PROBLEM OF MENTAL FATIGUE

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Abstract

Assistive technology has great potential for enhancing the capabilities of individuals with disabilities. In people with a severe neurological disability like chronic spinal cord injury (SCI) one strategy to overcome functional loss involves providing access to assistive technology that allows the severely disabled person to regain some level of control over their living environment. New types of assistive technologies include brain computer interface (BCI) based assistive technology systems. These are systems that interpret and translate voluntary changes in brain electrical activity to allow users to activate and control devices in their environment with their brain signals. However, BCI based assistive technologies require a great deal of attention and concentration from the user, especially if the user exerts control over extended periods of time. Any task that requires extended concentration and attention will undoubtedly result in elevated mental fatigue. Chronic mental fatigue is a common though negative symptom of many illnesses and disabilities. In this chapter we describe a device that utilizes changes in brain activity using EEG alpha waves (8-13Hz) as a switching mechanism for an environmental control system (ECS). The device functions by detecting changes in alpha activity during the opening and closing of the eyes. A rapid and substantial increase in alpha activity is observed when eyes are closed and there is a large attenuation of the 8-13Hz activity when the eyes are open. Switching occurs when alpha activity increases above a set threshold during eye closure. Although this hands-free ECS has been shown to be effective in severely disabled participants in their homes while operating a television set, little is known about the effects of mental fatigue on the operational capacity of this device when used by people with severe disabilities for long periods of time. Recent research on strategies for controlling the impact of fatigue will be presented and implications for BCI assistive technology discussed.

Introduction

Persons with severe disabilities, such as spinal cord injury (SCI), often suffer from limited mobility as well as difficulties in their ability to interact with their environment (Harrington et al., 2007). It is of great importance to try to help people with disabilities to achieve their potential and improve their quality of life with methods to aid mobility and communication (Wellings & Unsworth). An important aspect of the rehabilitation for those with disabilities such as SCI is to help them regain some independence and control over their environment and this can be achieved by restoring some function through technological assistance, such as via assistive technologies (AT) (Craig, et al., 2005). AT has been described as devices that assist or expand human function or capabilities (Lane & Mann, 1995). ATs are believed to help enhance the quality of life of the disabled person as well as their caregivers, through improving the person's sense of independence and self esteem, and lessening the burden on those who care for the disabled (Craig et al., 2002). They provide creative solutions that enable people with disabilities to be more independent, productive and able to contribute to society and community life. As such, AT has become an increasingly accepted intervention for people with disabilities as they offer optimal function and a degree of independence in areas such as computer use, mobility, communication devices and access to everyday appliances (Phillips & Zhoa, 1993).

AT that utilizes interfaces with existing functional capability have been collectively called environmental control systems (ECS). ECS are designed to provide some independence to disabled people through providing ‘hands-free’ control over their environment. Common data transmission mediums for ECS include infrared (IR), radio frequency (RF), ultrasonic and traditional copper wiring (Harrington et al, 2007). However, the weak link in most control systems is the method used for activating the switching mechanism, that is, the type of interface between the system and the user (the person operating the device) (Wellings & Unsworth, 1997). Many control systems rely upon the disabled person having some control over legs, arms or neck. Unfortunately, many profoundly disabled persons have little or no such control (such as high lesion tetraplegia). Typical methods of switching include "suck-puff" techniques, chin operated control sticks, mouth-sticks, voice control and eye-blink (Thornett, 1990). Other more experimental systems use feedback of physical responses such as electromyography (EMG) (Horn, 1972; Osamah, 2000). For instance, a touch switch placed upon a user’s cheek detects changes in surface muscle activity (when the user tenses their cheek) that acts as an interface, allowing a selection of options from a menu. Initial evaluation suggests this technique could be a viable alternative switch for the severely disabled (Osamah, 2000). Simple switches such as chin-press have also been used successfully (Hawley et al., 1992), however, this assumes that the person has control over head movement. Voice activated systems hold promise, though it has been estimated that 40% of disabled people who use an ECS are without speech (Barnes, 1994).

