In the blink of an eye: The circadian effects on ocular and subjective indices of driver sleepiness

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Abstract

Driver sleepiness contributes substantially to fatal and severe crashes and the contribution it makes to less serious crashes is likely to as great or greater. Currently, drivers' awareness of sleepiness (subjective sleepiness) remains a critical component for the mitigation of sleep-related crashes. Nonetheless, numerous calls have been made for technological monitors of drivers' physiological sleepiness levels so drivers can be 'alerted' when approaching high levels of sleepiness. Several physiological indices of sleepiness show potential as a reliable metric to monitor drivers' sleepiness levels, with eye blink indices being a promising candidate. However, extensive evaluations of eye blink measures are lacking including the effects that the endogenous circadian rhythm can have on eye blinks. To examine the utility of ocular measures, 26 participants completed a simulated driving task while physiological measures of blink rate and duration were recorded after partial sleep restriction. To examine the circadian effects participants were randomly assigned to complete either a morning or an afternoon session of the driving task. The results show subjective sleepiness levels increased over the duration of the task. The blink duration index was sensitive to increases in sleepiness during morning testing, but was not sensitive during afternoon testing. This finding suggests that the utility of blink indices as a reliable metric for sleepiness are still far from specific. The subjective measures had the largest effect size when compared to the blink measures. Therefore, awareness of sleepiness still remains a critical factor for driver sleepiness and the mitigation of sleep-related crashes.

Introduction

A substantial amount of research show that sleepiness has a detrimental effect on driving performance levels (Anund et al., 2008; Smith, Horswill, Chambers, & Wetton, 2009) and results in a increased risk for crashing (Åkerstedt, Connor, Gray, & Kecklund, 2008; Connor et al., 2002). The current best evidence estimates that the population attributable risk for fatal and severe crashes associated with sleepy driving is 19% (Connor, et al., 2002; Kecklund, Anund, Wahlström, & Åkerstedt, 2012). That is, if there was a cessation of all sleep-related crashes it would result in a 19% decrease of all fatal and severe crashes. The contribution of driver sleepiness to less severe crashes is likely to be as great or greater. Additionally, many crashes are often multifactorial (Shinar, 2007) and as such a degree of sleepiness may be involved in crashes that were primarily attributed to other factors.

Efforts to reduce the incidents of sleep-related crashes are largely reliant on educational campaigns and the driver's self-awareness of sleepiness. Educational campaigns provide drivers with information about the dangers of sleepy driving and the elevated crash risk, as well as typical signs of sleepiness. Informing drivers about the signs of sleepiness seek to ensure that drivers can recognise and be aware of their own sleepiness levels (i.e., their subjective sleepiness levels). The driver's awareness of their sleepiness levels is a critical aspect for reducing the risk for having a sleep-related crash. If drivers have awareness of when they are sleepy, they can then take the appropriate action of employing a sleepiness countermeasure (e.g., a nap or rest break) when feeling sleepy.

The association between subjective sleepiness levels and physiological sleepiness levels is inconsistent and complicated. A number of studies have found that perceptions of sleepiness have significant and positive relationships with physiological measures of cortical arousal levels measured via electroencephalography (e.g., Dorrian, Lamond, & Dawson, 2000; Kaida et al., 2006). Moreover, other studies show that increases in subjective sleepiness are positively related with poorer simulated driving performance (Reyner & Horne, 1998) as well as poorer on-road driving performance (Anund, Fors, Hallvig, Åkerstedt, & Kecklund, 2013). However, some studies suggest that subjective and physiological measures of sleepiness do not always correlate (e.g., Tremaine et al., 2010). Moreover, some studies suggest that not all drivers can adequately determine if they will fall asleep during periods of extreme sleepiness (e.g., Herrmann et al., 2010; Kaplan, Itoi, & Dement, 2007). These inconsistencies between subjective and physiological measures are possibly due to interference effects from extraneous activities that occur during laboratory testing sessions, such as: verbal interactions (Kaida, Åkerstedt, Kecklund, Nilsson, & Axelsson, 2007) and physical movements with task transitions (Watling, 2012). Consequently, this has resulted in efforts to utilise physiological measures of sleepiness.

