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Regional brain wave activity changes associated with fatigue

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Abstract

Assessing brain wave activity is a viable strategy for monitoring fatigue when performing tasks such as driving, and numerous studies have been conducted in this area. However, results of a systematic review on changes in brain wave activity associated with fatigue have revealed equivocal findings. This study investigated brain wave activity associated with fatigue in 48 nonprofessional healthy drivers as they participated in a simulated driving task until they fatigued. The results showed that as a person fatigues, slow wave activity increased over the entire cortex, in theta and in alpha 1 and 2 bands, while no significant changes were found in delta wave activity. Substantial increases also occurred in fast wave activity, though mostly in frontal sites. The results suggest that as a person fatigues, the brain loses capacity and slows its activity, and that attempts to maintain vigilance levels lead to increased beta activity.

Descriptors: Fatigue, Electroencephalography, Brain wave activity

Fatigue is a major cause of accidents and injury when driving and when performing boring or repetitive process work tasks (Åkerstedt, Kecklund, & Knuttson, 1991; Connor et al., 2002). This is not surprising given that the increased levels of tiredness associated with fatigue have been shown to result in slowed motor reaction times and decreased cognitive attention, with examples including a diminished ability to plan and recognize signs of danger and a reduced capability to take corrective action (Dinges et al., 1997; Lamond & Dawson, 1999; Lorist et al. 2000; Nilsson, Nelson, & Carlson, 1997; Williamson, Feyer, & Friswell, 1996). Brain activity is believed to be a sensitive measure of mental fatigue (Craig, Tran, Wijesuriya, & Boord, 2006), and there have been many studies that have attempted to determine the impact of mental fatigue on brain activity (Craig & Tran, in press). First, however, it is important to distinguish between terms such as sleepiness and fatigue, given the confusion and overlap of signs between the two states (Johns, 2000; Neu, Linkowski, & Le Bon, 2010; Shen, Barbera, & Shapiro, 2006). It has been argued that sleepiness refers to the probability of falling asleep at a particular time (Johns, 2000; Neu et al., 2010; Shen et al., 2006), and that it takes into account factors such as sleep propensity, which can vary according to time, posture, and situation. Fatigue has generally been referred to as an excessive feeling of tiredness and reduced alertness, which impairs both capability and willingness to perform a task (Craig et al., 2006; Johns, 2000; Shen et al., 2006).

A systematic review of the research literature using engines such as Medline and Google Scholar (key words used in the search included fatigue, drowsiness, EEG) isolated 17 studies, conducted over a span of at least 25 years, that have examined the association between fatigue and electroencephalography (EEG). These studies have employed EEG to measure brain activity, and have all involved an examination of the changes in the EEG as a person moves from an alert status to a fatigued status. See Table 1 for reference to these 17 studies and their main findings.

Summarizing the findings of the abovementioned studies, it is clear that fatigue is associated with significant changes in brain wave activity. However, any conclusion about where and what changes occur remains unclear. Some conclusions from the 17 studies include: (a) Delta wave activity (examined in six studies) was found to increase significantly in four studies, decrease in one study, with no change in one study. The status of delta wave change associated with fatigue needs further examination. (b) Theta wave activity (examined in 16 studies) was found to increase significantly in 14 studies, with no change found in two studies. No studies found significant decreases in theta activity. Given these findings, it is likely that theta activity increases when a person fatigues; however, we do not know where in the cortex this occurs. (c) Alpha wave activity (examined in all 17 studies) was found to increase significantly in 15 studies and to decrease significantly in two studies. Alpha wave activity most likely increases when a person fatigues, although differences in activity between lower and upper alpha still require exploration, and regional differences need attention. (d) Beta wave activity change was examined in five studies, and it was found to increase significantly in two studies, decrease in one study, with no change found in two studies. The status of beta wave activity associated with fatigue remains unclear.

Methodological limitations have occurred in the majority of the 17 studies, and this introduces additional uncertainty about how brain activity changes when a person fatigues. Limitations include: (1) the employment of low numbers of participants. Nine studies employed 10 or less, and only three studies employed over 20 participants. Low sample numbers reduces the ability to generalize

We thank the 50 nonprofessional drivers who participated allowing us to explore the fatigue process further.

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PSYCHOPHYSIOLOGY

Table 1. *Details of Studies That Have Investigated EEG Changes as a Person Fatigues*

Reference/Study	No. of participants	Delta	Theta	Alpha	Beta	Sites
Åkerstedt et al., 1991	25	NS	NS	↑	NR	1 (B)
Caldwell et al., 2002	10	↑	↑	↓	NS	6
Cajochen et al., 1995	9	NR	↑	↑	NR	2
Cajochen et al., 1996	8	NR	↑	↑	NR	2
Campagne et al., 2004	46	NR	↑	↑	NR	4
Dumont et al., 1997	9	NR	↑	↑	NR	1 (M)
Eoh et al., 2005	8	NR	NS	↑	↓	8
Kecklund & Åkerstedt, 1993	18	NR	↑	↑	NR	1 (B)
Lal & Craig, 2002	35	↑	↑	↑	↑	19
Macchi et al., 2002	8	NR	↑	↑	NR	8
Pal et al., 2008	13	NR	↑	↑	NR	1 (M)
Papadelis et al., 2006	20	↓	↑	↑	NS	16
Schier, 2000	2	NR	NR	↑	NR	4
Strijkstra et al., 2003	10	NR	↑	↓	NR	28
Tanaka et al., 1997	10	↑	↑	↑	↑	12
Torsvall & Åkerstedt, 1987	11	↑	↑	↑	NR	1 (B)
Trejo et al., 2005	16	NR	↑	↑	NR	30

