Sleep-related eye symptoms and their potential for identifying driver sleepiness

ASHLEIGH J. FILTNESS¹, ANNA ANUND², CARINA FORS², CHRISTER AHLSTRÖM², TORBJÖRN ÅKERSTEDT³ and GÖRAN KECKLUND³,⁴

¹Centre for Accident Research and Road Safety – Queensland (CARRS-Q), Queensland University of Technology, Kelvin Grove, Qld, Australia, ²The Swedish Road and Transport Research Institute (VTI), Linköping, Sweden, ³Stress Research Institute, Stockholm University, Stockholm, Sweden and ⁴Behavioural Science Institute, Radboud University, Nijmegen, The Netherlands

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Correspondence
Ashleigh Filtness, PhD, Centre for Accident Research and Road Safety – Queensland, Queensland University of Technology, K block, 130 Victoria Park Road, Kelvin Grove, Qld 4059, Australia.
Tel.: 61-7-3138-7713; fax: 61-7-3138-0111; e-mail: Ashleigh.filtness@qut.edu.au

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SUMMARY
The majority of individuals appear to have insight into their own sleepiness, but there is some evidence that this does not hold true for all, for example treated patients with obstructive sleep apnoea. Identification of sleep-related symptoms may help drivers determine their sleepiness, eye symptoms in particular show promise. Sixteen participants completed four motorway drives on two separate occasions. Drives were completed during daytime and night-time in both a driving simulator and on the real road. Ten eye symptoms were rated at the end of each drive, and compared with driving performance and subjective and objective sleep metrics recorded during driving. ‘Eye strain’, ‘difficulty focusing’, ‘heavy eyelids’ and ‘difficulty keeping the eyes open’ were identified as the four key sleep-related eye symptoms. Drives resulting in these eye symptoms were more likely to have high subjective sleepiness and more line crossings than drives where similar eye discomfort was not reported. Furthermore, drivers having unintentional line crossings were likely to have ‘heavy eyelids’ and ‘difficulty keeping the eyes open’. Results suggest that drivers struggling to identify sleepiness could be assisted with the advice ‘stop driving if you feel sleepy and/or have heavy eyelids or difficulty keeping your eyes open’.

INTRODUCTION
Driver sleepiness is an endemic problem that has been associated with vehicle crashes worldwide (Akerstedt, 2000; Connor et al., 2002; Dinges, 1995; Horne and Reyner, 1995). Mitigating sleep-related crashes is a difficult issue for road safety authorities. Current advice to drivers is simply, ‘do not drive when sleepy’. Most drivers have insight into their increasing sleepiness and, therefore, have the opportunity to cease driving prior to a crash occurring (Horne and Baulk, 2004; Ingre et al., 2006). However, some individuals struggle to comprehend the exact nature of their increasing sleepiness (Anund and Åkerstedt, 2010; Filtness et al., 2011; Reyner and Home, 1998), and in particular it is hard to pinpoint the exact moment sleep will occur (Kaplan et al., 2007). This lack of ‘final warning’ is observed both in simulators (Anund et al., 2008b) and on real roads (Åkerstedt et al., 2013). In lieu of an accurate and widely available sleepiness warning technology, drivers are solely responsible for the detection of their own sleepiness.

Using key symptoms as descriptors has potential for assisting the identification of sleepiness. Sleepiness symptoms have strong associations with objective measures of sleepiness and associated impaired performance (Forberg et al., 2010; Gillberg et al., 1994; Howard et al., 2014; Nilsson et al., 1997). Within such studies, participants are commonly asked to rate several symptoms that are aggregated to calculate an overall sleepiness level (Gillberg et al., 1994; Howard et al., 2014). In the context of driving, it is not only important that sleepiness can be identified, but that it is identified far enough in advance for driving to stop prior to an incident. Therefore, the use of a task descriptor such as ‘reactions were slow’ (Howard et al., 2014), the identification of which relies on a sleepy individual engaging in a situation including a reaction, may not be appropriate. Similarly, using a late symptom of sleepiness such as ‘head dropping down’
(Howard et al., 2014) requires an individual to reach a potentially dangerous level of sleepiness before awareness is possible. A further problem is avoiding generic symptoms, for instance ‘irresistible sleepiness’ (Gillberg et al., 1994) poses potential difficulty for those who may already struggle identifying sleepiness.

