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Author/s:

Alvaro, PK;Jackson, ML;Berlowitz, DJ;Swann, P;Howard, ME

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SCIENTIFIC INVESTIGATIONS

Prolonged Eyelid Closure Episodes during Sleep Deprivation in Professional Drivers

Pasquale K. Alvaro, PhD^{1,2}; Melinda L. Jackson, PhD^{1,3}; David J. Berlowitz, PhD^{1,4}; Philip Swann, PhD⁵; Mark E. Howard, PhD^{1,2,4}

¹Institute for Breathing and Sleep, Department of Respiratory and Sleep Medicine, Austin Health, Melbourne, Australia; ²School of Psychological Sciences Monash University, Melbourne, Australia; ³RMIT University School of Health and Biomedical Sciences, Melbourne, Australia; ⁴University of Melbourne Department of Medicine Austin Health, Victoria, Australia; ⁵Department of Road Safety, Vic Roads, Victoria, Australia

Study Objectives: Real life ocular measures of drowsiness use average blink duration, amplitude and velocity of eyelid movements to reflect drowsiness in drivers. However, averaged data may conceal the variability in duration of eyelid closure episodes, and more prolonged episodes that indicate higher levels of drowsiness. The current study aimed to describe the frequency and duration of prolonged eyelid closure episodes during acute sleep deprivation.

Methods: Twenty male professional drivers (mean age \pm standard deviation = 41.9 \pm 8.3 years) were recruited from the Transport Workers Union newsletter and newspaper advertisements in Melbourne, Australia. Each participant underwent 24 hours of sleep deprivation and completed a simulated driving task (AusEd), the Psychomotor Vigilance Task, and the Karolinska Sleepiness Scale. Eyelid closure episodes during the driving task were recorded and analyzed manually from digital video recordings.

Results: Eyelid closure episodes increased in frequency and duration with a median of zero s/h of eyelid closure after 3 h increasing to 34 s/h after 23 h awake. Eyelid closure episodes were short and infrequent from 3 to 14 h of wakefulness. After 17 h of sleep deprivation, longer and more frequent eyelid closure episodes began to occur. Episodes lasting from 7 seconds up to 18 seconds developed after 20 h of wakefulness. Length of eyelid closure episodes was moderately to highly correlated with the standard deviation of lateral lane position, braking reaction time, crashes, impaired vigilance, and subjective sleepiness.

Conclusions: The frequency and duration of episodes of prolonged eyelid closure increases during acute sleep deprivation, with very prolonged episodes after 17 hours awake. Automated devices that assess drowsiness using averaged measures of eyelid closure episodes need to be able to detect prolonged eyelid closure episodes that occur during more severe sleep deprivation.

Keywords: drowsiness, sleepiness, eyelid closure episodes, professional drivers, averaged data, automated devices

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INTRODUCTION

Sleep deprivation and resultant drowsiness are common causes of impaired performance and motor vehicle accidents (MVA) in both the general population and professional drivers.^{1,2} A lack of real-time drowsiness measures has hampered efforts to develop and assess interventions for sleep deprivation. Objective measures of real-time drowsiness that accurately identify sleepy individuals before and during driving events can potentially prevent MVAs by alerting the driver to significant drowsiness levels and in turn suggest the use of countermeasures, such as a nap or caffeine. They would also provide an opportunity to evaluate the impact of different driving schedules, identifying high risk schedules that result in drowsy driving and assisting with the design of safer work schedules.

Slow, prolonged eyelid closure is associated with drowsiness, and recent studies have suggested that the speed, duration, and amplitude of eyelid closure episodes are promising real-time indicators of drowsiness.^{3,4} Indeed, automated devices that measure eyelid closure episodes in real time have been developed.³ They rely on averaged values of these eyelid closure metrics rather than identifying individual episodes

BRIEF SUMMARY

Current Knowledge/Study Rationale: Measures of eyelid closure episodes accurately reflect drowsiness in drivers, but most ocular devices of eyelid closure episodes use average blink duration. Averaged data may conceal variability in duration of eyelid closure episodes, and more prolonged episodes indicate more extreme drowsiness.

