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Driver performance in the moments surrounding a microsleep

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Abstract

This study examined if individuals who are at increased risk for drowsy driving because of obstructive sleep apnea syndrome (OSAS), have impairments in driving performance in the moments during microsleep episodes as opposed to during periods of wakefulness. Twenty-four licensed drivers diagnosed with OSAS based on standard clinical and polysomnographic criteria, participated in an hour-long drive in a high-fidelity driving simulator with synchronous electroencephalographic (EEG) recordings for identification of microsleeps. The drivers showed significant deterioration in vehicle control during the microsleep episodes compared to driving performance in the absence of microsleeps on equivalent segments of roadway. The degree of performance decrement correlated with microsleep duration, particularly on curved roads. Results indicate that driving performance deteriorates during microsleep episodes. Detecting microsleeps in real-time and identifying how these episodes of transition between wakefulness and sleep impair driver performance is relevant to the design and implementation of countermeasures such as drowsy driver detection and alerting systems that use EEG technology.

Keywords: Obstructive sleep apnea syndrome; Microsleep; Driving performance; EEG; Driving simulators

1. Introduction

Driver sleepiness is a major cause of motor vehicle crashes and is responsible for approximately 40,000 injuries and 1500 deaths each year in the US alone (Knipling & Wang, 1995; Laube, Seeger, Russi, & Bloch, 1998; Lyznicki, Doege, Davis, & Williams, 1998). Royal (2003) estimated that 1.35 million drivers were involved in a drowsy driving related crash in the five years prior to a 2002 US Gallup poll. A US DOT – NHTSA study revealed that there are six million crashes annually resulting in an economic impact of over $230 billion (Blincoe et al., 2002). Thus, over four per cent of these costs are probably attributed to sleepiness and even this estimate may be relatively low. In a separate study conducted by McCartt, Ribner, Pack, and Hammer (1996), approximately 55% of 1000 drivers surveyed indicated that they had driven while drowsy and 23%

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had fallen asleep at the wheel. This confirms other findings that sleepiness may play a role in crashes that are erroneously attributed to other causes (Connor, Whitlock, Norton, & Jackson, 2001).

A subgroup of drowsy drivers has obstructive sleep apnea syndrome (OSAS), a common sleep disorder that affects 2–4% of middle-aged adults (Young et al., 1993). Drivers with OSAS have an increased crash risk that is in the neighborhood of 2–6 times that of the general population (Findley et al., 1995; George, Nickerson, Hanly, Millar, & Kryger, 1987; Teran-Santos, Jiminez-Gomez, & Cordero-Guevara, 1999; Wu & Yan-Go, 1996). Affected individuals typically have fragmented sleep periods associated with snoring and intermittent airway obstruction. This fragmentation of sleep leads to chronic sleep deprivation and excessive daytime sleepiness, and is a likely cause of the cognitive dysfunction that has been found in this population (Bedard, Montplaisir, Malo, Richer, & Rouleau, 1993; Feuerstein, Naegele, Pepin, & Levy, 1997; Kim et al., 1997). However, there are data suggesting that the cumulative effects of chronic repeated episodes of nocturnal hypoxia may also cause irreversible cognitive deficits (Nowak, Kornhuber, & Meyrer, 2006). Regardless of the mechanism by which these deficits occur, improperly treated OSAS has been estimated to cause over $11 billion in motor vehicle crash costs (Sassani et al., 2004). An additional problem is that some individuals with OSAS are unaware of the degree of their sleepiness and cognitive impairment (Engleman, Hirst, & Douglas, 1997; Horstmann, Hess, Bassetti, Gugger, & Mathis, 2000). This is clearly a problem that society cannot afford to ignore.

