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DOI:
10.1111/jsr.13933

Received: 1 February 2023 | Revised: 21 April 2023 | Accepted: 2 May 2023

DOI: 10.1111/jsr.13933

RESEARCH ARTICLE

Journal of Sleep Research ESRS

Subjective awareness of sleepiness while driving in younger and older adults

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Funding information
Australian Research Council, Grant/Award Number: LP160101193

Summary

Understanding whether drivers can accurately assess sleepiness is essential for educational campaigns advising drivers to stop driving when feeling sleepy. However, few studies have examined this in real-world driving environments, particularly among older drivers who comprise a large proportion of all road users. To examine the accuracy of subjective sleepiness ratings in predicting subsequent driving impairment and physiological drowsiness, 16 younger (21–33 years) and 17 older (50–65 years) adults drove an instrumented vehicle for 2 h on closed loop under two conditions: well-rested and 29 h sleep deprivation. Sleepiness ratings (Karolinska Sleepiness Scale, Likelihood of Falling Asleep scale, Sleepiness Symptoms Questionnaire) were obtained every 15min, alongside lane deviations, near crash events, and ocular indices of drowsiness. All subjective sleepiness measures increased with sleep deprivation for both age groups ($p < 0.013$). While most subjective sleepiness ratings significantly predicted driving impairment and drowsiness in younger adults (OR: 1.7–15.6, $p < 0.02$), this was only apparent for KSS, likelihood of falling asleep, and "difficulty staying in the lane for the older adults" (OR: 2.76–2.86, $p = 0.02$). This may be due to an altered perception of sleepiness in older adults, or due to lowered objective signs of impairment in the older group. Our data suggest that (i) younger and older drivers are aware of sleepiness; (ii) the best subjective scale may differ across age groups; and (iii) future research should expand on the best subjective measures to inform of crash risk in older adults to inform tailored educational road safety campaigns on signs of sleepiness.

KEYWORDS
ageing, driving impairment, drowsy driving, sleep loss, subjective sleepiness

1 | INTRODUCTION

Drowsiness is a major contributor to fatal and severe injury motor vehicle crashes (Hallvig et al., 2014; Lee et al., 2016), and is associated with a four-to-six-fold increase in crash risk and hazardous driving events (Anderson et al., 2018; Lee et al., 2016; Tefft, 2014). Many road safety campaigns rely on the driver's ability to self-monitor drowsiness, and encourage road users to "take a break" and cease driving when they "feel sleepy" (Fletcher et al., 2005). As these interventions rely on a driver being accurately aware of their level of sleepiness, it is important to understand how subjective sleepiness is impacted by sleep loss, and which subjective ratings best predict subsequent driving impairment and increased risk of crashes.

In a recent systematic review of 34 driving studies, we concluded that subjective sleepiness was associated with adverse driving outcomes (Cai et al., 2021). Specifically, Karolinska Sleepiness Scale (KSS) ratings during a drive were associated with subsequent adverse driving outcomes (Philip et al., 2005), particularly in those studies utilising low/high fidelity simulators (Ingre et al., 2006; Williamson et al., 2014). Best practice evidence to support public campaigns encouraging drivers to use subjective signs of sleepiness to pull-over and cease driving should be derived from on-road (track or naturalistic) study designs. Of the 34 studies examined systematically, only ten utilised this approach, and of these, none significantly assessed physiological outcomes (Cai et al., 2021). To address this, we recently examined the accuracy of subjective sleepiness and associated symptoms, in predicting both driving impairment and physiological signs of drowsiness using an on-road track design. Here, (some indices of) subjective sleepiness predicted near crash events, lane deviations, long eye closures, and microsleep events in shift workers driving post-night shift (Anderson et al., 2023).

While these data suggest that drivers should continually monitor their sleepiness symptoms, previous work has suggested individual differences may exist such that some drivers may be more (or less) aware of sleepiness symptoms and associated driving impairment (Akerstedt et al., 2010; Anund et al., 2008; Manousakis et al., 2021). One of these individual differences may relate to the age of the driver, particularly given the large differences observed in younger and older individuals in the behavioural response to sleep loss (Adam et al., 2006; Cai et al., 2021; Duffy et al., 2009; Filtness et al., 2012). From a driving perspective, younger drivers are more likely to be involved in a fall asleep crash, based on both epidemiological (Pack et al., 1996) and on-road experimental evidence (Cai et al., 2021). As older drivers comprise a large proportion of all road users, and may be at high risk for drowsy driving due to many being involved in shift work (Australian Bureau of Statistics, 2010; Wagner, 2021), the reduced prevalence of fall asleep crashes may be due to lowered vulnerability to falling asleep and/or because they are more likely to pull over and cease driving due to drowsiness (Watling et al., 2015). The extent to which older drivers are more aware of their sleepiness or more likely to take pre-emptive action however is unknown. Indeed, in our systematic review of the association between subjective sleepiness and driving outcomes only one simulated driving study directly compared subjective sleepiness with driving outcomes for both younger and older drivers (Filtness et al., 2012). Here strong correlations were reported between the KSS and electroencephalograph (EEG) drowsiness activity for both younger and older male drivers, but differences between age groups were not compared. The extent to which these results can translate to real driving outcomes, and whether younger and older drivers differ in the accuracy of their subjective sleepiness assessments form the basis of this study.

Our study utilises data from a previous study (Cai et al., 2021), which reported age differences in physiological and subjective sleepiness during a 2 h driving task following 29 h sleep deprivation. Based on the high proportion of current road users of working/commuting age, drivers were aged 20–35 years ("younger adults") and 50–65 years ("older adults"). While younger adults were more vulnerable to drowsy driving relative to older adults, the older drivers still exhibited poorer driving outcomes following sleep loss relative to when well rested. We now examine these age differences further with respect to the capacity to predict real-road driving impairment and physiological drowsiness using subjective sleepiness ratings. We hypothesise that subjective ratings of sleepiness will predict subsequent adverse driving outcomes, for both younger and older drivers, but that the observed associations may differ between the age groups.

2 | METHODOLOGY

2.1 | Participants

Sixteen younger drivers (25.2 ± 3.1 years [21–33 years], 7 females) and 17 older drivers (57.3 ± 5.2 [50–65 years], 8 females) took part in the study (Table 1). These ages were selected to represent drivers of "younger" and "older" age, but importantly to reflect a large proportion of on-road drivers (17.6%, 20.7%, respectively) and who may experience sleep deprivation (e.g., shift work). All participant slept 7–9 h per night, napping ≤2 times per week. Participants were good, experienced drivers having held a valid driver's licence for >3 years, driving >100 km per week, and without previous licence suspension. Participants had no past/current medical, psychiatric or sleep disorders, were free from medication, consumed <300 mg caffeine a day and <14 standard alcoholic drinks/week, were non-smokers and non-shift workers, and had not travelled across more than two time zones in the past 3 months. Female participants were not pregnant, breastfeeding, or using hormonal contraception. Participants underwent an electrocardiogram, had an $ODI_{4\%}$ < 5 (ApneaLink™, ResMed Corp. CA, USA), and underwent a semi-structured psychological assessment to ensure safety for sleep deprivation. Older adults also underwent neurocognitive testing to ensure no neurocognitive impairment (≤1.5 SD below age-matched norms [Petersen, 2004]). Ethical approval was obtained from the Monash University Human Research Ethics Committee. Participants provided written informed consent and were reimbursed for their time. See Supplementary Data S1 for the participant flowchart.

