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Electroencephalographic study of drowsiness in simulated driving with sleep deprivation

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Abstract

Drivers' drowsiness is one of the main causes of car accidents or near-missed accidents. This has been proven by many studies that established links between driver's drowsiness and road accidents. The objective of this study was to analyze the EEG changes in fatigued subjects while performing a simulated driving task. After a night of sleep deprivation, eight subjects were given a dose of caffeine to reduce drowsiness. During about 50 min of continuous driving, car movements and subject behaviors were recorded on video cameras, and 8 channels of EEG were also recorded. Three basic indices, three ratio indices, and two burst indices were calculated from preprocessed EEG signals. EEG α,β, β/α and $(\alpha+\theta)/\beta$ indices showed significant differences between driving periods. In the comparison of road type, EEG α,β, β/α and $(\alpha+\theta)/\beta$ indices of the straight section of the driving task were significantly different from those of the curved section. This study also analyzed EEG changes before and after car accidents, showing that β and $(\alpha+\theta)/\beta$ were related to the mental alertness level. In the analysis of burst activity, θ burst activity, which was not significant in the mean power analysis, was significantly different between driving sessions.

Relevance to Industry

Driver's drowsiness is a major cause of serious traffic accidents. This study deals with time variant EEG change of sleep-deprived drivers—an important aspect of driver drowsiness analysis.

The result of this study can be used to estimate overall alertness level of drivers.

Keywords: EEG; Driver's fatigue; Drowsiness; Driving simulator; Alpha burst

1. Introduction

Fatigued drivers cannot focus on driving and tend to commit manipulation errors. Their information

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processing speed and memory capacity are decreased and a drastic change in task performance occurs (Wylie et al., 1996). The existing statistical data and survey reports indicate that the driver's fatigue is one of the major causes of traffic accidents (Ryan, 1995; Shuman, 1992). However, research on countermeasures for traffic accidents focuses on the reinforcement of safety devices, elimination of road defects, and laws and regulations, with little attention given to the driver's human factors aspects.

Fatigue can lead to drowsiness and sleepiness. The terms 'sleepiness' and 'fatigue' are used synonymously to mean sleepiness resulting from the neurobiological processes regulating circadian rhythms and the drive to sleep (Dinges, 1995). Many studies show the close relationship among drowsiness, sleepiness, and fatigue. Sleepiness is one of the main factors of the driver's fatigue, and drowsiness can be used as a criterion for determining the driver's fatigue. There are various causes of the driver's fatigue such as duration of continuous driving, sleep deprivation, circadian rhythm, driving environment, and the driver's personal characteristics. This study focuses on the driver's drowsiness caused by sleep deprivation and its relation to car accidents.

The driver's drowsiness can be detected in several ways. It can be directly captured from video images (Summala et al., 1999), the rate and duration of the EOG (electrooculogram) (Horne and Reyner, 1996), and estimated through various analyses of EEG (Horne and Reyner, 1995; Khardi and Vallet, 1994; Lal and Craig, 2002). It can also be estimated from other biosignals such as ECG (electrocardiogram), body pressure, and respiration (Milosevic, 1997; Chung et al., 1999). This study adopted EEG as a proof of the driver's drowsiness.

It has been recognized that the changes in the EEG theta band and the alpha band reflect cognitive and memory performance (Klimesch, 1999). EEG beta band is related to alertness level, and as the activity of beta band increases, performance of a vigilance task also increases (Scerbo et al., 2000).

There have been several EEG studies related to driving. Åkerstedt and Thorsvall (1984) and Åkerstedt et al. (1991) reported that EEG power of alpha and theta bands was increased as the alertness level of the driver decreased. Petit et al. (1990) showed a close correlation between the movement of the steering wheel and the power of EEG alpha band. Waard and Brookhuis (1991) showed that the relative energy parameter ($(\alpha+\theta)/\beta$) of the driver decreased as the driving task continued. Lal and Craig (2002) showed that significant electroencephalographic changes of four bands occur during fatigue. Schier (2000) used a driving simulator to observe EEG during the driving task. Four channels (F3, F4, P3, P4) of EEG were measured from frontal and parietal lobes, and the results showed that the attention level of the driver decreased, and that the relative power of alpha waves increased as the repetitions of the same course increased. Though many studies on the driver's fatigue with EEG have been performed, most of them merely showed the binary difference between the opening part and ending part of the driving task. A few studies even showed conflicting results (Åkerstedt and Thorsvall, 1984; Brookhuis, 1995).

The objectives of this study were (1) to observe EEG changes as time proceeds, (2) to compare the EEGs of the driver on straight/curved roads, (3) to observe the EEG difference between pre-accident and post-accident, and (4) to analyze EEG alpha and theta burst and its relationship to microsleep.

2. Method

2.1. Subjects

The previous research found that there is a difference in the degree of fatigue felt by drivers older than 30 years of age and that felt by drivers younger than 30 (Brown, 1995). Ryan (1995) reported that the number of the traffic accidents caused by male driver's fatigue was different from that of women drivers. To reduce inter-subject differences, all subjects were males in their mid-20s with at least 2 years of actual driving experience. Average age of the selected participants was 26.1 years, and on the average they got up at 9:30 AM and went to bed at 2:15 AM. They drove after 10 P.M. approximately once a month.

2.2. Apparatus

Experiments were carried out to understand the EEG characteristics of drivers in drowsiness on the driving simulator. Grand Tourismo 2 (Polyphony, 1999), a well-known software for its high fidelity driving, was used on the Playstation (Sony, 1998) hardware. The maximum velocity of the vehicle is 140 km/h. The driving roadway, which looks like a stadium, consists of two straight sections and two curved sections (see Fig. 1). Only the subject's car moved on the one-way two lane road.