There is evidence that eye symptoms are sensitive to sleepiness, for instance ‘tired eyes’ increases prior to the point of no longer being able to drive in a simulator (Nilsson et al., 1997). ‘Difficulty keeping the eyes open’ is a commonly experienced feeling by drivers who have fallen asleep while driving (Nordbakke and Sagberg, 2007). Furthermore, ‘struggling to keep your eyes open’ under prolonged wakefulness is closely related to increased alpha and theta electroencephalogram activity (Howard et al., 2014).

The current study investigates sleep-related eye symptoms and their association with driver sleepiness (simulator and real road). It is hypothesised that: (i) not all eye symptoms will be sleep related, i.e. will not correlate with objective sleepiness measures (ii) subjective sleepiness and driving impairment will be greater when sleep-related eye discomfort is experienced.

**METHODOLOGY**

**Participants**

Sixteen healthy adults (eight males; eight females) mean age 41.3 years (SD 8.7) were recruited from the Swedish register of vehicle owners. Shift workers, professional drivers, those with poor health (including overweight) and those with sleep disorders were excluded. All participants provided informed consent and the study was approved by the regional ethical committee in Linköping, Sweden registration number 2010/153-31. Permission to conduct driving sessions with sleep-deprived drivers on public roads between 00:00 hours and 05:00 hours was given by the government, registration number N2007/5326/TR. Participants received 3000 SEK, approximately 300€ for their participation. The study was carried out within the project ‘Virtual Prototyping and Assessment by Simulation’ (ViP), which is a Centre of Excellence at the Swedish National Road and Transport Research Institute (VTI), full results are presented in Fors et al. (2013).

**Study overview**

To examine the impact of sleepiness on eye symptoms, participants attended the test centre on two occasions, each following 3 days home sleep/wake diaries, ensuring consistent sleep wake cycles of at least 7 h per night. Participants were required to sleep for at least 7 h on each of the three nights before the test days, going to bed no later than midnight and getting up no later than 09:00 hours. On the test days themselves participants got up no later than 07:00 hours.

On the first occasion, participants completed two driving tasks in an instrumented vehicle on the real road (Real Road; RR). On the second occasion (approximately 4 weeks later) participants completed two driving tasks in the VTI driving simulator III (Simulator; Sim). Due to logistical constraints two participants attended the test centre on each study day, the experimental design is shown in Table 1. The time slot an individual attended remained consistent. Intervening time between the day and night drives was spent at the test centre where participants were free to read or watch TV. No caffeine-containing beverages were consumed after 13:00 hours on each test day.

While driving, participants were not allowed to speak, listen to the radio or do anything else that may counteract their sleepiness. Participants were instructed to drive as they normally would (on the right side of the road). At the conclusion of each test day, participants were returned home by taxi.

**Instrumented vehicle**

The instrumented vehicle was an automatic Volvo XC70. Vehicle data were recorded at 10 Hz.

The real road test route was approximately 158 km long, and completed on the E4 motorway, Sweden. The drive lasted approximately 90 min. The speed limit was 110 km h⁻¹ throughout, with the exception of two 750-m sections where the speed limit was 90 km h⁻¹. The same route was driven during both the daytime and night-time drives.

A test leader was present in the front passenger seat throughout the drive. The car had dual command and there was a small screen in front of the test leader showing the driver’s face. The test leader was responsible for safety and was prepared to take control of the vehicle if the driver became too sleepy. Participants were allowed to stop for a break if they felt it necessary for their safety; however, if this occurred the test leader ended the drive. Prior to commencing the drive, participants were explicitly told to not exceed speed limits for safety reasons.

**Driving simulator**

The VTI driving simulator III is a moving base simulator with a Saab 9-3 cabin (automatic gearbox) and a 120 degrees forward field of view. Vehicle data were recorded at 10 Hz.

<table>
<thead>
<tr>
<th>Table 1 Driving session times</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Driving session</strong></td>
</tr>
<tr>
<td>1</td>
</tr>
<tr>
<td>2</td>
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<tr>
<td>3</td>
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<tr>
<td>4</td>
</tr>
</tbody>
</table>
A motorway scenario, similar to that of the real road test route was presented. The simulator test route was about 150 km, taking approximately 75–80 min to complete. The posted speed limit was 110 km h\(^{-1}\).