TABLE 1 Participant demographic summary ($n = 33$)

Demographics	Younger adults ($n = 16$)	Older adults ($n = 17$)	p value
Age (years)	24.3 (3.2)	57.3 (5.2)	
Sex (M:F)	9:7	9:8	$p = 0.867$
Body mass index (kg/m^2)	23.6 (3.3)	24.4 (2.8)	$p = 0.428$
Driving experience (years)	5.6 (2.1)	38.1 (4.8)	$p < 0.001$
Weekly driving (h)	12.0 (7.8)	8.4 (6.7)	$p = 0.099$
PSQI (/21)	2.5 (1.6)	2.4 (1.6)	$p = 0.912$
ESS (/24)	3.6 (2.0)	2.8(2.0)	$p = 0.263$
ISI (/28)	1.4 (1.4)	1.8 (1.8)	$p = 0.516$
MEQ (16–86)	38.7 (5.4)	42.1 (5.0)	$p = 0.071$
ODI4% (events/h)	0.5 (0.5)	1.3 (1.5)	$p = 0.058$

Note: Mean (SD).
Abbreviations: ESS, Epworth sleepiness scale; ISI, insomnia severity index; MEQ, morningness-eveningness questionnaire; ODI4%, oxygen desaturation index with 4% desaturation criteria; PSQI, Pittsburgh sleep quality index.

2.2 | Procedure

Participants drove an instrumented vehicle around a closed driving loop for 2 h, on two occasions: one after a night of 8 h time in bed and one following 1 night (29 h) of sleep deprivation. Drives were counterbalanced, with a minimum 1 week washout period between drives. Participants maintained a self-selected fixed 8:16 h sleep: wake schedule for 1 week at home prior to both conditions, confirmed with wrist actigraphy (Actiwatch 2, Phillips Respironics, USA), time-stamped call-ins at bed/wake times and a sleep diary (McMahon et al., 2020). For 24 h prior to admission for both conditions, participants consumed no caffeine, alcohol, nicotine, or medication (over the counter or prescription), confirmed by urine toxicology and breathalyser.

For the sleep deprivation session, participants remained in the laboratory and were continuously monitored by staff to ensure they remained awake. All drive sessions started 5 h post-wake for the well-rested condition and 29 h post-wake for the sleep-deprivation condition. All drives began between 11:00 and 14:00 with the times of each drive consistent within-participant. The study car was an automatic transmission Honda Jazz fitted with Seeing Machines' driver monitoring system (DMS; Seeing Machines, Canberra, Australia), a forward-facing camera (BlackVue, Pittasoft, Gyeonggido, Republic of Korea), and an emergency second brake. A qualified driving instructor (R.W. or D.S.) blinded to the condition of the study accompanied the participant and provided intervention if there was a risk of crashing (recorded as a near-crash event). A study technician sat in the back seat to prompt subjective sleepiness ratings every 15 min. Every 30 min, participants stopped at a red traffic light and completed questionnaires. Participants were asked to obey all road signs, speed limits, and general road rules applicable to naturalistic driving. Prior to each drive session, they completed three practice laps to orient them to the track route and study vehicle.

2.2.1 | Subjective sleepiness

Subjective sleepiness was measured with 11 outcomes: the Karolinska Sleepiness Scale (KSS) (Åkerstedt & Gillberg, 1990), the Likelihood of Falling Asleep (LFA) scale (Horne & Baulk, 2004), eight separate items on the Sleepiness Symptoms Questionnaire (SSQ) (Howard et al., 2014), and the SSQ global score. KSS and the LFA were verbally recorded every 15 min and the SSQ was completed every 30 min while at the stop light.

TABLE 2 List of sleepiness symptoms questionnaire individual items

Item	
1	Struggling to keep your eyes open
2	Vision becoming blurred
3	Nodding off to sleep
4	Difficulty keeping to the middle of the road
5	Difficulty maintaining the correct speed
6	Mind wandering to other things
7	Reactions were slow
8	Head dropping down

The KSS requires participants to rate their sleepiness in the past 5 min on a 9-point scale ranging from 1, "Extremely Alert" to 9, "Extremely Sleepy" (Åkerstedt & Gillberg, 1990; Reyner & Horne, 1998). For LFA, participants rated the likelihood of falling asleep in the next 5 min on a 5-point scale, ranging from 5, "Very Unlikely" to 1, "Very Likely" (Reyner & Horne, 1998). The SSQ asks the participant to rate the frequency of eight symptoms (items) of sleepiness on a 7-point scale, ranging from 1, "Not at all" to 7, "Most of the time" (Howard et al., 2014). Individual SSQ ratings are displayed Table 2. Each item was examined individually (out of 7), in addition to the SSQ global score (sum of all items, out of 56). Higher scores indicate greater frequency of sleepiness symptoms for all SSQ items.

2.2.2 | Driving impairment

Lane deviations, defined as at least two wheels crossing over the left or right lane markings (Anderson & Horne, 2013), were recorded during the drive by the driving instructor, and independently scored from the forward-facing camera by two scorers (A.C. and B.S.) blinded to condition/age group. Any lane deviation event that was identified by two out of three scorers (including the driving instructor assessments) was included in the final dataset. A near crash event occurred when the instructor had to intervene to maintain control of the vehicle. These metrics have been applied previously to indicate drowsy-related adverse driving outcomes (Cai et al., 2021; Lee et al., 2016).

2.2.3 | Oculography

Ocular metrics were recorded via the Seeing Machine's Driver Monitoring System (DMS). An eye blink was defined as the eye closing to below 50% (eye closing phase, start of blink), followed by a closure to <20% (eye "fully" closed), then reopening to at least 50% (reopening phase, end of blink) (Cai et al., 2021). Average blink duration (ms), number of long eye closures (blinks >500 ms), and the percentage of time the eyes were closed (<20%) per min (PERCLOS) were calculated as continuous variables and used as markers of physiological drowsiness (Cori et al., 2019; Dinges & Grace, 1998; Wierwille et al., 1994).

2.3 | Statistical analysis

For linear mixed models analyses, the 2 h drive data were binned into eight 15 min blocks for the KSS and LFA, and four 30 min blocks for the SSQ. For the predictive analyses, the blocks following a subjective sleepiness rating were used resulting in the final seven (out of eight) blocks for KSS and LFA, and three (out of four) blocks for SSQ.

To examine the impact of sleep loss and age on subjective sleepiness measures, linear mixed models (LMM) analysis was used. Fixed effects of condition, age group, and the interaction term were included in the model, with participant modelled as the random factor. For all LMM analyses, the covariance structure with the lowest Schwarz Bayesian Criterion (BIC) was used (Schwarz, 1978). To correct for multiple post-hoc comparisons, a false discovery rate (FDR) comparison was used to control for familywise error (Benjamini & Hochberg, 1995), with adjusted p values (p_{adj}) reported using the FDR "q" adjusted significance value. For the LMM analyses, transformations were applied to the data. For ease of interpretation, the LFA ratings were transformed using a reflect function, where a higher score indicates greater subjective sleepiness, in line with the other measures. Separate items of the SSQ were also transformed – SSQ2, SSQ5, SSQ6, and SSQ7 and SSQ Global score using a square root function, and SSQ3, SSQ4, and SSQ8 using a logarithm function to normalise data.

To examine the predictive capacity of subjective measures of sleepiness on continuous objective variables, generalised linear mixed model (GLMM) analysis was used. Subjective sleepiness ratings were predictors, and ocular metric/number of lane deviations as outcomes. For all GLMM analyses, the target distribution model and covariance structure that yielded that lowest Akaike's Information Criteria (AIC) was used (Casals et al., 2014).