While there was no side inclination on the straight section, on the curved section was a proper side inclination, which counterbalances the centrifugal force. Total length of the circuit was 5 km, and the ratio of the length of the straight section to the curved section was 3–2.

2.3. Experimental design

The independent variable was driving time, the duration of the continuous driving performed by one subject. Three units of the driving time—'period', 'section' and 'second'—were used for further analysis. One unit of 'period' consisted of three laps of driving. Since the whole driving experiment consisted of 15 consecutive laps, a total of five periods was produced. There were two types of 'section' unit. One type was the shape of road, and it was divided into a straight section and a curved section. The other type was the time band of the accident. Each treatment level of the accident sections is described in Section 3.2.3. The 'second' unit was used as a basic unit for the elimination of artifact and observation of power spectrum. Statistical analysis was applied to 'period' units and 'section' units. In addition to the driving experiment, reference EEGs were measured four times, which was called a session. Each treatment level of the session is described in Section 3.2.1. The length of one session was 3 min.

Dependent variables were task performance and EEG. Task performances were the number of accidents and lap time per cycle. Accidents comprise every stoppage of driving, slight contact with partition wall, driving in the off-road, and more than 20% deviation from the predetermined speed range (100–120 km/h). Accidents and lap time were measured from video after the completion of the experiment.

As shown in Fig. 2, EEG signals were collected from eight locations (Fp1, Fp2, T3, T4, P3, P4, O1, O2) following the international 10–20 systems (Andreassi, 1995).

2.4. Experiment set-up

The driving simulator consists of a driving software and hardware, a steering wheel, the pedals, the car seat, the beam project, and the screen. To reflect the real driving situation, a frame was made based on a real car dimensions and the pedals, the steering wheel, and the seat were installed. The size of the screen was large enough (160×110 cm) to cover driver's vision. Every movement of the vehicle and the subject was recorded for further analysis.

Fig. 3 represents the lineup and location of the experimental equipment. A beam projector placed

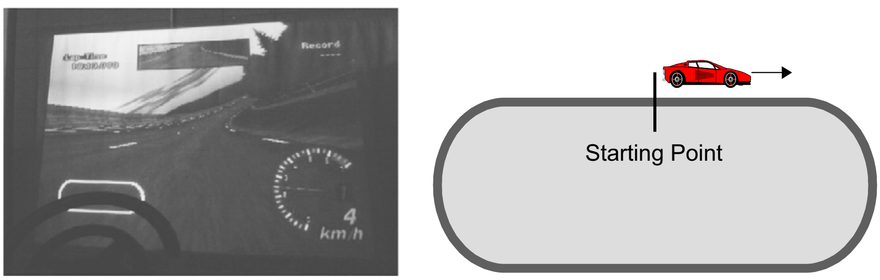

Fig. 1. Virtual driveway.

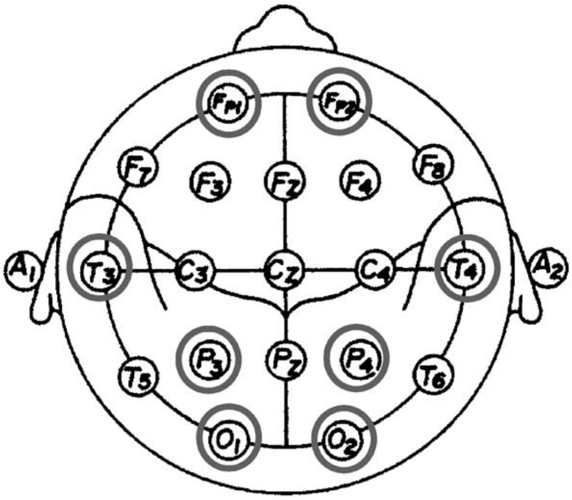

Fig. 2. Locations of the EEG channels.

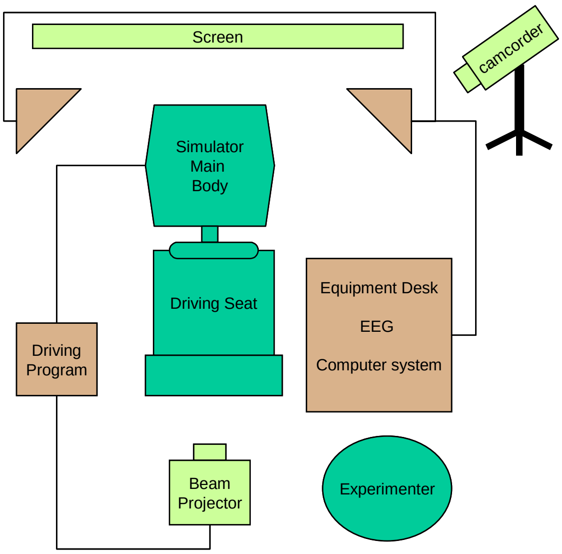

Fig. 3. Layout of experimental equipments.

behind the subject presented the virtual driving environment. Projected image was simultaneously transmitted to VCR to analyze the lap time and accident situations. The EEG instrument and the computer were located on the right side of the subject for the convenience of the experimenter. Every behavior of the driver was recorded on a camcorder.