Methods for quantifying driving performance errors associated with sleep onset are of key importance for reducing the number of sleep related crashes. Microsleep episodes are one such potentially useful indicator of sleep onset. They are identified by changes in the electroencephalogram (EEG), and are associated with brief episodes of loss of attention and blank stares (Thorpy & Yager, 1991). Microsleeps are commonly seen in individuals with excessive daytime sleepiness, and their presence may be a more sensitive indicator of sleepiness than the mean sleep latency from the multiple sleep latency test (Tirunahari, Zaidi, Sharma, Skurnick, & Ashtyani, 2003). During microsleep episodes, attention lapses can impair the ability to detect and respond to crucial stimuli and events (Dinges & Kribbs, 1991). Moreover, microsleeps have been associated with poor simulated driving performance (Risser, Ware, & Freeman, 2000; Paul, Boyle, Tippin, & Rizzo, 2005; Moller, Kayumov, Bulmash, Nhan, & Shapiro, 2006), and have previously been included as part of a multi-parametric alertness monitoring system (Heitmann, Guttkuhn, Aquirre, Trutschel, & Moore-Ede, 2001). Thus, the detection of microsleep episodes might be useful as a means of alerting and warning drowsy drivers.

The goal of this study was to determine if drowsy drivers have deterioration in driving performance during EEG verified microsleep episodes compared to performance during wakefulness. To address this goal we tested the hypotheses that (1) drivers have worse driving performance during microsleeps compared to matched non-microsleep segments and (2) longer microsleeps produce greater declines in driving performance. We tested these hypotheses in a sample of drowsy drivers with OSAS, as outlined in Section 2.

2. Methods

2.1. Participants

Twenty-four drivers with OSAS participated in this study (12 women and 12 men). Two of the participants did not complete the entire experiment and were deleted from subsequent analyses. Potential participants were recruited from the Sleep Disorders Clinic in the Department of Neurology at the University of Iowa and compensated $50 (US dollars) for their participation in this study. Participants were excluded if they were no longer driving, acutely ill, or had active, confounding medical conditions (i.e., dementia, major psychiatric and vestibular diseases, alcoholism or other forms of drug addiction, or used the following medications; stimulants, antihistamines, antidepressants, narcotics, anxiolytics, anticonvulsants and other major psychoactive medications). Potential subjects were also excluded if they had irregular sleep–wake cycles, consumed seven or more cups of coffee (or an equivalent amount of other caffeinated beverages) daily, or currently smoked cigarettes (Walsh, Muehlbach, Humm, Dickens, & Sugerman, 1990; Wetter & Young, 1994). Individuals with diseases of the optic nerve, retina, or ocular media were excluded only if they had a corrected visual acuity of less than 20/50.

The clinical criteria for the diagnosis of OSAS were (1) a complaint of excessive daytime sleepiness or insomnia, (2) witnessed or self-reported episodes of obstructed breathing during sleep, and (3) at least one of the following; snoring, morning headaches, or dry mouth upon awakening (AASM, 2005). Potential subjects were referred to the Sleep Disorders Clinic with a clinical suspicion of OSAS and were not yet treated with continuous positive airway pressure (CPAP). Recruitment occurred at the time of their clinic visit, which occurred between 8 a.m. and noon. The Epworth Sleepiness Scale (ESS) (Johns, 1991), which was completed during their visit, was used to assess subjective sleepiness. All subjects meeting clinical criteria for OSAS underwent the simulated drive at 2 p.m., with polysomnography (PSG) completed that night. All subjects had an apnea–hypopnea index of 5 or greater on PSG. Both apneas and hypopneas had a duration of at least 10 s. Hypopneas were defined as having a discernible or greater reduction in airflow or effort associated with either a 3–4% or greater drop in oxygen saturation or EEG arousal (Butkov, 1996).

2.2. Apparatus

The driving scenarios were implemented on the Simulator for Interdisciplinary Research in Ergonomics and Neuroscience (SIREN). This driving simulator has a four-channel, 150-degree forward view, and 50-degree rear view (Rizzo, McGehee, & Jermeland, 2000). All street signs and road scenarios conform to the requirements of AASHTO (American Association of State Highway and Transportation Officials) and MUTCD (Manual for Uniform Traffic Control Devices). External devices such as EEG and video collection were integrated into and synchronized with the simulator.