To examine the predictive capacity of subjective measures of sleepiness on dichotomous driving variables (e.g., lane deviations, near crash events), binary logistic regression with receiver operating characteristic (ROC) curve analysis was used. Lane deviations were dichotomised by having classified a positive state if a lane deviation had occurred in that 15 min bin. Raw data were used for GLMM and binary logistic regression analyses. Optimal cut-off scores for each measure were determined using Youden's index (Youden, 1950), and associated odds ratios were calculated with Haldane-Anscombe correction (Lawson, 2004) and significance tested via Fisher's exact test. Where uncertainty around the true accuracy of the OR exists (e.g., high OR/wide 95% CI), we report only ORs that are significant (via Fisher's exact) and of moderate effect size (OR >3.47), and in the discussion report only the lower limit 95% CI. This ensures that we have confidence in observing a medium effect size, while being cautious on interpreting the large effect size. The χ^2 statistic and associated p value for pairwise comparisons assessed the relative performance of each subjective measure at correctly classifying whether a participant has a lane deviation or near crash event.

RStudio V1.1 (RStudio, PBC, Boston, MA, USA) was used to derive the ocular variables. IBM SPSS Statistics V27 (IBM Corp, Armonk, NY, USA) was used to run all statistical analyses and normality assumptions, and GraphPad Prism V9.0 (GraphPad Software, San Diego, California USA) was used to visualise data.

2.3.1 | Missing data

Fourteen drives were terminated due to the instructor deeming the participant too impaired to continue, resulting in non-random missing data. For the LMM analysis for KSS and LFA, there were approximately 6% of missing data, and approximately 7% of missing data for the SSQ. For predictive analyses, there were approximately 7% of missing data for the KSS and LFA, and approximately 11% of missing data for the SSQ. Lane deviations were scored for 64 out of 66 drives due to technological issues. Lastly, ocular data was not collected in two younger adults, and one older adult, due to the driver's face being out of frame.

2.3.2 | Power analysis

A comparable study (Shiferaw et al., 2018) had nine participants, with ~1800 data points entered in to the logistic regression model for sleep loss with an odds ratio of 3.2 and an alpha level of 0.05. A priori power calculations suggest that we would require a minimum of 58 data points to power the logistic regressions of the subjective measures to predict lane deviations. With 462 data points, we have >99% power to detect similar effects in both younger and older groups for all subjective measures.

3 | RESULTS

Our two age groups did not differ in ODI, daytime sleepiness, or sex distribution (p < 0.058), but did differ in age and driving experience (p < 0.001) (Table 1). For mean differences between the groups and conditions for objective measures of drowsiness (ocular and driving metrics) (Table 3). For detailed discussion of the results for these metrics, see Cai et al. (2021).

TABLE 3 Mean ± SEM for subjective and objective sleepiness in well-rested and sleep-deprived condition, for both age groups

		Well rested		Total sleep deprivation		p value		
Item	Description	YA	OA	YA	OA	Condition	Age	Condition* age
Subjective sleepiness measures								
KSS	How sleepy have you felt in the past 5 min (1–9)	3.43 ± 0.39	3.60 ± 0.42	7.11 ± 0.43	6.55 ± 0.31	<0.001	0.68	0.25
LFA	Likelihood of falling asleep in the next 5 min (1–5)	4.48 ± 0.17	4.74 ± 0.09	3.20 ± 0.21	3.89 ± 0.20	<0.001	0.007	0.20
SSQ1	Struggling to keep your eyes open (1–7)	1.62 ± 0.28	1.57 ± 0.19	4.17 ± 0.36	3.21 ± 0.50	<0.001	0.15	0.18
SSQ2	Vision becoming blurred (1–7)	1.43 ± 0.31	1.47 ± 0.15	3.16 ± 0.46	2.66 ± 0.41	<0.001	0.66	0.37
SSQ3	Nodding off to sleep (1–7)	1.08 ± 0.04	1.09 ± 0.04	3.04 ± 0.37	1.99 ± 0.36	<0.001	0.020	0.019
SSQ4	Difficulty keeping to the middle of the road (1–7)	1.39 ± 0.13	1.12 ± 0.08	3.22 ± 0.33	1.81 ± 0.26	<0.001	<0.001	0.026
SSQ5	Difficulty maintaining the correct speed (1–7)	2.25 ± 0.33	1.38 ± 0.11	3.43 ± 0.42	1.99 ± 0.27	0.001	0.002	0.34
SSQ6	Mind wandering to other things (1–7)	2.76 ± 0.27	1.76 ± 0.16	3.58 ± 0.37	2.37 ± 0.37	0.013	0.003	0.79
SSQ7	Reactions were slow (1–7)	1.44 ± 0.13	1.24 ± 0.10	3.59 ± 0.41	2.12 ± 0.27	<0.001	0.008	0.013
SSQ8	Head dropping down (1–7)	1.05 ± 0.03	1.03 ± 0.03	2.23 ± 0.36	1.55 ± 0.27	<0.001	0.045	0.08
SSQ Global (1–56)		13.01 ± 1.12	10.66 ± 0.58	26.38 ± 2.15	17.69 ± 2.43	<0.001	0.001	0.08
Driving performance outcomes								
Blink duration (ms)		163.21 ± 7.82	195.47 ± 22.5	240.66 ± 36.40	213.29 ± 30.2	0.003	0.92	0.038
Long eye closure rate/15 min		4.43 ± 1.33	5.05 ± 2.48	14.63 ± 4.81	7.20 ± 2.93	0.007	0.10	0.08
PERCLOS		3.17 ± 0.46	3.51 ± 0.70	5.48 ± 0.95	3.85 ± 0.70	0.003	0.44	0.033

Abbreviations: KSS, Karolinska sleepiness scale; LFA, likelihood of falling asleep scale; OA, older adults; PERCLOS, percentage of time eyes are closed >80%; SEM, standard error of the mean; SSQ, sleepiness symptoms questionnaire; YA, younger adults.

3.1 | The effect of sleep loss on subjective sleepiness

All subjective sleepiness measures (KSS, LFA, eight SSQ items and SSQ Global) significantly increased with sleep loss ($p < 0.013$). With the exception of the KSS, struggling to keep eyes open, and vision becoming blurred, all measures showed an effect of age, whereby sleepiness was higher in younger adults across both conditions ($p < 0.045$). See Figure 1 for KSS, LFA and SSQ and Figure 2 for individual SSQ items. All LMM results are shown in Table 3. Only nodding off to sleep, difficulty keeping to the middle of the road, and longer reactions times showed an interaction (condition*age), such that younger adults reported a greater increase in symptom frequency following sleep loss ($p < 0.026$, see Figure 2c, d, g).

3.2 | Near crash events in younger drivers

All subjective measures (apart from mind wandering to other things, $p = 0.389$) significantly predicted increased odds of a near crash event occurring ($OR = 1.46$–15.6), with the majority showing good to excellent accuracy ($AUC = 0.85$–0.96) (Table 4). Each one-point increase in difficulty keeping to the middle of the road was associated with the highest increased odds (15.5×, although we urge caution in interpretation of the actual OR due to the wide 95% CI) of a near crash event occurring in the next 30 minutes ($p = 0.006$) with excellent accuracy in predicting an event occurring ($AUC = 0.95$). Despite difficulty maintaining the correct speed and head dropping down being associated with a 1.7 and 2.5 (respectively) increased odds of a near crash event ($p < 0.020$), the accuracy for predicting a near-crash event was fair-to-poor (AUC <0.71). Figure 3 shows the AUC for each measure/outcome, for each age group. There was no significant difference in the strength of the prediction between the KSS and LFA ($\chi^2 = 0.9$, $p = 0.36$), and no significant difference in accuracy between SSQ ratings that were good-to-excellent (AUC ≥0.8) predictors of near crash events ($\chi^2 = 0.01$–3.01, $p_{adj} > 0.069$).