To minimise alertness-enhancing factors, interaction with other traffic was limited. Throughout the drive, a car overtook the participant on average every 7 min. Halfway into the test route, the posted speed limit changed to 90 km h\(^{-1}\) for 1 km, to replicate the similar change on the real road. The same scenario was used for both the daytime and night-time drives.

**Measurements**

**Eye symptoms**

Ten eye symptoms were investigated: sore eyes; eye itching; gravel eyes; eye pain; eye strain; difficulty focusing; tearful; heavy eyelids; difficulty keeping the eyes open; and dry eyes.

Each symptom was rated at the conclusion of each drive using a five-point scale: (i) not at all (ii) somewhat, a little, slightly (iii) moderately (iv) fairly much/pretty much (v) very much.

Identification of the 10 symptoms was informed by two sources. Firstly, some items relating to eye experience had previously been investigated using the Accumulated Time with Sleepiness (ATS) scale (Gillberg et al., 1994). The ATS was designed to assess how sleepy a person is by using their symptoms of sleepiness. Secondly, symptoms were informed by three focus groups: young drivers; professional drivers; and commuters (Anund et al., 2003). Specifically, the focus groups were designed to investigate how fatigue/sleepiness is recognised, understanding of dangers associated with fatigued/sleepy driving and to inform how best to encourage drivers to take a break. This confirmed use of the four items from the ATS and further added: sore eyes; itching eyes; eye pain; eye strain; tearful and dry eyes. The item ‘gravel eyes’ is derived from a figurative term commonly used in Sweden. The cultural association of this term is acknowledged, as such it may not be appropriate for use with non-Swedish participants.

**Subjective sleepiness measures**

Every 5 min throughout each drive, participants rated their sleepiness on the nine-point Karolinska Sleepiness Scale (KSS): (i) extremely alert (ii) very alert (iii) alert (iv) rather alert (v) neither alert nor sleepy (vi) some signs of sleepiness (vii) sleepy, no effort to stay awake (viii) sleepy, some effort to stay awake; and (ix) very sleepy, great effort to keep awake, fighting sleep (Akerstedt and Gillberg, 1990).

Additionally, at the end of each drive, participants were asked to rate on a seven-point scale how much effort was required to stay awake (1 = no effort at all; 7 = very much effort).

**Objective eye measures**

Electrooculography (EOG) data were recorded at 512 Hz using a Vitaport 3 (TEMEC Instrument B.V., Kerkrade, The Netherlands). Eye blinks were detected from the EOG using the LAAS algorithm (Jammes et al., 2008), which also extracted the mean half-amplitude blink durations. Blink duration was calculated at half the amplitude of the upswing and the downswing of each blink, and defined as the time elapsed between the two. The performance indicators of interest were: mean blink duration; median blink duration; and blinks >0.15 s. Longer blinks were defined as those >0.15 s, because this threshold has been demonstrated to have promising sensitivity for sleepiness detection (Fors et al., 2011).

Eye gaze was tracked using the three-camera Smart Eye Pro 5.7 (Smart Eye AB, Gothenburg, Sweden), recorded at 60 Hz. Eye tracking data was excluded where good-quality tracking was obtained for <70% of the drive.

**Driving performance**

The number of line crossings per kilometre travelled was used to quantify impaired driving. Near-misses (including inappropriate line crossings) are predictive of both sleep- and non-sleep-related crashes (Philip et al., 2010). A line crossing was defined as an occasion when the distance between the front wheel and the lane demarcation line was <0 cm. If two or more line crossings occurred within 7 s, they were considered to be the same line crossings. Intentional line crossings, for instance during overtaking, were removed from the data prior to analysis.

**Statistical analysis**

All statistical analyses were conducted using IBM SPSS 20.0 statistical software (IBM Corp., Armonk, NY, USA). An alpha level of 0.05 was used to determine statistical significance (*). Cronbach’s alpha was used to assess the independence of scale items. Wilcoxon rank-sum test was used to investigate the sensitivity of each eye symptom to time of day differences (i.e. sleep-related change).