Notes. ↑ = significant increase in activity in EEG bands; ↓ = significant decrease in activity in EEG bands; NS = no significant change; NR = impact not reported. For single channel studies, (B) = bipolar configuration; (M) = monopolar configuration with reference to A1 or A2.

findings, as well as reducing statistical power below the accepted level of 80% (Cohen, 1988). Low statistical power will reduce chances of detecting true changes in brain wave activity (Cohen, 1988). For instance, assuming a moderate effect size of 0.5 (i.e., the standardized mean effect of fatigue on brain activity), samples of 10 to 20 will only provide 20% to 36% statistical power, respectively. (2) A second limitation involves the number of cortical sites used to assess EEG change. Low site numbers limits the ability to examine regional changes. In the 17 studies, only three employed 19 or more EEG channels, with the majority using fewer than six cortical sites. (3) A third limitation concerns the potentially high noise-to-signal ratio in the EEG wave that will occur during a task designed to cause fatigue. Artifact in the EEG recording arises from sources such as heart activity, eyeblinks, breathing, and head, facial, and neck muscle movement (Berg & Scherg, 1994; Jung et al., 2000; Mennes, Wouters, Vanrumste, Lagae, & Stiers, 2010; Tran, Craig, Boord, & Craig, 2004; Vigário, 1997). However, none of the 17 studies employed sophisticated artifact removal strategies, such as independent components analysis (ICA), capable of identifying specific sources of artifact and removing it while preserving the EEG signal of interest (Mennes et al., 2010). ICA has been shown to be a technique capable of identifying and removing artifact from the EEG signal (Dishman, Thom, Puetz, O'Connor, & Clementz, 2010; Mennes et al., 2010; Tran, Craig, Boord, & Craig, 2004). Assumptions for the effective use of ICA analysis with EEG activity have been discussed previously (Mennes et al., 2010).

The aim of this study was to measure and determine regional brain activity changes that occur as participants perform a monotonous cognitive-motor task until they showed signs of mental fatigue. The study was designed so that prior methodological weaknesses were addressed, including the use of multichannel EEG with a moderately large number of participants ($N = 50$) to ensure reasonable statistical power. Furthermore, the study was designed to control noise in the major EEG bands using artifact removal techniques.

Methods

Participants

Fifty adult participants were invited to participate in the study, who were randomly selected from a community population using a random number technique. The sample was stratified for males and females so that the proportion of male and female participants in the study would be similar, with the final number being 23 females and 27 males. The mean age of the sample was 32.6 years ($SD = 12.6$). However, data from two participants could not be used for the regional EEG analyses due to impedance problems in more than one electrode. These problems involved the presence of excessive artifact that occurred at some point during the study as a result of loss of contact of the electrode or signal drift, given that EEG recording occurred for at least 60 min. Since regional changes were a primary interest in the study, these two participants were eliminated from the analysis, leaving a final number of 48 participants. The final sample consisted of 23 females and 25 males. The mean age of the final sample of 48 was 31.5 years ($SD = 12.3$; range 18 to 55 years), and the males were similar in age to the females (male mean age = 30.5, female mean age = 32.5, $t(46) = 0.57$, p = ns).

Participants were admitted into the study only if they were free of chronic physical or psychiatric disease at the time of assessment before the study (determined by an in-house structured interview based on Diagnostic and Statistical Manual of Mental Disorders [DSM] guidelines), held a current driver's license, and reported no prior neurological disease or injury. Participants were screened for sleep disorder (self-reported) and were asked to refrain from alcohol consumption for 24 h and caffeine consumption for 12 h prior to the study. The study was approved by the University Research Ethics Committee, and participants were only entered into the study after informed consent. All participants were tested during one of two periods of the day (9:00–12:00 noon and 2:00–5:00 pm) in order to control the potential confounding influence of circadian rhythms. These two periods have been shown to be similar in circadian rhythm influence (Craig et al., 2006).

Design and Experimental Procedure

The design of the study involved a repeated measures experimental intervention. For all participants, the experimental procedure involved establishing baseline variability by assessing demographic, psychological, and electrophysiological (EEG and electrooculogram [EOG]) data. This occurred immediately before they participated in a monotonous simulated driving task. The simulated driving task involved the use of the Divided Attention Steering

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Simulator (DASS) (Stowood Scientific Instruments), which was used according to the manufacturer's instructions. The DASS has been validly used in other studies (Philip et al., 2003). Participants were instructed to "drive" in the center of the road (shown on the computer screen) till they showed signs of fatigue. The task was considered monotonous because the participants were required to drive at slow speeds (less than 60 km/h) for up to 120 min in a noise-, stimulus-, and temperature-controlled laboratory. The DASS program also required participants to perform a reaction time response to a target number that appeared in any of the four corners of the computer screen, and these were shown at random times during driving.