For the best predictors, the optimal cut-point for predicting a near-crash event was 24 for SSQ global score (100% sensitivity, 88% specificity, >7× increased odds (lower limit reported)), 7 for KSS (100% sensitivity, 72% specificity, >3.5 increased odds [lower limit]), and 3 for both difficulty keeping to the middle of the lane (100% sensitivity, 83% specificity, >4.7 increased odds (lower limit)), and reactions were slow (88% sensitivity, 83% specificity, with >4.7 increased odds [lower limit]). Optimal cut-off scores for all subjective ratings, sensitivity and specificity values, and associated odds ratios are shown in Table 5. Cut-off points maximising sensitivity and specificity are provided as Supplementary Data S2.

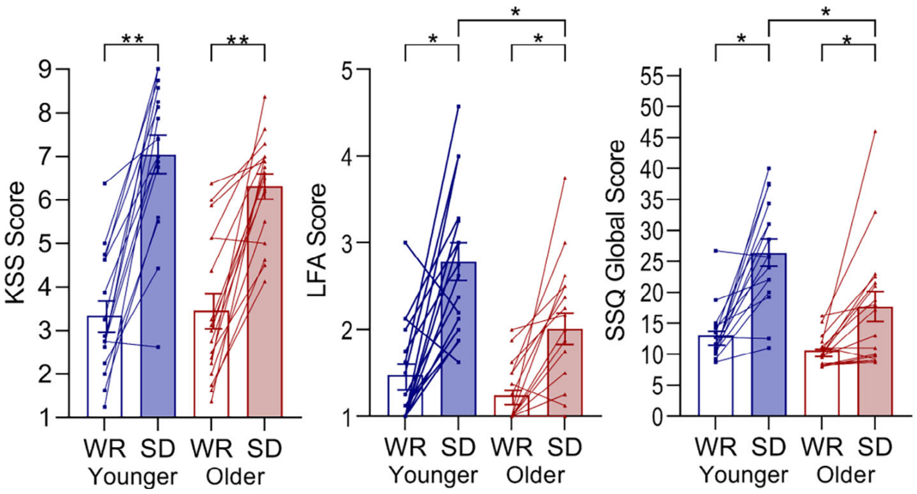


FIGURE 1 Individual and group data across the entire drive showing effect of condition, age, and interaction effects for the Karolinska sleepiness scale (KSS) score, likelihood of falling asleep (LFA) score, and sleepiness symptoms questionnaire (SSQ) global score. WR, well rested; SD, sleep deprived. $^{**}p_{adj} < 0.001$, $^{*}p_{adj} < 0.05$. False discovery rate corrections were used

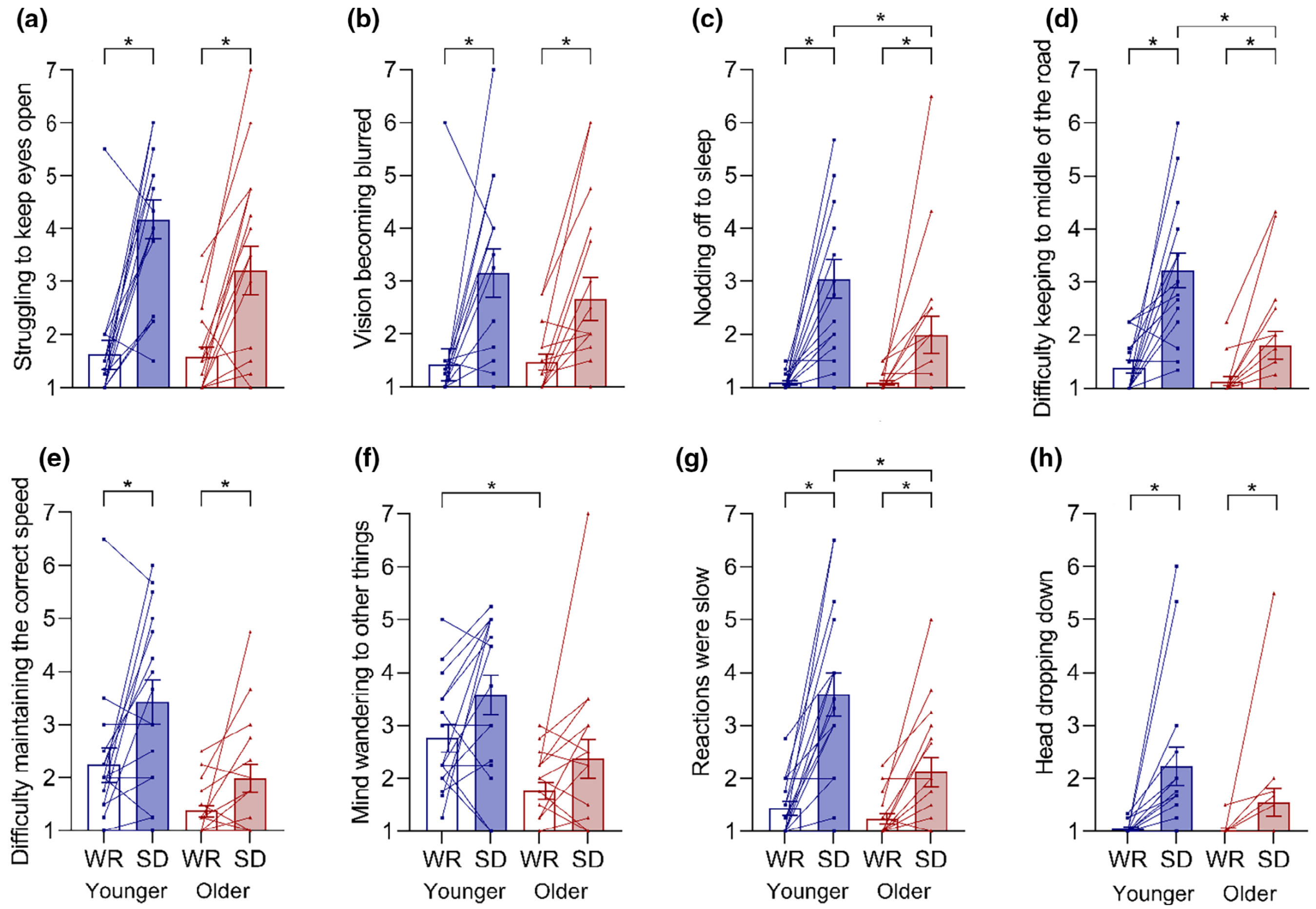


FIGURE 2 Individual and group data for each individual sleepiness symptoms questionnaire (SSQ) item: (a) SSQ1; (b) SSQ2; (c) SSQ3; (d) SSQ4; (e) SSQ5; (f) SSQ6; (g) SSQ7, and (h) SSQ8 scores across the entire drive showing effect of condition, age, and interaction effect. SD, sleep deprived; WR, well rested. $^{**}p_{adj} < 0.001$, $^{*}p_{adj} < 0.05$. False discovery rate corrections were used