2.5. Procedure

Experimental procedure was as follows (see Fig. 4). Training was performed 1 day before the experiment to prevent learning effects. No further training was given if the subject could drive five consecutive laps with no accident. The experiment started at 8 AM after a whole night sleep deprivation. Since the subjects were in highly drowsy conditions, they were given coffee to temporarily increase their arousal level. Before and after a dosage of coffee 3 min of EEG was measured. The driving task consisted of 15 laps of a 5 km circuit during which no questions were asked and no additional measurements were made, so as to maintain a monotonous and boring condition. After the driving task, 3 min of EEG were measured with both eyes opened and closed.

2.6. Data analysis

2.6.1. Data acquisition

The EEG measuring instrument was 8-channel LXE1008C (Laxtha, 2002). A/D conversion and signal recording was done by MP100WSW and Acknowledge 3.5.7 (BIOPAC System Inc., 1998). The monopolar recording technique was used, with a sampling rate of 256 Hz, and a gain of 9000. Each of the movement of the vehicle and the subject was recorded on separate video tapes and analyzed at 10 frames per second. Matlab 5.3 (MathWork Inc., 1999) and SAS 8.2 (SAS Institute Inc., 1999) were used to preprocess and analyze the raw data.

2.6.2. Preprocessing

EEG raw data were contaminated with noise, which had to be eliminated through a preprocessing procedure. Generally, the raw signals of the EEG larger than 50–70 μV were treated as artifact (Jung et al., 1997; Wilson et al., 1999). Under this assumption, the simple out-of-bounds test, which sets estimated artifacts to 0 based on the simple comparison of signal amplitude, was mainly used to eliminate the pure EEG signals above the criterion. This, however, may not extract artifacts below the criterion, since the mechanism is a simple comparison of the signal amplitude. Recent

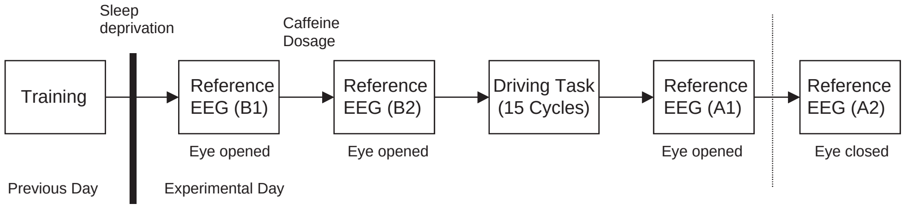

Fig. 4. Procedure of experiment.

advanced artifact elimination methods were employed in this study, using independent component analysis (Jung et al., 1998) and correlation density (Lee et al, 2002) to better reflect signal characteristics.

2.6.3. Data reorganization

The preprocessed data were separated into θ (4–8 Hz), α (8–13 Hz), and β (13–22 Hz) bands through band pass filtering. The δ (0.5–4 Hz) band was not included in our analysis, since it happens in a deep sleep state and usually overlaps with artifacts. Each band of the EEG signals was reorganized by units of second, section, and cycle for the convenience of analysis. To observe the variations of the subject's sleepiness state, three cycles of driving were grouped into one period. A total of five periods of driving time were generated from 15 laps.

2.6.4. Indices

The EEG indices, classified into three groups—the basic index, the ratio index, and the burst index, were derived from the reorganized data. The basic index means the relative power of the EEG θ,α and β bands. The relative power equation of the θ band is represented as

$$\text{Relative power of } \theta = \frac{\text{power of } \theta}{(\text{power of } \theta + \text{power of } \alpha + \text{power of } \beta)}. \quad (1)$$

Since the basic indices have a tendency to 'contradict each other', the ratio indices were calculated to amplify the difference. The known ratio indices β/α, θ/α, and $(\theta+\alpha)/\beta$ were analyzed in previous studies (Brookhuis and Waard, 1993; Ryu et al., 1997; Pyun and Kim, 2000).

Kecklund and Akerstedt (1993) had reported that the increased alpha or theta power density in response to sleepiness occurs rather in a few, short 'burst' of activities. The mean value of the first 30 min EEG was set as the threshold value, and the number of bursts above 100–200% of the threshold value was calculated. The results showed that the burst approach yielded significant effects in contrast to the simple average. In addition to the previously used 7.5 s epoch, a 1 s epoch approach was tried in this study. The criteria of the burst was also varied in the range of 100–500% to find adequate values.

3. Results

3.1. Driving performance

The subjects were required to maintain a vehicle speed range of 100–120 km/h. Although, theoretically, there should be no time difference between the first and the last period, the actual lap time gradually increased from the first period to the last period (p-value = 0.053), and the number of accidents also increased (p-value = 0.074), because of the increased drowsiness and decreased attention level of the subjects(see Fig. 5a). There was a high correlation ($r = 0.96$) between the lap time and the mean number of accidents that occurred.

For Participant 4, who had no accidents, the maximum difference of lap times was only 12 s, and there was no tendency of lap time to increase as the period increased. For all participants, net lap time with the exception of the accident time showed a decreasing tendency from the start to the end of the whole driving.

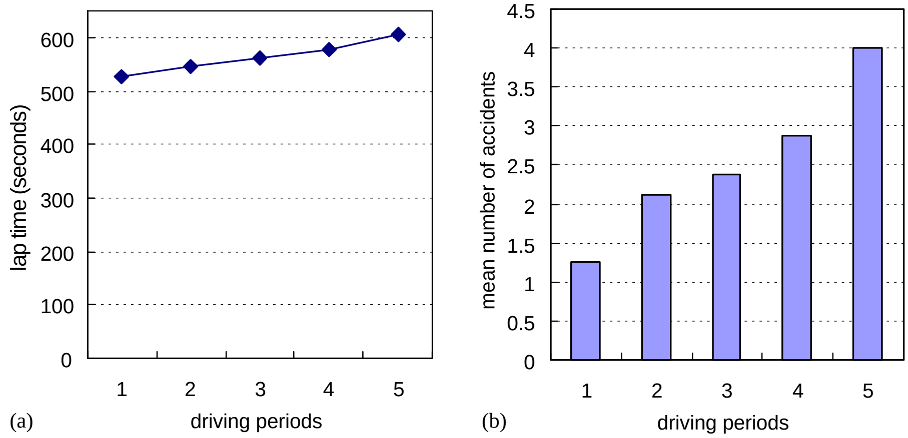

Fig. 5. Driving performance.