Recognition of Fatigue Status During the Task

Fatigue status was identified by a two-step process described below, and verified using EOG recording analysis of eye closure time. First, participants' faces were video recorded continuously during the simulated driving, and fatigue was assumed to occur when the person's face showed fatigue-related facial signs. To ensure reliable identification of fatigue onset, one of the researchers was trained using a checklist that included primary fatigue-related behaviors such as extended eye closure, increased eyeblinks, head nodding, and yawning. The video recordings were used offline to determine when participants fatigued. To determine interrater reliability of the fatigue-related behaviors, 10% of the video recordings were randomly chosen and identification of the facial symptoms assessed by a second researcher. A 90% agreement occurred between the two raters, suggesting that fatigue recognition based on facial behaviors was a reliable technique. Participation in the task was terminated when participants consistently showed any of the fatigue-related facial behaviors. Second, participation in the task was also terminated if participants made driving performance errors such as deviating off the road for more than 15 s or failure to react to the numbers appearing in the corners of the screen. Any participant who failed to show at least some of these signs of fatigue within 120 min of driving was to be eliminated from the study, and another participant randomly selected to replace them. However, no participants were eliminated, as all 48 participants showed definite signs of fatigue during the task.

EOG was recorded throughout the simulated driving. Fatigue status was verified by examining the EOG recording of all participants for increased eyeblink closure times when participants were identified as fatigued by either identification of facial behaviors or when participants made serious simulated driving errors. Eyeblink closure time approaching 400 ms is considered evidence that participants are fatigued, and this is based on the findings of Caffier, Erdmann, and Ullsperger (2003) who showed that eye closure time increases from around 200 ms when alert to around 400 ms when fatigued. EOG data was recorded using two pairs of active electrodes placed across the eyes diagonally.

Electroencephalography Measures

The Biosemi Active-Two System was used (www.biosemi.com) to record the EEG and EOG activity. Thirty-two EEG channels over the entire cortex were measured following the International 10–20 Montage System, referenced to linked ears and sampled at 1025 Hz (Klem, Luders, Jasper, & Elgar, 1999). The EEG data was subjected to fast Fourier transform (using a Hanning window) so that the following frequencies (Andreassi, 2000) could be monitored: delta activity (0.5–3.5 Hz), theta activity (4–7.5 Hz), low alpha activity (8–10 Hz), upper alpha activity (10.5–13 Hz), and beta activity (14–30 Hz). Brain activity was measured while participants, seated in an upright position, were engaged in the monotonous simulated driving task. Baseline EEG recordings were taken during a 30-s eyes-open period followed by 30 s of eyes closed. A further 2 min of data were recorded while participants had their eyes closed. EEG was then assessed throughout the simulated driving to the point when participants became tired. The 32 EEG channels were divided into nine regional areas, and these consisted of left frontal (FP1, AF3, F7, F3), right frontal (FP2, AF4, F8, F4), central left (FC5, CP5, T7, C3), central right (FC6, CP6, T8, C4), midline frontal (FC1, FC2, Fz), midline central (CP1, CP2, Cz), posterior left (PO3, P7, P3, O1), posterior right (PO4, P8, P4, O2), and midline posterior (Pz and Oz).

Psychological Measures

All participants were required to complete a validated fatigue questionnaire called the Chalder Fatigue Scale or CFS (Cella, & Chalder, 2010; Chalder et al., 1993). The CFS provides an overall indicator of fatigue symptoms, and it also provides data on physical fatigue (e.g., "Do you have problems with tiredness?" "Do you need to rest more?") and mental fatigue symptoms (e.g., "Do you have difficulty concentrating?" "Do you have problems thinking clearly?"). The 14 fatigue items were rated using a four-point Likert scale (0–3), with a maximum score of 42 and high CFS scores suggesting high levels of fatigue (Chalder et al., 1993; Deale, Chalder, Marks, & Wessely, 1997). The CFS scale has been shown to have high reliability and validity (Chalder et al., 1993). Results for the total physical and mental CFS fatigue symptom scores are reported before and after the simulated driving task.

EEG Artifact Removal

EEG signals are often contaminated by many different types of artifact and disturbance caused by eyeblinks, eye movement, muscle activity, line noise, and heart signals, making analyses of the underlying processes difficult (Delorme & Makeig, 2004). Artifact from the EEG was removed using EEGLAB toolbox (Delorme & Makeig, 2004), and specialized EEGLAB plug-ins that utilize ICA and related strategies to remove artifact from sources such as eye and muscle. In addition, there were four participant datasets that contained high levels of artifact in one channel due to loss of contact, and these channels were replaced using the spherical spline interpolation method (Perrin, Pernier, Betrand, & Echallier, 1989), which was sourced from an EEGLAB plug-in. Details of the artifact removal techniques for this toolbox can be found in Delorme and Makeig (2004). To remove artifact from the EEG in this study, second-order blind source separation (SOBI) and canonical correlation analysis (CCA) techniques were used. SOBI was used to identify and remove ocular artifact, while for the removal of shorter duration muscle bursts, CCA was used (Tran, Thuraisingham, Craig, & Nguyen, 2009). Further details on removal of artifact using these procedures from this dataset can be found elsewhere (Tran et al., 2009).