In recent years, there has been great interest in brain-computer interfaces (BCIs) as they have potential to be implemented into such control systems. BCIs utilize voluntarily changes in one’s brain activity as the hands-free interface and can be particularly useful to those who suffer from severe disabilities such as SCI and in particular tetraplegia (damage to the spinal cord at neck level), as these patients have no or very limited movement below the neck level (Wijesuriya et al., 2008). With the aid of an ECS, patients can be trained to use their brain activity to operate effectively and reliably devices such as computers, televisions and other assistive technology (Craig et al., 1999; Craig et al., 2002, Kirkup et al., 1997). The brain activity utilized by BCIs are commonly measured by electroencephalography (EEG), which records cortical postsynaptic electrode potentials that can be categorized in to four major bands based on their frequency: delta (0.5-3.5), theta (4-7.5Hz) and alpha (8-13Hz) beta rhythms (14-32Hz). One such system that has been successfully demonstrated in a group of spinal cord injured participants, is the Mind Switch ECS. This system utilizes the changes in alpha waves (8-13Hz brain activity) associated with eye closure to be used as a ‘switch’ in an ECS. During eye closure, there is a significant increase in alpha or 8-13Hz activity, which is believed to be due to reduction in visual input (Adrian & Matthews, 1934). This alpha increase with eye closure can be seen in most people, and has been shown to be reliable and quick enough to be used as a switching mechanism, in both able-bodied and people with disabilities (Craig et al., 1999; Craig et al., 2002, Kirkup et al., 1997).

However, the operation of a BCI based assistive technology system will require a great deal of attention and concentration from the user, especially if this occurs over extended periods of time and this will result in elevated mental fatigue. Kennedy and colleagues (2000) have also argued that even automated mechanisms could also be affected when the user becomes fatigued. Little research has been conducted on the effects of mental fatigue during the operation of BCI. Mental fatigue has been shown to be associated with changes in EEG and is known to affect a person's alertness and concentration (Craig et al., 2011; Wijesuriya, 2008). Activation and use of BCIs would require a great deal of concentration and mental demand and could be expected to cause fatigue in the user. This could pose a challenge in a population such as those with SCI, who experience fatigue and psychological distress on a daily basis (eg. from pain, depression or infection). It is therefore important to study the effects of increased cognitive demand and fatigue on the brain activity of those with SCI in order to know whether these changes may compromise the efficacy of BCIs.

Brain Computer Interfaces (BCIs)

BCIs give their users a means of communication or control that is not dependent on the brain's normal output channels or peripheral nerves and muscles (Wolpaw et al., 2000). The interest in BCI development comes mainly from the hope that this strategy can be an option for those with severe motor disabilities that prevent them from using conventional AT that require voluntary muscle control (Wolpow et al., 2000). A BCI has been defined by Wolpaw and Wolpaw (2012) as:

"A BCI is a system that measures central nervous system (CNS) activity and converts it into artificial output that replaces, restores, enhances, supplements, or improves natural CNS output and thereby changes the ongoing interaction between the CNS and its external or internal environment" pp. 3

Therefore a BCI can be used to interpret and translate voluntary changes in brain electrical activity to activate and control communication devices by, for instance, selecting commands to control a computer or a neuroprosthesis (Kübler & Neumann, 2005), hence replacing and restoring CNS natural output (Wolpow & Wolpow, 2012). In addition, a BCI could also be used to 'enhance' natural CNS output through applications such as the detection of fatigue and alerting the user of any attentional lapses (Wolpaw & Wolpow, 2012).

In order to control a BCI, there are three essential steps: first, the user must produce specific brain activity patterns, then these are identified by the system and finally translated into commands (Lotte et al., 2007). Therefore, the basic design and operation of a BCI can be described as:

1. Signal Acquisition, the recording of brain activity: Brain activity can be measured using either invasive methods, whereby the electrodes are implanted epidurally or subdurally from the cortex or from the scalp (e.g. electrocorticogram (ECoG) or non-invasive methods (e.g. electroencephalography (EEG), magnetoencephalography (MEG), and functional magnetic resonance imaging or fMRI).

2. Feature Extraction: Once the recorded signals are digitized, amplified and artifact is removed, the brain activity signal goes through a process called feature extraction. Feature extraction refers to the isolation of a desired brain activity component such as an EEG spectral band of a specific frequency (i.e. mu, alpha, beta) or event related potentials such as the P300 (Daly & Wolpaw 2008; Kübler & Neumann, 2005).

3. *Feature Translation, translating the brain signals into 'commands':* The translation algorithm converts the extracted brain activity components into a command that is capable of performing the desired function that act on the outside world or the body itself, such as operating a neuroprosthesis, selecting letters or options in a menu, and switching devices on or off (Daly & Wolpaw 2008; Kubler & Neumann, 2005; Wolpaw, et al., 2002).

