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RESEARCH ARTICLE

Sleepy drivers on a slippery road: A pilot study using a driving simulator

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Summary

Sleepy drivers have problems with keeping the vehicle within the lines, and might often need to apply a sudden or hard corrective steering wheel movement. Such movements, if they occur while driving on a slippery road, might increase the risk of ending off road due to the unforgiving nature of slippery roads. We tested this hypothesis. Twelve young men participated in a driving simulator experiment with two counterbalanced conditions; dry versus slippery road × day (alert) versus night (sleepy) driving. The participants drove 52.5 km on a monotonous two-lane highway and rated their sleepiness seven times using the Karolinska Sleepiness Scale. Blink durations were extracted from an electrooculogram. The standard deviation of lateral position and the smoothness of steering events were measures of driving performance. Each outcome variable was analysed with mixed-effect models with road condition, time-of-day and time-on-task as predictors. The Karolinska Sleepiness Scale increased with time-on-task ($p < 0.001$) and was higher during night drives ($p < 0.001$), with a three-way interaction suggesting a small increased sleepiness with driving time at night with slippery road conditions ($p = 0.012$). Blink durations increased with time-on-task ($p < 0.01$) with an interaction between time-of-day and road condition ($p = 0.040$) such that physiological sleepiness was lower for sleep-deprived participants in demanding road conditions. The standard deviation of lateral position increased with time-on-task ($p = 0.026$); however, during night driving it was lower on a slippery road ($p = 0.025$). The results indicate that driving in demanding road condition (i.e. slippery road) might further exhaust already sleepy drivers, although this is not clearly reflected in driving performance.

KEYWORDS
driver fatigue, Karolinska Sleepiness Scale, sleepiness

1 | INTRODUCTION

Attentional lapses and slower reaction times are characteristics of increased acute sleepiness (Dinges & Mallis, 1998). Therefore, it is expected that in activities that require sustained attention, the reaction of those who are sleepy might be if not completely absent then delayed and consequently more intense if the level of required reaction depends on the passed time. This is exactly what happens with sleepy drivers who have problems in keeping the vehicle within the lines (higher standard deviation of lateral position [SDLP] and more line crossing; Ingre et al., 2006; Philip et al., 2005) and less often make corrective steering wheel movements, which are, however, of higher amplitude (Thiffault & Bergeron, 2003; Verwey & Zaidel, 1999) and might lead to overcorrection and oversteering (Penmetsa et al., 2018). Hard-braking events are also positively related to sleepiness (Mollicone et al., 2019).

If such sudden or hard corrective movement or braking is applied in slippery road conditions, the risk of skidding and losing control of a vehicle might increase due to the unforgiving nature of slippery roads. To our knowledge, the hypothesis that sleepy drivers are at higher risk when driving on slippery roads has not been tested or even mentioned as a possibility in the literature. There are at least two possible reasons for this neglect.

First, it is generally accepted that fatigue-related problems are more profound in monotonous driving situations and therefore in many simulator studies dealing with driver fatigue and sleepiness, the demand level of a primary task (driving) is usually low (driving on a straight motorway with no other traffic). Driving on slippery roads might be considered more demanding and alerting similar to driving on curvy roads. It has been shown more than once that driving on curvy road sections produces less fatigue-related driving impairment compared with driving on straight sections (Desmond & Matthews, 1997; Farahmand & Boroujerdian, 2018; Matthews & Desmond, 2002; Oron-Gilad & Ronen, 2007). Therefore, driving on slippery roads might be more stressful and therefore alerting, at least for some time. However, prolonged stressful workload can produce additional fatigue in already sleepy drivers (Desmond & Matthews, 1997; Matthews & Desmond, 2002). This might further compromise their driving performance as the detrimental effects of fatigue on performance are well established (Dawson et al., 2011, 2021).

