

Inter-hemispheric electroencephalography coherence analysis: assessing brain activity during monotonous driving

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Abstract

The current study investigated the effect of monotonous driving on inter-hemispheric electroencephalography (EEG) coherence. Twenty-four non-professional drivers were recruited to perform a fatigue instigating monotonous driving task while 30 channels of EEG were simultaneously recorded. The EEG recordings were then divided into 5 equal sections over the entire driving period for analysis. Inter-hemispheric coherence was computed from 5 homologous EEG electrode pairs (FP1-FP2, C3-C4, T7-T8, P7-P8, and O1-O2) for delta, theta, alpha and beta frequency bands. Results showed that frontal and occipital inter-hemispheric coherence values were significantly higher than central, parietal, and temporal sites for all four frequency bands ($p < 0.0001$). In the alpha frequency band, significant difference was found between earlier and later driving sections ($p = 0.02$). The coherence values in all EEG frequency bands were slightly increased at the end of the driving session, except for FP1-FP2 electrode pair, which showed no significant change in coherence in the beta frequency band at the end of the driving session.

Keywords: Fatigue; Inter-hemispheric coherence; Electroencephalography;
Monotonous driving; Countermeasure

1. Introduction

Fatigue has been identified as an occupational hazard for long-distance or professional drivers who are under pressure to reach the scheduled destination (Brown, 1997; Williamson & Boufous, 2007). Prolonged monotonous driving can cause fatigue, which impairs cognitive skills and affects the ability to monitor and assess the drivers' ability to monitor and assess their fitness to continue driving (Brown, 1997; Lal & Craig, 2002). Fatigue can be avoided if drivers are willing to stop driving to have a quick rest when feeling fatigued or unable to drive safely (Brown, 1994). However, most drivers would ignore obvious signs of fatigue and would continue driving (Smith et al., 2005). Therefore, automatic fatigue detection monitors would be useful to warn drivers of their fatigue levels and prevent accidents (Brown, 1994; Lal & Craig, 2001).

Several methods of fatigue detection have been researched, and the electroencephalography (EEG) has been found to be one of the most reliable fatigue indicator (Artaud et al., 1994). Several fatigue detection algorithms that utilise the different frequency bands of brain activities have been proposed (Eoh et al., 2005; Jap et al., 2007, 2009; Lal et al., 2003; Tietze, 2000). However, EEG coherence changes have not been researched in detail as a possible means for a fatigue detection technique.

The EEG coherence analysis is a non-invasive technique that can be applied to study functional relationships between spatially separated scalp electrodes and to estimate the similarities of waveform components generated by the mass action of neurons in

the underlying cortical regions (French & Beaumont, 1984; Shaw, 1984; Wada et al., 1996a). EEG coherence is a statistical measure for the correlation of the spatially separated signals within a certain frequency band (Volf & Razumnikova, 1999), or in other words, it is a correlation analysis as a function of EEG frequency (Shaw, 1981). There are four frequency bands that are normally derived from EEG recordings, which are delta (0-4 Hertz (Hz)), theta (4-8 Hz), alpha (8-13 Hz), and beta (13-35 Hz) (Fisch, 2000; Stern & Engel, 2005).

Several studies in the past have used EEG coherence analysis to investigate functional changes in different situations, such as in normal subjects when controlling simple and complex motor functions (Pulvermüller et al., 1995), in comparison between normal elderly and those with Alzheimer's disease (Kikuchi et al., 2002), and in effects of aging in normal subjects (Duffy et al., 1996).

Some studies have analysed EEG coherence during sleep (Armitage et al., 1993; Corsi-Cabrera et al., 1996; Dumermuth et al., 1983). During sleep, decreasing pattern of inter-hemispheric coherence from the waking state until sleep stage 4 was observed in all EEG frequency bands, although synchronisation of slow frequency bands was still considerably high (Banquet, 1983). However, there is still some controversy with other studies reporting that inter-hemispheric coherence increases during sleep (Dumermuth et al., 1983; Dumermuth & Lehmann, 1981).