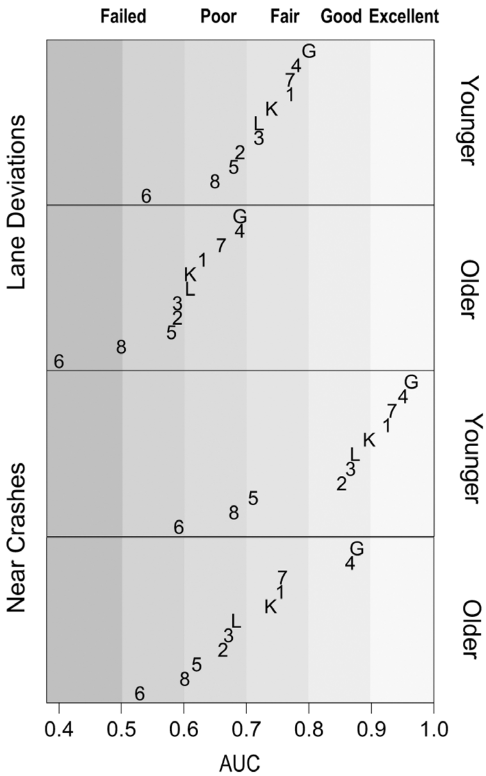
3.3 | Near crash events in older adults

In contrast to younger drivers, only the LFA and difficulty keeping to the middle of the road was associated with significantly increased odds of an impending near crash event (Table 4). However, while ROC curve analysis showed that LFA accurately predicted the event occurring ($AUC = 0.87$, $p = 0.029$), difficulty keeping to the middle of the road did not ($AUC = 0.75$, $p = 0.135$). Despite not being associated with increased odds of a near crash event in older adults ($p = 0.074$), the KSS had good accuracy in predicting an actual event ($AUC = 0.88$, $p = 0.025$) (Figure 3). For those subjective ratings that accurately predicted a near crash in both younger and older drivers (e.g., KSS and LFA), age had no impact on the strength of this prediction ($p > 0.79$). For older adults, the optimal cut-point for the KSS was 7 with 100% sensitivity and 70% specificity. Although difficulty keeping to the middle of the road was also significant at a cut-point of 2, we urge caution

TABLE 4 Odds ratios and AUC values for near crash events and lane deviations in younger and older adults

		Younger adults				Older adults			
Item	Descriptor	OR [95%CI]	*p*-value	AUC [95%CI]	*p*-value	OR [95%CI]	*p*-value	AUC [95%CI]	*p*-value
Near crash events									
KSS		2.82 [1.41, 5.61]	0.003	0.90 [0.83,0.96]	<0.001	2.76 [0.91, 8.41]	0.074	0.88 [0.76, 0.99]	0.025
LFA		3.11 [1.74, 5.53]	<0.001	0.87 [0.79, 0.95]	<0.001	2.86 [1.18, 6.92]	0.020	0.87 [0.72, 1.00]	0.029
SSQ1	Struggling to keep eyes open	3.02 [1.55, 5.92]	0.001	0.93 [0.86, 0.99]	<0.001	1.47 [0.85, 2.55]	0.173	0.76 [0.57, 0.94]	0.130
SSQ2	Vision becoming blurred	2.15 [1.38, 3.34]	0.001	0.85 [0.67, 1.00]	0.001	1.48 [0.79, 2.76]	0.221	0.62 [0.26, 0.98]	0.477
SSQ3	Nodding off to sleep	2.51 [1.47, 4.31]	0.001	0.87 [0.72, 1.00]	0.001	1.51 [0.82, 2.75]	0.184	0.74 [0.42, 1.00]	0.161
SSQ4	Difficulty keeping to the middle of the road	15.59 [2.21, 110.03]	0.006	0.95 [0.90, 1.00]	<0.001	2.76 [1.17, 6.51]	0.021	0.75 [0.42, 1.00]	0.135
SSQ5	Difficulty maintaining the correct speed	1.70 [1.09, 2.65]	0.020	0.71 [0.49, 0.93]	0.052	1.97 [0.75, 5.19]	0.170	0.67 [0.33,1.00]	0.312
SSQ6	Mind wandering to other things	1.28 [0.73, 2.23]	0.389	0.59 [0.35, 0.84]	0.424	0.98 [0.38, 2.54]	0.965	0.53 [0.22, 0.84]	0.861
SSQ7	Reactions were slow	4.62 [1.95, 10.90]	<0.001	0.93 [0.85, 1.00]	<0.001	1.67 [0.76, 3.70]	0.202	0.68 [0.35, 1.00]	0.279
SSQ8	Head dropping down	2.52 [1.28, 4.96]	0.007	0.68 [0.45,0.91]	0.097	1.16 [0.35, 3.82]	0.804	0.60 [0.25, 0.96]	0.550
SSQ Global		1.46 [1.14, 1.88]	0.003	0.96 [0.92, 1.00]	<0.001	1.07 [0.97, 1.17]	0.186	0.66 [0.32, 1.00]	0.338
Lane deviations									
KSS		1.53 [1.33, 1.77]	<0.001	0.77 [0.70, 0.84]	<0.001	1.35 [1.17, 1.57]	<0.001	0.69 [0.62, 0.76]	<0.001
LFA		3.29 [2.24, 4.86]	<0.001	0.77 [0.70, 0.85]	<0.001	1.91 [1.36, 2.68]	<0.001	0.69 [0.61, 0.77]	<0.001
SSQ1	Struggling to keep eyes open	2.00 [1.40, 2.87]	<0.001	0.78 [0.68, 0.89]	<0.001	1.24 [0.97, 1.58]	0.090	0.61 [0.50, 0.73]	0.064
SSQ2	Vision becoming blurred	1.51 [1.06, 2.15]	0.023	0.65 [0.53, 0.78]	0.021	1.30 [0.96, 1.76]	0.086	0.66 [0.55, 0.77]	0.010
SSQ3	Nodding off to sleep	2.62 [1.41, 4.87]	0.002	0.74 [0.63, 0.86]	<0.001	1.14 [0.78, 1.66]	0.501	0.59 [0.47, 0.72]	0.126
SSQ4	Difficulty keeping to the middle of the road	2.59 [1.48, 4.56]	0.001	0.72 [0.60, 0.84]	0.001	1.80 [1.03, 3.15]	0.039	0.63 [0.51, 0.75]	0.039
SSQ5	Difficulty maintaining the correct speed	1.68 [1.16, 2.43]	0.006	0.68 [0.56, 0.80]	0.006	1.22 [0.77, 1.94]	0.396	0.58 [0.46, 0.70]	0.183
SSQ6	Mind wandering to other things	1.12 [0.81, 1.57]	0.491	0.54 [0.41, 0.68]	0.510	0.66 [0.42, 1.03]	0.066	0.40 [0.28, 0.52]	0.093
SSQ7	Reactions were slow	2.21 [1.34, 3.64]	0.002	0.72 [0.61, 0.84]	0.001	1.11 [0.73, 1.69]	0.627	0.59 [0.47, 0.70]	0.167
SSQ8	Head dropping down	6.71 [1.84, 24.44]	0.004	0.69 [0.56, 0.81]	0.005	0.79 [0.40, 1.53]	0.477	0.50 [0.38, 0.62]	0.932
SSQ Global		1.17 [1.08, 1.26]	<0.001	0.80 [0.70, 0.90]	<0.001	1.02 [0.97, 1.08]	0.426	0.61 [0.49, 0.72]	0.085

Abbreviations: AUC, area under the curve; CI, confidence interval; KSS, Karolinska sleepiness scale; LFA, likelihood of falling asleep; OR, odds ratio; SSQ, sleepiness symptoms questionnaire.



Outcome		Description
K	KSS	How sleepy did you feel in the past 5 minutes?
L	LFA	How likely are you to fall asleep in the next few minutes?
1	SSQ1	Struggle to keep eyes open
2	SSQ2	Vision becoming blurred
3	SSQ3	Nodding off to sleep
4	SSQ4	Difficulty keeping to the middle of the road
5	SSQ5	Difficulty maintaining the correct speed
6	SSQ6	Mind wandering to other things
7	SSQ7	Reactions were slow
8	SSQ8	Head dropping down
G	SSQ Global	Summed SSQ 1-8 score

FIGURE 3 Area Under the Curve values for lane deviations and near crashes for younger and older drivers. KSS, Karolinska Sleepiness Scale; LFA, Likelihood of Falling Asleep scale; SSQ, Sleepiness Symptoms Questionnaire

around the true accuracy of the OR (see methods) (Table 5) (and S1 for cut-off points maximising sensitivity and specificity).