Secondly, crash statistics suggest that fatigue-related crashes predominantly occur on non-slippery roads (Radun & Radun, 2006). However, this is not surprising as investigating police officers might give more attention to easily observable adverse road conditions than to driver fatigue, an inner state, whose detection is extremely difficult, especially after the crash has occurred. Furthermore, operational definitions of fatigue-related crashes used by researchers reinvestigating crash statistics typically include only crashes occurring in good weather conditions (Horne & Reyner, 1995; Philip et al., 2001).

Given the foregoing consideration, it is very likely that the role of fatigue/sleepiness as a contributing factor to crashes occurring in difficult road conditions, namely slippery roads, might be underestimated both in traffic safety research as well as in crash statistics. The aim of this study was to test whether sleepy drivers, compared with rested drivers, might indeed be at higher risk when driving on a slippery road. More specifically, we posited two hypotheses.

The first hypothesis is that the demanding nature of driving on a slippery road will actually have alerting effects on sleep-deprived participants whose driving will then deteriorate to a lesser degree compared with when driving in normal dry road conditions. In other words, we expect the interaction between task difficulty (slippery road) and state of the driver (sleep deprived).

The second hypothesis is that the above interaction will be task dependent such that sleepiness increases and driving performance decreases faster over time in participants who are already sleepy. In other words, we expect a three-way interaction between task difficulty (slippery road), state of the driver (sleep deprived) and time-on-task.

2 | METHODS

A two (day versus night driving) by two (dry versus slippery road conditions) counterbalanced within-subject experiment was carried out using an advanced simulator (Sim III) at the Swedish National Road and Transport Research Institute (VTI), Linköping, Sweden.

2.1 | Simulator

The driving simulator at VTI is one of the most advanced simulators in the world. Its moving base allows motion in four degrees of freedom, and drivers can experience acceleration, deceleration and centrifugal forces. Ecological validity is further enhanced by the cabin design, which includes the front part of a Saab 9–3 with a manual 5-shift gearbox, and resembles the noise and vibration levels of those normally experienced inside a real car. The front view was 120 × 30 degrees.

2.2 | Road conditions (friction)

Following the experience of previous studies (Markkula et al., 2013), we selected the friction coefficient of 0.24 μ for the slippery road condition and 0.98 μ for the dry road condition. These values were evaluated in the pilot testing, and were kept throughout the experiment.

2.3 | Participants

Twelve young male volunteers were recruited for the study from the VTI's register of test participants. Inclusion criteria based on self-reported information were: no physical, mental health or sleep problems, no shift work within 3 months before the experiment, no use of medication, non-smoker, body mass index < 25 kg m^{-2}, driver license holder, age between 19 and 21 years. The majority (9/12) of the participants were single, secondary school graduates (9/12), reported drinking alcohol 2–4 times per month (10/12), and had low yearly driving mileage (M = 1425 km). The main reason for selecting young males is the fact they are overrepresented in sleep-related crashes (Radun, 2009). Each individual received 3000SEK (about 350€ at the time of data collection) for participation in the study.

2.3.1 | Driving scenario

The scenario was a two-lane rural road, with occasional curves and other oncoming traffic that made the situation more realistic but not intrusive. This means the driving task was quite monotonous without the need for overtaking or adjusting the speed because of other traffic. Drivers were instructed to follow the speed limit of 90 km hr^{-1}. At the very end of each driving session, the participants had to negotiate five cones positioned in the middle of the road. All conditions resembled daylight winter conditions with a small amount of fog. The participants were told that during normal dry road conditions salt had been used on the surface, while during the slippery conditions they were told that no salt was used. The visual difference between the two road conditions was slightly more white traces on the surface in slippery road conditions in order to increase ecological validity (see Figure S1 in Appendix S1).

Originally, the duration of the drives was supposed to be time based (35 min); however, due to miscommunication during the programming of the simulator, the duration of the drive was set as kilometer based (52.5 km; 35 min * 90 km h^{-1}). As a consequence, there was a variation in time-on-task, as well as in timings of Karolinska Sleepiness Scale (KSS) rating – instead of every 5 min, which is typical in similar experiments, the rating was performed every 7.5 km. The implications of this deviation from the original design are discussed in the Limitations section.