Studies have also looked at EEG coherence while performing mental processing activities, while the subjects are in an alert state (Busk & Galbraith, 1975; Çiçek & Nalcaci, 2001; Gasser et al., 1987). Busk and Galbraith (1975) observed higher inter-

hemispheric coherence with an increase of task difficulty, while practice reduced the inter-hemispheric coherence as a result of a decrease in task difficulty. Çiçek and Nalcaci (2001) supported the observation by Busk and Galbraith (1975) that greater bilateral alpha activity was correlated with higher performance.

However, only a few studies have looked at the effect of fatigue on EEG coherence. Changes in the inter-hemispheric coherence was observed during transition from alert state to light fatigue (Boldyreva & Zhavoronkova, 1991), which suggested an alteration of cerebral functional organisation between the two states (Wada et al., 1996b). Inter-hemispheric coherence was found to be significantly lower when subjects were in light fatigue state than during the alert state for alpha and beta frequency bands (Wada et al., 1996b). Boldyreva and Zhavoronkova (1991) also found decreased inter-hemispheric coherence when subjects are in a state of fatigue.

Although some studies in the literature have investigated the changes in inter-hemispheric coherence during light fatigue, little has been reported on changes in the inter-hemispheric EEG coherence during monotonous driving sessions. Hence, the aim of the current study was to investigate the inter-hemispheric EEG coherence changes during a monotonous driving task in light of future development of fatigue countermeasure system.

2. Materials and Methods

Twenty-four participants (12 males and 12 females, age range: 20 – 70 years, mean: 29.5 ± 12.4 years), who were non-professional drivers holding a current driver's

license, were recruited to perform monotonous driving for the study. The Institute's Human Research Ethics approval was obtained. All participants had provided informed consent prior to participating in the study. In order to participate in the study, participants had to comply with the following: "no medical contraindications such as severe concomitant disease, alcoholism, drug abuse, and psychological or intellectual problems likely to limit compliance" (Craig et al., 1996).

This study was conducted in a temperature-controlled laboratory around noon \pm 1.5 hours (starting at approximately 10 – 10:30 am to approximately 13:30 pm). Studies have shown that caffeine and alcohol intake can affect the brain activity (Kenemans & Lorist, 1995; Lumley et al., 1987). Therefore, nicotine, caffeine, tea, and food intake were restricted for approximately 4 hours, while alcohol intake was restricted for 24 hours prior to the study. Participants reported compliance with these instructions. A fatigue Likert scale questionnaire that asked the current state of the participants (alert, slightly drowsy, moderately drowsy, and markedly drowsy) was administered prior to and after the study.

The driving simulator used was Grand Prix 2 software (version 1.0b, 1996, Microprose Software, Inc., USA). The computer screen displayed other cars, driving environment, the current speed, and other road stimuli. The simulator consisted of a car frame with an in-built steering wheel, brakes, accelerator, and gears.

All participants were required to complete 2 types of driving sessions, which are the alert driving task for 10-15 minutes and the monotonous driving task for about 1 hour. During the alert driving task, participants were provided a track that involved driving

with many cars and other road stimuli. All other cars and road stimuli were removed for the monotonous driving task, and participants were asked to maintain a driving speed between 60-80 km/h.

Simultaneous physiological measurements were obtained during the two driving sessions, i.e., the alert and the monotonous driving sessions. The NeuroScan physiological recording system (Compumedics, Australia) was used to record the physiological data. Thirty channels of electroencephalography (EEG), sampled at 1000 Hz, were acquired simultaneously during both driving sessions. The international standard 10-20 system of electrode placement was applied (Jasper, 1958). A referential montage was used for acquiring data with the reference point located at the position between the midline central electrode (Cz), and the midline central parietal electrode (CPz). Vertical electrooculogram (VEOG) was also acquired and used to identify blink artefacts in the EEG recording.