"Mind Switch" BCI

The Mind Switch ECS is a device designed to detect voluntarily manipulated changes in brain waves to switch "on" or "off" selected electrical devices and hence provide hands free remote control. It was developed so that the severely disabled are able to control electrical devices, such as the television or computer in their homes. The technology is dependent on changes in brain wave activity measured from EEG signals. The brain wave frequency involved in the functioning of the Mind Switch is the alpha rhythm (8-13Hz). Alpha wave signal strength can be consciously controlled by different mechanisms, the most reliable and established method being the opening and closing of eyes (Adrian &Matthews, 1934, Craig et al., 1999). Eye closure, which is associated with a reduction of visual input, increases alpha wave amplitude and this can be reversed with the opening of eyes. The Mind Switch ECS is essentially a brain activity (EEG) based system that detects synchronization of alpha wave activity, when the EEG signals received on the ECS exceeds a predetermined threshold, a transmitter is activated, which will then remotely activate an electrical device such as a television, radio, or light a switch (Kirkup et al., 1997). Mind Switch integrated BCI technology has been shown to be an effective ECS for those with very restricted upper body movement. It is hoped that this assistive technology will continue to be developed so it will utilized by severely disabled persons to control their environment and thus improve their wellbeing.

Mental Fatigue

Mental fatigue is a major cause of accidents and injury when driving and when performing boring or repetitive process work tasks (Akerstedt et al., 1991; Connor et al., 2002). It is also a common symptom of many illnesses and disabilities. Mental fatigue is a psychobiological state and refers to the feeling people may experience during or after long periods of cognitive engagement (Boksem & Tops, 2008). It is characterized by subjective feelings of tiredness, drowsiness, as well as elevated risks of performance decrements, and even exhaustion or an aversion to continue with the present activity (Boksem & Tops, 2008; Craig et al., 2006).

Brain activity is believed to be a sensitive and viable measure of mental fatigue and there have been many studies that have attempted to determine the impact of mental fatigue on brain activity (Craig & Tran, 2011). In 18 papers systematically reviewed, Craig et al., 2012 found that the occurrence of mental fatigue has been shown to alter brain activity. Delta wave activity was found to increase significantly in four of the seven studies reporting delta changes. Theta wave activity (examined in 17 studies) was found to increase significantly in 15 studies, with no change found in two studies. Given these findings, it is likely that theta activity increases when a person fatigues. Alpha wave activity (examined in all 18 studies) was found to increase significantly in 16 studies and to decrease significantly in two studies. Alpha wave activity most likely increases when a person fatigues. Beta wave activity change was examined in six studies, and it was found to increase significantly in three studies, decrease in one study, with no change found in two studies. The status of beta wave activity associated with fatigue remains unclear. Given these alterations in brain activity associated with mental fatigue, fatigue could well be an potential barrier to using BCI-based AT effectively, and is therefore an issue that requires attention when designing ECS and BCIs that rely on brain activity, as the altered EEG signals associated with fatigue may negatively affect their performance or function.

The Effects of Mental Fatigue on Alpha Wave Synchronization

The main objective of this chapter is to present findings on the effects of switching and alpha wave synchronization following a cognitively demanding and mentally fatiguing battery of tests. The participants completed a set of cognitive tasks, which were designed to increase in complexity and cognitive demand. Increased cognitive demand is expected to cause mental fatigue (Cook et al., 2007). Changes in 8-13Hz activity from eyes open (EO) and eyes closed (EC) conditions before and after the cognitive task were examined.

Participants

Thirty participants (12 males, 17 females) were included in this study. The mean age of participants was 37 years (SD=15.8) ranging from 17 to 69 years. Participants were excluded if they reported prior brain injuries or head trauma, a history of psychopathologies or neurological illnesses. The study was approved by the institutional research ethics committee and participants were only entered into the study after informed consent.

Procedure

All participants took part in a laboratory session whereby their EEG signals were acquired. At the start of recording during a baseline alert condition, participants were asked to open (EO) or close their eyes (EC) for 30 second intervals. Three sets of EO/ EC were taken. To induce mental fatigue, participants were then asked to complete a series of psychophysiological/cognitive measures as part of a larger study. This psychophysiological battery of tests included auditory habituation, auditory oddball, go-no-go task, eye tracking and visual working memory. These tasks took around 90 minutes to complete. At the end of the psychophysiological battery, the EEG of the participants during three sets of EO/ EC was taken once again. This resulted in a total of six switches from which to assess the effects of fatigue.

