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Slow eyelid closure as a measure of driver drowsiness and its relationship to performance

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Abstract

Objective: Slow eyelid closure is recognized as an indicator of sleepiness in sleep-deprived individuals, although automated ocular devices are not well validated. This study aimed to determine whether changes in eyelid closure are evident following acute sleep deprivation as assessed by an automated device and how ocular parameters relate to performance after sleep deprivation. Methods: Twelve healthy professional drivers (45.58 ± 10.93 years) completed 2 randomized sessions: After a normal night of sleep and after 24 h of total sleep deprivation. Slow eye closure (PERCLOS) was measured while drivers performed a simulated driving task. Results: Following sleep deprivation, drivers displayed significantly more eyelid closure ($P < .05$), greater variation in lane position ($P < .01$) and more attentional lapses ($P < .05$) compared to after normal sleep. PERCLOS was moderately associated with variability in both vigilance performance ($r = 0.68$, $P < .05$) and variation in lane position on the driving task ($r = 0.61$, $P < .05$). Conclusions: Automated ocular measurement appears to be an effective means of detecting impairment due to sleep loss in the laboratory.

Keywords

performance, relationship, its, drowsiness, driver, measure, closure, eyelid, slow

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ABSTRACT

Objective: Slow eyelid closure is recognized as an indicator of sleepiness in sleep deprived individuals, although automated ocular devices are not well validated. This study aimed to determine whether changes in eyelid closure is evident following acute sleep deprivation as assessed by an automated device, and how ocular parameters relate to performance after sleep deprivation. **Methods:** Twelve healthy professional drivers (45.58 ± 10.93 years) completed two randomized sessions; after a normal night of sleep and after 24-hours of total sleep deprivation. Slow eye closure (PERCLOS) was measured while drivers performed a simulated driving task. **Results:** Following sleep deprivation, drivers displayed significantly more eyelid closure ($p < 0.05$), greater variation in lane position ($p < 0.01$) and more attentional lapses ($p < 0.05$) compared to after normal sleep. PERCLOS was moderately associated with variability in both vigilance performance ($r = 0.68$, $p < 0.05$) and variation in lane position on the driving task ($r = 0.61$,

$p < 0.05$). **Conclusions:** Automated ocular measurement appears to be an effective means of detecting impairment due to sleep loss in the laboratory.

Keywords: Sleep deprivation, slow eyelid closure, professional drivers, simulated driving, vigilance, standard deviation of lateral position, reaction time

INTRODUCTION

Sleepiness is an on-going occupational hazard amongst professional heavy vehicle drivers as a result of long work hours, sleep restriction, circadian influences, irregular shifts and sleep disorders, all of which are related to increased accident risk (Folkard, 1997; Howard et al., 2004). A large proportion of heavy vehicle crashes are attributed to driver sleepiness (Maycock, 1997; National Transportation Safety Board, 1995; Sabbagh-Ehrlich, Friedman, & Richter, 2005). Accidents resulting from sleepiness can be a direct consequence of the driver falling asleep at the wheel, or having a lapse in attention at a critical moment while driving. Periods of inattention of even a few seconds can be long enough to result in an accident on the road (O'Hanlon & Beatty, 1977). Therefore, the detection of driver sleepiness has important implications for reducing the incidence of motor vehicle accidents, and the associated human and financial costs.

A number of potential measures for objective measurement of state-related sleepiness or performance impairment in active, awake individuals have been proposed. These include driver-related physiological measures, such as ocular measures, including blink duration and slow eyelid closures (Wierwille & Ellsworth, 1994; Åkerstedt, Peters, Anund, & Keckland, 2005; Anund et al., 2008; Åkerstedt et al., 2010) and electroencephalography (EEG) algorithms (Cajochen et al., 1999; Horne & Reyner, 1996), or vehicle-related measures, such as lane departure measures (May & Baldwin, 2009; Mortazavi, Eskandarian, & Sayed, 2009). Eyelid closure appears to be a promising method for indicating driver drowsiness in real-time (Dinges, Mallis, Maislan, & Walker-Powell, 1999; Ftouni et al., 2012). When a person becomes drowsy, there is a reduction in inputs to the thalamic motor projections to the face, including the eyelids,