3.4 | Lane deviations in younger adults

Ten out of 11 subjective measures (except mind wandering) significantly predicted increased odds of a lane deviation event in the next 15 or 30 min, with medium to fair accuracy ($AUC = 0.65–0.80$), as shown in Table 4 and Figure 3. While struggling to keep the eyes open and global SSQ were the strongest predictor of lane deviations, they were not significantly more accurate than any other measure except for vision becoming blurred (AUC difference $= 0.13$, $\chi^2 = 7.29$, $p_{adj} = 0.036$, AUC difference $= -0.14$, $\chi^2 = 10.72$, $p_{adj} = 0.013$, respectively). The optimal cut-points for these predictors were 19 for SSQ Global (60% sensitivity, 83% specificity) with 7.5× increased odds, and 2 for struggling to keep eyes open (86% sensitivity, 60% specificity) with 8.8× increased odds of a lane deviation in the next 15–30 min. Optimal cut-off scores with sensitivity and specificity values and associated odds ratios are shown in Table 5.

3.5 | Lane deviations in older adults

In contrast to the younger drivers, only three out of 11 subjective measures significantly predicted increased odds of a lane deviation event in the subsequent 15 or 30 minutes. Higher ratings of the KSS, LFA, and difficulty keeping to the middle of the road significantly predicted increased odds of lane deviations ($OR = 1.35–3.22$), although the accuracy was poor ($AUC = 0.63–0.69$) (Table 4, Figure 3). There were also no significant differences in accuracy for these three significant predictors within the older driver group ($p_{adj} > 0.75$).

For those subjective ratings that accurately predicted an adverse event in both younger and older drivers (e.g., KSS and LFA), age had no impact on the strength of the prediction ($p = 0.094–0.12$). The optimal cut-points for significant predictors were 4 for KSS (98% sensitivity, 40% specificity) with >4.9× increased odds (lower limit reported), 4 for LFA (72% sensitivity, 64% specificity), and 2 for difficulty keeping to the middle of the road (38% sensitivity, 88% specificity), each with 4× increased odds. See Table 5. Cut-off points maximising sensitivity and specificity are provided as Supplementary Data S2.

3.6 | Subjective sleepiness and prediction of ocular indices of drowsiness: Effect of age

Nine out of 11 subjective measures significantly predicted increased relative risk of long eye closures in the subsequent 15 or 30 minutes in younger adults ($B = 0.03–0.52$, $p < 0.008$). Only the LFA and mind wandering did not significantly predict long eye closures occurring in the next 15 minutes ($p > 0.064$). For older adults, seven out of 11 subjective measures predicted long eye closures ($B = 0.04–0.47$). The KSS, LFA, difficulty maintaining the correct speed, and reactions were slow were not significant predictors of long eye closures ($p > 0.12$). Risk ratios and beta coefficients for younger and older groups are shown in Table 6. Of note, difficulty keeping to the middle of the road appeared to be a stronger predictor of long eye closures for older

TABLE 5 Optimal subjective sleepiness measure cut-off scores and odds ratios for predicting near crashes and lane deviations in younger and older adults

Item	Description	Threshold	Sens.	Spec.	OR [95% CI]	*p*	Threshold	Sens.	Spec.	OR [95% CI]	*p*
Near Crashes		*Younger Adults*					*Older Adults*				
KSS	Subjective sleepiness	7	1.00	0.72	27.70 [3.5, 219.8][ab]	<0.001	7	1.00	0.70	9.20 [1.0, 83.8][a]	0.035
LFA	Likelihood of falling asleep	3	0.90	0.77	29.46 [3.6, 238.9][b]	<0.001	2	1.00	0.56	*n.s*[a]	*n.s*
SSQ1	Struggle to keep eyes open	4	1.00	0.83	40.15 [4.7, 345.3][ab]	<0.001	2	1.00	0.53	*n.s*[a]	*n.s*
SSQ2	Vision blurred	4	0.75	0.91	31.50 [5.2, 191.7][b]	<0.001	6	0.33	0.96	*n.s*	*n.s*
SSQ3	Nodding off to sleep	3	0.88	0.90	62.00 [6.6, 580.2][b]	<0.001	2	0.67	0.80	*n.s*	*n.s*
SSQ4	Difficulty keeping to middle of road	3	1.00	0.83	40.15 [4.7, 345.3][ab]	<0.001	2	0.67	0.80	12.00 [1.2, 121.9][b]	0.033
SSQ5	Difficulty maintaining correct speed	5	0.63	0.86	8.86 [1.8, 43.5]	0.012	2	0.67	0.61	*n.s*	*n.s*
SSQ6	Mind wandering	4	0.57	0.65	*n.s*	*n.s*	2	0.67	0.42	*n.s*	*n.s*
SSQ7	Reactions are slow	3	0.88	0.83	33.25 [3.7, 295.9][b]	<0.001	2	0.67	0.65	*n.s*	*n.s*
SSQ8	Head dropping	2	0.50	0.80	*n.s*	*n.s*	2	0.33	0.88	*n.s*	*n.s*
SSQ Global score		24	1.00	0.88	62.00 [7.0, 549.1][ab]	<0.001	16	0.67	0.75	*n.s*	*n.s*
Lane Deviations		*Younger Adults*					*Older Adults*				
KSS	Subjective sleepiness	7	0.63	0.85	9.67 [4.7, 19.6]	<0.001	4	0.98	0.40	36.00 [4.9, 266.2][b]	<0.001
LFA	Likelihood of falling asleep	3	0.56	0.90	11.85 [5.4, 25.8]	<0.001	4	0.72	0.64	*n.s*	*n.s*
SSQ1	Struggle to keep eyes open	2	0.86	0.60	8.82 [2.9, 27.3]	<0.001	2	0.62	0.58	*n.s*	*n.s*
SSQ2	Vision blurred	2	0.54	0.74	3.35 [1.3, 8.7]	0.019	2	0.74	0.61	4.33 [1.7, 10.8]	0.001
SSQ3	Nodding off to sleep	2	0.60	0.88	11.10 [3.5, 35.2]	<0.001	2	0.35	0.84	2.95 [1.1, 7.8]	0.041
SSQ4	Difficulty keeping to middle of road	3	0.46	0.91	8.00 [2.3, 27.3]	<0.001	2	0.38	0.88	4.33 [1.6, 11.9]	0.005
SSQ5	Difficulty maintaining correct speed	3	0.51	0.76	3.39 [1.3, 9.0]	0.017	2	0.53	0.67	*n.s*	*n.s*
SSQ6	Mind wandering	4	0.41	0.67	*n.s*	*n.s*	6	0.00	0.95	*n.s*[a]	*n.s*
SSQ7	Reactions are slow	2	0.74	0.62	4.69 [1.8, 12.5]	0.003	2	0.50	0.72	2.56 [1.1, 6.1]	0.046
SSQ8	Head dropping	2	0.43	0.93	9.75 [2.5, 37.7]	<0.001	2	0.12	0.88	*n.s*	*n.s*
SSQ Global score		19	0.60	0.83	7.50 [2.6, 21.6]	<0.001	15	0.41	0.80	2.75 [1.1, 6.9]	0.034

Note: Dichotomous OR – change in odds of a subsequent severe/moderate event occurring when the predictor value is above the identified threshold, compared with when below.

[a]Odds ratio calculated with Haldane-Anscombe correction and significance via Fisher's exact test.

[b]Odds ratio is inflated due to low *n* in the false-negatives section of the contingency table. Interpretation/reporting of the lower bound 95% confidence interval is recommended. Where the lower limit <3.47, confidence around a medium effect size cannot be met (See methods).

drivers relative to younger drivers as reflected by the higher RR and non-overlap in the 90% confidence intervals (Table 6).