The acquired EEG data of the active and monotonous driving sessions were segmented into 1-second epochs. The EEG recording for the monotonous driving session was divided into 5 equal sections of approximately 10 minutes per section. Sixty artefact-free epochs from the middle data segment of each monotonous driving section and active driving session were selected to compute the cross-power spectra or coherence between homologous inter-hemispheric electrode pairs. Five homologous inter-hemispheric electrode pairs were chosen to represent 5 different brain sites, which were frontal (FP1-FP2), central (C3-C4), temporal (T7-T8), parietal (P7-P8), and occipital (O1-O2) (refer to Figure 1). Frequency bands, for which coherences

were computed, were delta (1.5-4 Hz), theta (4-8 Hz), alpha (8-13 Hz), and beta (13-35 Hz).

Insert Figure 1 about here

The coherence spectrum function, C_{xy} , for two given signals, x and y , is defined as, $C_{xy}(f) = |P_{xy}(f)|^2 / (P_{xx}(f) \cdot P_{yy}(f))$, with f denoting frequency, and P power or cross-power (Achermann & Borbély, 1998). $|P_{xy}(f)|$ is the cross-spectrum between signals x and y , while $P_{xx}(f)$ and $P_{yy}(f)$ are the auto-spectrum of the signals x and y respectively (Guevara & Corsi-Cabrera, 1996).

Statistica software (for Windows, version 7, 2005, StatSoft Inc, USA) was used for the data analysis. One factor Analysis of Variance (ANOVA) was performed to identify significant differences between coherence values (dependent) at different electrode pairs (independent), as well as between the 5 sections during monotonous driving and the alert baseline (independent). This analysis was performed for all EEG frequency bands, delta, theta, alpha, and beta. Significant level was reported at $p < 0.05$.

3. Results and statistical analyses

The average driving time was 67 ± 11 minutes. Continuous and monotonous driving for approximately 30 minutes has been previously demonstrated to lower alertness levels of a driver (Gillberg et al., 1996). Participants reported to be in an alert state at

the beginning of the study, and reported to be moderately fatigued at the end of the study.

Analysis of Variance (ANOVA) results revealed some significant differences between the different electrode pairs. Significant differences reported in the result section could be related to the micro-sleep periods as the result of fatigue instigating monotonous driving session. Significant differences were found with delta ($F(4,19)=67.79$, $p<0.0001$), theta ($F(4,29)=125.06$, $p<0.0001$), alpha ($F(4,33)=179.2$, $p<0.0001$), and beta ($F(4,22)=124.6$, $p<0.0001$). Significant differences were also found between the different driving sections, which were only found in delta ($F(5,1)=2.44$, $p=0.03$), and alpha activities ($F(5,1)=2.76$, $p=0.02$). Post-hoc Bonferroni analysis was then performed for each ANOVA result that was significantly different to identify the electrode pairs and driving sections at which these differences existed.

3.1 Differences between electrode pairs

Post-hoc Bonferroni analysis for the different electrode pairs revealed significant differences between frontal (FP1-FP2) site compared to central (C3-C4) (lower coherence) ($p < 0.0001$), parietal (P7-P8) (lower coherence) ($p < 0.0001$), and temporal (T7-T8) (lower coherence) ($p < 0.0001$) sites in all frequency bands (delta, theta, alpha, and beta). The coherence values in frontal and occipital (O1-O2) (lower coherence) sites were significantly different only for delta ($p = 0.0004$), theta ($p = 0.03$), and beta ($p = 0.0002$) activities. Coherence values in both parietal ($p < 0.02$) and occipital ($p < 0.0001$) sites were significantly different from the temporal sites (lower coherence) for all frequency bands, while significant difference between

temporal and central sites (lower coherence) was only found in alpha frequency band ($p = 0.02$). Coherence at central (lower coherence) and occipital sites (higher coherence) were significantly different from the parietal site for delta ($p < 0.003$), theta ($p < 0.0001$), and alpha ($p < 0.0001$) activities, while significant difference was only found between the parietal and occipital (higher coherence) for beta ($p < 0.0001$). Coherence values at central and occipital (higher coherence) sites were significantly different for all frequency bands ($p < 0.0001$).