causing these muscles to relax, resulting in increasingly longer periods of eyelid closure (Culebras, 2002). Thus, increased duration of eyelid closure often occurs in sleepy subjects who are trying to remain awake with their eyes open (Cajochen et al., 1999). As slow eyelid closure is observed to precede sleep onset, this physiological response has been examined as a potential leading indicator of sleepiness in active individuals (Santamaria & Chiappa, 1987). The metric “PERCLOS” is assessed as the percentage of time that the eyes are 80% closed (Wierwille & Ellsworth, 1994). Manually scored PERCLOS was originally developed using video recordings of the face in sleep-deprived, truck drivers, during a simulated driving task, and was found to be a valid predictor of drowsiness (Wierwille & Ellsworth, 1994). One laboratory experiment assessed six different drowsiness detection technologies, including eye blink monitors, EEG monitoring, head position monitors and video-scored PERCLOS under conditions of 42 hours of sleep deprivation (Dinges, Mallis, Maislan, & Walker-Powell, 1998). PERCLOS was found to be the most valid measure of drowsiness, producing the highest correlation with performance measures of lapses in attention for all subjects. PERCLOS was also found to be predictive of observed lapses within the first 22 hours of waking time, and more strongly related to performance than individual subjects rating of subjective sleepiness.

More recently, automated eye closure systems have been developed, using infrared oculography (Grace, et al., 1999; Johns, et al., 2007). Such devices can be considered advantageous as they are comparably unobtrusive to the driver, and can assess drowsiness in real-time. Automated measures of oculography have been found to be highly related to simulated driving metrics in well-rested (Mortazavi, Eskandarian, & Sayed, 2009) and sleep-deprived healthy individuals

(Johns, et al., 2007; Anderson et al., 2013; Ftouni et al., 2013). However, the current evidence supporting the effectiveness of automated technologies for detecting drowsiness and performance impairment is scarce, and such devices require further validation in sleep deprived subjects, particularly among commercial drivers. It is also well established in sleep research that large and unpredictable individual differences in response to sleep loss are observed across objective and subjective assessments of sleepiness, mood and performance (Van Dongen, Baynard, Maislin, & Dinges, 2004; Franzen, Siegle, & Buysse, 2008). This variability has also been demonstrated on ocular measures of drowsiness, including blink parameters (Ingre et al., 2006). It is therefore important to assess individual variations in automated ocular measures during sleep loss.

The aim of the current study was to 1) validate the use of an automated and unobtrusive ocular measure for assessing drowsiness (PERCLOS), to assess drowsiness under conditions of sleep deprivation in a sample of healthy professional drivers, 2) to examine the relationship between objectively measured PERCLOS (eyelid closure) and subjective drowsiness measures, driving errors, vigilance and reaction time, and 3) assess individual variations in the automated measure of PERCLOS.

METHODS

Participants

Twelve professional drivers (one female) aged between 23 and 62 years (mean age: 45.6 ± 10.9 years) were recruited. These participants comprised a sub-set of individuals who were involved in our previous study (Jackson et al., 2013) who had complete PERCLOS, driving and PVT data.

Data presented in the Jackson et al (2013) study comprised a sample of 19 participants aged between 23 and 62 years (mean age (sd) = 45.3 (9.1) years) however did not present PERCLOS analyses as this was not available for all 19 individuals for both testing sessions, and thus additional evaluation of these factors was considered beyond the scope of the previous manuscript. Thus, the current study presents sub-analyses of these individuals who had complete data for both Sleep and Sleep Deprivation sessions (N=12), and presents new information regarding the associations between previously described performance variables and PERCLOS. Inclusion criteria for participation were: a current heavy vehicle driver's license; no previous use of drugs that alter performance; and English as a first language. Exclusion criteria were: medical contraindications for the sleep deprivation protocol; a sleep disorder or sleep apnea (assessed by the Multiple Apnea Prediction Score questionnaire (score >0.5) (Maislin et al., 1995) and the Epworth Sleepiness Scale (ESS) (score >10) (Johns, 1993)); pregnancy; participants who could not tolerate having no cigarettes in a 12-hour period; high-level caffeine users, defined as five or more caffeinated beverages per day (Lenne, Triggs, & Redman, 1998); and visual impairment not correctable with glasses. There was a large range of hours spent driving for work per week in the group, ranging from 8 to 80 hours per week, with an average of 42.4 hours. The study was approved by the Swinburne University Human Research Ethics Committee.