3.2. Basic and ratio indices of EEG

3.2.1. Comparison of reference EEG

Reference EEG values were measured twice before and twice after the driving task. They were designated as B1 (eye-open EEG before a dosage of coffee); B2 (eye-open EEG after a dosage of coffee); A1 (eye-open EEG after the driving task); A2 (eye-closed EEG after the driving task), as described in Fig. 4. Three basic indices and three ratio indices were calculated from each reference EEG, and ANOVA was used for further analysis. A two-factor within subject design was adopted for ANOVA, and the electrode location and the session were assigned to each main factor.

ANOVA results of the six basic and ratio indices are presented in Table 1. All indices except θ showed significant difference in location, and all indices except θ and θ/α showed significant difference in session.

No indices showed a significant difference of interaction effect. SNK) Student–Newman–Keuls (SNK) post hoc analysis for the factor of location showed that the temporal lobe (T3, T4), the frontal lobe (Fp1, Fp2), and the others (P3, P4, O1, O2) are separated into statistically different groups ($\alpha = 0.05$). In the post hoc analysis for the factor of session, index β/α was separated into three different groups—(B1, B2), (A1), and (A2), and the other three indices were separated into two different groups—(B1, B2, A1) and (A2). EEG plots of four indices whose main factor was statistically significant are shown in Fig. 6. Index values consistently trended A2 > A1 > B1 > B2, or the opposite.

Table 1
ANOVA summary for reference EEG

Index	Location	Session	Interaction
θ	<.0794	0.9032	0.2403
α	<.0001**	0.0040**	0.8746
β	<.0001**	<.0001**	0.1373
θ/α	0.0008**	0.6529	0.9875
β/α	0.0003**	<.0001**	0.0600
$(\alpha+\theta)/\beta$	<.0001**	<.0001**	0.0757

*Significant at $\alpha = 0.05$, **Significant at $\alpha = 0.01$.

3.2.2. EEG analysis for driving task

The ANOVA results of EEG measured during the driving task are summarized in Table 2.

In the comparison of location, index α and index β/α were found to be statistically significant (see Table 2). In the comparison of period, α, β, β/α and $(\alpha+\theta)/\beta$ showed a significant difference, which was the same as the result of reference EEG comparison. In the post hoc analysis for the factor of location, no location was grouped to significantly different between each other. In the post hoc analysis for the factor of period, first part, middle part and last part were grouped to significantly different each other (see Fig. 7).

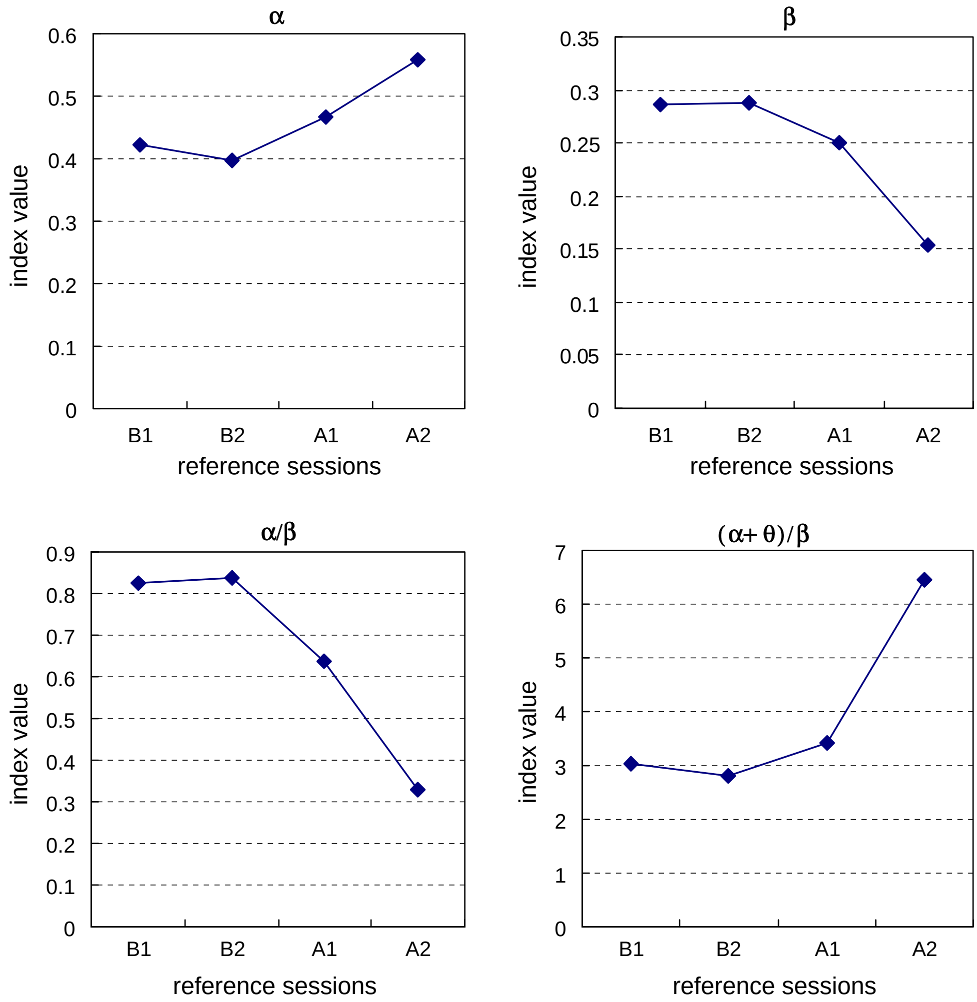

Fig. 6. EEG indices plot (four reference EEG).