The occurrence of fatigue was validated using a self-report questionnaire, that is, the IOWA fatigue scale, an 11-item questionnaire that assesses a person's fatigue levels, based on four areas: cognition, fatigue, energy and productivity (Harz et al., 2003). Participants were asked to record their fatigue level based on how they felt at a given moment. Each item was scored on a scale of 1 (not at all) to 5 (extremely). The questionnaire was administrated twice during the assessment, first at the very beginning of the assessment, and a second time following the 90 minute psychophysiological assessment (when participants were reasonably tired after the intense testing). The IOWA questionnaire has been shown to be both reliable (Cronbach's $\alpha = 0.9$) and valid (Harz et al., 2003).

EEG Procedure

In this study, brain activity was measured using a Quick Cap™ (Compumedics, USA), employing 26 Ag/AgCl surface electrodes that were attached to the scalp to measure EEG. The electrodes were positioned over standardized positions FP1, FP2, F3, F7, Fz, F4, F8, FC3, FCz, FC4, T3, C3, Cz, C4, T4, CP3, CPz, CP4, T5, P3, Pz, P4, T6, O1, Oz, and O2 cortical sites. EEG data was recorded with reference to the average A1 and A2 sites that were located on the mastoid (the bony area behind each ear). The impedance at all recording sites were kept under 5 kΩs, and data was recorded at a sampling rate of 500Hz. NuAmp and Scan 4.3 software were used to amplify and digitize the signals. However, as the ECS using EO/ EC switching operates using the EEG site O2, data from this channel was extracted for reporting data in this paper.

Method to evaluate EO/ EC switching

EO/ EC switching was emulated using in-house software written in the Matlab™ (version 7) software environment. The program detected the occurrence and time taken to switch, based on changes in EEG alpha activity during eye closure from an EO state. The EEG recorded consisted of 30 seconds EO (baseline) followed by 30 seconds EC (switch) and repeated three times. Initial variation in alpha wave activity from the first EO state was used to calculate the switching baseline. This was calculated using short Fast Fourier Transform (FFT) to obtain the power from the alpha frequency band of 8-13Hz. Alpha activity from the FFT was then smoothed using a 5-point moving average smoother. An average of 10 seconds of EO taken about 10-20 seconds after the start of EEG recording was used for the baseline calculation. This baseline level needs to be determined for each individual user before they can use the ECS device. A switching threshold was then set at between 125% to 200% of the baseline alpha wave level. Once alpha wave activity reached the threshold level, switching was said to have occurred. Determination of the threshold was dependent on the level of alpha activity in each participant. For example, if participants have high levels of alpha during EC, this baseline was set closer to the higher range to prevent the occurrence of false positive switching, that is switching during an EO state. If participants had lower EC alpha changes the threshold was set lower to prevent false negative switching. False negative switching was defined as no switching during the EC state as alpha activity levels were unable to reach the set threshold. Data from the two sets of EO/ EC (during the alert state and tired state) was then concatenated to form one file, so that the effects of fatigue can be assessed with the same initial baseline. EO/ EC of the of the fatigue state was also assessed separately using a reset baseline of the first EO in the fatigue state EO/ EC file, so as to test whether this would improve the switching rates.

Results

The level of mental fatigue before and after the 90 minute assessment task was taken using the IOWA fatigue scale. Using dependent t-tests, results showed that participants reported significantly higher levels of fatigue in the IOWA total scores as well as in all four domains (cognitive, fatigue, energy and productivity), after performing the task. Table 1 shows the IOWA results.

Table 1: Shows Iowa Fatigue Scores before and after the psychophysiological battery of tests. Means, t values and probabilities of difference are shown.

Variable	Before Task (Alert) M Score	After Task (Fatigue) M Score	t values	p values
Overall IFS	25.13	29.63	5.11	<0.001
Cognitive	8.03	9.50	3.89	<0.001
Fatigue	4.07	5.60	4.95	<0.001
Energy	8.87	9.80	2.97	0.006
Productivity	4.17	4.73	2.60	0.015

Figure 1 shows the EEG power in the concatenated EO/ EC files in one representative sample participant. The alert EO/ EC portion occurs from 0-180 seconds and the fatigue EO/ EC portion occurs from 181-360 seconds. The blue line shows the EEG power changes over time and the red line shows the smoothed signal using a 5-point moving average. The arrows indicate the points where switching occurred based on a threshold set at 150%. Switching times for this participant was detected at time 34, 91, 151, 215, 273 and 334 seconds, which is equivalent to a switching time of 4, 1, 1, 5, 3, and 4 seconds after EC. There was an increase in switching time with the onset of mental fatigue.