Blink duration and PERCLOS yielded similar results to long eye closures, where younger adults had more significant predictors of increase blink duration or PERCLOS than older adults. Mind wandering was also a significant predictor for increased physiological drowsiness for older adults, but not younger adults. This is provided as Supplementary Data (S3 and S4, respectively).

4 | DISCUSSION

This study examined the association between subjective sleepiness and drowsy driving outcomes in younger and older adults. All subjective sleepiness reports were significantly higher following sleep deprivation for both younger and older drivers, with 100% of younger and 94% of older drivers reporting an increase in the severity of sleepiness symptoms following sleep loss. Self-reported sleepiness (KSS, LFA) and sleepiness symptoms (SSQ) were strong predictors of driving impairment in the next 15–30 min in both younger and older adults, with many symptoms, particularly those involving the eyes, having high to excellent accuracy in predicting a severe event (e.g., near crash event). Accuracy was lower for predicting impairment that was less severe however (e.g., lane deviation), and fewer symptoms accurately predicted outcomes in older drivers relative to the younger drivers. These data suggest that drivers are largely aware of sleepiness, but these symptoms do differ between young and older drivers, and in relation to the severity of the outcome.

Following sleep loss, KSS increased, on average from a 3 ("alert") to 7 ("sleepy but no effort to keep awake"). For both age groups, a KSS of 7 predicted severe impairment (near crashes) with perfect sensitivity and a false-positive rate of 28%–30%. For moderate impairment (lane deviations) the optimal threshold was the same for younger drivers (KSS >7), yet for older drivers much earlier signs of sleepiness (KSS >4 ["fairly alert"]) were more strongly associated with greater risk of lane deviations; although we note that, sensitivity was 98%, and specificity was low (40%). Despite this, as both KSS and LFA were strong predictors for early (lane deviations) and late (near crashes) impairment in both age groups, our data suggest that drivers should routinely ask themselves how sleepy they feel, and how likely they might fall asleep in the next few minutes, particularly during long drives and/or after driving following a night of insufficient sleep (Anderson et al., 2018; Hallvig et al., 2014). Our findings are consistent with previous simulated and naturalistic studies examining the predictive capacity of the KSS for lane deviations (Anderson et al., 2023; Anund et al., 2017; Hallvig et al., 2014; Philip et al., 2005; Williamson et al., 2014), and driving metrics indicating severe impairment, such as crash events (Ingre et al., 2006; Williamson et al., 2014) and emergency brake procedures (Anderson et al., 2023). Although these studies collectively cover a wide age range (18–60) within their samples, our study builds on these data by systematically examining the impact of age on the predictive value of subjective ratings on drowsy driving outcomes.

Subjective sleepiness symptoms significantly predicted (ocular derived) drowsiness, including increased blink duration, PERCLOS, and long eye closures in both age groups. Ocular metrics are highly reflective of physiological drowsiness, and have been shown to increase with sleep loss (Anderson et al., 2013), and during on-road driving tasks when the driver is drowsy (Lee et al., 2016; Shiferaw et al., 2018). We have previously demonstrated that younger adults exhibit increased PERCLOS, blink duration, and long eye closures following sleep loss compared with older adults (Cai et al., 2021). While the KSS and LFA did not predict ocular-defined drowsiness in the older drivers, SSQ symptoms specifically related to drowsiness did (i.e., struggling to keep eyes open, vision becoming blurred, nodding off to sleep, head dropping). Although the mechanism surrounding this is unclear, these data suggest that using actual sleepiness symptoms in education campaigns around signs of sleepiness may be more beneficial to a wider demographic of drivers. In support of this, mind wandering to other things was a significant predictor of physiological drowsiness for older, but not younger drivers. Mind wandering is defined as the change of endogenous attention from the required task, shifting to task-unrelated thoughts (Smallwood & Schooler, 2006), and has been shown to be impacted by both sleep loss (Jubera-Garcia et al., 2021) and ageing (Maillet & Rajah, 2013). One possible explanation for our findings may relate to possible age-related differences in the trajectory of drowsiness. For instance, mind wandering is related to external distractibility (Unsworth & McMillan, 2014), and we have previously suggested (in younger adults) that distractibility is an earlier manifestation of sleep loss (Anderson et al., 2010; Anderson & Horne, 2006; Lee et al., 2015). Due to the differential vulnerability of younger and older adults to sleep loss (Adam et al., 2006; Duffy et al., 2009), one night without sleep may cause more end-state drowsiness symptoms in younger drivers (e.g., struggling to keep eyes open, head nodding), yet result in a lesser degree of drowsiness symptoms in older adults (e.g., mind wandering). Future studies examining the trajectory of drowsiness in younger and older adults exposed to sleep loss, and across a wide range of measures, would provide much needed insight into this observation.

Our findings should be considered with several limitations/caveats in mind. First, our study was conducted on a closed track loop in a vehicle with the driving instructor and study technician. Despite no communication between the study team and the participant during the drive, the presence of the study team may have increased driver alertness and hypervigilance of awareness of alertness/sleepiness, compared with a non-observed drive (Lee et al., 2016; Shiferaw et al., 2018). Moreover, this environment may not perfectly mirror real-world driving, where individuals may feel the need to continue driving to reach their destination and ignore/diminish their subjective ratings of sleepiness. Second, participants were asked to verbally rate their level of sleepiness and the likelihood of falling asleep every 15 min during the drive, and took a short (1-minute) break every 30 min to administer the SSQ, which may induce a brief alerting effect lasting up to 2 minutes (Schmidt et al., 2011); although this is likely comparable between conditions and would presumably lessen (not

TABLE 6 Coefficient *B*, risk ratios, and *p*-values for long eye closures in younger and older adults

		Younger adults			Older adults		
Item	Descriptor	Coefficient B	RR [95% CI]	*p*-value	Coefficient B	RR [95% CI]	*p*-value
KSS		0.06	1.06 [0.03, 0.10]	0.001	0.01	1.01 [−0.02, 0.03]	0.516
LFA		0.07	1.07 [−0.004, 0.14]	0.064	0.02	1.02 [−0.05, 0.09]	0.583
SSQ1	Struggling to keep your eyes open	0.10	1.11 [0.04, 0.16]	0.001	0.11	1.11 [0.03, 0.18]	0.005
SSQ2	Vision becoming blurred	0.10	1.10 [0.03, 0.16]	0.008	0.12	1.13 [0.02, 0.22]	0.017
SSQ3	Nodding off to sleep	0.27	1.31 [0.15, 0.39]	<0.001	0.16	1.18 [0.04, 0.29]	0.012
SSQ4	Difficulty keeping to the middle of the road	0.17	1.18 [0.06, 0.28]	0.002	0.47	1.61 [0.34, 0.61]	<0.001
SSQ5	Difficulty maintaining the correct speed	0.13	1.14 [0.04, 0.22]	0.006	0.09	1.09 [−0.02, 0.20]	0.115
SSQ6	Mind wandering to other things	−0.02	0.98 [−0.11, 0.07]	0.674	0.09	1.09 [0.02, 0.16]	0.016
SSQ7	Reactions were slow	0.19	1.21 [0.11, 0.27]	<0.001	0.07	1.07 [−0.03, 0.17]	0.173
SSQ8	Head dropping down	0.52	1.68 [0.40, 0.63]	<0.001	0.32	1.37 [0.15, 0.48]	<0.001
SSQ Global		0.03	1.03 [0.02, 0.05]	<0.001	0.04	1.04 [0.02, 0.06]	<0.001

Abbreviations: CI, confidence interval; KSS, Karolinska Sleepiness Scale; LFA, Likelihood of Falling Asleep; RR, risk ratio; SSQ, Sleepiness Symptoms Questionnaire.

