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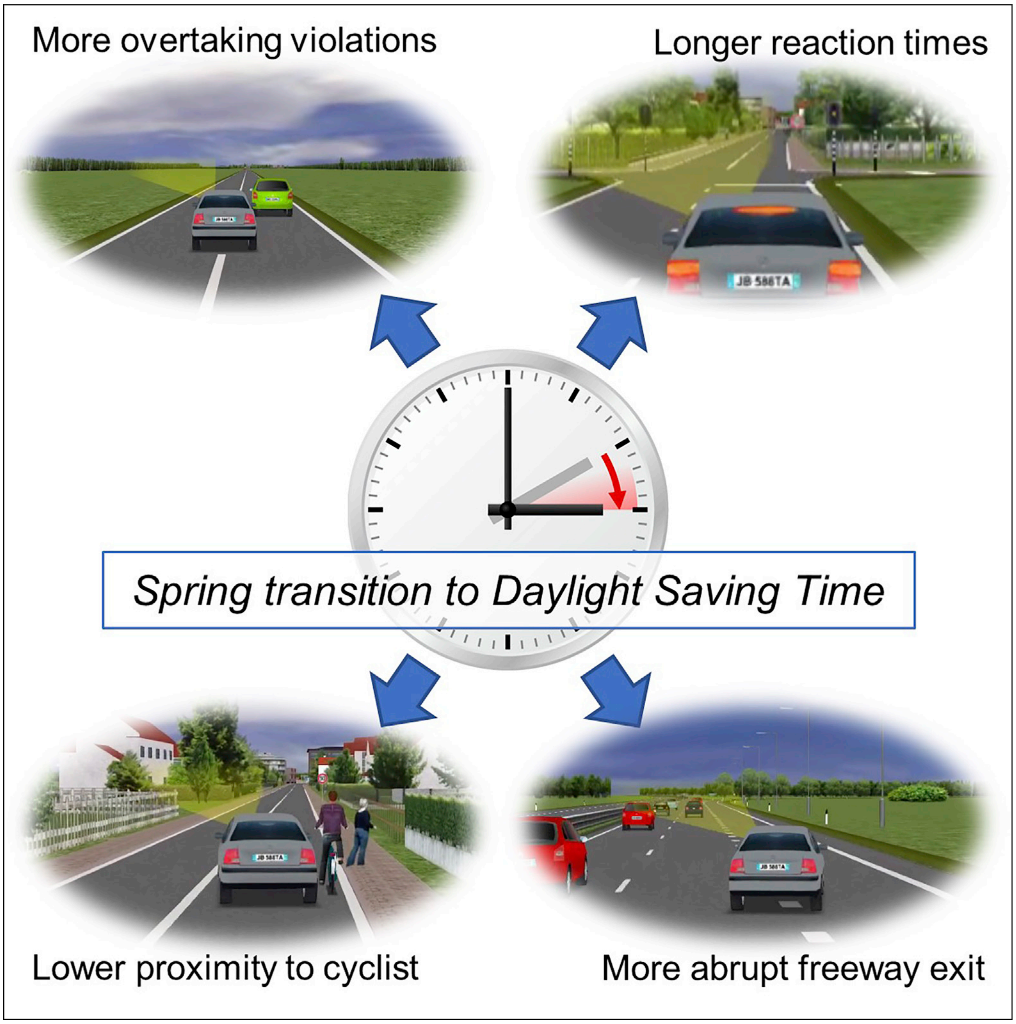
Driving simulator performance worsens after the Spring transition to Daylight Saving Time



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Highlights

A simulator was used to study the effects of DST transition on driving behavior

Several driving variables were negatively affected by DST transition

These included reaction times, situation awareness and risk behavior

DST-related circadian desynchrony is likely to result in driving impairment

Orsini et al., iScience *25*, 104666
July 15, 2022
https://doi.org/10.1016/j.isci.2022.104666

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Driving simulator performance worsens after the Spring transition to Daylight Saving Time

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SUMMARY

Circadian desynchrony and sleep deprivation related to the Spring transition to Daylight Saving Time (DST) have been associated with several unfavorable outcomes, including an increase in road traffic accidents. As previous work has mainly focused on analyzing historical crash/hospitalization data, there is virtually no literature investigating the effects of DST on specific driving performance indicators. Here, the effect of the Spring transition to DST on driving performance was investigated by means of a driving simulator experiment, in which participants completed two trials (one week distance, same time and day of the week) on exactly the same simulated route, the second trial taking place in the week after the transition to DST. Results were compared to those of a control group (who also underwent two trials, both before the DST transition), and documented significant worsening of driving performance after DST, as measured by a comprehensive set of simulator-derived indices.