EEG was recorded in all drivers for identification of microsleep episodes and was performed using a Neurofax EEG-2100 (Nihon Khoden Corp., Tokyo) with 16-bit A/D conversion and sampling frequency of 200 Hz. Electrodes were placed according to the international 10–20 system (Klem, Luders, Jasper, & Elger, 1993) with C3/4–A1/2 and O1/2–A1/2 used as the primary scoring channels, with bipolar derivations (e.g., C3/4–T3/4 and O1/2–T5/6) used when tracings were ambiguous or obscured by artifact. The electro-oculogram (EOG) was recorded to monitor eye movement artifacts. Electrodes were placed lateral and above the left outer canthus, and lateral and below the right outer canthus, with both referenced to A1 (Rechtschaffen & Kales, 1968).

2.3. Experimental design

The independent variables in the analysis were road type (curve, straight), and occurrence (yes, no) and duration (short, medium, long) of microsleep episodes. Microsleep episodes were identified by visual inspection of the EEG, and were defined as 3–14 s artifact-free episodes during which 4–7 Hz (theta) activity replaced the waking 8–13 Hz (alpha) background rhythm (Harrison & Horne, 1996; Moller et al., 2006). A neurologist certified by the American Board of Sleep Medicine (author Tippin) interpreted the EEG and was blinded to the subjects' driving performance. It was not uncommon to have small fragments of alpha activity (<0.5 s in duration) intermixed with theta during microsleeps. Similarly, alpha often slowed in frequency at the beginning of a microsleep episode. These fragments and adjacent portions of persisting alpha activity were included in the microsleep if the frequency of alpha had declined from baseline by more than 1 Hz. The inclusion of this alpha activity is reasonable as alpha slowing of this degree has been shown to accompany vigilance errors (Valley & Broughton, 1983). Portions of EEG wherein changes in alpha were ambiguous or explained by the physiological blocking response (Niedermeyer, 2005), or those in which EEG was obscured by artifact were excluded from analysis. The goal of the study was centered on examining whether or not driving performance declines during well-defined microsleeps and for that reason, no attempt was made to calculate an artifact rate. As noted previously, EOG was used to monitor eye movement artifacts. This activity never interfered with the identification of alpha, especially in the occipital areas (both central and occipital channels were used to identify alpha).

Dependent measures of driver performance were speed, lane keeping, and steering control. The mean vehicle speed assessed how well drivers maintained speed control during microsleep episodes as in previous studies of OSAS in a driving simulator (Risser et al., 2000). Lane keeping behavior was assessed by the standard deviation in lane position (SDLP) and was calculated as the distance between the vehicle midline and lane centerline. SDLP is a frequently used metric (George, 2004; Risser et al., 2000; Summala, Nieminen, & Punto, 1996) that indexes road tracking error or "weaving". This increases as a driver loses control over the vehicle's lateral position (de Waard & Brookhuis, 1991; Lenne, Triggs, & Redman, 1998; Ramaekers, 2003). The standard deviation of steering wheel angle (SDSWA) was also measured. High SDSWA is strongly correlated with poor steering control due to drowsiness or increased workload (Furukawa, Takei, Kobayashi, & Kawai, 1990). The minimum time to lane crossing (TLC) provided another safety index, as in previous studies of drowsy drivers (van Winsum, Brookhuis, & De Waard, 2000). The TLC is the time that it takes the vehicle to reach one of the lane boundaries (i.e., road shoulder or oncoming traffic lane) assuming the driver maintains the same steering wheel angle (Lin & Ulsoy, 1995). Greater TLCs are considered safer (Godthelp, 1986; Kwon et al., 1999; Lin & Ulsoy, 1995).