Table 2
ANOVA summary for driving EEG

Index	Location	Period	Interaction
θ	0.2783	0.9982	<.0001**
α	0.0376*	0.0003**	0.1969
β	0.1623	0.0002**	0.0351*
θ/α	0.1374	0.7967	0.0131*
β/α	0.0423*	0.0018**	0.2194
$(\alpha+\theta)/\beta$	0.5613	<.0001**	0.7893

*Significant at $\alpha = 0.05$, **Significant at $\alpha = 0.01$.

Fig. 8 presents four EEG indices whose main factor of period was statistically significant. Index α and index $(\alpha+\theta)/\beta$ showed a gradually increasing tendency, and index β and index β/α showed gradually decreasing tendency by time elapsed.

3.2.3. Analysis for specific situation

3.2.3.1. Comparison by road type. The driving road of this experiment consists of a straight section and a curved section. Since the curved section forced the driver to continually change direction with its shape and the side slope, it can be assumed that the attention level required to drive on the curved section is higher than that required by the straight section. The results of ANOVA for road type support this assumption (see Table 3).

α

SNK Group		Mean	N	period
	A	0.327	64	5
B	A	0.316	64	4
B		0.308	64	3
B	C	0.300	64	2
	C	0.288	64	1

β

SNK Group		Mean	N	period
	A	0.341	64	1
B	A	0.329	64	2
B		0.320	64	3
B	C	0.313	64	4
	C	0.299	64	5

α/β

SNK Group		Mean	N	period
	A	1.711	64	1
B	A	1.561	64	2
B	A	1.497	64	3
B		1.417	64	4
B		1.325	64	5

(α+)/β

SNK Group		Mean	N	period
	A	3.514	64	5
	B	3.291	64	4
C	B	3.192	64	3
C	D	3.063	64	2
	D	2.897	64	1

(Means with the same letter in first column are not significantly different)

Fig. 7. SNK result of four significant indices.

The same four indices, which were significant in the analysis of reference EEG and driving EEG, showed a significant difference between road types. No interaction effect was significant. As described in Fig. 9, EEG index α and $(\alpha+\theta)/\beta$ of the straight section were larger than those of the curved section, and EEG index β and β/α of the curved section were larger than those of the straight section in each period.

3.2.3.2. Analysis of accident EEG. As described in Section 2.3, every event that went out of control was defined as an accident in this research. As described previously, analyses were performed after the elimination of the accident section. In this subsection, EEG changes from the onset of the accident to the returning to normal driving were analyzed. In order to do a consistent analysis, the prescribed overall categories of accidents were narrowed down to stopped car movements due to spin. This narrowed scope of accidents can be separated by three points: 'accident onset', 'return to driving road', and 'starting of normal driving (reaching 80 km/h)'. Four sections were defined for the analysis of accidents in detail (see Fig. 10). Section 1 corresponds to the time range from '10 s before the accident onset' to 'accident onset'. Section 2 corresponds to the time range from 'accident onset' to 'return to driving road.' Section 3 corresponds to the time range from 'return to driving road' to 'starting of normal driving'. Section 4 corresponds to the time range from 'starting of normal driving' to '10 s after normal driving'.

ANOVA results for accident analysis are presented in Table 4. EEG index β and $(\alpha+\theta)/\beta$ were found to be statistically significant.

Fig. 11 presents the EEG plots of two significant indices. Index β, whose value was low before the accident onset, increased directly after the accident onset and gradually decreased with the elapse of time. Index $(\alpha+\theta)/\beta$ showed an opposite tendency.

3.3. Burst indices of EEG

The mean value of the first 30 min out of 6 h of entire driving was defined as a criterion of 'burst' in a previous research (Kecklund and Akerstedt, 1993). The time interval for 1 epoch was 7.5 s. Every artifact-free epoch was analyzed for the number of bursts above 100–200% of the criterion, and the number of bursts during each hour was averaged. In this study, the first 5 min out of the total 50 min of driving was used as a criterion of 'burst'. Two kinds of time intervals, 7.5 and 1 s, were used as the size of one epoch. The numbers of bursts above 100–500% of criterion were counted