2.4 | Protocol

During the initial telephone interview, the participants were requested to abstain from alcohol for 72 hr prior to the test days, and from smoking and coffee 3 hr before arrival at the laboratory. In the night session, they were brought to the laboratory and taken home by taxi. On the first testing day, they were briefed about the procedures and signed a standard consent form. No specific ethical approval was obtained for this study because the set-up did not differ from previous studies in our research group, except that roads were slippery in half of the drives. Before the experiment, the participants had a 10-min practice drive in the simulator. Each participant came twice to the lab (day and night testing) and drove two sessions (dry and slippery road conditions) on each testing day. The order of conditions was counterbalanced. During each testing day, two participants participated in the following order: participant A started his first drive at 09:00 hours and his second at about 11:00 hours, while participant B started his first drive at about 10:00 hours and his second drive at about 12:00 hours. During the night session, starting times were at about 03:00 hours and 05:00 hours for one participant, and at about 04:00 hours and 06:00 hours for the other. During the break between sessions, the participants spent time in the local cafeteria, and were offered a sandwich, red tea or decaffeinated coffee or water.

2.5 | Measurements

Three types of measures were collected: driving performance measures, physiological and subjective measures of sleepiness. Driving performance measures included altogether four indicators. First, the SDLP on the track was calculated from interpolated samples at 1-m intervals on the track. This is the most widely used measure for measuring driving impairment (Brookhuis, 2014; Verster & Roth, 2013) sensitive to the effects of sleepiness (Åkerstedt et al., 2005; Hallvig et al., 2013). Secondly, the mean steering wheel movement amplitudes (Stw amplitude) and mean steering wheel movement peak velocities (Stw velocity) were measures of the smoothness of the steering actions. They were calculated by identifying steering wheel movements, and then calculating the total change (amplitude) and the peak velocity of the change during each of the events before averaging the statistics for each segment. Smaller steering wheel turns of less than 0.5° were labelled as unintentional jitter and filtered out during the calculations. The final performance measure was the number of cones hit during the cone driving.

Subjective sleepiness was assessed with the KSS (Åkerstedt & Gillberg, 1990), which is a widely used, easily administered, valid and reliable measure of acute sleepiness (Åkerstedt et al., 2014). Physiological data (electroencephalogram [EEG] and electrooculogram [EOG]) were recorded using the Vitaport III system (Temec Instruments BV, Kerkrade, Netherlands). Six electrodes were used to record the EOG, four vertical (above and under the left and right eyes) and two horizontal. The EOG was DC (direct current) recorded with a sampling rate of 512 Hz. EEG data are not presented in this paper, while blink durations (BDs) were extracted from EOG using a MATLAB program developed by Dr A. Muzet and Thierry Pebayle, from the Center for Applied and Environmental Physiology CEPA, Strasbourg, France. As explained by Anund et al. (2008), this programme "essentially involves a lowpass filter to establish a stable baseline for the signal, establishing a threshold that has to be exceeded to score a blink (done visually) with computation of the start and end point of the blink based on the slope and computation of BDs done at midslope. To reduce problems with concurrent eye movements and eye blinks, BDs were calculated as half the amplitude of the upswing and downswing of each blink, and then the time elapsed between the two was computed".

2.6 | Statistical analysis

The data were analysed with mixed-effects multilevel models; ordinal logistic regression was used for the KSS, linear regression for BDs, and performance measures and logistic regression for cone hit data. All the analyses were performed in R version 3.6.3. A cumulative link mixed model function (clmm) from the package *ordinal* was used for ordinal regression, and lmer function from package lme4 was used for linear regression. The models were built stepwise by adding intercepts and slopes to the random effects part of the model. The increase in model fit was evaluated with log-likelihood criterion, and the model with the best fit and a sensible theoretical interpretation was selected. Log-transformations were done for all the continuous dependent variables to reduce skewness. Time variables were global mean centred to reduce multicollinearity. For significance testing, the Wald test was used for the ordinal model estimates and F-test with Satterthwaite approximation for the linear model estimates.