3.2 Differences between driving sections

Post-hoc Bonferroni analysis for the five driving sections only revealed significant difference for alpha frequency band, between driving sections 1 and 5 ($p = 0.02$) (increased coherence). Other driving sections did not reveal any significant differences in activity for all frequency bands.

3.3 Differences between electrode pairs for each driving section

When Post-hoc Bonferroni analysis was performed between electrode pairs for each driving section, several significant differences were revealed.

For delta frequency band, both central ($p < 0.007$) and temporal ($p < 0.02$) sites were significantly different to the frontal sites for all driving sections, while only a few driving sections were found to be significantly different between frontal and parietal sites ($p < 0.02$), and between occipital site and both central ($p < 0.04$) and temporal ($p < 0.04$) sites.

Theta EEG activity at both central ($p < 0.0001$) and temporal ($p < 0.002$) sites were significantly different to the frontal site for all driving sections, and almost all driving sections revealed significant differences between frontal and parietal sites ($p < 0.03$), and between occipital and both parietal ($p < 0.03$) and temporal ($p < 0.03$) sites.

Coherence at the frontal site was significantly different to central ($p < 0.0001$), parietal ($p < 0.002$), and temporal ($p < 0.0001$) sites for all driving sections for both alpha and beta frequency bands, and coherence at the occipital site was significantly different to central ($p < 0.0001$) and temporal ($p < 0.003$) sites for all driving sections, and to parietal site ($p < 0.04$) for most driving sections.

Figures 2-5 show the coherence results for the five electrode pairs plotted over the driving sections for all frequency bands. In all frequency bands, the frontal (FP1-FP2) and occipital (O1-O2) electrode pairs always showed higher coherence values than other electrode pairs, with the frontal electrode pair showing highest coherence values for almost all driving sessions in all frequency bands, except for beta, in which the occipital electrode pair showed the highest coherence values.

Post-hoc Bonferroni results between the electrode pairs and the driving sections showed significant differences in driving sections between the frontal and the central, parietal, and temporal sites, and between the occipital and the central, parietal, and temporal sites. This can clearly be observed in Figures 2-5. The coherence values for frontal and occipital sites in all driving sessions were well above the coherence values for the other sites, and hence were significantly different from coherence values for the central, parietal, and temporal sites.

Insert Figure 2 about here

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4. Discussion

EEG coherence is a frequency specific measure of the degree of pairing between spatially separated brain electrode locations (Ford et al., 1986a; French & Beaumont, 1984; Shaw, 1984). Since coherence is derived from correlation measures, coherence are usually interpreted as a reflection of functional and structural connectivity (Ford et al., 1986b; Guevara & Corsi-Cabrera, 1996). Inter-hemispheric EEG coherence is affected by several factors, such as age and sex (Beaumont et al., 1978; Marosi et al., 1993; Wada et al., 1994), tasks (Jaušovec & Jaušovec, 2000; Rescher & Rappelsberger, 1999), as well as the arousal level of the subject (Wada et al., 1996b).

The current study has investigated EEG coherence changes during a monotonous - driving task, and focused on establishing whether there was any EEG coherence changes associated to monotonous driving, and whether coherence analysis could be used as a marker of changes in monotonous driving activity. Five electrode-pairs (FP1-FP2, C3-C4, P7-P8, T7-T8, and O1-O2) were selected to represent the five brain

sites, which are frontal, central, parietal, temporal, and occipital. The result of the current study showed that inter-hemispheric coherence was higher at the frontal and occipital sites, while other sites showed lower coherence level throughout the driving sessions. Busk and Galbraith (1975) suggested that areas of the brain that were active during a particular task would show higher inter-hemispheric coherence. Higher coherence levels at the frontal and occipital areas of the brain might show higher motor (frontal) and visual processing (occipital) while driving, and hence required higher synchronisation of both brain hemispheres (Ellis, 1992; Kiernan, 1987). Frontal region of the brain houses the motor cortex, and appears to perform intellectual processing (Ellis, 1992), while occipital region is known to perform visual processing to provide full recognition and understanding of images from the eyes (Kiernan, 1987).