Direct physiological measures of an individual appear to have potential as a reliable measure of sleepiness. One of the many physiological measures that has some potential as a measure of sleepiness are ocular indices (Stern, Boyer, & Schroeder, 1994). Ocular indices that can be derived include: blink rate, blink duration, blink amplitude, percentage of eyelid closure, eyelid closing/opening speed or ratios of these indices. These ocular indices have the potential to be recorded by technological monitors that can 'warn' drivers if they approach a certain threshold of sleepiness. An advantage of ocular indices is that they can be recorded via non-contact methods, including video (e.g., Dinges & Grace, 1998) or infrared reflectance oculography (e.g., Johns, Chapman, Crowley, & Tucker, 2008) recording methods. These non-contact recording methods are an advantage as drivers will not have to be concerned about correctly applying a sensor/s when using the technological monitor.

One ocular index that appears to have some utility as a measure of sleepiness is blink rate. Increases in the rate of blinking has been associated with increases in sleepiness (Stern, et al., 1994). For instance, examinations of sleep deprived individuals reveal positive correlations between blink rate and the amount of time spent awake (Barbato et al., 2007). Moreover, subjective sleepiness has been positively correlated with time spent awake. Blink rates have also been found to increase during a 40 minute daytime vigilance task (McIntire, McKinley, Goodyear, & McIntire, in press). These studies suggest that increases in blinking rates have an association with increases in sleepiness.

The duration of eyelid closure (i.e., blink duration) is also suggested to be a sensitive measure of sleepiness. For instance, it has been found that blink durations (but not blink rate) increased between morning and evening testing sessions (Caffier, Erdmann, & Ullsperger, 2003). A study performed by Ingre, Åkerstedt, Peters, Anund, & Kecklund (2006) examined the changes in driving performance (i.e., standard deviation of lateral position), blink duration, and subjective sleepiness during a two hour morning drive. It was found that all three measures significantly increased over the duration of the drive, with steeper increases of blink duration and poorer driving performance occurring with the highest levels of subjective sleepiness. It has also been shown that blink durations increase during simulated night-time driving with younger drivers (Anund, et al., 2008). Increases in blink durations have also been found to increase during a three hour on-road morning drive (Häkkänen, Summala, Partinen, Tiihonen, & Silvo, 1999).

Circadian Rhythm Influences

A factor that could affect subjective and physiological sleepiness levels is the endogenous circadian rhythm. The circadian rhythm promotes alertness during the daytime and sleepiness during the night time. Specifically, the circadian rhythm has a sinusoid function during a 24 hour period that has an ascending phase that begins approximately 06:00, peaks prior to mid-day, with the descending phase beginning in the early afternoon (Carskadon & Dement, 1992). As such, the descending circadian phase could lead to an increase in sleepiness levels starting from early afternoon.

The effect of the descending circadian phase on driving performance and measures of sleepiness has been noted previously. Sleep-related crashes have been found to occur more frequently during the descending phase of the circadian rhythm, with late night-time driving having the highest incidence rates (Connor, et al., 2002; Pack et al., 1995). Increases in physiological indices as well as decrements in simulated driving performance during the descending circadian phase have also been observed during afternoon (Horne & Reyner, 1996) and evening driving (Sandberg et al., 2011). Last, subjective measures of sleepiness have shown to be sensitive to circadian changes both in the simulated (Akerstedt et al., 2010) and on-road driving settings (Sandberg, et al., 2011).

Extensive evaluations of the effect of the descending circadian phase on ocular indices are lacking. The few studies that have examined the circadian effects on blink rates have some inconsistent findings. For instance, an examination of blink rates from 10:00, 13:30, 17:00, and 20:30 only found a significant increase in blinking rate at the 20:30 testing session (Barbato et al., 2000). In contrast, De Padova, Barbato, Conte, & Ficca (2009) found no difference between blink rates across the same testing times, even though subjective and cortical arousal levels recorded via electroencephalography increased across the day. Regarding the circadian effects on blink duration, increases in blink duration have been found to occur between day and night-time driving (Sandberg, et al., 2011). Similarly, an overall increase in blink duration was found to occur across a simulated driving testing session that spanned an entire day and night (Akerstedt, et al., 2010). However, specific differences between morning and afternoon driving were not examined.

The cited literature suggests that ocular indices have the potential to be measures of sleepiness. Although findings to date are somewhat inconsistent, overall ocular indices of blink rate and blink duration are sensitive to differences in sleepiness between day and night-time testing sessions. However, the sensitivity of these ocular indices between morning and afternoon testing sessions has not been extensively demonstrated. Therefore, the aim of the current study was to examine the circadian effects on blink rate, blink duration and subjective sleepiness levels.