strengthen) the predictive accuracy. Third, as described previously (Cai et al., 2021), the older drivers had fewer near crash events compared with the younger drivers, which may be responsible for the non-significant predictive results for older adults in relation to near crash events. This (reduced power) was not the case for physiological drowsiness measures, however, where a higher number of events were observed for both age groups following sleep loss, and somewhat consistently, older drivers still had fewer subjective signals that were associated with elevated risk of drowsiness. Fourth, we had stringent criteria for healthy participants with no prior or current sleep, medical or psychological disorders, and thus our results should be interpreted with a healthy population in mind. Given older adults may be more likely to experience sleep and/or medical issues that may exacerbate sleepiness and poor driving outcomes, future work should systematically examine the extent to which this may alter the capacity for some drivers to be aware of sleepiness and subsequent poor driving outcomes. Finally, although our study uses individual level data to determine the accuracy of predicting poor driving outcomes based on subjective ratings, we are unable to ascertain (due to low *n*) whether some individuals contribute more or less to the group-level accuracy parameters. For instance, while 100% of near-crash events were preceded by a KSS above 7 or frequent struggling to keep the eyes open, other measures exhibited some false-positives and/or false-negatives. As we were unable to determine whether some individuals were consistently less aware of sleepiness (i.e., consistently having false-positives/false-negatives), future research should unravel which individuals (if any) are less able to accurately report sleepiness, and why. Despite these limitations, our study methodology was as close to real-world driving conditions as safely possible, providing the highest level of evidence for subjective and objective sleepiness following total sleep loss. We also met the "gold-standard" criteria set by a systematic review on subjective sleepiness and objective outcomes (Cai et al., 2021), such that we conducted a controlled real driving study, utilising the KSS and predictive analysis for both physiological sleepiness and driving impairment. We also ensured our groups were balanced for sex, accounting for any potential sex differences to sleep loss (Vidafar et al., 2018). Finally, we included a wide range of subjective measures in our analyses. While the KSS is most used in driving studies examining the association between subjective and objective sleepiness (Alvaro et al., 2016; Cai et al., 2021; Filtness et al., 2012; Kosmadopoulos et al., 2017; Williamson et al., 2014), our study includes the LFA, which is highly predictive of near crash events in both older and younger adults, and the SSQ which has been shown in younger drivers to predict adverse driving outcomes in both simulator (Howard et al., 2014) and on-road (Anderson et al., 2023) studies. Alongside the high face validity of the scales we used, and ease of understanding/accessibility for the majority of the driving population, our data suggest that the KSS, LFA, and SSQ may be useful for educational campaigns on a group level.

To summarise, we replicate and expand on previous studies showing that young drivers can accurately predict physiological drowsiness and driving impairment and extend these findings to older drivers. Although older adults reported less overall subjective sleepiness and show less effect of sleep loss, drowsiness-related symptoms can be used to predict earlier signs of driving impairment such as lane deviations and long eye closure. We show that the profile of subjective sleepiness symptoms in predicting adverse drowsy driving outcomes differs between younger and older adults, suggesting a possible need for tailored interventions and educational campaigns for older and younger drivers to help reduce drowsiness related motor vehicle crashes, and associated serious injuries and fatalities.

AUTHOR CONTRIBUTIONS

Anna W.T. Cai: Data curation; formal analysis; investigation; methodology; writing – original draft. **Jessica E Manousakis:** Conceptualization; formal analysis; methodology; project administration; supervision; writing – review and editing. **Bikram Singh:** Data curation; formal analysis; investigation; methodology; writing – review and editing. **Elly Francis-Pester:** Data curation; formal analysis; methodology; writing – review and editing. **Jonny Kuo:** Writing – review and editing. **Katherine J Jeppe:** Data curation; formal analysis; resources; writing – review and editing. **Shantha M.W. Rajaratnam:** Funding acquisition; writing – review and editing. **Michael G Lenné:** Funding acquisition; investigation; methodology; writing – review and editing. **Mark E Howard:** Conceptualization; funding acquisition; investigation; methodology; supervision; writing – review and editing. **Clare Anderson:** Conceptualization; formal analysis; funding acquisition; investigation; methodology; project administration; supervision; writing – review and editing.

ACKNOWLEDGEMENTS

We thank the study participants for their time and dedication to the research. We also thank the technicians, staff and students at the Monash University Sleep and Circadian Medicine Laboratory and METEC driver training centre who contributed to data collection. We specifically acknowledge the contribution of Robert Western and Darren Smillie for their diligence in accompanying each drive and ensuring the safety of our participants, Kathryn Collier for her assistance and support in the scheduling of track sessions, and Dr Bei Bei for her oversight of psychological assessments. We additionally acknowledge the contribution of Seeing Machines Ltd in the provision of the instrumented test vehicle, Driver Monitoring System, and associated technical support. Open access publishing facilitated by Monash University, as part of the Wiley - Monash University agreement via the Council of Australian University Librarians.

FUNDING INFORMATION

The study was supported by an ARC Linkage grant awarded to C.A. (LP160101193) and additional cash funding from Seeing Machines Ltd.

CONFLICT OF INTEREST STATEMENT

Jonny Kuo and Michael Lenne are employees of Seeing Machines Ltd. While the remaining authors report no conflicts of interest related to the results reported in this paper, in the interest of full disclosure: Anna Cai received Scholarship funding from the Cooperative Research Centre for Alertness Safety and Productivity. Jessica Manousakis has received contract research support from VicRoads/The Victorian Department of Transport and the Australian Automobile Association. Shantha Rajaratnam is the Director of the Sleep Health Foundation, and has received grants from Vanda Pharmaceuticals, Philips Respironics, Cephalon, Rio Tinto, BHP Billiton, and Shell. He also has received equipment support and consultancy fees through his institution from Optalert, Compumedics, Teva Pharmaceuticals, and Circadian Therapeutics. He was the Program Leader for the Cooperative Research Centre for Alertness Safety and Productivity. Mark Howard has received research funding from the Cooperative Research Centre for Alertness Safety and Productivity, contract research support from Vicroads, Shell International, Rio Tinto and equipment support for research from Optalert and Seeing Machines. He has served as a consultant for Vicroads, the National Transport Commission, Victoria Police and Bus Safety Victoria and received lecturing fees from TEVA Pharmaceuticals, Biogen, and Astra-Zeneca. Clare Anderson has received a research award/prize from Sanofi-Aventis; contract research support from VicRoads, Rio Tinto Coal Australia, National Transport Commission, Tontine/Pacific Brands, and AAA Foundation; industry funding through ARC Linkage scheme with Seeing Machines and Cogstate Ltd; and lecturing fees from Brown Medical School/Rhode Island Hospital, Ausmed, Healthmed, and TEVA Pharmaceuticals; and reimbursements for conference travel expenses from Philips Healthcare. In addition, she has served as a consultant to the Rail, Bus and Tram Union, the Transport Accident Commission (TAC), the National Transportation Committee (NTC), VicRoads, and Melius Consulting. She has also served as an expert witness and/or consultant in relation to fatigue and drowsy driving, and was a Theme Leader in the Cooperative Research Centre for Alertness, Safety and Productivity at the time of this work.

DATA AVAILABILITY STATEMENT

Data will be uploaded to an online repository (BRIDGES) and available on request in writing to the corresponding author.

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How to cite this article: Cai, A. W. T., Manousakis, J. E., Singh, B., Francis-Pester, E., Kuo, J., Jeppe, K. J., Rajaratnam, S. M. W., Lenné, M. G., Howard, M. E., & Anderson, C. (2023). Subjective awareness of sleepiness while driving in younger and older adults. *Journal of Sleep Research*, e13933. https://doi.org/10.1111/jsr.13933