INTRODUCTION

The Spring transition to Daylight Saving Time (DST) has been associated with an increase in overall mortality (Poteser and Moshammer, 2020) and higher autopsy rates (Lindenberger et al., 2019). As most forms of desynchrony between the endogenous circadian clock and the natural environment, DST has been associated with unfavorable health outcomes, including reduced sleep duration and impaired sleep quality (Lahti et al., 2006; Rishi et al., 2020), cardiovascular accidents (Janszky et al., 2012; Janszky and Ljung, 2008; Kirchberger et al., 2015) and the likelihood of reaccessing Accident & Emergency services within 96 h of a first visit (Ferrazzi et al., 2018). However, a significant proportion of the recorded, excess fatalities are believed to relate to work and road traffic accidents (RTAs), and thus to major trauma. Depending on the type of registries analyzed and the time frame and type of analyses, the estimated DST-related increase in the incidence of RTAs varies from 6 to 50% (Coren, 1996; Fritz et al., 2020; Nohl et al., 2021; Robb and Barnes, 2018). An increase in fatal RTAs has been documented on the Monday following the Spring shift (Varughese and Allen, 2001), and the influence of DST is extremely likely to exceed the short post-DST phase on which most studies have focused (Pfaff and Weberz, 1982; Robb and Barnes, 2018). Driving is a complex function, involving a wide and intricate combination of cognitive abilities (Ledger et al., 2019), including vigilance, attention, inhibition, executive function, memory and visuospatial skills, which are affected to different extents by desynchrony and/or sleep deprivation (Demos et al., 2016; Killgore and Weber, 2014; Lowe et al., 2017). Chronotype, i.e. one's natural inclination to be more or less active in different parts of the 24-h day (morning vs. evening individuals, Roenneberg et al., 2003) might also modulate the effects of DST on cognitive performance. Finally, there is virtually no information in the literature as to the effects of DST-related misalignment on specific components of the driving experience. Here we assessed driving by means of a simulator in 23 young males (24.1 $\pm$ 3.6 years) before and after the enforcement of DST in the Spring of 2021 (one week distance between the two evaluations, same day of the week). To control for learning/familiarization effects, 22 males of comparable age (24.1 $\pm$ 2.6 years) were also studied twice, on both occasions in the two weeks immediately prior to the last one before the enforcement of DST (one week distance, same day).

RESULTS AND DISCUSSION

The sociodemographic and sleep characteristics of the two groups (Table S1) were compared by MANOVA, which did not show significant differences in age, driving experience (years or average

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https://doi.org/10.1016/j.isci.2022.104666

Table 1. Contingency table of overtaking decisions for the experimental group in each trial

Experimental group		Trial 2: No overtake	Trial 2: Overtake	Total
Trial 1	No overtake	14	6	20
	Overtake	0	3	3
Total		14	9	23

kilometers driven per year), daytime sleepiness (Epworth Sleepiness Scale; ESS), night sleep quality (Pittsburgh Sleep Quality Index; PSQI), chronotype (midsleep during work days or free days). As, when considering individual ANOVAs, midsleep during free days was borderline significant [$F(1,43) = 3.6$, $p = 0.065$], this was included as a covariate in subsequent analyses.

In each experimental trial, participants were asked to drive an 11.5 km route, which included both rural and urban roads, built to mimic the route commuters would travel to reach the city of Padua from the East. Along their route, drivers encountered several different driving situations, which are fully described in the next paragraphs and in the STAR Methods.

Overtaking violation during a car-following task

After about 3 km from the start of the route, drivers found themselves behind a vehicle on a long, straight stretch of a rural road, with a speed limit of 80 km/h. The leading vehicle was programmed to maintain a variable speed between 60 and 90 km/h, and to turn right on a secondary road after 1.2 km; the behavior of the leading vehicle was identical for all participants. The centerline was continuous and there was light oncoming traffic in the opposite lane.

During the experiment, some drivers followed the leading vehicle throughout the road stretch, whereas others opted for an overtaking maneuver, despite the presence of the continuous centerline. To analyze this behavior, contingency tables were built (Tables 1 and 2), counting how many overtaking maneuvers were performed in each trial, by group [control group (CG) versus experimental group (EG)]. The drivers' behavior was similar in the two groups in trial 1, with 9% of the drivers opting for the overtaking maneuver. During trial 2, the CG participants maintained a similar behavior (Table 2), while a relevant proportion of the EG participants (39%) overtook the leading vehicle, with six individuals in this group performing the maneuver only in the second trial (Table 1). The behavior of the EG was statistically different in the two trials ($p = 0.016$; McNemar mid-*p* test). In addition, the two groups exhibited significantly different behavior in trial 2 ($p = 0.035$; Fisher's exact test). When considering the chronotype of the EG participants, it was observed that morning type participants maintained a similar behavior in the two trials (2 overtakes out of 11 morning type participants in the first one, four in the second one, with no statistical significance). By contrast, only one out of 12 evening type participants overtook the leading vehicle in the first trial, while four more did so in the second one, which was borderline significant ($p = 0.063$; McNemar mid-*p* test). No effect of chronotype was observed for CG participants.