As a secondary goal, the results of SDLP, SDSWA, and min TLC measures are compared to another measure known as steering entropy (SE), a measure of randomness of steering control (Nakayama, Futami, Nakamura, & Boer, 1999) to determine whether these measures would yield similar or complementary results (Paul, Boyle, Boer, Tippin, & Rizzo, 2005). SE is based on a Taylor series expansion of steering over time, has been used to evaluate workload changes due to alcohol (Rakauskas & Ward, 2005) and driver distraction (Donmez, Boyle, & Lee, 2006), and may provide additional evidence on changes in driver workload and vigilance across changing driving environments.

2.4. Procedure

Each participant completed a simulated drive scenario lasting approximately 60 min. Prior to beginning the experiment, a research assistant conducted a "warm-up and training" session lasting 5–10 min to familiarize the drivers with the vehicle controls as was done in previous work using this simulator (McGehee, Lee, Rizzo, Dawson, & Bateman, 2004). The familiarization session was conducted on a segment of a simulated two-lane highway that was similar to what the drivers would be immersed in during data collection. Afterward, drivers completed a brief checklist of vehicle knowledge and operations to assure a level of proficiency sufficient to proceed with the experiment.

During the experiment, participants drove on a simulated two-lane highway comprising three identical drive segments. Each drive segment included two straight road types and two gradual curves (radii = 600 m). There were approximately 24,800 m of straight road and 5600 m of curved sections for each segment. The participants were instructed to drive at the posted speeds of 55 mph ($\sim$89 km/h). The drive scenario contained minimal traffic or distractions and was representative of drives that may induce drowsiness. The simulator drive was performed at a fixed time in the afternoon (2 pm), in order to maximize driver sleepiness, increase the likelihood of recording microsleeps, and minimize confounding effects of the circadian fluctuation in alertness (Van Dongen & Dinges, 2005).

2.5. Statistical analysis

A case-crossover analysis compared case (microsleep) to control (non-microsleep) episodes. In this analysis, each participant served as his or her own control, minimizing confounding effects of age, gender, training, driving record, and other fixed characteristics (Maclure, 1991). The experimental drive comprised three repeating segments of identical roadway terrain. This allowed a 2:1 matched approach in which the driving performance on a segment where a microsleep occurred was matched with the performance at the corresponding location in the other two segments (when a microsleep did not occur).

The analyses of the dependent measures was conducted using mixed linear models (i.e., PROC MIXED statement in SAS version 9.1). In the case-crossover design, a drive segment containing a microsleep is compared to the other two segments where a microsleep episode did not occur. However, the specific segment is not known and is therefore accounted for as a covariate in our model. Randomness associated with each microsleep event was also accounted for in the model. Dependent variables were appropriately transformed in order to support the normality assumption of an ANOVA model.

A preliminary analysis demonstrated a strong correlation between SDLP and SDSWA ($\rho = 0.88$, $p < 0.0001$), followed by SDLP and SE ($\rho = 0.34$, $p = 0.044$). However, there was no significant correlation between SDSWA and SE ($\rho = 0.25$, $p = 0.146$). Because the dependent steering measures are correlated, MANOVA is performed on these variables to control for overinflation of the Type I error. Significant findings are followed-up with univariate ANOVAs to assess the magnitude of the effect that each dependent variable has on the independent variables.

3. Results

The mean ages of the drivers were 46.9 (s.d. = 11.5) years for men and 52.1 (s.d. = 6.8) years for women. The mean ESS score was 11.0 (s.d. = 5.0). A score greater than 10 is generally accepted as an indicator of excessive subjective sleepiness (Johns, 1991). There were over 150 microsleep episodes identified among the OSAS drivers used for the subsequent analysis.