Method

Designs

A representation of the data collection points for the study can be seen in Figure 1. A mixed factorial design was utilised to examine the study aim. The within-subjects factor was the baseline and concluding measurements of subjective and ocular indices of sleepiness. The between-subjects factor was the time of day of testing (i.e., morning or afternoon) to examine circadian effects. Participants were randomly allocated to participate in a morning or afternoon testing session.

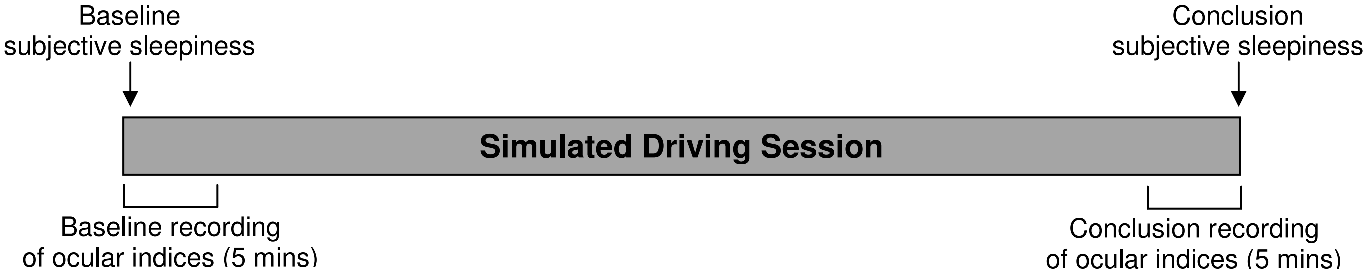

Figure 1. Placement of the data points for the current study.

Statistical Analysis

As the current study had a between subjects factor (i.e., time of day of testing) it was prudent to examine for differences between variables that could affect the between groups analysis. The first analysis entailed a series of comparisons between the morning and afternoon groups on key variables (i.e., demographic and sleep quality and sleep timing variables) that could affect sleepiness levels. Any differences were considered as covariates in the main analyses. The main analysis involved a series of repeated measures analysis of variance with a set of planned comparisons on the ocular indices of blink rate and blink duration and subjective sleepiness with a between groups variable of time of day of testing (i.e., morning or afternoon).

Participants

Participants were recruited with an email sent throughout the intranet of a Queensland university. In total, 26 participants were involved in the study. The gender split was 19 females and 7 males; the mean age of the participants was M = 23.77 years (SD = 2.32; range = 20-28). Participants had been licenced for M = 5.65 years (SD = 2.46; range = 2-10) with the participants driving on average 14, 028.01 kilometres per year over the last three years (SD = 14,028.01; range = 1,040-70,000). In the previous three years six participants reported that they had been involved in a crash (i.e., where they were the driver and there was damage to property or persons). Participants were paid $100 AUD for their involvement in the study.

Exclusion criteria

A number of exclusion criterions were set. Participants were excluded if they were a shift worker, had travelled overseas in the past month, had a habitual bedtime later than 12 midnight, had significant health problems, took prescription medications or illicit drugs, had sleeping difficulties (Pittsburgh Sleep Quality Index score of < 5: Buysse, Reynolds, Monk, Berman, & Kupfer, 1989), or had excessive daytime sleepiness (Epworth Sleepiness Scale of > 10: Johns, 1991).

Measures

Demographic information

The demographic information collected included participant age and gender. Traffic-related demographic data, such as the duration of licensure, a measure of driving exposure (i.e., number of hours driven per week), and the amount of crashes in the last three years was also collected.

Sleepiness Questionnaire

The sleepiness questionnaire was used by the current study as a measure to determine if any differences between the morning and afternoon groups existed. The sleepiness questionnaire was comprised of several published questionnaires, including the Pittsburgh Sleep Quality Index (PSQI: Buysse, et al., 1989) a measure of sleep quality, the Epworth Sleepiness Scale (ESS: Johns, 1991) a measure of daytime sleepiness, the Sleep Timing Questionnaire (STQ: Monk et al., 2003) a measure of habitual sleep and wake times that are combined to form a stability measure. Participants were also required to provide a list of the signs of sleepiness that lets them know they are sleepy. Previous work (i.e., Kaplan, et al., 2007) has suggested that limited knowledge of the signs of sleepiness can affect self-perception of sleepiness levels.