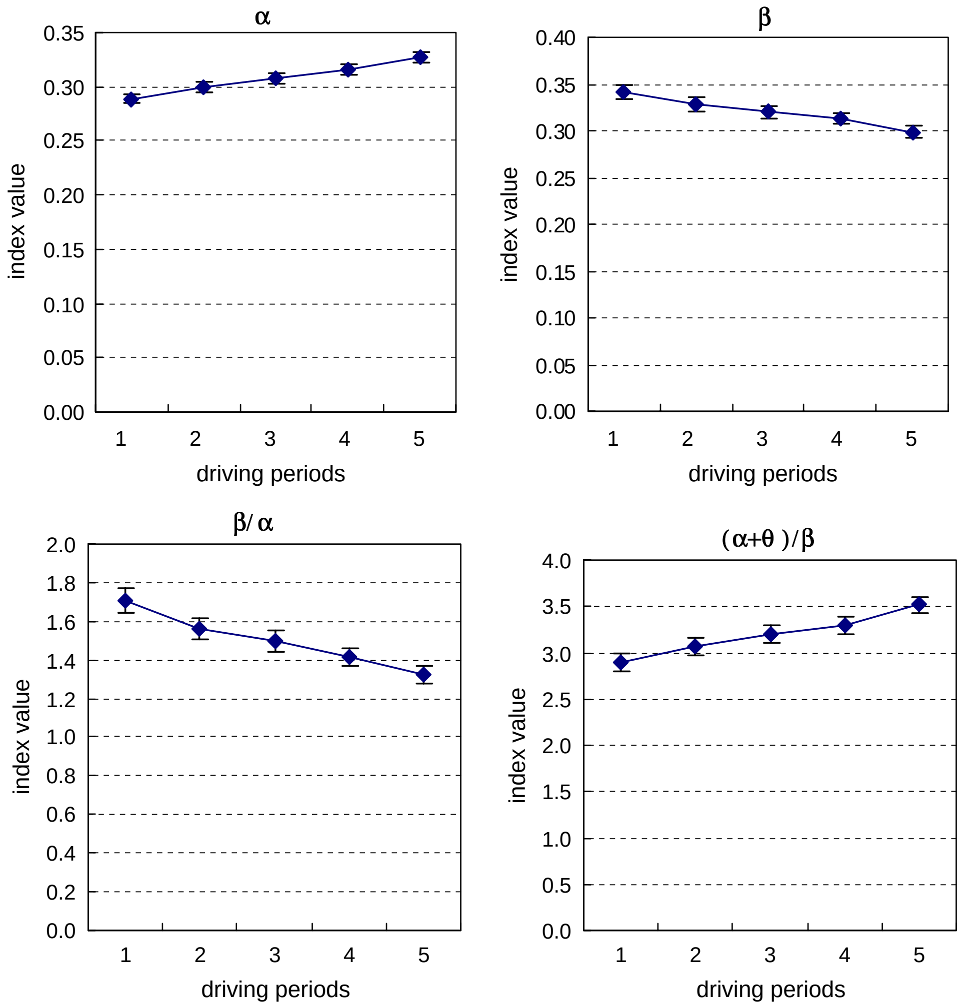

Fig. 8. EEG indices plot by driving period.

Table 3
ANOVA summary of the road type comparison

Index	Road type	Period	Interaction
θ	0.093	0.998	0.882
α	0.035*	0.004**	0.365
β	0.0004**	0.002**	0.790
θ/α	0.631	0.881	0.705
β/α	0.001**	0.012*	0.402
$(\alpha+\theta)/\beta$	0.005**	<.0001**	0.506

*Significant at $\alpha = 0.05$, **Significant at $\alpha = 0.01$.

per minute for 15 driving laps, and they were averaged for each driving period. Analysis results of the α-burst and θ-burst are presented in Table 5.

Both α-burst (1 s) and α-burst (7.5 s) showed a significant difference between driving periods regardless of the threshold size. The θ-burst (1 s) showed the same results, but the θ-burst (7.5 s) showed a significant difference at the only two threshold levels, 100% and 150%. SNK post hoc analysis for α-burst (1 s) showed that the threshold

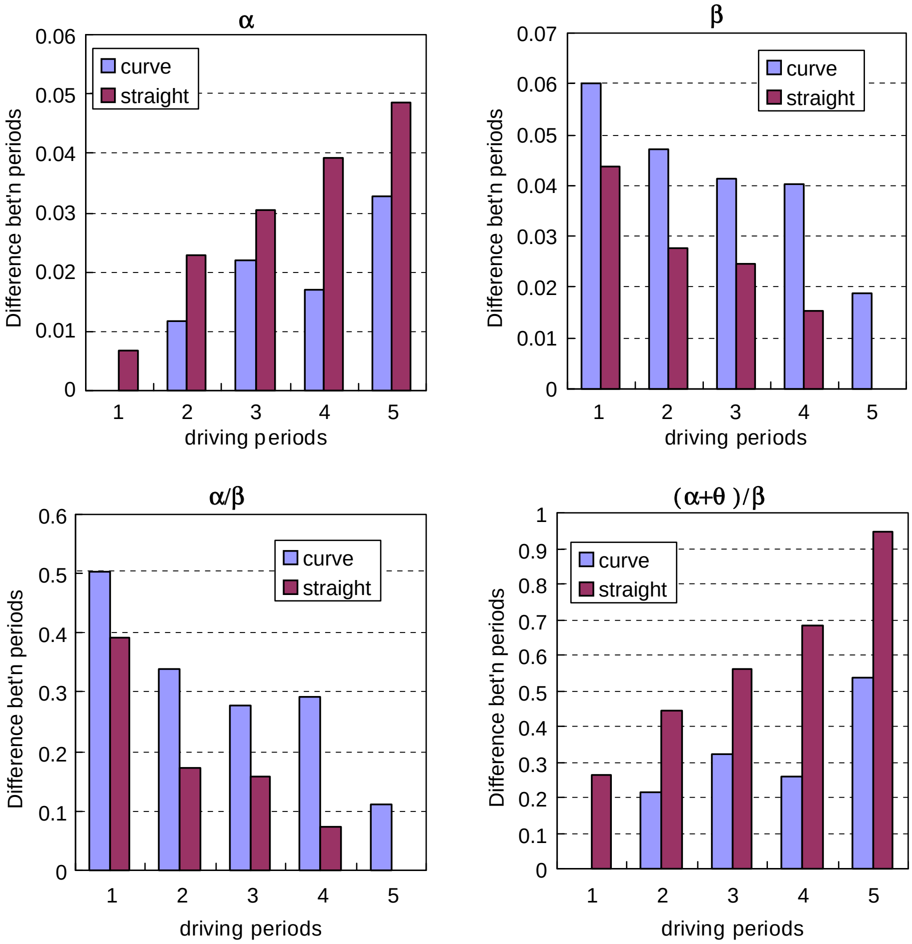

Fig. 9. Comparison of straight section and curved section.