3.1. Microsleep occurrence and performance measures

Differences in performance between segments with and without microsleep episodes were evaluated based on mean speed, SDLP, SDSWA, and steering entropy. The averages for each performance measure stratified by microsleep episodes (present or not) and road type (straight or curve) are provided in Table 1.

3.1.1. Speed control

Significant differences in mean speeds were observed with higher speeds observed during non-microsleep episodes ($F(1,418) = 4.57$, $p < 0.05$). Differences were also observed among the three drive segments ($F(2,417) = 16.57$, $p < 0.05$) with mean speed increasing with each subsequent segment, but no interaction effects were observed between drive segments and microsleeps ($p > 0.05$). There were also no differences observed in the mean speed between roadway types ($p > 0.05$).

3.1.2. Lateral control

The MANOVA results indicated that differences existed between straight and curved roads (Wilks' Lambda $F(3,414) = 8.34$, $p < 0.0001$), which were attributable to the differences observed in SDSWA (univariate

Table 1
The effects of microsleeps (and comparison non-microsleeps) on driving performance measures by road type

Dependent variables	Roadway	Episodes[a]	*N*	Mean	s.d.
Mean speed (km/h)	Straight	Microsleep	117	26.363	3.263
		Non-microsleep	231	26.576	2.669
	Curve	Microsleep	34	26.354	3.132
		Non-microsleep	68	26.633	2.129
SDLP (m)	Straight	Microsleep	117	0.160	0.122
		Non-microsleep	231	0.142	0.104
	Curve	Microsleep	34	0.209	0.127
		Non-microsleep	68	0.169	0.101
SDSWA	Straight	Microsleep	117	1.967	1.763
		Non-microsleep	231	1.782	1.735
	Curve	Microsleep	34	2.946	1.840
		Non-microsleep	68	2.882	1.862
Steering entropy	Straight	Microsleep	117	0.564	0.049
		Non-microsleep	231	0.551	0.060
	Curve	Microsleep	68	0.557	0.062
		Non-microsleep	34	0.567	0.397
Minimum TLC	Straight	Microsleep	117	3.828	3.062
		Non-microsleep	231	3.082	2.215
	Curve	Microsleep	68	0.766	0.530
		Non-microsleep	34	0.997	0.837

[a] *Note:* Driving performance on a drive segment where a microsleep occurred are matched with the performance at the corresponding location in the other two segments.

$F(1, 416) = 22.51$, $p < 0.0001$) and SDLP ($F(1, 416) = 14.56$, $p = 0.0002$), but not in steering entropy ($F(1, 416) = 0.28$, $p = 0.596$). Thus, as expected, greater variation was observed in vehicle position and steering control on curves. Differences in lateral performance was also observed between the microsleep and non-microsleep episodes (Wilks' Lamda $F(3, 414) = 2.65$, $p = 0.049$). Univariate ANOVAs showed that this difference was due to SDLP ($F(1, 416) = 4.75$, $p = 0.030$) and steering entropy ($F(1, 416) = 4.02$, $p = 0.0457$). However, no significant differences were observed in SDSWA ($F(1, 416) = 0.71$, $p = 0.400$). There was also a significant difference in drive segments (Wilks' Lambda $F(6, 828) = 3.67$, $p = 0.0013$) but this was attributed solely to differences observed in SE (univariate $F(2, 416) = 11.08$, $p < 0.0001$). More specifically, SE significantly increased in the last drive segment ($M = 0.568$) when compared to the first segment ($M = 0.548$). No other differences (in main effects or interactions) were observed among these performance measures.

The minimum TLC was significantly different between road types ($F(1, 473) = 102.69$, $p < 0.05$) with mean times significantly lower (overall mean = 0.41) on curves compared to straight roads (overall mean = 2.22). There were no other statistically significant differences observed at $p < 0.05$.