Karolinska Sleepiness Scale

The Karolinska Sleepiness Scale (KSS; Åkerstedt & Gillberg, 1990) is a self-report measure of the level of subjective sleepiness an individual is experiencing. Individuals are required to indicate on a nine point Likert scale how sleepy they are currently feeling. The modified version of the KSS (Reyner & Horne, 1998) includes verbal anchors for every step (1 = "extremely alert", 2 = "very alert", 3 = "alert", 4 = "rather alert", 5 = "neither alert nor sleepy", 6 = "some signs of sleepiness", 7 = "sleepy, no effort to stay awake", 8 = "sleepy, some effort to stay awake", and 9 = "very sleepy, great effort to keep awake, fighting sleep"). The question posed to the participants is "Right now how sleepy are you feeling?" The KSS is a reliable and valid measure of subjective sleepiness, when compared with objective physiological measures (Gillberg, Kecklund, & Åkerstedt, 1994; Kaida, et al., 2006).

Ocular Indices of Sleepiness

The physiological measurement of ocular activity was recorded with electrooculography (EOG) and was sampled at 256 Hz (i.e., 512 samples per second). Disposable self-adhesive electrodes were placed above and below the eyes. The skin area where the electrode was to be placed was lightly abraded until an impedance of five kΩ was achieved; as per guidelines for physiological recordings (Leary, 2007).

Prior to extracting the ocular indices a 0.5 Hz high pass filter and a10 Hz low pass filter were applied to the signal. An eye blink was defined as a sharp high amplitude wave that was greater than 100 µV and was also visually confirmed as blinks on the EOG signal. The properties if each blink was calculated from the start, peak and end point of the blink. Blink durations were measured in milliseconds at half the blink amplitude of the down- and upswing to mitigate problems from concurrent eye movements during an eye blink. Measuring blink durations at half the amplitude is consistent with previous work (e.g., Ingre, et al., 2006; Sandberg, et al., 2011). The time periods selected for the EOG data was five minutes at the beginning of the drive (baseline) and five minutes immediately before stopping driving (conclusion). The ocular indices were all averaged over both these five minute periods for the baseline and conclusion time periods. Increases in blink rate and blink duration are indicative of greater sleepiness.

Driving Stimulus

The driving stimulus used for the current study was the Hazard Perception test. Hazard perception is the skill to anticipate that a traffic scenario may result in a dangerous/hazardous situation, requiring a reaction from the driver to avoid an incident (McKenna & Crick, 1991). The Hazard Perception test requires the participants to watch a series of video clips and to indicate with a mouse click if they identify a hazardous situation. The video footage was of real on-road driving, recorded from the driver's perspective (during daylight hours). Hazard Perception is the only driving skill that has a consistent relationship with crash involvement, with faster hazard perception associated with decreased on-road crash occurrences (e.g., Drummond, 2000; Hull & Christie, 1992; Pelz & Krupat, 1974; Pollatsek, Narayanaan, Pradhan, & Fisher, 2006). Hazard perception is an important driving skill as it has criterion validity with actual on-road crashes.

To be consistent with current road safety recommendations (i.e., "Stop, Revive, and Survive" campaign) the maximum duration of the Hazard Perception test was two hours. The current study was solely interested in the effects of sleepiness on subjective and ocular indices, not the impairment of performance from sleepiness. As such, the Hazard Perception test was used as a driving stimulus only in the current study. The effect of sleepiness on Hazard Perception performance can be found in previous work (i.e., Smith, et al., 2009). The hazard perception video was displayed on a 17 inch monitor with a 4:3 ratio aspect.

Procedure

Ethical and Health and Safety clearances were obtained from the Queensland University of Technology Human Research Ethics Committee and Health and Safety Division respectively. The study protocol required participants to wake up at 05:00 on the testing day. They also could not consume any caffeine or alcohol until after participating in the study. On arrival at the testing laboratory, all participants were given written and oral information regarding the study procedure. All participants signed a written consent form prior to their participation. After obtaining signed consent the EOG electrodes attached to the participant. All participants received the instruction to stop driving once they believed they were too sleepy to drive safety on the road. The participants' subjective sleepiness was assessed immediately before they began the driving simulation. The participants spoke into a microphone to let the researcher know that they believed they were too sleepy to drive safely. The researcher noted the duration of the participants driving session then entered the testing room and assessed the participants' subjective sleepiness once more. The participants completed the driving simulation in a light, noise, and temperature-controlled environment, which was devoid of all time cues.