Procedure

Drivers attended a screening session to test eligibility and practice the performance tasks. Drivers then completed two randomized conditions in a counterbalanced order; one following a normal night of sleep with eight hours time in bed (Sleep); and one after 24 hours of acute sleep

deprivation in the laboratory (Sleep Deprivation). Drivers were asked to have their normal amount of sleep during the night prior to each session, and instructed to complete the sleep diary for the week prior to each study day. The sleep diary measured total sleep per night and sleep latency each night, and these were averaged across the week. Blood and urine samples, taken at the start of each session to verify that there was no recent drug use, were analyzed using the GC/MS method. Testing times during each session were identical in order to control for circadian variations in performance. For the Sleep Deprivation session, drivers were asked to wake at 07:00h on the morning of their session, and attend the sleep laboratory at 22:00h following a normal eight-hour day driving shift. Drivers stayed awake until the following morning, and were monitored by the laboratory staff. During the night drivers watched videos, read, or played games. The following morning at 10:00h, drivers completed a 30-minute simulated driving session during which PERCLOS was recorded. Following the driving task, drivers performed a 10-minute Psychomotor Vigilance Test.

The Sleep session was identical to the Sleep Deprivation session, differing only in that drivers arrived at the sleep laboratory by taxi at 09:00h after a normal day shift followed by a normal night of sleep at home. No caffeine (e.g., coffee, tea, cola, chocolate) or other stimulants were allowed for six hours before and during each session. Smoking was not allowed throughout experimental sessions due to the possible stimulating effect.

Copilot

The Copilot is a device that measures eyelid closure, represented by the percentage of time that pupils are covered more than 80% (PERCLOS; Grace et al., 1999). This video-based system uses two infrared illumination sources of different wavelengths that reflect off the retina. The Copilot

calculates the difference between each light source ten times per second and calculates the percentage of time the eyes are closed, excluding normal blinks, which is averaged over the prior minute (Grace et al., 1999). The device is designed to provide the driver with feedback if drowsiness reaches a certain threshold, by way of a visual gauge and an auditory tone, but this was deactivated in the present study. This small device was placed on the desk in front of the subject during the driving simulator task. Drivers were asked to position the device until their eyes are visible in the small screen, and to minimise head movement during the task, to ensure that the device could detect slow eyelid closure throughout the whole task. Data were collected three times per second throughout the driving task. The average percentage of eye closure for the 30 minute driving session and the 10 minute PVT was calculated.

AusEd driving simulator

Driving performance was assessed on the AusEd driving simulator task, a PC based programme, which has been describe in detail previously (Howard et al., 2007; Jackson et al., 2013). Briefly, the task involves a 30-minute night time highway drive in a darkened room (Desai et al., 2007). Drivers were instructed to maintain their position in the middle of the left-hand lane on the road (in accordance with Australian driving code), and to keep their speed between 60 and 80 km/h. During the drive, ten slowly moving trucks appeared intermittently, driving in the same direction as the subject's vehicle. Drivers were instructed to brake as quickly as possible when they saw a truck appear in front of them. Drivers undertook a 5-minute practice drive prior to testing, to become familiar with the road layout and driving instrumentation (Desai et al., 2007). Outcome measures used in the current study were standard deviation of lateral lane deviation (from the

median lane position, averaged every 40s), variation in speed (outside the safe speed zone of 60 to 80 km/h), braking reaction time (milliseconds) and mean number of crashes (driving off the road, hitting the back of a truck or remaining stationary for more than 10 seconds).