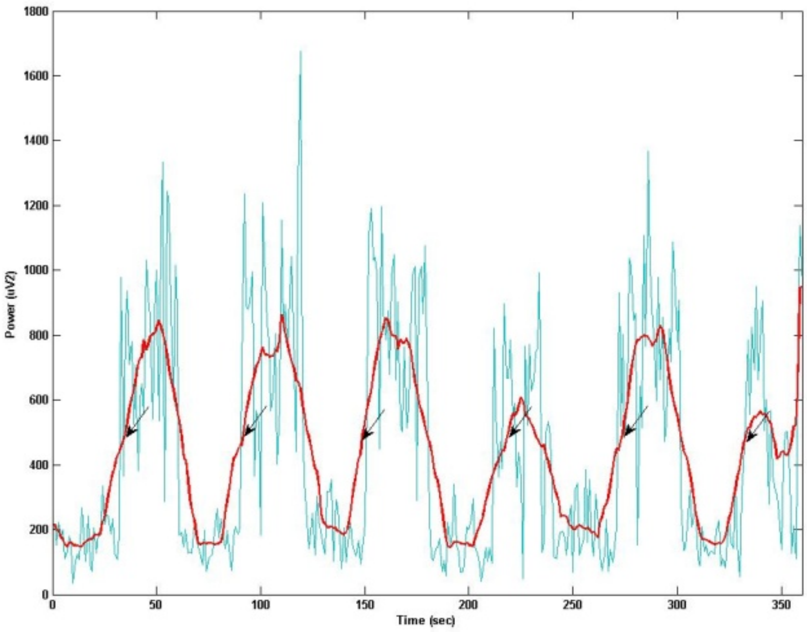

Fig. 1. Shows the EEG EOEC states for alert (0-180seconds) and fatigue (181-360seconds) conditions (adapted from Craig et al., 2011).

Figure 2 shows the mean switching times for the alert phase, as well as times for the fatigue phase (A) which represented the switching times using the same baseline calculation as the start of the task, and finally, the fatigue phase (B), which represented the switching times with the new baseline adjusted and calculated from the first EO state of the fatigue EO/ EC session. Using dependent t-tests, there were no significant differences in switching times between the alert state and fatigue (A) or fatigue (B) states. While the mean switching time did increase in the alert state from 3.6s (SD=3.4) to 4.4s (SD=3.1) in the fatigue state (A), the lack of significance is partly explained by the large variability in the switching measure. There was, however, a significant decrease in switching time between fatigue (A) and fatigue (B) ($t=2.1$, $p<0.05$). The mean switch time for the fatigue (B) decreased to 3.4s (SD=2.9s) when the baselines were adjusted.

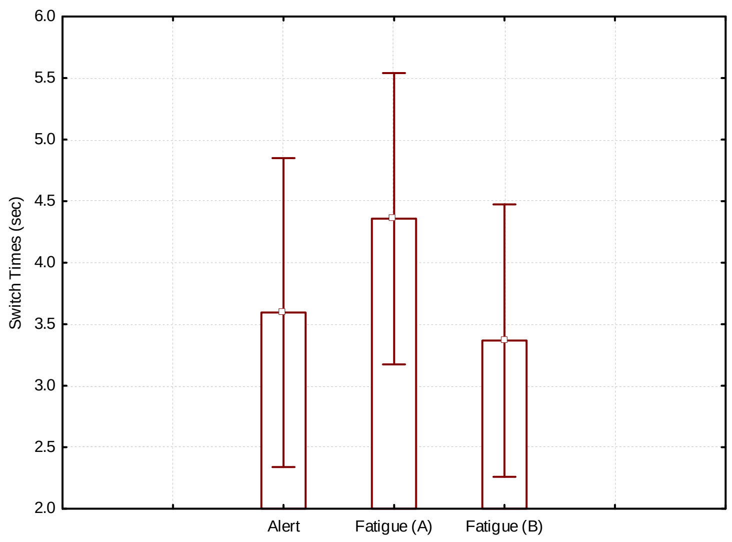

Fig. 2. Mean time taken for switching to occur following EC in Alert, Fatigue (A) and Fatigue (B). The bars represent 95% confidence intervals (adapted from Craig et al., 2011).