To describe which symptoms best correlate to sleepiness, an exploratory approach was taken, whereby a variety of variables known to be associated with sleepiness were used for partial correlation comparison. Results from the daytime and night-time were combined so that each variable investigated contained a full range of data (i.e. alert and sleepy), accordingly partial correlations were undertaken controlling for time of day. The results of the partial correlations were used to identify key sleepiness-related eye symptoms. As the sensitivity of symptoms to sleepiness varied between the real road and the simulator, results are presented separately for these two conditions.

To compare sleepiness indicators between drives resulting in ‘eye discomfort’ (rating four or five on key symptoms) and
‘no eye discomfort’ (rated 1–3 on key symptoms), a series of one-way ANOVA (normally distributed data) and Mann–Whitney U-tests (skewed data) were completed. Finally, each drive was classified as having included at least one right line crossing or no right line crossings, and a similar series of one-way ANOVA compared the prevalence of the four key eye symptoms.

Where required, log transformation was used to correct for skewness (note: for eye pain and tearful transformation did not correct skew).

RESULTS

Three participants required corrected vision, two by wearing contact lenses and one wearing glasses.

The prevalence of eye symptoms is presented in Fig. 1. All 10 symptoms were sensitive to change between daytime and night-time conditions in the simulator. However, only ‘eye strain’ and ‘difficulty to focus’ significantly differed between the day and night conditions on the real road.

Table 2 displays the partial correlation results for the 10 eye symptoms and indicators of sleepiness. The mean and standard deviation of sleepiness indicators used for the correlation analysis are presented in Table 3. Overall, four eye symptoms were identified as having some correlation to indicators of sleepiness, when driving on the real road: ‘heavy eyelids’, ‘difficulty to keep eyes open’, ‘eye strain’ and ‘difficulty to focus’. With the exception of ‘Difficulty to focus’, these same symptoms had some correlation to sleepiness variables in the simulator. Two further items were also significant in the simulator but not on the real road: ‘sore eyes’ and ‘tearful’.

To investigate the internal consistency of eye symptoms, a series of Cronbach’s alpha results were undertaken (Table 4). Using only the four key symptoms (four items) identified on real roads, Cronbach’s alpha improved compared with using all 10 symptoms. This improvement was observed both for real road driving and in the simulator during the daytime. In comparison, when including the additional two symptoms identified in the simulator (six items), Cronbach’s alpha worsened compared with the four items for both real road driving conditions and the simulator during the day. This indicates that the four eye symptoms are related measures that can be combined into a single measure of eye discomfort. Consequently, using the four key symptoms: ‘heavy eyelids’, ‘difficulty to keep the eyes open’, ‘difficulty focusing’ and ‘eye strain’, each drive was classified as having resulted in sleep-related eye discomfort or not. Of the 16 drives completed in each condition, the number of drives resulting in eye discomfort was: RR daytime = 3; RR night-time = 8; Sim daytime = 5; Sim night-time = 15.

Both on the real road and in the simulator, drives resulting in eye discomfort had significantly higher maximum KSS (RR: eye discomfort = 7.36, no eye discomfort = 6.48, $F_{1,30} = 13.039, P = 0.001$; Sim: eye discomfort = 8.60, no eye discomfort = 6.26, $F_{1,30} = 71.652, P < 0.001$), and required significantly more effort to stay awake (RR: eye discomfort = 5.18, no eye discomfort = 2.86, $F_{1,30} = 9.673, P = 0.004$; Sim: eye discomfort = 6.50, no eye discomfort = 3.67, $F_{1,30} = 16.380, P < 0.001$). Additionally, significantly more left line crossings per km occurred during drives resulting in eye discomfort than in drives where eyes discomfort was not experienced (RR: eye discomfort = 0.07 per km, no eye discomfort = 0.02 per km, $U = 51.0, P = 0.026$; Sim: eye discomfort = 0.11 per km, no eye discomfort = 0.01 per km, $U = 51.0, P = 0.005$). There was no significant difference in right line crossings per km between those with eye discomfort and not; however, these occurred less frequently than left line crossings. These three significant variables are displayed in Fig. 2. A further difference was found in the simulator, where mean blink duration was greater in those with eye discomfort (eye discomfort = 0.16 s, no eye discomfort = 0.13 s, $U = 68.0, P = 0.43$).