Psychomotor Vigilance Test (PVT)

The PVT (Dinges & Powell, 1985) is a ten minute, computerized task that assesses sustained attention and reaction time, and requires continuous attention to detect randomly occurring stimuli. Drivers were required to observe the display screen and press a response button with their dominant hand as quickly as possible in response to a visual stimulus presented at random intervals (2 – 10 seconds). The PVT is free of aptitude and learning effects, and is sensitive to performance variations due to sleepiness (Doran, Van Dongen & Dinges, 2001; Dinges & Powell, 1985). Median reaction time (RT) and number of lapses in attention (reaction time > 500ms), response speed (1/RT), and fastest 10% of RT were measured.

Karolinska Sleepiness Scale (KSS)

The KSS is a single item scale designed to assess state subjective sleepiness. The KSS is a well-validated measure, and is highly correlated with EEG measures of sleepiness (Åkerstedt & Gillberg, 1990). Respondents are required to rate their current state of sleepiness on a 9-point scale. Possible scores range from one to nine, with higher scores representing greater subjective sleepiness. Participants' subjective sleepiness ratings were collected immediately following the completion of the PVT in both the sleep and sleep deprivation conditions.

Statistical Analysis

SPSS Version 21 (SPSS, Inc., Chicago, IL) was used for all statistical analyses. Performance variables on the AusEd driving simulator and PVT that were not normally distributed were transformed to produce normally distributed data. If this was not feasible appropriate non-parametric tests were used. Mixed model ANOVA were used to examine mean differences in PERCLOS, simulated driving and PVT performance and subjective sleepiness between the Sleep Deprivation and Sleep sessions. Mean differences in performance variables as measured by PERCLOS, PVT and driving simulator between the control (Sleep condition) and active (Sleep deprivation) sessions were calculated and were used in regression analyses to account for baseline variation in performance (difference scores). Linear regression models were conducted to examine relationships between PERCLOS, and subjective sleepiness and performance measures.

RESULTS

Effect of Sleep Deprivation on PERCLOS, Performance and Subjective Sleepiness

Table 1 displays the means and standard deviations of the PERCLOS, performance measures and subjective sleepiness data for each session. There was a significant difference in the PERCLOS measurements recorded during the driving task between the two sessions, with a higher frequency of slow eyelid closure in the Sleep Deprivation session ($F(1, 11) = 5.60, p < .05$; see Fig. 1). The range of PERCLOS scores in the Sleep session was 0.00% to 3.34%, and in the Sleep Deprivation session was 0.14% to 8.06%. Figures 2 and 3 displays the distribution of each driver's PERCLOS score relative to the mean difference scores on the performance measures

between the Sleep and Sleep deprivation sessions. There was no association between drivers' eye closure level at baseline and their mean difference score after sleep deprivation on either performance measure. Three of the 12 drivers displayed significant levels of eyelid closure following sleep deprivation (Figure 2), with one driver having moderate levels of eyelid closure in both sessions (Fig. 3).

On the driving simulator, significantly more speed variation ($F(1, 11) = 8.42, p < .01$) and standard deviation of lateral position ($F(1, 11) = 19.63, p < .001$) was observed in the Sleep Deprivation session in comparison to the Sleep session. Drivers were also significantly slower to brake in response to up-coming trucks when sleep deprived ($F(1, 11) = 7.07, p < .05$). There was no significant difference in the number of crashes during the driving simulator task between sessions ($p = 1.00$).

One driver did not complete the PVT either session, and one drivers KSS score was not collected, leaving 11 participants for the PVT and KSS analyses. Median RT was significantly slower in the Sleep Deprivation session compared to the Sleep session ($F(1, 10) = 12.75, p < .01$). There was a significant increase in the number of PVT lapses in the Sleep Deprivation session compared to the Sleep session ($F(1, 10) = 6.06, p < .05$). Response speed ($p = .08$) and fastest 10% of reaction times ($p = .055$) approached significance, with slower responses observed in the Sleep Deprivation session compared to the Sleep session. Subjective sleepiness ratings, as measured by the KSS, were significantly higher in the Sleep Deprivation session compared to the Sleep session ($F(1, 10) = 33.85, p < .001$).