3 | RESULTS

Subjective sleepiness (KSS) was higher during the night (z = 5.60, p < 0.001) and increased over time (z = 8.77, p < 0.001; Table S1 Appendix S1; Figure 1). There was no interaction between time-of-day and time-on-task (z = −1.86, p = 0.063); however, a three-way interaction was found between time-of-day, road condition and time-on-task (z = 2.50, p = .012), suggesting that subjective sleepiness increased more with passing time when participants were already sleepy and the conditions were demanding (i.e. driving on a slippery road). Most (10/12) of the test participants reached the maximum sleepiness score of 9 by the end of the driving sessions. Predictions based on clmm estimates and observed KSS scores are visualized in Figure S1 (see Appendix S1).

Blink durations also increased with time-on-task ($F_{1,34.27}$ = 8.78, p = 0.005); however, at a progressively slower pace as indicated by the negative coefficient of time-on-task squared ($F_{1,287.40}$ = 8.83, p = 0.003; Table S2 Appendix S1; Figure 1). A squared time-on-task variable was used to model polynomial growth (instead of only linear growth). The inclusion of this variable increased the model fit significantly. There was no main effect of time-of-day; however, an interaction between time-of-day and road condition ($F_{1,280.07}$ = 4.25, p = 0.040) indicates that BDs were longer when participants were sleep-deprived and driving in demanding conditions.

Time-on-task was positively correlated with the SDLP ($F_{1,27.14}$ = 5.51, p = 0.026) and time-on-task squared with the steering wheel movement amplitude ($F_{1,293.29}$ = 8.78, p = 0.003). The three-way interaction did not approach significance in any of the performance indicators; however, the interaction between time-of-day and road condition was negatively correlated with all three performance variables: SDLP ($F_{1,282.95}$ = 5.11, p = .025); Stw amplitude ($F_{1,282.72}$ = 7.19, p = 0.008); and Stw velocity ($F_{1,282.81}$ = 9.47, p = 0.002). Additionally, the interaction between time-of-day and time-on-task was positively correlated with the Stw amplitude ($F_{1,283.06}$ = 4.42, p = 0.033) and Stw velocity ($F_{1,283.37}$ = 9.04, p = 0.003). Participants generally performed better when their initial sleepiness was combined with demanding conditions; however, their performance in steering decreased over time when they started in a fatigued state.

The number of driving sessions where cones were hit and the total number of cone hits are summarized in Table S3 (Appendix S1). The road condition was the only significant predictor of cone track performance (z = 2.048, p = 0.041). Most of the runs where cones were hit were driven on a slippery road. The distribution of the total number of cone hits is consistent with the number of driving sessions where cones were hit.

4 | DISCUSSION

We found partial support for both hypotheses. The first hypothesis, stating that increasing task demand (i.e. driving on a slippery road) improves performance and reduces signs of subjective and objective sleepiness, was confirmed in performance only. Sleep-deprived participants had smaller changes in lateral positioning, and smaller and smoother steering wheel movements when driving in slippery conditions. On the other hand, BDs increased during nighttime driving on a slippery road, which is in contrast with the hypothesis, while no effect was observed for subjective sleepiness. If the accumulation of subjective and physiological sleepiness had slowed due to more demanding driving conditions, this would have indicated a reduction in passive task-related fatigue. Because this did not occur, it is more likely that improved performance was due to motivation-related mechanisms. Drivers were forced to change their coping strategies and pay more attention to both lane positioning and steering wheel manipulations because of the increased difficulty of driving and the dangers involved. This behavioural explanation is further supported by the time-of-day having no significant main effect on the driving performance. Thus, sleep-deprived participants performed better in demanding conditions despite the accompanied increase in physiological sleepiness.