Finally, all drives were classified as containing a right line crossing or not. Right line crossings are the most severe line crossings in the simulator and real road.

Figure 1. Mean eye symptoms separated by scale item for each of the four situations: daytime real road; night-time real road; daytime simulator; and night-time simulator. Error bars represent standard error. * denotes significant differences ($P < 0.05$).
Table 2 Partial correlation controlled for time of day and significance

<table>
<thead>
<tr>
<th></th>
<th>Sore eyes</th>
<th>Itching eyes</th>
<th>Gravelly</th>
<th>Eye pain</th>
<th>Eye strain</th>
<th>Difficult to focus</th>
<th>Tearful</th>
<th>Heavy eyelids</th>
<th>Difficult to keep eyes open</th>
<th>Dry eyes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Real road</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Blinks &gt; 0.15 s</td>
<td>-0.188</td>
<td>-0.204</td>
<td>0.086</td>
<td>-0.167</td>
<td>-0.304</td>
<td>-0.062</td>
<td>-0.104</td>
<td>0.066</td>
<td>0.083</td>
<td>0.065</td>
</tr>
<tr>
<td>Mean blink duration</td>
<td>-0.237</td>
<td>-0.209</td>
<td>-0.053</td>
<td>-0.108</td>
<td>-0.389*</td>
<td>-0.056</td>
<td>-0.076</td>
<td>0.171</td>
<td>0.170</td>
<td>0.136</td>
</tr>
<tr>
<td>Median blink duration</td>
<td>-0.323</td>
<td>-0.231</td>
<td>-0.146</td>
<td>-0.129</td>
<td>-0.434*</td>
<td>-0.108</td>
<td>-0.022</td>
<td>0.122</td>
<td>0.086</td>
<td>0.056</td>
</tr>
<tr>
<td>Max KSS</td>
<td>-0.217</td>
<td>0.197</td>
<td>0.176</td>
<td>-0.008</td>
<td>-0.073</td>
<td>0.076</td>
<td>0.074</td>
<td>0.093</td>
<td>0.118</td>
<td>-0.209</td>
</tr>
<tr>
<td>Mean KSS</td>
<td>-0.201</td>
<td>0.210</td>
<td>-0.117</td>
<td>-0.048</td>
<td>-0.129</td>
<td>-0.043</td>
<td>0.126</td>
<td>-0.058</td>
<td>-0.092</td>
<td>-0.198</td>
</tr>
<tr>
<td>Effort to stay awake</td>
<td>0.149</td>
<td>0.247</td>
<td>0.125</td>
<td>-0.093</td>
<td>0.356*</td>
<td>0.458*</td>
<td>-0.135</td>
<td>0.444*</td>
<td>0.514†</td>
<td>-0.062</td>
</tr>
<tr>
<td>Left line crossing per km</td>
<td>-0.067</td>
<td>-0.280</td>
<td>0.007</td>
<td>-0.118</td>
<td>0.073</td>
<td>0.142</td>
<td>-0.015</td>
<td>0.186</td>
<td>0.158</td>
<td>0.108</td>
</tr>
<tr>
<td>Right line crossing per km</td>
<td>0.006</td>
<td>-0.048</td>
<td>0.153</td>
<td>-0.052</td>
<td>0.179</td>
<td>0.243</td>
<td>-0.186</td>
<td>0.554†</td>
<td>0.578†</td>
<td>0.196</td>
</tr>
</tbody>
</table>

KSS, Karolinska Sleepiness Scale.

*P < 0.05; †P < 0.01 for eye symptoms and sleepiness indicators.

Bold text denotes significant results.