EEG and Statistical Analyses

In order to explore the relationship between regional brain activity and fatigue, the EEG was first spectrally analyzed for each of the nine cortical regions and then subjected to ICA for artifact removal (Tran, Thuraisingham, Wijesuriya, Nguyen, & Craig, 2007). For

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each cortical region, the EEG data for the cortical sites involved was averaged, producing a single EEG data point for each EEG band for each region. EEG was reported in the form of log transformed power spectral values or decibels (dB or $\mu v^2/Hz$). To determine change associated with fatigue, 1 min of EEG activity was selected while the participant was alert, and 1 min of EEG activity was selected immediately before the participant showed definite signs of fatigue. Differences in EEG activity between the alert and fatigue periods were then determined by using repeated measures multivariate analysis of variance (MANOVA). If the MANOVA was significant, univariate *F* tests were then employed to reveal where differences occurred. Eta-squared (η^2) values are provided as an estimate of the size of the difference between the two samples. An η^2 of around .03 is considered small, .13 is considered a medium difference, and over .2 is considered a large and substantial difference (Cohen, 1988). The retrospective statistical power of the MANOVA tests is also provided. All analyses were performed using Statistica Software (Version 9, Statsoft).

Results

Evidence of Fatigue Resulting from Participating in the Task

The sample was found to have significantly increased self-reported fatigue symptoms (assessed by the total CFS) as a result of the task (premean total CFS score = 12.1, $SD = 7$; postmean total CFS score = 16.9, $SD = 8$; $F(1,47) = 16.7$, $p < .001$, $\eta^2 = 0.26$). The sample also had significantly increased signs of physical fatigue (premean physical CFS score = 7.8, $SD = 4$; postmean physical CFS score = 11.3, $SD = 5$; $F(1,47) = 20.7$, $p < .001$, $\eta^2 = 0.31$), as well as significantly increased signs of mental fatigue (premean mental CFS score = 4.3, $SD = 3$; postmean mental CFS score = 5.6, $SD = 3$; $F(1,47) = 6.9$, $p < .05$, $\eta^2 = 0.13$). Eyeblink rates and eye closure time have been shown to increase when a person fatigues (Caffier et al., 2003). The rate of eyeblinks significantly increased after the participants had completed the task (premean eyeblink score = 13.5, $SD = 10$, postmean eyeblink score = 20.4, $SD = 13$, $t(47) = -3.3$, $p < .01$). Eye closure time significantly increased as a result of the fatiguing task (premean eye closure = 330 ms, $SD = 69$, postmean eye closure = 390 ms, $SD = 94$, $t(47) = 4.8$, $p < .001$).

Circadian Influence of EEG Levels as a Function of the Task

Similar changes in brain wave activity associated with the simulated driving task were found in those participants ($n = 19$) assessed in the morning (9:00–12:00 noon) compared with those ($n = 29$) assessed in the afternoon (2:00–5:00 pm). For example, no significant differences were found for frontal alpha 1 activity (left, mid, and right regions) as a function of time measured (Wilks' lambda = .91, $F(3,45) = .97$, p = ns). Similar nonsignificant results were found for the other bands. Therefore, the participants were examined as a single group for regional changes in brain activity.

Regional Changes in Brain Activity

Male and female participants did not significantly differ in their EEG activity as a function of the simulated driving task. Thus, both male and female participants were assessed as a single sample for their regional brain activity changes. Figure 1 shows spectral power changes resulting from fatigue in comparison to the alert status. Figure 2 shows topographical power changes for theta, alpha 1, alpha 2, and beta wave activity for all 48 participants.

Delta wave results. No significant changes occurred in the delta band associated with fatigue for frontal (Wilks' lambda = 0.98, $F(3,45) = .16$, p = ns), central (Wilks' lambda = 0.90, $F(3,45) = 1.7$, p = ns), or posterior regions (Wilks' lambda = 0.90, $F(3,45) = 1.6$, p = ns).

Theta wave results. Significant changes in theta wave activity power were found in frontal regions (Wilks' lambda = 0.69, $F(3,45) = 6.6$, $p < .01$; $\eta^2 = 0.31$, power = 96%), central regions (Wilks' lambda = 0.77, $F(3,45) = 4.4$, $p < .01$, $\eta^2 = 0.22$,