Errors in this study were measured as frequency counts. False positive switching was counted when switching occurred during an EO state and false negative switching was counted when there was no switching during the EC state. Table 1 shows the false positive and false negative errors during the alert, fatigue (A) and fatigue (B) phases, as well as percentages of errors falling into the error categories. Errors during the alert phase had similar counts of false positive and false negative errors, while errors in the fatigue (A) phase were primarily false positives (86%). Errors were similar in total counts between the alert phase and fatigue (A) phase, due perhaps to the large variability in the alpha wave activity when the participants were alert. Errors were found to reduce by around 50% in fatigue (B) when fatigue (A) baselines were adjusted for the influence of fatigue.

Table 2: Shows switching errors during the alert and fatigue conditions for all participants.

Condition	False Positive Errors	False Negative Errors	Total
Alert	11 (55%)	9 (45%)	20
Fatigue (A)	18 (86%)	3 (14%)	21
Fatigue (B)	8 (80%)	2 (20%)	10

Discussion

The effects of mental fatigue on alpha wave synchronization and the effectiveness of the switch from the BCI-based Mind Switch ECS was investigated and presented in this chapter. Users of the Mind Switch ECS have been shown to be able to switch and activate the ECS via conscious control of alpha wave activity by deliberate opening and closing of the eyes (Craig et al., 2002). Increases in alpha wave activity during EC (alpha synchronization) has been utilized effectively as a switching mechanism to control an ECS for people with severe disabilities where controlling electrical devices in their environment requires caregiver assistance. The Mind Switch ECS has been shown to be effective in controlling a television (eg. turning the television off and on, changing channel and volume) for severely disabled people with disorders such as tetraplegia, polio and severe stroke (Craig et al., 2002). However, the effects of using an alpha wave based ECS for an extended period of time in which mental fatigue will occur has not been previously evaluated. Given that alpha activity was found to have increased in 16 papers from a total of 18 papers systematically reviewed (Craig et al., 2012), the effects of mental fatigue on alpha wave synchronization needs to be evaluated.

Results showed that the participants in this study did become fatigued after completing the 90 minute assessment task, compared to their pre-task alert state. The increased levels of fatigue were scientifically demonstrated using a validated psychometric instrument, and furthermore, all four IOWA domains were shown to be affected, including the participants' cognitive and productivity capacity. The total IOWA fatigue score was also significantly elevated as a result of the task (see Table 1). For comparison sake, an IOWA score of 30 or above indicates clinical levels of fatigue typical of disorders such as sleep disorders (Harz et al., 2003) The mean IOWA score after the psychophysiological battery of tests was 29. Switching times were compared between the alert and fatigue states. Surprisingly, and in contrast to the expected detrimental effect of fatigue on behavioural and cognitive performance (Craig et al., 2006), switching times in the fatigue state were only about one second longer compared to switching times when in the alert state (Fatigue A), and this difference was not significant. Nonetheless, we were also interested in investigating whether adjusting the baseline EO alpha activity for the effects of fatigue would result in improved switching times. Results showed that by adjusting the EO baseline, switching times were reduced significantly similar to that when participants were alert. Furthermore, error counts were substantially reduced when the EO fatigue (A) baseline was re-adjusted. Given the reduced errors once the baselines are adjusted during fatigue, it would be interesting in a future study to investigate whether the baseline during fatigue would be reliable when the person becomes alert once again. This would establish whether baselines need to be re-adjusted with the changes in alertness.

The results show that although mental fatigue has been shown to alter EEG alpha activity, resulting in an increase in alpha, this did not affect the switching times of an ECS that utilizes increases in EEG alpha activity. Furthermore, errors in switching during the fatigue state were similar to those made when participants were alert. However, we have shown that the reliability of using the hands-free ECS when fatigued can be significantly improved by adjusting the EO alpha wave baseline of the fatigue state. The Mind Switch ECS was designed for use by those who are severely disabled, who would require to use the system for extended periods of time, and under fatiguing conditions. Thus the findings of the present study are encouraging for the usability of the Mind Switch ECS, suggesting that users of a hands-free ECS will be able to continue to use the system even after they become fatigued. It is expected that the next stage of our ECS development will incorporate intelligence that can adjust EO baselines when users become fatigued.

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