3.2. Performance measures and microsleep duration

The duration of microsleep episodes were segmented into three categories: short ($3 \leqslant t < 4.74$ s), medium ($4.74 \leqslant t < 7.00$ s), and long durations ($t \geqslant 7.00$ s). The values used were based upon the calculated median microsleep duration (4.74) and the calculated 75th percentile (Q3) of all microsleep durations (7.00). The number of episodes of short, medium and long duration used are shown in Table 2. There were no differences observed in mean speed regardless of the microsleep duration ($F(2, 138) = 0.71$, $p = 0.49$).

As was done previously, the steering measures were evaluated using MANOVA. The findings showed that significant differences did exist on road type (Wilks' Lamda $F(3, 143) = 4.59$, $p = 0.0042$), for microsleep durations ($F(6, 286) = 3.92$, $p = 0.0009$), and the interaction between road type and microsleep durations ($F(6, 286) = 4.47$, $p = 0.0002$). In terms of the contribution of each steering measure, univariate ANOVA showed that SDLP was significantly different for road type ($F(1, 145) = 3.95$, $p = 0.0486$) and for microsleep durations ($F(2, 145) = 6.61$, $p = 0.0018$). As shown in Fig. 1a, SDLP was significantly higher on curves (mean SDLP = 0.20) than on straight segments (mean = 0.16) and also increased with longer microsleep durations.

With respect to SDSWA, significant differences were observed for road type ($F(1, 145) = 13.94$, $p = 0.0003$) and the interaction of road type with microsleep durations ($F(2, 145) = 7.06$, $p = 0.0012$). More specifically, SDSWA increased sharply on curved road segments when the microsleep durations increased from medium (mean = 2.33) to long (mean = 4.61) (Fig. 1b). SE significantly decreased on curves during microsleep durations of medium length ($F(2, 145) = 3.33$, $p = 0.039$) (Fig. 2).

The minimum TLC did not significantly differ among the microsleep durations ($F(2, 143) = 1.84$, $p > 0.05$). There was, however, a significant difference between road types ($F(1, 141) = 33.85$, $p < 0.0001$) with an overall mean TLC being 2.85 s on straight segments and 0.59 s on curves (Fig. 3). No interaction effect was observed between microsleep duration and road types ($F(2, 143) = 0.30$, $p > 0.05$).

4. Discussion

This study examined the momentary effects of microsleeps on the performance of drivers who are at particular risk for drowsy driving because of OSAS. We tested the hypothesis that drowsy drivers would show

Table 2
Number of microsleep episodes for each microsleep duration and road type

Road type	Microsleep durations			Total
	Short	Medium	Long	
Straight	57	34	26	117
Curved	17	7	10	34
Total	74	41	36	151

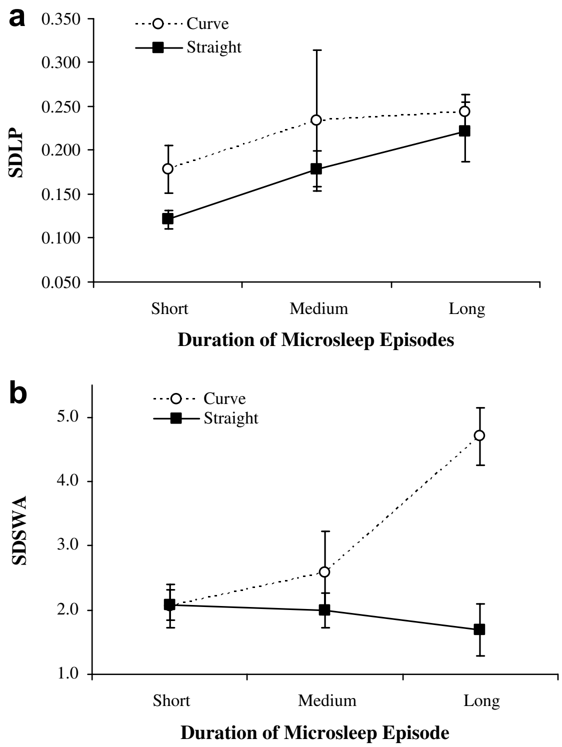

Fig. 1. The effect of microsleep duration on lateral controls: (a) SDLP and (b) SDSWA.