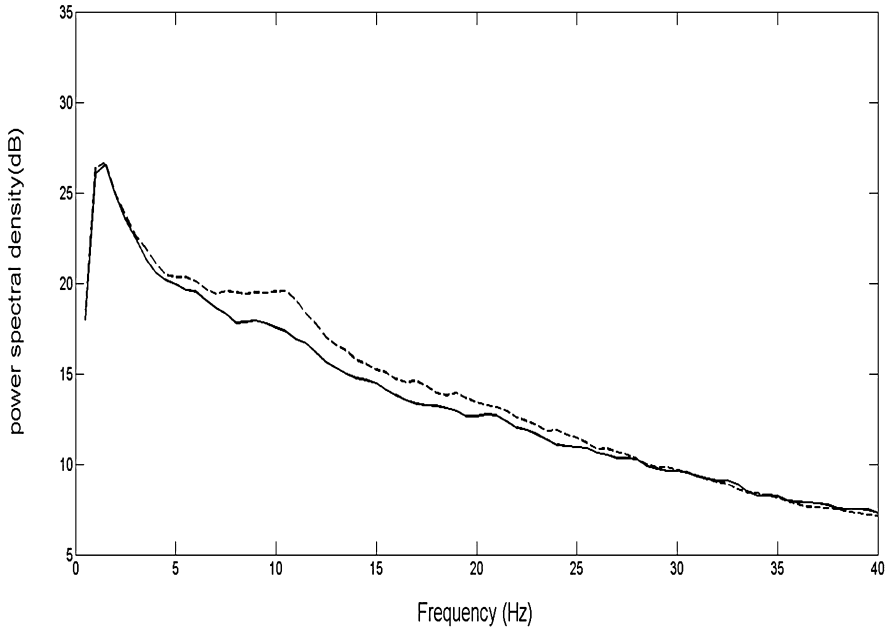

Figure 1. EEG power spectrum from alert (solid line) to fatigue (dashed line) from 32 channels in the 48 participants.

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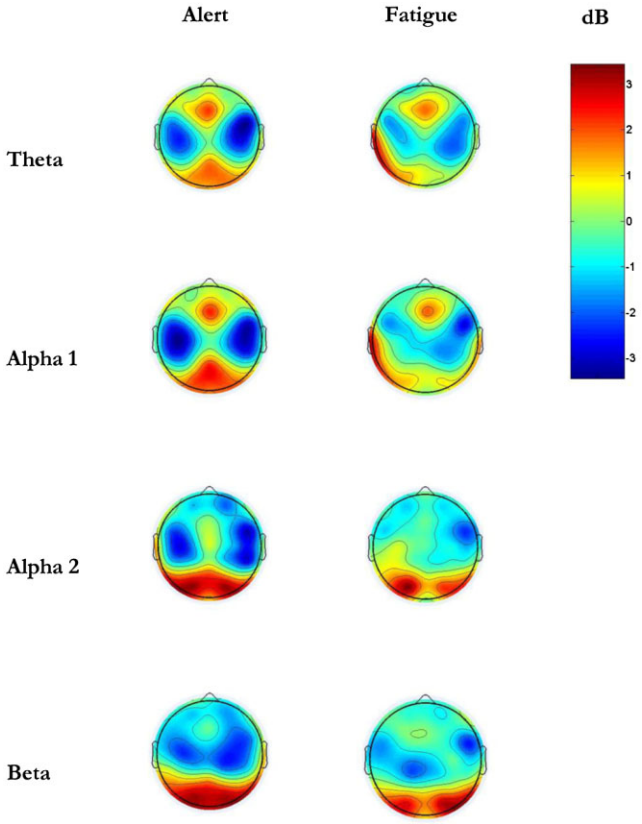

Figure 2. Topographical head maps of the mean power (dB) during alert and fatigue conditions in theta, alpha 1, alpha 2, and beta bands for all 48 participants.

power = 84%), and posterior regions (Wilks' lambda = 0.68, $F(3,45) = 7.1$, $p < .01$, $\eta^2 = 0.32$, power = 97%). Table 2 shows the demographic data for the "alert" versus "fatigue" EEG power spectral densities across the nine regions, as well as the ANOVA results. Theta wave power significantly increased in all regions and the size of the fatigue effect (η^2) was large, with eta squared averaging around 0.2.

Alpha 1 wave results. Significant changes in alpha 1 wave power were found in frontal regions (Wilks' lambda = 0.60, $F(3,45) = 10.0$, $p < .001$; $\eta^2 = 0.40$, power = 99%), central regions (Wilks' lambda = 0.52, $F(3,45) = 13.7$, $p < .001$, $\eta^2 = 0.48$, power = 99%), and posterior regions (Wilks' lambda = 0.52, $F(3,45) = 13.8$, $p < .001$, $\eta^2 = 0.48$, power = 99%). Table 3 shows demographic data for the "alert" versus "fatigue" EEG power spectral densities across the nine regions, as well as the ANOVA results. Alpha 1 wave power significantly increased in all nine regions. The size of the fatigue effect (η^2) for increased alpha 1 wave activity was large all over the cortex; however, there seemed to be a trend for larger increases towards the central and posterior regions, as shown by consistently large η^2 values of 0.4 or greater.

Alpha 2 wave results. Significant changes in alpha 2 wave activity power were found in frontal regions (Wilks' lambda = 0.62, $F(3,45) = 9.3$, $p < .001$; $\eta^2 = 0.38$, power = 99%), central regions (Wilks' lambda = 0.58, $F(3,45) = 10.8$, $p < .001$, $\eta^2 = 0.42$, power = 99%), and posterior regions (Wilks' lambda = 0.65, $F(3,45) = 8.2$, $p < .001$, $\eta^2 = 0.35$, power = 99%). Table 4 shows demographic data for the "alert" versus "fatigue" EEG power spectral densities across the nine regions, as well as the ANOVA results. Alpha 2 wave power significantly increased in all nine regions. The size of the fatigue effect (η^2) for increased alpha 2 wave activity was large all over the cortex, with η^2 values consistently around 0.3 or over.

