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Switching Rate Changes Associated with Mental Fatigue for Assistive Technologies

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Abstract—**This paper presents research that investigated the effects of mental fatigue on brain activity associated with eyes open and eyes closed conditions. The changes associated with electroencephalography (EEG) alpha wave activity (8-13Hz) during eye closure has previously been shown to be an effective strategy for switching and activating devices as an environmental control system (ECS) designed for people with severe disability like spinal cord injury (SCI). The results showed that switching times did increase due to fatigue, however, these increases were not large (around 1 second longer to switch) and this difference was not significant. When baselines were readjusted taking into account the change in alpha wave activity due to the fatigue, switching reduced to times typically seen when the person was alert. Error rates were similar between the alert and fatigue sates. Implications of these results for a hands-free ECS are discussed.**

I. INTRODUCTION

PEOPLE with a severe neurological disability like spinal cord injury (SCI) can suffer substantial personal and social loss that can negatively affect quality of life [1]. For example, SCI persons with higher breaks such as tetraplegia, may result in a loss of walking and arm/hand function and this also means that they lose the ability to control devices in their immediate environment such as their television or computer [2]. A strategy to overcome this impairment involves providing access to assistive technology that allows the severely disabled person to regain some level of control over their living environment. Assistive technology has great potential for enhancing the capabilities of individuals with disabilities [3]. Assistive technologies (AT) have been described as devices that assist or expand human function or capabilities [4]. They provide creative solutions that enable people with disabilities to be more independent, productive and able to contribute to society and community life [5]. As such, AT has become an increasingly accepted intervention for people with disabilities [5] as they offer optimal function and a degree of independence in areas such as computer use, mobility, communication devices and access to everyday appliances.

AT that utilize interfaces with existing functional capability have been collectively called Environmental Control Systems or ECS [2]. ECS are devices that provide a switching mechanism to activate and control household and vocational devices important for daily living, such as lights, computers, televisions and other electrical equipment [6]. AT is believed to help enhance the quality of life of the disabled person as well as their caregivers, by improving the person's sense of independence and self esteem, and lessening the burden on those who care for the disabled [7]. ECS devices vary largely based on their method of activation or the switching mechanism. For instance, they range from relatively simple devices with levers and joysticks, that are activated using head, chin or finger movements to more technologically advanced voice-activated, eye movement-controlled devices, and brain computer interfaces (BCI) [2]. In the case of BCI based systems, the BCI interprets and translates voluntary changes in brain electrical activity, allowing the user to activate and control an ECS device, for instance, selecting commands to control a computer [8]. However, the operation of a BCI AT system will require a great deal of attention and concentration from the user, especially if this occurs over extended periods of time. Any task that requires extended concentration and attention will undoubtedly result in elevated mental fatigue. Kennedy and colleagues (2000) [9] have also argued that automated mechanisms could also be affected when the user becomes fatigued.

Mental fatigue is a common though negative symptom of many illnesses and disabilities. It has mental and physical components, and has been described as a change in a person's psychophysiological state due to sustained mental performance [10]. Mental fatigue symptoms consist of tiredness, drowsiness and consequent elevated risks of performance decrements [10]. The occurrence of mental fatigue has been shown to alter brain activity signals. Increases in electroencephalography (EEG) alpha (8-13Hz) and theta (3-7.5Hz) activity have been commonly reported at the onset of mental fatigue [11]. Therefore, mental fatigue is an important potential barrier to using 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.

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In this paper we describe a device that utilizes changes in brain activity using EEG alpha waves (8-13Hz) as a switching mechanism for an 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 [12]. 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 [13], 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. This paper presents results of EEG eyes open and eyes closed signals emulating a set of 3 switches while alert, followed by another set of eyes open and eyes closed switches taken up to 90 minutes later when participants were in a fatigued state. To achieve a fatigued state, participants completed a range of psychophysiological and cognitive tasks over a period of 90 minutes, and which are known to be mentally tiring.

II. METHODS

A. 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.

B. 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 30second 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 [14]. 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 [14].

C. EEG

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.

D. 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.

III. 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 ($p<0.01$)

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.

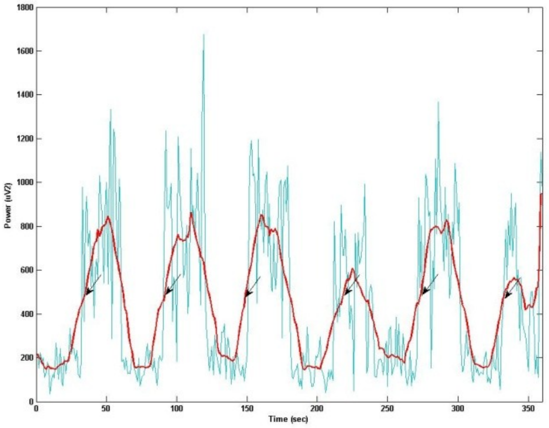

Fig. 1. Shows the EEG EOEC states for alert (0-180seconds) and fatigue (181-360seconds) conditions.

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.

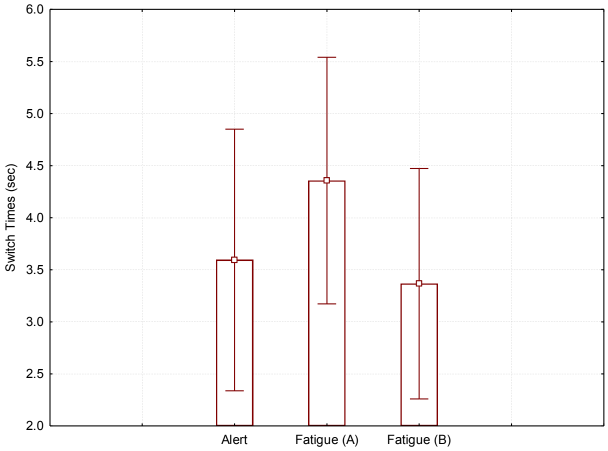

Fig. 2. Mean time taken for switching to occur following EC in Alert, Fatigue (A) and Fatigue (B). The bars represent 95% confidence intervals.

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 1
SWITCHING ERRORS DURING 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

IV. DISCUSSION

The effect of mental fatigue on the effectiveness of a hands-free ECS was investigated and presented in this paper. Users of the 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. Increases in alpha wave activity during EC 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 [13]. Our hands-free 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 [13]. 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 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 [14].

Switching times were compared between the alert and fatigue states. Surprisingly, and in contrast to the expected detrimental effect of fatigue on behavioral and cognitive performance [10], 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 was not a significant difference. Nonetheless, we were 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, errors 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 [11], 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, 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. This paper provides encouraging data that suggests 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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