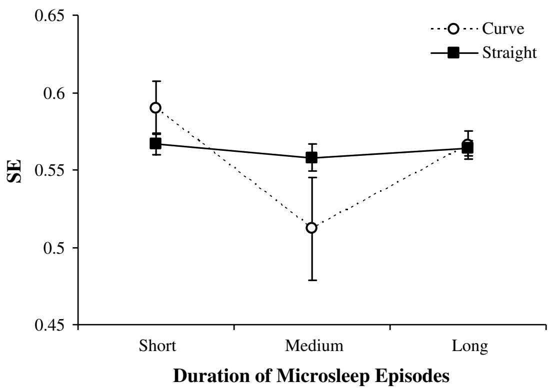

Fig. 2. The effects of microsleep duration on steering entropy by road type.

measurable changes in driving performance during microsleep compared to matched non-microsleep segments. The results of this study showed significant differences in driver control that were related to both the occurrence and duration of microsleeps. Drivers showed lower speeds during microsleep episodes, indicating that drowsy drivers exert less control over the accelerator pedal during microsleeps by failing to continue to depress it as needed to maintain the recommended speed. Changes such as momentary vehicle slowing are not likely to have much effect on a vacant rural road, but might produce interactions that alter the traffic flow in highly congested areas, when sleepy drivers are returning home during peak traffic periods. Risser et al. (2000) found greater speed variability in drowsy drivers with OSAS compared to controls over an entire

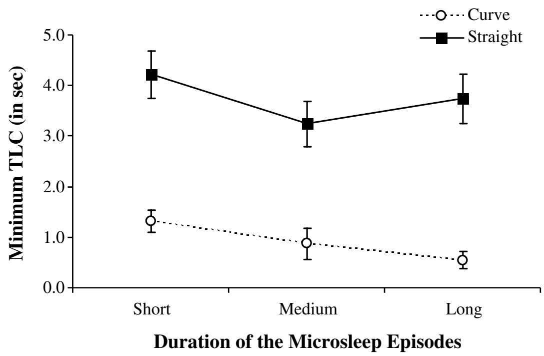

Fig. 3. The effects of microsleep duration on minimum TLC by road type.

simulator drive, but did not assess momentary changes related to microsleeps. They also noted that lane position variability correlated with the frequency and duration of EEG-defined "attention lapses".

Although there was no effect for SDSWA due to microsleeps, drivers with OSAS showed greater variability in maintaining lane position during microsleep episodes compared to non-microsleep episodes. SE increased during microsleep episodes and with successive drive segments, a finding not observed with the other lateral measures. Unlike the other steering measures, SE is related to moment predictability and will increase as drivers make more error corrective maneuvers. The finding that entropy increased with each drive segment indicates that sleepy drivers with microsleep episodes showed worse vehicle control the longer they drove.

The finding of lower minimum TLC on curves, calculated using the method of van Winsum and Godthelp (1996), suggests that changes in road geometry may lead to a greater crash risk. Minimum TLCs were longer on straight segments, probably due to invariant road geometry and lack of external challenges. These findings suggest that drivers can maintain a relatively high TLC on straight segments during microsleep episodes of differing durations even if they may not be controlling the vehicle as actively.

Use of a fixed-base driving simulator in this study allowed us to make safe observations of sleepy driver behavior with a high degree of experimental control. A drawback of this approach is that feedback to the driver in any simulator differs from that in a moving vehicle. Drivers in actual road conditions get more tactile and vibratory feedback from the steering wheel, seat and vehicle frame, as well as vestibular feedback, all of which provide potential cues for drivers to exert control over the vehicle.