Beta wave results. Significant changes in beta wave activity power were found in frontal (Wilks' lambda = 0.49, $F(3,45) = 15.6$, $p < .001$; $\eta^2 = 0.51$, power = 99%), central regions (Wilks' lambda = 0.57, $F(3,45) = 11.2$, $p < .001$, $\eta^2 = 0.43$, power = 99%), and posterior regions (Wilks' lambda = 0.76, $F(3,45) = 4.8$, $p < .01$, $\eta^2 = 0.24$, power = 88%). Table 5 shows demographic data for the "alert" versus "fatigue" EEG power spectral values across the nine regions, as well as the ANOVA results. Beta wave power significantly increased in all nine regions, with a trend for the increase in beta activity associated with fatigue to become smaller towards the posterior region of the cortex.

Discussion

This study investigated regional brain wave activity changes associated with a simulated driving task designed to fatigue the 48 healthy adult participants. The participants were shown to fatigue as a consequence of the task based on (a) the significant increase in

Table 2. *Averaged Power Spectral Values (dB) for Theta Wave Activity Across Nine Regions for the 48 Participants*

Region	Alert Mean (*SD; SE*)	Fatigue Mean (*SD; SE*)	ANOVA				Direction of change
			F	*p*	η^2	Power	
Frontal							
Left	29.5 (2.7; 0.4)	30.4 (2.7; 0.4)	19.6	<.001	0.29	99	↑
Mid	29.7 (2.2; 0.3)	30.4 (2.6; 0.4)	9.3	.004	0.17	85	↑
Right	29.9 (2.8; 0.4)	30.5 (2.7; 0.4)	10.9	.002	0.19	90	↑
Central							
Left	27.6 (2.5; 0.4)	28.3 (2.8; 0.4)	11.8	.001	0.20	92	↑
Mid	28.2 (2.0; 0.3)	28.7 (2.5; 0.4)	6.1	.017	0.12	68	↑
Right	27.3 (2.4; 0.4)	27.9 (2.6; 0.4)	12.0	.001	0.20	92	↑
Posterior							
Left	30.1 (2.1;0.3)	31.0 (2.1; 0.3)	18.1	<.001	0.28	99	↑
Mid	30.3 (2.3; 0.3)	31.1 (2.1; 0.3)	18.2	<.001	0.28	99	↑
Right	30.0 (2.7; 0.4)	30.8 (2.5; 0.4)	16.5	<.001	0.26	98	↑

Notes. Effect size (η^2) and power expressed as a percentage. *SD* = standard deviation; *SE* = standard error of the mean; ↑ = significant increase; degrees of freedom for the ANOVA = (1,47).

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Table 3. *Averaged Power Spectral Values (dB) for Alpha 1 Wave Activity Across Nine Regions for the 48 Participants*

Region	Alert Mean (*SD*; *SE*)	Fatigue Mean (*SD*; *SE*)	ANOVA				Direction of change
			F	*p*	η^2	Power	
Frontal							
Left	24.6 (3.1; 0.4)	26.6 (3.9; 0.6)	28.9	<.001	0.38	99	↑
Mid	24.5 (2.8; 0.4)	26.4 (3.9; 0.6)	25.8	<.001	0.35	99	↑
Right	24.9 (3.1; 0.4)	26.8 (3.7; 0.5)	28.9	<.001	0.38	99	↑
Central							
Left	23.4 (3.4; 0.5)	25.5 (4.3; 0.6)	24.2	<.001	0.34	99	↑
Mid	23.9 (2.7; 0.4)	26.3 (3.6; 0.5)	32.6	<.001	0.41	99	↑
Right	22.9 (3.0; 0.4)	25.2 (3.9; 0.6)	36.0	<.001	0.43	99	↑
Posterior							
Left	26.0 (2.7; 0.4)	28.2 (3.9; 0.6)	36.9	<.001	0.44	99	↑
Mid	26.1 (2.8; 0.4)	27.9 (3.5; 0.5)	33.0	<.001	0.41	99	↑
Right	25.9 (3.3; 0.5)	27.9 (4.0; 0.6)	41.1	<.001	0.47	99	↑

Notes. Effect size (η^2) and power expressed as a percentage. *SD* = standard deviation; *SE* = standard error of the mean; ↑ = significant increase; degrees of freedom for the ANOVA = (1,47).

self-reported fatigue levels assessed by the CFS, and (b) the significant increase in blink rate and eye closure time. Sources of artifact in the EEG signal, such as upper body movement and eyeblinks, were successfully removed by using ICA analysis, leaving a low noise-to-signal ratio, thus retaining the EEG signal of interest. Thirty-two channels of EEG were recorded, allowing the determination of spectral changes (see Figure 1) and regional changes in brain wave activity (see Figure 2). The study also employed a heterogeneous sample of adults with a sufficient sample size that resulted in statistical power of greater than 90% for the majority of the analyses (Cohen, 1988).