Results

Examining between groups differences

To examine if any differences were present between the morning and afternoon groups for the demographic and sleep variables a series of comparisons were performed and can be seen in Figure 1. As shown none of the variables were significantly different between morning and afternoon testing groups. There was no significant difference between the number of males or females participating in morning or afternoon testing groups $\chi^2(1) = 0.19$, $p = .67$. Therefore, the main analysis proceeded without having to add any covariates.

Table 1. Examination of difference between morning and afternoon groups with demographic, sleep related, and testing outcomes

	Time of Day of Testing		
	Morning (n = 13)	**Afternoon (n = 13)**	**Significance test**
Data Source	**Mean (*SD*)**	**Mean (*SD*)**	***t*-test (*p*)**
Age	24.38 (1.98)	23.15 (2.54)	1.38 (.18)
Years licenced	6.39 (1.98)	4.92 (2.75)	1.56 (.13)
Km/year driven	6889.23 (5671.95)	15760.00 (18036.02)	-1.69 (.10)
PSQI	3.31 (0.75)	2.92 (0.95)	1.14 (.27)
ESS	6.69 (2.32)	6.77 (1.79)	-0.10 (.93)
STQ stability score	.66 (.49)	.72 (.36)	-0.25 (.81)
Signs of Sleepiness	5.08 (1.80)	4.23 (1.01)	1.48 (.15)
Baseline KSS	6.54 (0.78)	6.77 (0.60)	-0.85 (.41)
Driving duration	34.58 (14.47)	37.69 (20.92)	-0.44 (.66)

Ocular and subjective analyses

The means standard deviations and outcomes from the planned comparisons can be seen in Table 2. Regarding the morning testing sessions there were significant increases in the blink duration and subjective sleepiness indices. In contrast, during the afternoon sessions only a significant increase was found for the subjective sleepiness index. The blink rate analysis showed no significant differences between baseline and the conclusion measurements for the morning or afternoon sessions.

Table 2. Means, standard deviations, and planned comparison results for the ocular and subjective indices.

	Time of Day of Testing

	Morning (n = 13)			Afternoon (n = 13)		
	Baseline	Conclusion	Significance test	Baseline	Conclusion	Significance test
Data Source	Mean (*SD*)	Mean (*SD*)	Mean Diff (*p*)	Mean (*SD*)	Mean (*SD*)	Mean Diff (*p*)
Mean blink duration	96.80 (10.02)	117.11 (29.62)	-20.31 (.01)	108.98 (13.44)	117.49 (20.63)	-8.51 (.20)
Mean blink rate	129.15 (38.59)	138.46 (49.77)	9.31 (.32)	111.00 (54.54)	104.23 (62.99)	6.77 (.47)
Subjective sleepiness	6.54 (0.77)	8.00 (0.41)	1.46 (< .001)	6.77 (0.60)	8.31 (0.48)	1.54 (< .001)

Discussion

The current study sought to examine the circadian effects on ocular and subjective sleepiness indices. Overall, the subjective sleepiness measure was sensitive to changes in sleepiness during the simulated driving task in the morning and afternoon sessions. In contrast, the ocular indices had some sensitivity to changes in sleepiness during the morning but no sensitivity during the afternoon driving sessions.

During morning and afternoon testing sessions significant increases were found to occur for the subjective sleepiness measure. This result is consistent with previous work, such that subjective sleepiness has been found to be the most sensitive measure of increasing sleepiness during simulated (Akerstedt, et al., 2010) and on-road driving studies (Sandberg, et al., 2011). This finding that participants could monitor their subjective perceptions of their sleepiness levels and could retire from the simulated driving task before falling asleep is encouraging for road safety.