Relationship between PERCLOS and Performance

To examine whether PERCLOS (averaged over the 10 minute PVT and 30 minute driving simulator task separately) was predictive of PVT and driving simulator performance, linear regression analyses were performed using the variable difference scores between the sleep and sleep deprivation conditions. PERCLOS was significantly related to PVT lapses ($r = .68, p < .05$) and standard deviation of lateral position on the driving simulator ($r = .61, p < .05$; see Fig. 3), accounting for 46% and 37% of the variance respectively. PVT Median RT ($p = .36$), speed variability ($p = .71$), braking reaction time ($p = .88$) and number of crashes ($p = .99$) were not significantly associated with PERCLOS, nor were subjective sleepiness ratings ($p = .32$).

DISCUSSION

This study demonstrated increased slow eyelid closure following acute sleep deprivation, using an automated ocular monitoring device, the Copilot. PERCLOS was related to impaired driving performance and vigilance, suggesting that automated measures of slow eyelid closure may be useful indicators of performance impairment resulting from sleep deprivation in the laboratory setting. The results are in keeping with the limited number of previous studies evaluating automated ocular devices, however further work is required to assess the relationship between eyelid closure and other measures of performance and sleepiness, in larger samples, and in more naturalistic settings.

PERCLOS measured during simulated driving was sensitive to one night of sleep deprivation. There was a small but significant increase in the percentage of eyelid closure, from less than 1% at baseline to 2.5% after sleep deprivation. This represents the mean value during a 30-minute

drive; hence, there are periods with much higher values during the drive. Previous studies have also reported an increase in assessed ocular metrics with increasing hours awake during simulated driving (Morris & Miller, 1996; Johns et al., 2007; Caffier, Erdmann, & Ullsperger, 2003) and during actual driving following a night shift (Ftouni et al., 2012). Given that eye blinks are associated with visual obstruction, and can lead to lapses in performance (Anderson, Wales & Horne, 2010) (as found in our PVT measure), increases in eyelid closures can have significant implications for driving safety.

There was a large individual variability in the amount of eye closure recorded following sleep deprivation, as seen by the large standard deviations in the current study. Previous studies have also noted that physiological and behavioural measures taken during sleep deprivation can have large between-subject variation (Åkerstedt et al., 2010; Ingre et al., 2006; Van Dongen, Baynard, Maislin, & Dinges, 2004). One limitation, therefore, of the use of eyelid closure as a detection method for sleepiness is that the detection level for when to alert the driver that they are too drowsy to continue to drive is likely to be different for each driver. The underlying cause of this individual variation in physiological responses to sleepiness needs to be identified in order for such systems to have better specificity for detecting drowsiness in different individuals. Alternatively, ocular detection methods may need to be individually tuned to each driver in order to overcome individual variations in physiological responses to sleepiness. Examination of individual differences in ocular measures, and how they relate to performance impairment, is an important future step in the validation process of these devices.

Our sleep deprivation protocol was sufficient to induce performance impairments on the simulated driving task and PVT. Specifically, variability in lateral lane position significantly increased when drivers had lowered alertness levels, consistent with previous studies using the AusEd driving simulator (Howard et al., 2007; Vakulin et al., 2007), on other driving simulator tasks (George, 2000; George, Boudreau, & Smiley, 1996; Lenne, Triggs, & Redman, 1998), and during on-road driving (Philip, et al., 2005; Ramaekers & O'Hanlon, 1994). Previous studies have also noted significant variations outside the prescribed speed range with sleep loss (Arnedt, Wilde, Munt, & MacLean, 2001; Lenne, Triggs, & Redman, 1998), consistent with the current study. Whilst driving simulator performance does not provide an absolute measure of crash risk, it is related to on road driving performance (Philip et al., 2005) and these behaviors are indicative of unsafe driving (Brookhuis, De Waard, & Fairclough, 2003).