The study confirmed the findings of prior research in that brain activity was shown to change significantly as a person fatigues (Craig & Tran, in press). The findings clarify (a) which EEG bands change, and (b) whether these changes are global or regionally based. Greatest change associated with fatigue was found in the 4–13 Hz band. Significant global cortical change was found for the theta, alpha 1, and alpha 2 bands with large to very large effect sizes occurring. Notably, no significant change was found below 4 Hz in any cortical region, that is, in the delta wave activity band. Significant regional increases in spectral power were also found in the 14–20 Hz band, that is, in beta wave activity. Substantial increases in beta spectral power were found in frontal sites and the midcentral site, while smaller changes were found in the left and right central sites and in the three posterior sites.

In an alert brain, the variation in theta and alpha band power is related to complex cognitive and memory performance (Klimesh, 1999; Klimesh, Schack, & Sauseng, 2005). Synchronization in the theta band is possibly related to working memory function, alpha 1 activity may be related to attention, while upper alpha may be related to long-term memory function (Klimesh, 1999). Furthermore, depending on cognitive demands, Klimesh (1999) contended that cognitive performance is related to either an increase in alpha wave power contingent with a decrease in theta power, or a phasic event-related decrease in alpha wave power contingent with an increase in theta power. Sauseng, Klimesh, Schabus, and Doppelmayr (2005) showed that a decrease in anterior upper alpha activity was related to prefrontal executive function such as working memory. Jensen and Tesche (2002) found that frontal theta activity was related to working memory, while Aftanas and Golocheikine (2001) showed that a positive emotional state was related to increased frontal and midline theta activity combined with lowered alpha activity.

In contrast, the global increases found in this study in the 4–13 Hz band support the conclusion that the brain is slowing its activity resulting in reduced cognitive capacity seen when someone

Table 4. *Averaged Power Spectral Values (dB) for Alpha 2 Wave Activity Across Nine Regions for the 48 Participants*

Region	Alert Mean (*SD*; *SE*)	Fatigue Mean (*SD*; *SE*)	ANOVA				Direction of change
			F	*p*	η^2	Power	
Frontal							
Left	23.8 (3.1; 0.4)	25.5 (3.6; 0.5)	25.7	<.001	0.35	99	↑
Mid	23.1 (3.0; 0.4)	25.0 (3.8; 0.6)	23.7	<.001	0.34	99	↑
Right	24.0 (3.0; 0.4)	25.7 (3.6; 0.5)	28.3	<.001	0.38	99	↑
Central							
Left	22.8 (3.1; 0.4)	24.8 (3.5; 0.5)	32.0	<.001	0.41	99	↑
Mid	22.9 (2.9; 0.4)	24.8 (3.5; 0.5)	29.4	<.001	0.38	99	↑
Right	22.4 (3.9; 0.4)	24.3 (3.5; 0.5)	25.8	<.001	0.35	99	↑
Posterior							
Left	25.9 (3.0; 0.4)	27.8 (3.9; 0.6)	24.0	<.001	0.34	99	↑
Mid	25.5 (3.1; 0.4)	27.1 (3.6; 0.5)	24.1	<.001	0.34	99	↑
Right	25.7 (3.6; 0.5)	27.8 (4.5; 0.7)	21.5	<.001	0.31	99	↑

Notes. Effect size (η^2) and power expressed as a percentage. *SD* = standard deviation; *SE* = standard error of the mean; ↑ = significant increase; degrees of freedom for the ANOVA = (1,47).

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Table 5. *Averaged Power Spectral Values (dB) for Beta Wave Activity Across Nine Regions for the 48 Participants*

Region	Alert Mean (*SD*; *SE*)	Fatigue Mean (*SD*; *SE*)	ANOVA				Direction of change
			F	*p*	η^2	Power	
Frontal							
Left	28.8 (2.4; 0.3)	29.8 (2.5; 0.4)	24.8	<.001	0.34	99	↑
Mid	27.5 (1.9; 0.3)	28.6 (1.8; 0.3)	35.1	<.001	0.43	99	↑
Right	29.2 (2.4; 0.4)	30.2 (2.5; 0.4)	29.0	<.001	0.38	99	↑
Central							
Left	27.8 (2.2; 0.3)	28.4 (2.2; 0.3)	8.7	.005	0.16	82	↑
Mid	26.8 (1.9; 0.3)	27.9 (1.9; 0.3)	34.3	<.001	0.42	99	↑
Right	27.7 (2.1; 0.3)	28.4 (2.3; 0.3)	8.8	.005	0.16	83	↑
Posterior							
Left	30.1 (1.9;0.3)	30.8 (1.9; 0.3)	14.9	<.001	0.24	97	↑
Mid	29.5 (2.4; 0.4)	30.6 (2.4; 0.3)	10.2	.003	0.18	88	↑
Right	30.1 (1.9; 0.3)	30.0 (2.0; 0.3)	6.0	.018	0.11	67	↑

Notes. Effect size (η^2) and power expressed as a percentage. *SD* = standard deviation; *SE* = standard error of the mean; ↑ = significant increase; degrees of freedom for the ANOVA = (1,47).