Study Impact: This study identified increasing frequency and duration of prolonged eyelid closure lasting up to 18 seconds after 17–23 hours of sleep deprivation, both emphasizing the substantial risk of driving after acute sleep deprivation and the necessity for ocular based alertness monitors to detect these prolonged episodes.

of prolonged eyelid closure. For example, the percentage of eyelid closure (PERCLOS)⁵ reflects the proportion of time an eyelid covers more than 80% of the pupil during a 1-min time interval. PERCLOS is associated with increased drowsiness,⁴ decreased vigilance and psychomotor performance, and lane departures and crashes during simulated driving in sleep deprived drivers.^{4–8} Similarly, the average blink duration and amplitude and velocity of eyelid movements are related to impaired vigilance, frequent lapses in attention, and real-life

adverse driving events.^{3,9,10} However, average measures could mask the variability in duration of eyelid closure episodes and more prolonged episodes that indicate higher levels of drowsiness. Previous studies have yet to describe the frequency and duration of prolonged eyelid closure episodes during acute sleep deprivation. Such information would inform methods for automated measurement, and hence is the topic of this study. We hypothesized that prolonged episodes of eyelid closure would become more frequent with increasing acute sleep deprivation in professional drivers.

METHODS

Participants

Twenty male professional drivers (mean age \pm SD = 41.9 \pm 8.3 years) were recruited via the Transport Workers Union newsletter and newspaper advertisements. Each participant must have driven for \geq 30 h/week for a period $>$ 12 months to be eligible. Participants with contraindications to sleep deprivation, symptoms of excessive sleepiness or a sleep disorder, medical conditions (e.g., depression, stroke, dementia), a history of learning disability, drug abuse, or a brain injury that might affect neuropsychological performance were excluded from the study.¹¹

Protocol

Participants attended a screening session followed by a 24-h test session on a separate day. In the first session, written informed consent was obtained, and the participants were screened against the inclusion criteria and undertook a practice session on the driving task to overcome learning effects. Participants completed a sleep diary for one week before the 24-h test session.

For the second session, participants were instructed to wake at 07:00 and arrive at the laboratory by 08:30 on the morning of the test session following a full night of sleep (7.2 \pm 1.4 h) as documented by a sleep diary. They remained awake for 24 h and were continuously monitored by laboratory staff. A test battery including the driving task, the psychomotor vigilance task and the Karolinska Sleepiness Scale was completed 7 times during the 24-h acute sleep deprivation period at 09:00, 12:00, 16:00, 20:00, 24:00, 03:00, and 06:00. Participant sleepiness was recorded immediately after the driving simulation. Participants undertook passive activities in between testing sessions, such as reading or watching videos. They were also prohibited from caffeine consumption on the day of the test session and from smoking for 30 min prior to a test battery. Taxis were provided to and from the laboratory. Participants were reimbursed AU\$200 to cover the time they spent involved in the study. This study was approved by the Human Research and Ethics Committee at Austin Health, Melbourne, Victoria.

Outcome Measures

The AusEd driving simulator (AusEd, Woolcock Institute, Sydney, Australia)¹² was used to measure driving performance. The drive included a 30-min nighttime drive on a two-lane highway, with standard lane divisions, road edges marked

with reflective posts, and a series of curved and straight components. The instructions for drivers were to stay in the center of the left lane (consistent with Australian driving rules) and remain within a 60 to 80 km/h speed on the speedometer. Lateral lane position, variation in speed, braking reaction time (ms), and mean number of crashes (off road, stoppage events, and truck collisions) were recorded. Each drive session contained identical road conditions and truck presentation times. This driving simulation program is sensitive to sleep deprivation and alcohol.^{13,14}

Slow eyelid closure was assessed manually during the simulated driving task via digital video recordings of the face, using infrared light.⁵ A scorer (MH) scrolled through the video in 0.5-s frames, recording each eyelid closure episodes (80% closure as per PERCLOS) \geq 1 s and the duration of the episode.⁵ The scorer was blinded to the participant details, the time and date of the recording and the driving simulation outcomes. The frequency and duration of eyelid closure episodes were calculated for each 30-min driving simulation session.