Table 3 Mean and standard deviation of sleepiness indicators

<table>
<thead>
<tr>
<th></th>
<th>Real road</th>
<th>Simulator</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>Standard deviation</td>
</tr>
<tr>
<td>Mean of blinks &gt;0.15 s (s)</td>
<td>0.113</td>
<td>0.129</td>
</tr>
<tr>
<td>Mean blink duration (s)</td>
<td>0.115</td>
<td>0.025</td>
</tr>
<tr>
<td>Median blink duration (s)</td>
<td>0.108</td>
<td>0.015</td>
</tr>
<tr>
<td>Maximum KSS</td>
<td>6.781</td>
<td>1.699</td>
</tr>
<tr>
<td>Mean KSS</td>
<td>5.700</td>
<td>1.417</td>
</tr>
<tr>
<td>Effort to stay awake</td>
<td>3.656</td>
<td>2.149</td>
</tr>
<tr>
<td>Left line crossings per km</td>
<td>0.038</td>
<td>0.068</td>
</tr>
<tr>
<td>Right line crossings per km</td>
<td>0.008</td>
<td>0.125</td>
</tr>
</tbody>
</table>

KSS, Karolinska Sleepiness Scale.

crossing because lateral position shifts towards the centre of the road during night-time real road driving (Sandberg et al., 2011); subsequently, right line crossings represent a greater unintentional deviation (more severe) than left line crossings. On the real road, 36% of drives resulting in eye discomfort contained a right line crossing and 38% of drives without eye discomfort contained a right line crossing. In the simulator, right line crossings occurred in 60% of drives resulting in eye discomfort and 25% of drives not resulting in eye discomfort.

For real road data there was no significant effect of sleep-related eye symptoms on right line crossings ($\chi^2 = 3.689$, Fisher’s exact test $P = 0.076$).

Figure 3 compares the four key eye symptoms between drives with and without right line crossings. Each symptom displays a directional trend of being more likely to be experienced during drives containing right line crossings. Oneway ANOVA revealed that this difference was significant for ‘heavy eyelids’ (RR: right line crossing = 2.75, no right line crossing = 2.00, $P = 0.016$; Sim: right line crossing = 2.94, no right line crossing = 2.18, $P = 0.046$) and ‘difficulty keeping the eyes open’ (RR: right line crossing = 2.67, no right line crossing = 1.67, $P = 0.015$; Sim: right line crossing = 3.31, no right line crossing = 2.18, $P = 0.037$).

DISCUSSION

Four eye symptoms were identified as being associated with sleepiness: ‘eye strain’; ‘difficulty focusing’; ‘heavy eyelids’; simulator driving there was a trend for those with sleep-related eye symptoms to be more likely to cross the right lane ($\chi^2 = 3.689$, Fisher’s exact test $P = 0.076$).
The identification of these four symptoms has practical implications for road safety authorities wishing to advise drivers on the identification of sleepiness. As each one is correlated to an established sleepiness indicator, drivers experiencing one or more of these eye symptoms are likely to have a high KSS, require greater effort to remain awake and be more likely to have unintentional line crossings. In particular, it is the experience of ‘heavy eyelids’ and ‘difficulty to keep the eyes open’ that coincide with unintentional line crossings. In the simulator, those with eye discomfort also have longer blinks, a distinction not found on real roads. This difference may be as a result of participants becoming sleepier (higher KSS) in the simulator than on the real road. Additionally, ‘sore eyes’ and ‘tearful’ are symptoms associated with sleepiness in driving simulators but not on real roads. These results are important to consider if implying real world advice from simulator research.

The four key eye symptoms appear to be good indicators of sleepiness and could be used to suggest potential impaired driving. It was important to investigate the association between eye symptoms and subjective sleepiness because KSS is strongly related to accident risk and lane departures (Ingre et al., 2006; Reyner and Horne, 1998). Eye symptoms that are related to KSS could potentially be used to help drivers identify sleepiness. Inappropriate line crossings are a sign of sleepiness-related impaired driving, both in simulators and on real roads (Anund et al., 2008a; Filtness et al., 2012; Horne and Reyner, 1996; Otmani et al., 2005). The current work established that subjective sleepiness (KSS) and driving impairment (line crossings) are more common during drives where eye discomfort was reported. Here, left and right line crossings were considered separately.
These more serious (and less frequent), right line crossings have a relationship with ‘heavy eyelids’, as right line crossings per km were correlated with ‘heavy eyelids’ during real road driving, and ‘heavy eyelids’ were more common in drives containing a right line crossing than when right line crossings did not occur. It is possible that age of participants may have provided some protection from the impact of sleep loss, as it has been demonstrated that younger drivers are more vulnerable to sleep loss than older drivers (Fittness et al., 2012). Therefore, if younger participants had been recruited, a greater difference in driving performance between daytime and night-time drives may have been observed. Nevertheless, the driving impairment that was observed had a relationship with eye symptoms.