Lapse events on the PVT significantly increased in the sleep deprivation session, consistent with previous studies (Dinges et al., 1997; Koslowsky & Babkoff, 1992; Rogers, Dorrian & Dinges, 2003). Linear regression also revealed that differences in PERCLOS values accounted for nearly half of the variance in PVT lapses (differences between conditions) recorded on the PVT in our sleep deprived drivers, which is consistent with findings presented among similar studies which have demonstrated an association between eyelid movements and lapses in behavioural parameters among sleep deprived individuals (Wilkinson et al, 2013). The neural processes associated with attentional lapses are currently unclear - they may reflect a period of eye closure where a sleepy subject simply misses the visual stimulus; they may be caused by a "microsleep" or period of sleep measured by EEG; or they may result from deterioration in cognitive or visual

processing relating to sleep deprivation, where the eyes are open but the stimulus is missed. PERCLOS explained a large proportion of the variance in the performance impairment that occurred with acute sleep deprivation; however other factors may contribute to some of the remaining variance. These “microsleeps” can be assessed using EEG measures of drowsiness (Cajochen et al., 1999; Horne & Reyner, 1996; Howard, Gora, Swann, & Pierce, 2002a). It is also possible that other subtle cognitive factors implicated in driving, such as deficits in visual scanning as a result of driver distraction (Shiferaw, Stough & Downey, 2014), or additional underlying cognitive processes, such as impairment of visual encoding of information or slowing motor responses, may also lead to performance degradation following sleep loss (Jackson et al., 2008). PERCLOS detects performance impairment at a very late stage of drowsiness, when performance lapses are already occurring. Ideally, drowsiness detection devices should be able to pick up earlier signs of drowsiness to warn drivers prior to lapse events occurring. Newer methods of eye lid closure detection and algorithms incorporating different ocular metrics may prove to be more sensitive measures of drowsiness than PERCLOS alone (Hanowski et al., 2008).

In the current study, PERCLOS accounted for a significant amount of the variance in standard deviation of lateral position, a driving measure that is sensitive to sleep deprivation (Arnedt, Wilde, Munt, & MacLean, 2000; Arnedt, Wilde, Munt, & MacLean, 2001; Jackson et al., 2013). Strong relationships have also been described previously between PERCLOS and simulated driving performance (r -values of 0.40 to 0.78) using different methods for measuring PERCLOS (Dingus et al., 1987; Wierwille, 1999; Mortazavi, Eskandarian & Sayed, 2009). In real-world

driving, a brief period of inattention or driver distraction at a critical point in time may result in running off the road and failure to respond quickly enough to avoid a crash (O'Hanlon & Betty, 1977; Shiferaw, Stough & Downey, 2014). These results suggest that an accurate measure of slow eyelid closure may be able to identify drivers that are impaired by sleep deprivation; however this still needs to be demonstrated beyond the laboratory setting. In addition, our project did not identify a relationship between PERCLOS and other measures of driving performance (variation in speed, number of crashes and braking reaction time), although the study may have been under powered for this purpose.

Objectively measured eye closure (PERCLOS) was not associated with subjective ratings of sleepiness in the current study, reflecting findings of previous studies (Leproult et al., 2003). Indeed, PERCLOS was only associated with some measures of objective performance impairment. Recent research has indicated the possible efficacy of subjective symptom ratings as a predictor of objectively measured driving impairments (Howard et al, 2014). It is possible that drivers in this study were not accurate at determining their level of drowsiness, despite similar sample characteristics. This could be interpreted as dissociation between how an individual senses and describes how they are feeling, and their physiological response to sleep deprivation, as well as measurable individual differences in the level of self-perceived impairment. Alternatively, sleep loss may have differential effects on neural processes underlying subjective and physiological responses among individuals. Given this discrepancy, the current finding that ocular measures have a stronger association with objective measures than subjective assessments, provides support for automated drowsiness detection devices, given that drivers

may not be able to accurately determine when they are not safe to drive (Howard, Gora, Swann, & Pierce, 2002b). It is conceded, however, that the typically limited sampling procedure (two time-points only) employed in the current study also restricted the ability to accurately assess these effects, and thus any true associations may have not been detected.