Reaction time was measured by the Psychomotor Vigilance Task (PVT), a 10-min computer based timed task that involves reacting to a visual stimulus that is presented at varying intervals 10 times per minute.¹⁵ Median reaction time and the number of lapses (reaction time $>$ 500 ms), both of which are sensitive to circadian effects and sleep deprivation,¹³ were recorded for each session. Sustained attention and a rapid stimulus response are required for The PVT and driving a motor vehicle.^{16,17}

The Multivariable Apnea Predictor Questionnaire (MAPQ)¹⁸ is a measure of sleep disordered breathing that contains items on age, gender, body mass index, and the frequency of snorting or gasping, loud snoring, and episodes of choking, breathing stopping, or struggling for breath at night. The total scores vary from 0 to 1.0, with higher scores indicating higher probability of sleep disordered breathing. Studies have validated the MAPQ in clinical populations to differentiate between low risk and at least mild risk of sleep disordered breathing, with a cut-off score of 0.5 yielding an acceptable combination of sensitivity (88%) and specificity (55%).¹⁸

The Epworth Sleepiness Scale (ESS) is a measure of subjective sleepiness.¹⁹ The ESS is an 8-item self-report questionnaire that asks about tendency to fall asleep in different everyday life situations over the past 4 weeks. Total scores range from 0 to 24, with higher scores suggesting higher levels of sleepiness. ESS Scores $>$ 10 suggest clinically significant sleepiness.¹⁹

The Karolinska Sleepiness Scale (KSS) is a 9-item self-report measure for subjective sleepiness.²⁰ Scores range from 1 to 9, with lower scores indicated alertness and higher scores indicating sleepiness. The KSS has been validated as a measure of sleepiness against electroencephalography and performance vigilance measures.^{20,21}

Statistical Analysis

Stata 12.0 was used to calculate all statistics. Means and standard deviations were used for demographic variables. Three participants had missing values replaced, because they were too sleepy to complete the final test session, by linear extrapolation and interpolation.²² Log transformations were computed

Table 1—Demographic information of professional drivers.

Demographic Variable	Mean	Standard Deviation
Age	41.9	8.3
Driving per week (h)	45.6	15.4
Working per week (h)	41.1	10.8
Shift work (%)	70.6	n/a
ESS	5.6	3.0
MAPS	0.36	0.2
Sleep prior week (h)	52.2	9.5
Sleep prior night (h)	7.2	1.4

ESS, Epworth Sleepiness Scale; MAPS, Multivariable Apnea Prediction Score

Table 2—Correlations between slow eyelid closure, performance and subjective sleepiness.

	Slow Eye Closure sec/h	
	r*	p
AusEd driving simulator		
Variation in lane position	0.60	< 0.01
Variation in speed	0.30	< 0.01
Braking reaction time	0.50	< 0.01
Crashes	0.43	< 0.01
Psychomotor vigilance task		
Reaction time	0.49	< 0.01
Lapses	0.51	< 0.01
Karolinska Sleepiness Scale	0.52	< 0.01

*r for Spearman correlation.

for speed and lateral lane position to produce a normal distribution.¹¹ The duration of eyelid closure episodes lasting ≥ 1.0 s were recorded, grouped into 3-s bins, and the frequency per hour reported for each drive. Seconds per hour of eyelid closure was also calculated for each drive. The Friedman test was used to assess the effect of hours awake on the rate of slow eyelid closure. The relationship between seconds per hour of eyelid closure, driving performance, and vigilance measures and subjective sleepiness was assessed using the Spearman correlation.

RESULTS

The professional drivers were on average 42 years old (SD = 8.3), drove 45 h per week and worked 41 h per week. Most worked shift work, and the average ESS and MAPS scores did not indicate clinically significant symptoms of sleepiness or sleep apnea. They averaged 52 h of sleep in the previous week, and 7.2 h of sleep the night before the study. **Table 1** displays the demographic information for the professional drivers.