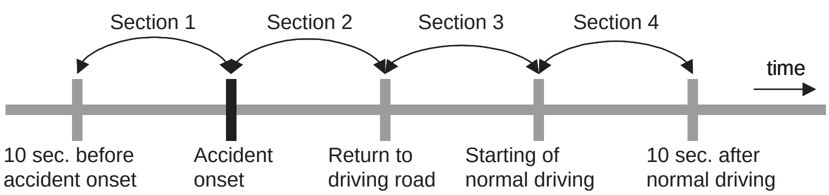

Fig. 10. Section definition for accident analysis.

levels of 200% and 300% were best for the statistical discrimination of each driving periods. In the case of α-burst (7.5 s), 150% was best and in case of θ-burst (7.5 s), 100% and 150% were best. There was no difference between the threshold levels of θ-burst (1 s) for the discrimination of driving periods. An example of the burst indices change is presented in Fig. 12. The burst indices gradually increased from the start of driving to the end of driving.

4. Discussion

Sleep deprivation can increase subjective drowsiness and fatigue (Davis and Parasuraman, 1982). Reyner and Horne (2002) studied the effect of caffeine as a countermeasure of driver's drowsiness and showed the efficacy of caffeine for the reduction of sleepiness. Caffeine acts as an inhibitor of the potent sleep promoter, adenosine receptors. On the other hand, it acts on the synthesis of catecholamines, which appears on the excitement of the sympathetic nervous system (Radulovacki, 1995; Porkka-Heiskanen et al., 1997; Battig and Welsl, 1993). To accelerate fatigue and drowsiness, the subject was deprived of a whole night's sleep before the experiment, and caffeine was given just before the experiment. In the comparison of reference EEGs B1 and B2, the alpha wave of B1 was higher than that of B2, and the beta wave of B2 was higher than that of B1, but the differences were statistically insignificant (see Fig. 6). Previous research done by Reyner and Horne (2002) could not show a significant difference between active and control groups classified by caffeine dosage. It just showed that subjective sleepiness and number of incidents identified by lateral lane drifting of the active group were significantly higher than those of the control group.

In studies of fatigue and drowsiness, it is not necessary to assess all the four stages of sleep, but only the phase between the awake stage and the first stage of sleep–sleep onset (Lal and Craig, 2001). Beta waves are associated with increased alertness and arousal, alpha waves occur during relaxed conditions, at decreased attention levels and in a drowsy but wakeful state, and theta waves mainly occur at sleep state 1 (Grandjean, 1988; Okogbaa et al., 1994; Rains and Penzien, 2003). Alpha and beta waves showed a significant change while driving in a drowsy state in this study, and the directions of their changes were consistent with previous studies. In contrast to previous studies (Åkerstedt et al., 1991; Lal and Craig, 2001), theta waves did not show significant change in this study. Though the dull and monotonous driving

Table 4
ANOVA summary of accident analysis

Index	Location	Session	Interaction
θ	0.7007	0.4437	0.4174
α	0.4468	0.1884	0.2706
β	0.5890	0.0350*	0.6790
θ/α	0.5748	0.9115	0.7843
β/α	0.4548	0.4484	0.8739
$(\alpha+\theta)/\beta$	0.7921	0.0072**	0.8933

*Significant at $\alpha = 0.05$, **Significant at $\alpha = 0.01$.

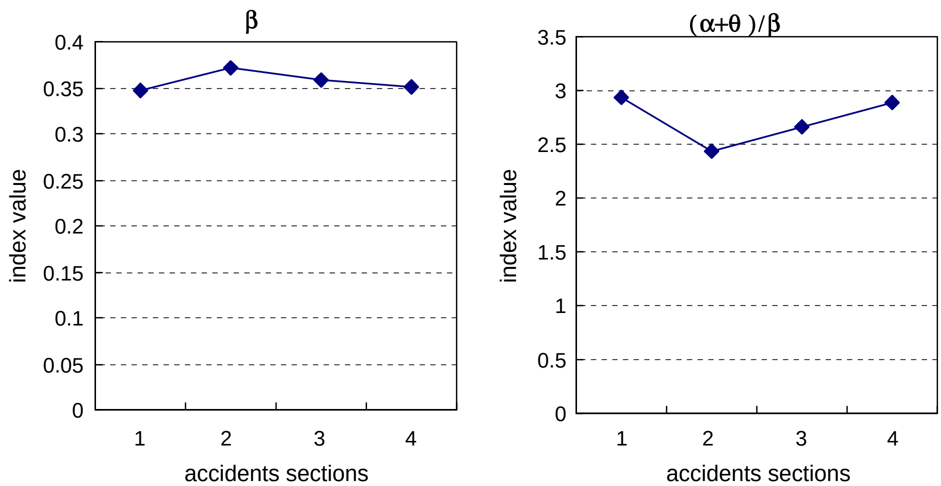

Fig. 11. EEG plots of accident sessions.