Partial support was also found for the second hypothesis, stating that the performance of sleepy drivers deteriorates and sleepiness increases over time when driving in slippery conditions. Here, the effect appeared in self-reported sleepiness only. The three-way effect was not significant in physiological- or performance-related measures. Steering wheel manipulations became more sudden and larger over time when participants were already sleepy; however, this change did not increase with task difficulty. Based on previous research and because by the end of the slippery trials 10 out of 12 sleep-deprived participants had reached maximum subjective sleepiness, it is slightly unexpected that increasing task difficulty did not negatively affect driver performance. Previous research has shown that well-rested drivers can drive for several hours before signs of performance impairment are observed (Philip et al., 2005; Reyner & Horne, 1998); however,

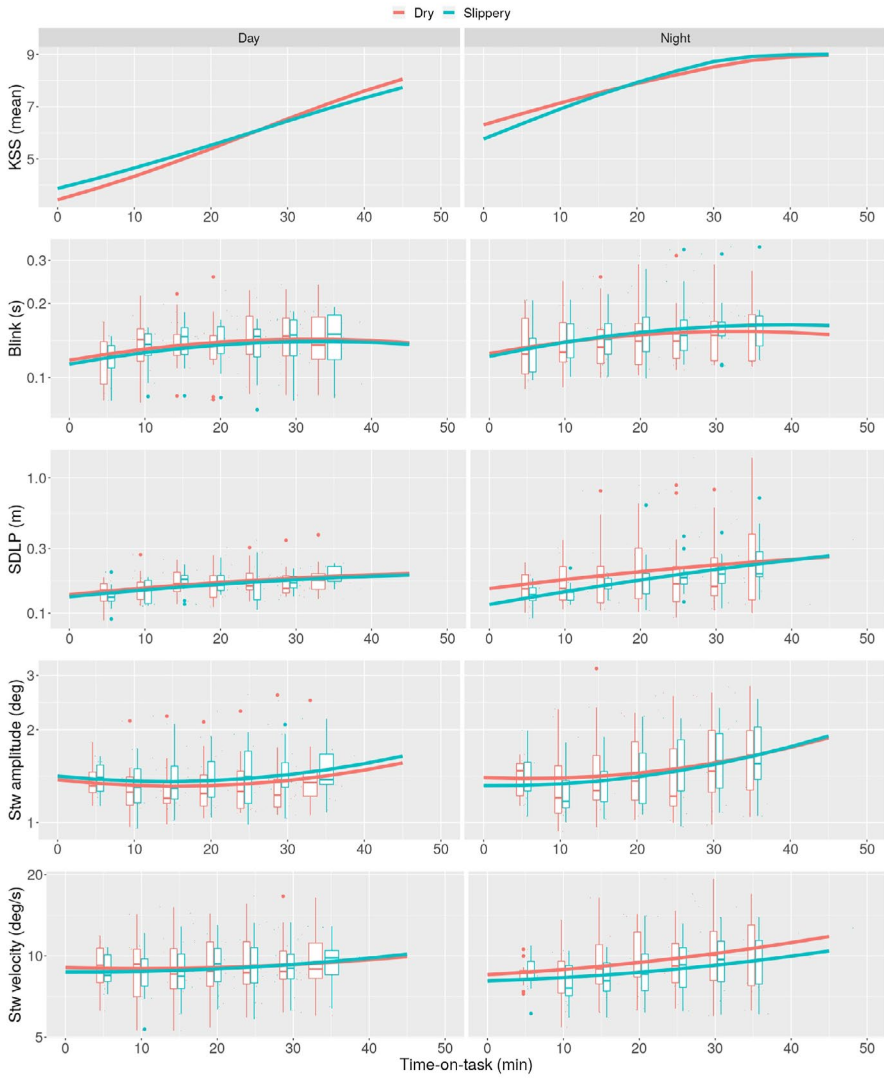

FIGURE 1 Model predictions based on the estimated fixed-effects plotted over box plots of the original data (except for Karolinska Sleepiness Scale [KSS]). Box plots are located at the average end time points of each of the 7.5-km measurement segments. Note that the *y*-axes are log-scaled (except for KSS) to reduce skewness and improve readability

after a night shift even 20–25 min of driving becomes problematic (Åkerstedt et al., 2005). For our participants it took 25–46 min to complete the 52.5-km trip. Even for the longest drives, the exposure time might still have been too short for performance impairment to occur. On the other hand, time-on-task effect on subjective sleepiness was strong even during the daytime, with KSS reaching high levels probably reflecting a well-known simulator effect (Hallvig et al., 2013).