Infrequent episodes of eyelid closure were evident from 3 to 14 h of wakefulness, mainly of short duration between 1 to 3 s (**Figures 1 and 2**). There was a progressive increase towards longer and more frequent eyelid closure episodes after 17 h

Figure 1—Frequency of eyelid closure episodes by duration of time (hours) awake.

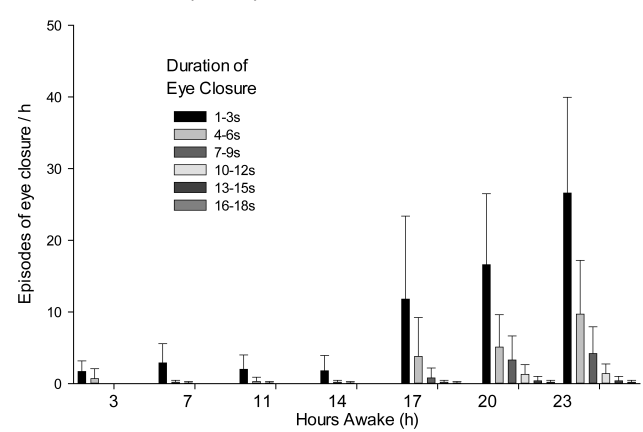
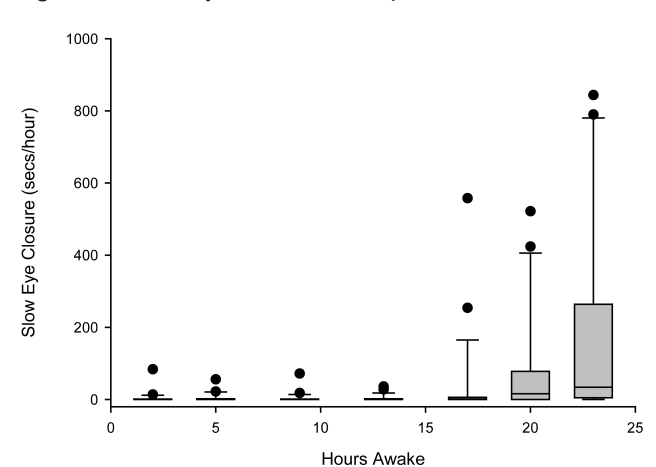


Figure 2—Slow eyelid closure compared to hours awake.



awake, where 6-s episodes became common. Episodes lasting from 7 s up to 18 s developed after 20 h of wakefulness (**Figure 1**). Increased frequency of eyelid closure was significantly correlated with the standard deviation of lateral lane position ($r = 0.60$, $p < 0.01$), braking reaction time ($r = 0.50$, $p < 0.01$), and crashes ($r = 0.43$, $p < 0.01$). There were also moderate correlations with impaired vigilance and subjective sleepiness (**Table 2**).

Figure 2 shows slow eye closure (seconds per hour) during each driving session compared to hours awake, and the box plots for the outliers at the 90th, 75th, 50th, 25th, and 10th percentiles. The Friedman test demonstrated an effect of hours awake on the rate of slow eyelid closure, $\chi^2 = 64.1$, $p < 0.01$.

DISCUSSION

This study found that episodes of prolonged eyelid closure were infrequent during the first 14 hours of sleep deprivation, but spiked and continued to increase in both duration and frequency after 17 hours of sleep deprivation, lasting much longer than previously suggested from automated measures.^{3,23} The

changes in prolonged eyelid closure reflect previously documented decrements in behavioral performance and increased subjective sleepiness during acute sleep deprivation,²³ and were related to impaired driving performance and vigilance in this study.