fatigues (Klimesh, 1999). When someone mentally tires, the complex synchronization–desynchronization patterns seen in the 4–13 Hz band associated with alert functioning (Klimesh, 1999) can be assumed to be disrupted. Lowered cognitive capacity associated with increased performance decrement due to fatigue seems to be related to global increase in theta, alpha 1, and alpha 2 wave power. Indeed, others have shown that theta and alpha band power increases are associated with decreased arousal (Klimesh, 1999; Markand, 1990). Klimesh (1999) has also argued that the increased alpha 1 power associated with fatigue is related to increased mental effort to maintain vigilance levels. Dirnberger, Duregger, Trettler, Lindinger, and Lang (2004) studied the relationship between movement-related cortical potentials and fatigue. They found that lower amplitudes in movement potentials were associated with greater levels of fatigue. Dirnberger et al. (2004) suggested this supports the notion that fatigue reduces cortical arousal leading to lowered cognitive capability. Lehmann, Grass, and Meier (1995) conducted canonical analyses between cognitive capacity and EEG spectral power profiles. They concluded that fatigue was associated with reduced cortical arousal demonstrated by reduced cognitive performance such as poor orientation and low recall ability. Interestingly, global increases in the 4–13 Hz band have also been found to occur in contexts that result in fatigue-like effects, such as when someone drinks alcohol excessively (Tran, Craig, Bartrop, & Nicholson, 2004). Global increases in 4–13 Hz wave activity were found in people ingesting moderate doses of alcohol up to a blood alcohol concentration of .03% (Tran, Craig, Bartrop, & Nicholson, 2004).

The majority of studies reviewed above that included delta wave activity in their experimental assessment found significantly increased delta wave activity associated with fatigue. However, our study failed to find significant increases in delta wave power associated with fatigue. This was not a surprising finding. Delta wave activity is believed to be either a natural sleep wave or a pathological slow wave (Steriade, Gloor, Llinas, Lopes da Silva, & Mesulam, 1990). Therefore, one would not have expected to find prominent increases in delta wave activity in the sample of 48 adults when they became mentally fatigued. Also, the sample was relatively healthy, making it unlikely that the participants would have prominent pathological slow wave activity in their EEG. It is possible, then, that prior studies that have found increased delta wave power associated with fatigue are confounded, such as the study by Lal and Craig (2002). That is, the increased delta wave activity is a product of a failure to remove artifact from the EEG signal, given that artifact substantially invades low EEG frequencies in the 1–4 Hz range (Makeig, Jung, Bell, & Sejnowski, 2002).

Beta wave activity is not well understood, and its functional role remains only partially explained (Jensen et al., 2005). For instance, research has shown that increased beta wave activity generated in the motor cortex is related to slowed motor behavior (Pogosyan, Gaynor, Eusebio, & Brown, 2009). A decrease of beta wave power (i.e., desynchronization) is believed to be an indicator of movement preparation, execution, and motor imagery (Pfurtscheller & Neuper, 1997; Zhang, Chen, Bressler, & Ding, 2008). An arousal-based theory approach to brain activity (Andreassi, 2000) may help explain the increase beta wave activity found when someone fatigues. The arousal theory suggests increased beta activity is associated with increased mental activity or arousal (Andreassi, 2000). It is therefore possible that the large increases in beta wave power, found in the frontal and midcentral cortical regions, were a result of the participants exerting increased mental effort to remain vigilant during the simulated driving. The exertion is an attempt to counteract the influence of increasing fatigue levels. This may explain why large increases in levels of beta activity were found mostly in the frontal sites, where functions such as working memory and decision making are believed to reside (Andreassi, 2000). Alternatively, the increased beta wave activity could be a result of slowed motor activity due to the participants tiring during the task.

A minor limitation in this research included the sample size being reduced from 50 to 48 due to a loss of signal in some electrodes. However, an *N* of 48 did provide acceptable retrospective statistical power of at least 90%, mostly because the standardized changes (effect sizes) in brain activity were large. Future research should also assess EEG power changes over the entire period of the fatiguing task, so as to better understand how the brain changes its function over time as fatigue levels increase. It may also be beneficial to examine fatigue changes using nonlinear and complexity signal processing approaches such as second-order difference plots or fractal dimension analyses (Tran, Thuraisingham, Boord, Nguyen, & Craig, 2007; Tran, Thuraisingham, Wijesuriya, et al., 2007), as this may enhance our understanding of the complex way that fatigue influences the brain. Further, the use of self-report for chronic alcohol and substance use may need to be reinforced by objective measures such as blood alcohol content, given that

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chronic substance abuse may affect fatigue symptoms (Tran, Craig, Bartrop, & Nicholson, 2004). In conclusion, the findings of this research have helped to clarify the EEG frequencies affected by fatigue, as well as which regions of the cortex are affected. This provides enhanced opportunities to design smart fatigue countermeasure technology based on brain activity that is able to target known changes in EEG band frequency and power, as well as which specific regions to assess. It is hoped these findings provide a rich source of information that can be applied to lower risks of fatigue-related accidents.

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