Several studies have suggested that many individuals cannot sufficiently gauge if they will fall asleep when sleepy (e.g., Herrmann, et al., 2010; Kaplan, et al., 2007). However, these studies have typically been conducted when the participants are experiencing extreme levels of sleepiness and are ‘fighting’ sleep onset to maintain wakefulness. While sleep onset can be determined with a moderate degree of certainty from physiological measures, subjectively this is not the case. Previous work suggests that during the process of falling asleep the subjective perceptions of sleep onset is blurred and uncertain (Bonnet & Moore, 1982). The results from the current study and others (e.g., Akerstedt, et al., 2010; Sandberg, et al., 2011) suggests that subjective perceptions of sleepiness are adequate to gauge an individual’s sleepiness level. However, subjective perceptions may have less sensitivity when experiencing an extreme level of sleepiness such as when fighting sleep onset.

The current study found no effect for blink rate during the simulated driving task for the morning or afternoon sessions. This finding is consistent with previous work that has found blink rates did not increase during daytime testing (e.g., Barbato, et al., 2000; De Padova, et al., 2009). Similarly, on-road driving assessments show blink rate does not increase over the duration of the drive (Häkkänen, et al., 1999). Previous work suggests that blink rate does increase with long duration testing sessions and increases in sleepiness (Stern, et al., 1994), but high perceptual demands can negate these increases in blink rate (Recarte, Pérez, Conchillo, & Nunes, 2008). It is likely that the Hazard Perception test has a high perceptual demand as proficient hazard perception requires high levels of visual searching (Underwood, Crundall, & Chapman, 2002). As such the perceptual demands of the Hazards Perception test may have negated any increases in blink rate due to increasing sleepiness.

The sensitivity of the blink duration index to detect increasing sleepiness was mixed. Specifically, during the morning session the blink duration measure significantly increased from baseline to the conclusion of the simulated drive. However, during the afternoon testing session no statistical difference was found from baseline to the conclusion of the simulated drive. It is possible that the descending circadian phase could have contributed to the lack of statistical difference result for the blink duration measure. When the descending circadian phase begins increases in physiological (Carskadon & Dement, 1992) and subjective sleepiness (Akerstedt, et al., 2010) occur. This increase in sleepiness could have limited the range for which an increase in sleepiness could occur. The mean difference from the blink duration planned comparisons support this interpretation. As the morning session mean difference (-20.31) was greater than the afternoon session mean difference (-8.51).

Continued evaluations are however needed to determine the utility of blink duration as a sensitive measure of sleepiness. While the current study did not find any difference in blink duration in the afternoon sessions, other studies have found increases in blink duration to occur during night-time testing when the descending circadian phase has even greater strength (e.g., Anund, et al., 2008; Sandberg, et al., 2011). During the afternoon testing other alertness promoting aspects may have affected the obtained results. For instance, motivation to perform has been shown to effect physiological indices other than ocular indices (Hsieh, Li, & Tsai, 2010) and participants could have been more motivated during afternoon sessions. However, this is unlikely as all participants received the same instructions from the experimenter.

Limitations and Future Research

A limitation of the current study was that the exact position of the participant's circadian phase was not assessed. Participants that had circadian phases that were slightly different from one another could have affected the obtained results. The current study's exclusion criteria required participants to have a habitual bedtime before midnight and as such would have limited the circadian phase variability between participants. Future research could more closely control for the differences between participants circadian phases. For instance, autographic monitoring of sleep-wake times can give an estimate of circadian phase positioning when used with the appropriate biomathematical model of sleep-wake. Additionally, the current study used young adults for it participants and previous work suggests that ocular indices may vary between younger and older participants (e.g., De Padova, et al., 2009). Future research could assess the sensitivity of ocular indices for sleepiness with older participants. Last, a number of other ocular indices (e.g., blink amplitude, eyelid closing velocity, etc) need evaluating for their utility as a sleepiness indicator, future work could include these measures as well.

Conclusion

Driver sleepiness contributes substantially to fatal and severe crash incidents. Drivers' awareness of their sleepiness levels (subjective sleepiness) remains a critical component for the mitigation of sleep-related crashes. Several physiological indices of sleepiness show potential as a reliable measure of drivers' sleepiness levels, including ocular indices. The current study sought to examine the circadian effects on ocular and subjective indices while participants completed a simulated driving task. Overall, the subjective sleepiness index was more sensitive to increases in sleepiness levels. In contrast, only the ocular index of blink duration was sensitive to increasing sleepiness during morning testing sessions. Further testing of these and other ocular indices are necessary before a suitable physiological measure of sleepiness can be introduced as a mainstream monitor of driver sleepiness levels.

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