The changes in eyelid closure likely resulted from the combined effects of accumulating homeostatic and circadian sleep pressure due to acute sleep deprivation that continued into and beyond the circadian nadir. Such changes likely reflect increased alpha and theta activity from wakefulness on an electroencephalogram (EEG).²⁴ The findings were unlikely to be due to a sleep disorder or previous sleep restriction, as professional drivers with obstructive sleep apnea and high levels of self-reported sleepiness were excluded from the study, and each participant reported over seven hours of sleep the morning before participation.¹¹ The findings suggest that severe physiological impairment can occur during acute sleep deprivation even in those without underlying sleep disorders or prior sleep restriction, a situation that is commonly faced by transport drivers working shift work.²

Episodes of eyelid closure while driving were longer than previously suggested by averaged data from automated devices, particularly after 17 hours of sleep deprivation.^{3,23} Consequently, while the results support the pursuit of simple automated methods for measuring ocular movements to assess and monitor drowsiness, they suggest that averaged data are influenced by a large range of eyelid closure episode length, particularly during extended sleep deprivation. Given the low variability in duration and frequency of eye closure episodes before but high variability after 17 hours of wakefulness, averaged measures of eyelid closure episodes may be useful during shorter periods of sleep deprivation but may fail to detect the true magnitude of eyelid closure episodes, and hence severity, of drowsiness after sleep deprivation of over 17 hours. Indeed, sleep-related driving events are positively and strongly associated with higher maximum blink durations in real-life settings.¹⁰

The increased frequency of prolonged eyelid closure episodes after 17 hours awake is particularly important given that it takes less than three seconds to run off the road when driving at approximately 100 km per hour.²⁵ These results enhance our understanding of the mechanisms underlying impaired vigilance and attention in professional and nonprofessional drivers^{26,27} and the associated crash risk. They suggest that automated devices for drowsiness detection based on ocular measures should be capable of detecting discrete and prolonged episodes of eyelid closure, while acknowledging that other ocular measures may detect more subtle signs of drowsiness. The results support trials of devices that can accurately measure eyelid movements to monitor drowsiness in drivers. Trials need to demonstrate accuracy in field settings and the efficacy of devices for changing driver behavior and reducing risk.²⁸ Devices that measure fatigue have often been released before scientific evaluation has determined their accuracy.²⁹ Dawson et al.²⁸ suggest a due diligence guideline to ensure drowsiness detection devices are validated before commercial use including: independent peer-reviewed, laboratory studies that validate the measure (e.g., eyelid closure episode); determination

of cutoff scores for dangerously high levels of drowsiness; and finally, devices should be validated in field studies, including evaluating their impact on relevant occupational adverse events such as crashes.

A potential limitation of this study is the questionable applicability to nonprofessional drivers, as scholars have argued that professional drivers self-select to become more resistant to sleep deprivation.³⁰ However, recent studies have found no difference in measures of sleepiness and driving performance between professional and nonprofessional drivers during sleep deprivation.¹¹ Given this it is likely that eyelid closure episodes in sleep deprived nonprofessional drivers are likely to be at least as long as those in professional drivers. Confirming these changes in nonprofessional drivers would help gauge the generalization of these results.

The current study found that episodes of very prolonged eyelid closure were more frequent and prolonged when driving after being awake for 17 hours, with episodes of eyelid closure as long as 18 seconds, while prolonged episodes were much less frequent up to 14 hours of wakefulness. The results support restricting shift duration for professional drivers to avoid driving after prolonged periods of wake. Furthermore, the results suggest that while averaged measures of eyelid closure episodes can accurately reflect drowsiness in less sleep deprived individuals, automated devices should also be capable of detecting prolonged eyelid closure episodes that occur during more severe sleep deprivation. Trials are required to demonstrate the accuracy of such devices in field settings, and whether they provide the impetus for drivers to take preventive measures to avoid drowsy driving and appropriate countermeasures when they become impaired.

ABBREVIATIONS

ESS, Epworth Sleepiness Scale
h, hour(s)
km, kilometer(s)
KSS, Karolinska Sleepiness Scale
MAPQ, Multivariable Apnea Prediction Questionnaire
min, minute(s)
MVA, motor vehicle accident
PERCLOS, percent of time with eyelids closed
PVT, Psychomotor Vigilance Task
s, second(s)
SD, standard deviation

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Address correspondence to: Mark E. Howard, Bowen Centre, Austin Hospital, 145 Studley Road, Heidelberg, Victoria, 3084; Tel: +61 03 9496 3663; Fax: +61 03 9496 5768; Email: mark.howard@austin.org.au

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