Driving simulators can be effectively used to demonstrate increased sleepiness due to prior sleep loss (Fittness et al., 2012) and time of day (Akerstedt et al., 2005), whilst eliminating the risks associated with sleepy driving on real roads. However, there are some notable differences between sleepy driving in simulators and on real roads, for instance, simulators result in greater subjective sleepiness, increased number of line crossings and increased lateral variability (Hallvig et al., 2013; Philip et al., 2005). The current study also noted differences between the simulator and real road driving. For instance, the importance of six eye symptoms (as demonstrated by an improved Cronbach’s alpha) during night-time simulator driving as opposed to four key symptoms for real road driving. It is not possible to determine the cause of this difference from the current protocol, but there is potential that a higher concentration of infra-red light (more infra-red pods in a smaller space) within the simulator, or the bright display in a darkened room may have influenced ‘sore/tearful eyes’, creating symptoms not apparent on the real roads. It is interesting that ‘sore eyes’ was negatively associated with longer blink durations in the simulator but not the real road, suggesting longer blinks may be necessary to reduce sore eyes when driving simulators.

Eye symptoms had a weaker association with objective eye measures than subjective sleepiness. Longer blinks are a recognised sign of sleepiness, associated with sleep-related events when driving (Caffier et al., 2003; Flouni et al., 2013; Schleicher et al., 2008). The only symptom with a positive correlation to an objective eye measures was ‘eye strain’ (correlated to median blink duration on real roads), suggesting that eye symptoms are more about personal experience than physical changes.

It is acknowledged that the current results are limited by a fairly small sample size (16 participants; 64 drives). The outcomes of the correlations conducted to identify sleep-related eye symptoms were generally low; despite some significant results, the relationships were generally weak. Further, due to the exploratory nature of this first component of analysis, each variable was analysed 10 times. This analysis was necessary to identify which eye symptoms were key to sleep-related discomfort, but the exploratory nature means that there is potential for some significance to be found at random.

Participants experienced a greater level of subjective sleepiness during simulator driving than real road driving. This restricted range of sleepiness limits the prospect of significant correlations to sleep-related eye symptoms within the real road data. Unfortunately, occasional technical problems were experienced with the simulator resulting in sporadic sudden stops or absence of sound. Segments of data containing these undesired events were removed prior to analysis. Future research may wish to consider the progression of the key eye symptoms identified here over an extended driving period. Such a methodology could be used to confirm if the symptoms are identified prior to line crossings, and investigate if using these symptoms assists people known to have difficulty identifying sleepiness, for instance treated patients with obstructive sleep apnoea (Fittness et al., 2011). However, the applicability of these eye symptoms for patients with sleep disorders would first have to be established, as all of the participants in the current work were healthy. Additionally, monitoring subjective eye symptoms in conjunction with subjective sleepiness over an extending driving time would allow for differences between time-on-task fatigue and sleepiness to be identified. This could be in a similar manner to that which differences between subjective sleepiness and subjective fatigue have been investigated (Sagaspe et al., 2008).

**CONCLUSION**

In conclusion, this study demonstrated that four eye symptoms are reflective of driver sleepiness: ‘eye strain’; ‘difficulty focusing’; ‘heavy eyelids’; and ‘difficulty keeping the eyes open’. Two further symptoms (‘sore eyes’ and ‘tearful’) are associated with driver sleepiness in simulators. Critically, experiencing these eye-related symptoms is associated with higher subjective sleepiness and impaired driving performance. In particular, ‘heavy eyelids’ and ‘difficulty keeping the eyes open’ are common when unintentional line crossings occur. Including these eye symptoms in road safety advice has potential for assisting drivers identify sleepiness.

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**AUTHOR CONTRIBUTIONS**

AJF: analysis, writing paper; AA: concept, design, data collection, analysis, writing paper; CF: data collection, analysis, writing paper; CA: data collection, analysis, writing paper; TA: concept, writing paper; GK: original concept, writing paper.
CONFLICT OF INTEREST
No conflicts of interest declared.

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