One of the limitations of laboratory studies is that participants are likely to rate or detect sleepiness and mood differently to what they would report or how they would act in real-world situations. Driving simulators pose less pressure and distractions compared to real driving, and therefore our drivers' sleepiness ratings, and alertness and/or motivation levels are likely to differ. It has been noted that driving simulators can produce premature performance and sleepiness impairment when compared to real driving (Philip, et al., 2005). The homogeneity of our sample and use of healthy professional drivers, in addition to the small sample size, reduces the generalizability of our findings, although it provides preliminary evidence of performance impairment associated with sleep loss in a population in who sleepiness is commonly reported (Howard et al., 2004; Howard et al., 2014). Moreover, although the sample used in the current study comprised a sub-set of individuals who participated in the Jackson et al (2013) study, further reducing participant numbers and somewhat impeding study generalisability, access to complete PERCLOS profiles of these individuals provides valuable insight into the association between performance variables and relative eye closure during different sleep conditions. Further, although we acknowledge a general overrepresentation of men in this study; such distribution can be considered typically characteristic of this industry, and thus we do not consider that this negatively impacts our reported findings. We did not record EEG while

subjects were driving; hence it is not possible to comment on whether brief sleep periods or other EEG indicators were present in conjunction with the increased PERCLOS. EEG has typically been used to record periods of actual sleep as opposed to drowsiness, whereas slow eye closure methods may have the potential to detect earlier signs of sleepiness. Technical, device-related factors may affect the measurement of eyelid closure, such as drivers turning their head away from stationary devices such as the Copilot, which can result in false positive readings. Additionally, more comprehensive algorithms, such as the variability in PERCLOS or the maximum over a set interval, or devices that incorporate additional ocular (Johns, et al., 2007) or driving (Hanowski, et al., 2008) metrics, may have greater sensitivity and specificity for detecting drowsiness. Devices that overcome these limitations may provide better measurements of eyelid closure that more closely reflect the relationship with earlier signs of drowsiness related performance impairment. Future studies will benefit from examining ocular drowsiness measures during actual driving, to see how the findings from laboratory studies translate to real-world driving, and using a variety of devices.

This study highlights the potential use of automated slow eyelid closure measures as an indicator of sleepiness in professional drivers; however, this requires further validation, particularly in on-road study environments and in a larger sample. While eyelid closure is a promising physiological measure of drowsiness, accurate automated determination of eyelid closure which accounts for individual differences in physiological responses to drowsiness remains to be achieved. Our results support further validation of automated measures of eye closure in an effort to develop simple and accurate measures of objective drowsiness.

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Table 1

Means and standard deviations of the PERCLOS, Psychomotor Vigilance Test (PVT), AusEd simulated driving task and Karolinska Sleepiness Scale (KSS) between the Sleep and Sleep Deprivation sessions

Variable	N	Sleep		Sleep Deprivation	
		Mean	Std. Dev.	Mean	Std. Dev.
PERCLOS ^	12	0.79	0.92	2.45	2.41
PVT Median RT ^	11	234.00	21.62	257.31	39.90
PVT Lapses *	11	1.91	3.11	5.36	6.70
PVT Fastest 10% RT	11	182.65	30.23	191.97	36.24
Lane Position (cm) #	12	44.81	8.01	57.90	15.14
Speed Deviation (km/h)^	12	2.16	1.01	3.33	2.33
Braking RT (ms)*	12	1199.16	157.67	1400.08	308.02
Crashes	12	0.08	0.29	0.08	0.29
KSS #	11	3.36	2.29	7.42	0.79

RT = reaction time; km/h = kilometers per hour; cm = centimeters; ms = milliseconds

* = $p < 0.05$; ^ = $p < 0.01$; # = $p < 0.001$

Fig. 1. Average PERCLOS recorded during the simulated driving task in the Sleep Deprivation and Sleep sessions. Errors bars represent standard deviations.

Fig. 2. Scatterplot of the differences in scores between the "sleep" and "sleep deprivation" conditions, for PERCLOS and the number of lapses (RT>500 ms) on the Psychomotor Vigilance Test (PVT) by driver.

Fig. 3. Scatterplot the differences in scores between the "sleep" and "sleep deprivation" conditions, for PERCLOS and the standard deviation of lane position (SDLP) in the driving simulator task by driver