There are also challenges in using EEG to study sleepy driving. Because movement and muscle artifacts may hinder EEG interpretation, this study analyzed only artifact-free EEG data. Microsleeps occurring during uninterpretable portions would be missed. Although we used expert visual inspection of the EEG to identify microsleeps according to generally accepted criteria, this technique is inherently subjective. However, Moller et al. (2006) were also able to demonstrate that an increased number of EEG defined microsleeps correlates with poorer simulated driving performance in sleep-deprived drivers. Several studies have used "quantitative" EEG methods to identify driver sleepiness (de Waard & Brookhuis, 1991; Eoh, Chung, & Kim, 2005; Horne & Reyner, 1996; Kecklund & Akerstedt, 1993; Lal & Craig, 2002). Alpha and theta power (usually expressed as the relative power of alpha + theta/beta), and the frequency of alpha and theta bursts typically increase during prolonged driving, and are associated with poor driving performance. As these techniques typically average EEG activity over several seconds (up to 1 min), detection of brief microsleep episodes, as studied here, would not be possible. Eoh et al. (2005) showed that the numbers of short (1 s) alpha bursts and driving incidents increased with driving duration. However, instead of finding bursts occurring at the time of an incident, they noted a drop in alpha + theta/beta power in the seconds after incidents compared to the preceding 10 s. Although the current study did not include spectral analysis of EEG data, decline in alpha + theta/beta power probably reflects post-event alerting, while microsleep episodes reflect both pre- and post-event EEG changes. Risser et al. (2000) found that "attention lapses", comprising EEG episodes of increased alpha or theta activity lasting more than 3 s (which differs from the conventional definition of microsleeps) correlated with lane position variability and crash frequency. The best techniques for identifying impending driver sleepiness by EEG are targets for future research.

A variety of physiological measures have been proposed for identifying and alerting drowsy drivers. One of the most investigated is PERCLOS (or PERcent CLOSure), a measure of drowsiness associated with slow eye closures (Grace et al., 1998; Hayami, Matsunaga, Shidoji, & Matsuki, 2002; Pilutti & Ulsoy, 1997). However, PERCLOS does not identify drivers with "blank stares", whose eyes remain open while they are drowsy. EEG changes, including microsleep episodes, may provide complementary evidence of impending sleep in these drowsy drivers. Paul et al. (2005) showed that drivers had greater variation in steering and lane position during microsleep episodes when compared to the periods before and after a microsleep. Lal and Craig (2002) identified early signs of sleepiness in a driving simulator task using EEG that was later proposed for fatigue-detection countermeasure systems (Lal, Craig, Boord, Kirkup, & Nguyen, 2003).

Combining EEG and PERCLOS data may permit the design of an onboard system that could alert sleepy drivers to unsafe situations before lid closure occurs. While the current study did not directly study this issue, EOG recordings (made to exclude potential artifacts during EEG recordings) showed that eye blinks often continued during microsleeps, indicating that the eyes were at least partially open. In fact, eye closure characteristically leads to an increase in alpha (Niedermeyer, 2005), rather than the decrease that was used as the primary criterion for determining the presence of a microsleep. Further studies are needed to establish the extent to which EEG and eye closure information provide complementary information.

This study used a within subject design and was specifically aimed at evaluating driver performance related to microsleeps in an enriched population of drowsy drivers. It did not address the relationship between overall performance and EEG changes, or correlate findings with subjective measures of sleepiness such as the ESS. The costs and benefits of EEG monitoring of drivers, and how the findings discriminate between groups of safe and unsafe drivers with varying degrees of sleepiness or sleep disorders are topics for future studies.

In conclusion, drowsy drivers with OSAS show deterioration in simulated driving performance during EEG-verified microsleeps. The degree of deterioration correlated with microsleep duration and was worse when microsleeps occurred on curved road segments. Identifying how microsleep episodes influence driving behavior may prove to be relevant to the design and implementation of countermeasures, such as drowsy driver detection and alerting systems.

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