Table 5
ANOVA summary of α-burst and θ-burst (p-values for factor 'period')

Threshold (%)	α-burst (1 s)	α-burst (7.5 s)	α-burst (1 s)	α-burst (7.5 s)
100	0.0007**	0.0007**	0.0053**	0.0032**
150	<0.0001**	<0.0001**	0.0048**	0.0099**
200	<0.0001**	<0.0001**	0.0087**	0.1072
300	<0.0001**	0.0008**	0.0139*	0.0876
400	<0.0001**	0.0038**	0.0241*	0.0653
500	<0.0001**	0.0110*	0.0191*	0.1582

*Significant at $\alpha = 0.05$, **Significant at $\alpha = 0.01$.

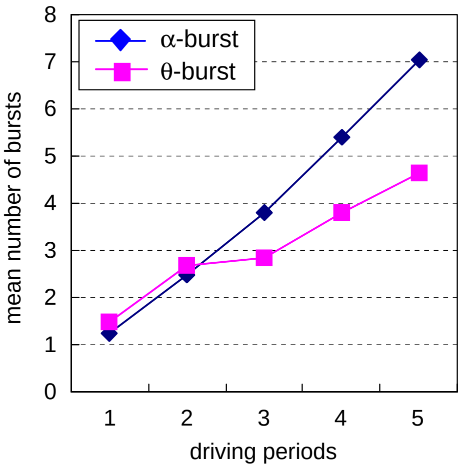

Fig. 12. Burst changes by driving period (epoch: 1 s, threshold: 300%).

may lead the subjects to microsleep, which would cause a instant change of theta waves, it could not lead the subject to a continuous sleep state. Hence it was hard to observe significant changes of theta mean power. Theta waves that were insignificant at mean power comparison showed a significant change in the burst analysis because of the burst activity caused by microsleep. A few subjects fell into a continuous sleep state during reference session A2, and theta waves showed dominant activities at that time.

Among the ratio indices, index β/α and index $(\alpha+\theta)/\beta$ were statistically significant in this experiment. Index $(\alpha+\theta)/\beta$ was the best discriminator of driving periods to statistically significant groups in the SNK analysis, and it also discriminated period 5 which no other indices could do (see Fig. 7). In spite of the insignificance of the basic index θ, index $(\alpha+\theta)/\beta$ showed different statistical characteristics compared to index β/α due to the mutual addition effect of alpha waves and theta waves during the repetitive phase transition between wakefulness and microsleep. According to the EEG study of long distance driving done by Macchi et al. (2002), theta waves alone showed insignificant effect, but the index containing both theta and alpha band showed significant effect.

There were significant differences between EEG indices before and after the accidents. The difference was highest between Section 1 and Section 2, and it gradually decreased from Section 2 to Section 4. This means that the alertness level, whose value was low just before the accident, took a high value immediately after the accident onset and reduced as time went. If the main cause of the accident was drowsiness, index $(\alpha+\theta)/\beta$ of Section 1 was similar or higher than that of latter driving periods. However, the actual index value of Section 1 was similar to that of the former driving periods. Two potential factors might have affected this phenomenon. One factor is the road type. Eighty percent of the accidents from a total of 45 accidents occurred on the curved section. Since the attention level required for driving on the curved section is higher than the level required for driving on the straight section, index $(\alpha+\theta)/\beta$ measured at the accident was a relatively low value. The other factor is the calculation method. Since the EEG indices of driving periods were calculated after the exclusion of the accident sections, EEG indices of driving periods might have been overestimated.

EEG changes of the theta and the alpha bands caused by drowsiness could appear in the form of bursts, and these changes might not be recognized if they were averaged over a long time band. Kecklund and Akerstedt (1993) suggested the analysis of burst activity for long distance night driving. They showed a significant difference in alpha and theta bursts between the first 4 h of the driving task and the remaining 2 h of the driving task. They also suggested that the criteria for burst be lower than 200% of mean value of the starting period. If the criteria were higher than 200%, a large portion of EEG variability would have been eliminated in the previous study. In this study, however, criteria were varied from 100% to 500% and EEG burst indices were analyzed at each of the criteria. When the time interval was set at 7.5 s, the burst value of the former driving part was zero at the criteria of 200%. This result was the same as the result of the previous study. When the time interval was set at 1 s, the burst value of the former driving part was zero at the criteria of 500%.

Characteristics of the EEG when the subjects fell in sleep at the wheel could be caught by simultaneous observation of the EEG time series and the subject behavior video. When the subjects closed their eyes for more than 3 s and nodded their head, the high amplitude of alpha band from the parietal and the occipital lobe could be observed. The observed duration of alpha burst was 1–3 s, and the increase of the amplitude was more than 2 times the usual amplitude. Since the actual duration of burst was less than 3 s, a time interval of 7.5 s may be too long to validly analyze burst activity. It is suggested that the proper time interval be 1 s and the proper criterion be within the range of 200–400%.

5. Conclusion

EEG analysis of drowsy drivers was performed using a driving simulator after a whole night of sleep deprivation. While previous studies showed a binary difference from long time driving, this study discriminated the driving task into more than three different groups from a relatively short driving time. In the EEG analysis for the driving task, alpha waves, beta waves, index β/α and index $(\alpha+\theta)/\beta$ were found to be statistically significant. The same four indices were significant in the road type analysis. Only the beta waves and index $(\alpha+\theta)/\beta$ were significant in the accident analysis. Since the accidents that occurred in this experiment were not controlled, they were not equally distributed to each subject and each driving period. To analyze the accident EEG in more detail, a well-planned and controlled generation of accidents is required in future studies. The burst analysis showed significant changes in theta waves that were insignificant in the mean power analysis. The result of the burst analysis showed that the criteria level suggested by previous researches was too low, and a proper level of criteria should be considered in future studies.

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