In the current study, the coherence level showed a small increase from the beginning to the end of the monotonous driving session at almost all electrode pairs for almost all EEG frequency bands. This contradicted the result found in the literature. For example, Wada et al. (1996b) has found that inter-hemispheric coherence decreased with the decrease of alertness level for alpha and beta bands. This may be due to the completely different tasks performed in the two studies. When conducting their experiment, Wada et al. (1996b) required the subjects to sit and stay still while trying to stay alert for approximately 20 minutes, and on another day the subjects were allowed to get drowsy. Subjects in their experiment were not required to perform mental processing tasks, while subjects in the current study were required to drive monotonously for over an hour. Task difficulty will also increase the inter-hemispheric coherence levels (Busk & Galbraith, 1975).

The change has been reported as actual change in coherence during driving. Each subject acts as his or her own control. Sitting in front of the simulator is simulating a driver driving for a long time (a monotonous task). Hence control recordings are not relevant since effects of a monotonous task on inter-hemispheric coherence were being examined.

Ford, Goethe and Dekker (1986b) believed that EEG coherence may be able to be used as an indicator of arousal level, as previous study has showed significant decrease of coherence level during light fatigue (Wada et al., 1996b). However, the current study found increases in EEG coherence during continued monotonous driving. Gasser, Jennen-Steinmetz and Verleger (1987) found poor test-retest reliability for EEG coherence, which may be attributed to the differing state of the subject affecting the inter-hemispheric brain coupling. One of the requirements for a good fatigue detection technique is high reliability and robustness to avoid false alarms (Dinges et al., 1998). Fatigue countermeasure device may also need to acquire and compute EEG coherence levels at different sites of the brain. Coherence values are known to change as task difficulties change (Busk & Galbraith, 1975), and a driving task in real-driving environment has different difficulties, such as sharp corners, straight lanes, traffic lights, pedestrians, or amount of traffic, and these may affect the inter-hemispheric coherence during the duration of driving. Future studies need to confirm test-retest reliability of inter-hemispheric EEG coherence during continued driving tasks.

Figures 2-5 showed that the frontal and occipital sites had significantly higher coherence values than central, parietal, and temporal sites. A comparison between these two sites and the central, parietal, and temporal sites during driving may be able to be used to indicate changes in alertness. Future studies may need to investigate the differences between electrode pairs during each driving section, instead of comparing individual electrode pairs for the entire driving task.

5. Conclusion

Inter-hemispheric coherence is important in monitoring of monotonous tasks since it may provide a marker for driver impairment and fatigue during driving. It may serve as a potential measure of driver fatigue. The current study has investigated the effect of fatigue-inducing monotonous driving and effects on EEG coherence. Inter-hemispheric coherence level was shown to be significantly higher at the frontal and occipital sites compared to the central, parietal, and temporal sites throughout the driving sessions. Coherence level had increased at the end of the monotonous driving session. Further research needs to be carried out to look at the test-retest reliability of inter-hemispheric changes during monotonous driving session. Studies may also need to focus on differences between electrode pairs to identify an indicator of fatigue as opposed to investigating coherence at individual pairs of electrodes. Future studies may also start the investigation between different methods of fatigue indications, in order to identify the most accurate method.

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Figure 1 Homologous inter-hemispheric electrode pairs

Figure 2 Delta coherence mean values for 5 electrode-pairs during alert and 5 monotonous driving sessions (A = Alert, D1-D5 = Driving sessions 1-5)

Figure 3 Theta coherence mean values for 5 electrode-pairs during alert and 5 monotonous driving sessions (A = Alert, D1-D5 = Driving sessions 1-5)

Figure 4 Alpha coherence mean values for 5 electrode-pairs during alert and 5 monotonous driving sessions (A = Alert, D1-D5 = Driving sessions 1-5)

Figure 5 Beta coherence mean values for 5 electrode-pairs during alert and 5 monotonous driving sessions (A = Alert, D1-D5 = Driving sessions 1-5)