These results are consistent with previous research showing that increased driving task demand can improve performance in tired drivers (Desmond & Matthews, 1997; Matthews & Desmond, 2002; Oron-Gilad & Ronen, 2007; Saxby et al., 2008). On the other hand, when the main task is monotonous, secondary tasks have been used to increase alertness and task engagement, and improve performance (Atchley & Chan, 2011; Neubauer et al., 2014). However, the main question for both the demanding primary and secondary tasks remains: how long does it take for the initial alerting benefit to switch to the even more negative effects? Even though none of our participants lost control of the vehicle on the slippery road, it is still plausible to argue that any sleepiness-related mistake (i.e. larger corrective steering wheel movements or hard braking) while driving on a slippery road might be costly.

Consistently with previous studies in a similar (Ingre et al., 2006) or a laboratory setting (Frey et al., 2004; Van Dongen et al., 2004), we observed large individual variability in response to sleep deprivation. The impact of these factors on performance was surprisingly large considering that the participants in the current study formed a relatively homogenous group of young males aged 19–21 years. The model fit statistics reveal that while fixed-effects coefficient estimates could model the subjective sleepiness relatively well, the marginal R^2 values for performance-related variables are low. This indicates that the fixed-effects poorly explain the variability in performance. If this is compared with high conditional R^2 values, indicating total model fit, most of the variability is in individual differences. Huge differences in individual responses to the experimental conditions are also apparent from the boxplots in Figure 1. Clearly, unexplained, potentially internal factors exist, influencing both the baseline driving performance and how individuals react to changes in fatigue levels and road conditions. These factors were not captured by this study design.

4.1 | Limitations of the study

The main (and new) hypothesis of this study was a three-way interaction between task difficulty (slippery road), the state of the driver (sleep deprived) and time-on-task. However, the number of participants was not determined in a power analysis for this three-way interaction; it was deducted from the available funding for data collections costs. This is what Lakens (2021) calls *resource constraints* as justification for the sample size in a study. Therefore, it is possible that the study was underpowered in particular for the three-way interaction; however, all participants came from a very homogenous group of young males (19–21 years old). Due to the error in simulator programming for this study, instead of driving a fixed time of 35 min, different participants drove for different durations to finish the 52.5-km trip (M = 35.36, SD = 3.5). This possibly enabled the participants to adjust the total time-on-task by using different sleepiness coping strategies. Some participants may have chosen to driver faster to increase alertness or go home sooner, others perhaps decided to drive more slowly to minimize the risk of mistakes, while some indeed tried to stick to the recommended driving speed of 90 km hr^{-1}. The experiment was not designed to research differences in individual coping strategies, which might have been lost in variation between individuals. Finally, although the SDLPs and steering wheel movements are commonly used as driving performance metrics, they offer only limited information on the link between sleepiness and crash risk.

5 | CONCLUSION

This pilot study shows that an increased demand of the primary task (i.e. driving on a slippery road) may have negative consequences if combined with initial sleepiness and prolonged driving. This probably happens because slippery roads reduce the error margin, and drivers are forced to invest more of their already strained cognitive resources in order to minimize sharp and sudden vehicle manoeuvres. Future studies should consider whether an actual crash risk is higher in such circumstances, and expand the focus to other demographic groups such as women, older and more experienced drivers.

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CONFLICT OF INTEREST

No significant financial interest/other relationship to disclose.

AUTHOR CONTRIBUTIONS

Conceptualization: I.R., M.W., J.R. and G.K.; Methodology: I.R., M.W., J.R. and G.K.; Formal analysis: I.R., A.L., O.L. and M.I.; writing-original draft: I.R. and A.L.; writing-review and editing: all.

DATA AVAILABILITY STATEMENT

Data available on request from the authors.

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SUPPORTING INFORMATION

Additional Supporting Information may be found in the online version of the article at the publisher's website.

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