These results indicate a potential impact of the DST transition on risk-taking behavior, with evening type EG participants being more prone to commit overtaking violations in the post-DST trial compared to both their own pre-DST trial and to controls. This is consistent with several published studies linking sleep loss/circadian desynchrony with risk-taking behavior (Alvaro et al., 2018; Fritz et al., 2020; Goel et al., 2009; Killgore, 2015; Womack et al., 2013). In addition, road safety literature identifies risk-taking behavior as a mediating

Table 2. Contingency table of overtaking decisions for the control group in each trial

Control group		Trial 2: No overtake	Trial 2: Overtake	Total
Trial 1	No overtake	20	1	21
	Overtake	0	1	1
Total		20	2	22

variable between sleep quality and crash involvement (Shams et al., 2020), and several studies have documented correlations between sleepiness/fatigue and traffic violations (Mahajan et al., 2019; Naderi et al., 2018; Useche et al., 2017).

Reaction time at a signalized intersection

Drivers reached a signalized intersection at the end of the straight rural road. The traffic light was set to turn yellow when the driver's time-to-intersection (calculated as the ratio between the distance to the intersection stop line and current speed) was less than 5 s. The duration of the yellow light phase was set at 4 s, which implies that participants were outside the boundary of the 'dilemma zone' (Zhang et al., 2014) and thus required to stop the vehicle in order not to run into a red light. The drivers' reaction time was computed as the interval between the onset of the yellow light and the start of braking. A participant in the control group was excluded from the analysis because he was already braking before the onset of yellow light during trial 1.

Repeated measures ANOVA was carried out considering Trial as a main factor (2 levels, trial 1 and trial 2), Group as a between factor (2 levels, CG and EG), and midsleep during free days as a covariate. Here, the main focus was not the difference in Trial or Group effects, but rather their interaction, as this would highlight a difference in behavior related to the DST transition. Interestingly, the interaction Trial*Group was significant [$F(1,41) = 4.8$, $p = 0.033$, $\eta_p^2 = 0.11$] with reaction times increasing in EG participants in the second trial and decreasing in CG participants (Figure 1A). In absolute terms, there was a 0.74 s difference between groups in trial 2, which is comparable to the reduction in performance observed in drivers under the influence of alcohol in other driving simulator studies (Yadav et al., 2020; Yadav and Velaga, 2019). No significant effect of the covariate was documented.

The tendency of CG drivers to reduce their reaction times in the second trial run is most likely related to the fact that the route was identical in the two trials, thus participants were 'expecting' the traffic light to turn yellow and were ready to intervene. However, the EG group showed the opposite trend in the post-DST trial. Here, the effect of sleep deprivation/circadian desynchrony was most likely twofold, as it increased reaction times, in line with published studies (Choudhary et al., 2016; Gillberg and Åkerstedt, 1998; Van Den Berg and Neely, 2006), and it reduced the ability to remember the experience of the first trial (Goel et al., 2009; Harrison and Horne, 2000) and implement changes in behavior based on recently acquired information (Aidman et al., 2019; Goel et al., 2009; Harrison and Horne, 1999; Herscovitch et al., 1980; Hsieh et al., 2007).

Bicycle overtaking

Further along their route, drivers encountered a cyclist on a straight urban road, with a continuous centerline and a speed limit of 50 km/h. The simulator-controlled cyclist kept a constant speed of 8 m/s (28.8 km/h), and a constant lateral distance of 0.15 m from the roadside. Additional details are provided in Figure S1A. There was no oncoming traffic or any other cars in front of the cyclist. If the drivers did not overtake, they had to follow the cyclist for about 750 m. After that, the cyclist would make a right turn on a secondary road. However, in the vast majority of the runs (86 out of 90), participants overtook the cyclist.

A series of repeated measures ANOVAs with the same factors considered in the previous paragraph were performed. Here, the analysis included several variables, chosen in accordance with a previous study on a similar scenario (Rossi et al., 2021a): the minimum time-to-collision (TTC, i.e. the ratio between distance and speed difference between the driver and the cyclist, which can be computed regardless of whether the overtaking maneuver is performed), rear and lateral passing distances and mean passing speed.

In most cases, the interaction Trial*Group was not significant, and neither was the effect of the covariate. However, a borderline significant interaction was observed for TTC [$F(1,42) = 3.6$, $p = 0.064$, $\eta_p^2 = 0.08$]. As shown in Figure 1B, the two groups showed opposite tendencies, with the CG increasing absolute TTC in the second trial, and the EG decreasing it (i.e. worsening their performance in terms of safety).

Although the overtaking maneuver was carried out with similar speed and passing distance in both groups, the reduction in TTC of the EG participants in trial 2 is concerning from a safety point of view, because it poses a serious hazard to a vulnerable road user. This behavior after the DST transition could be either intentionally riskier (as observed for the overtaking violation during the car-following task) or because of a reduced situation awareness (Wijayanto et al., 2016, 2021), which would have lead participants to react

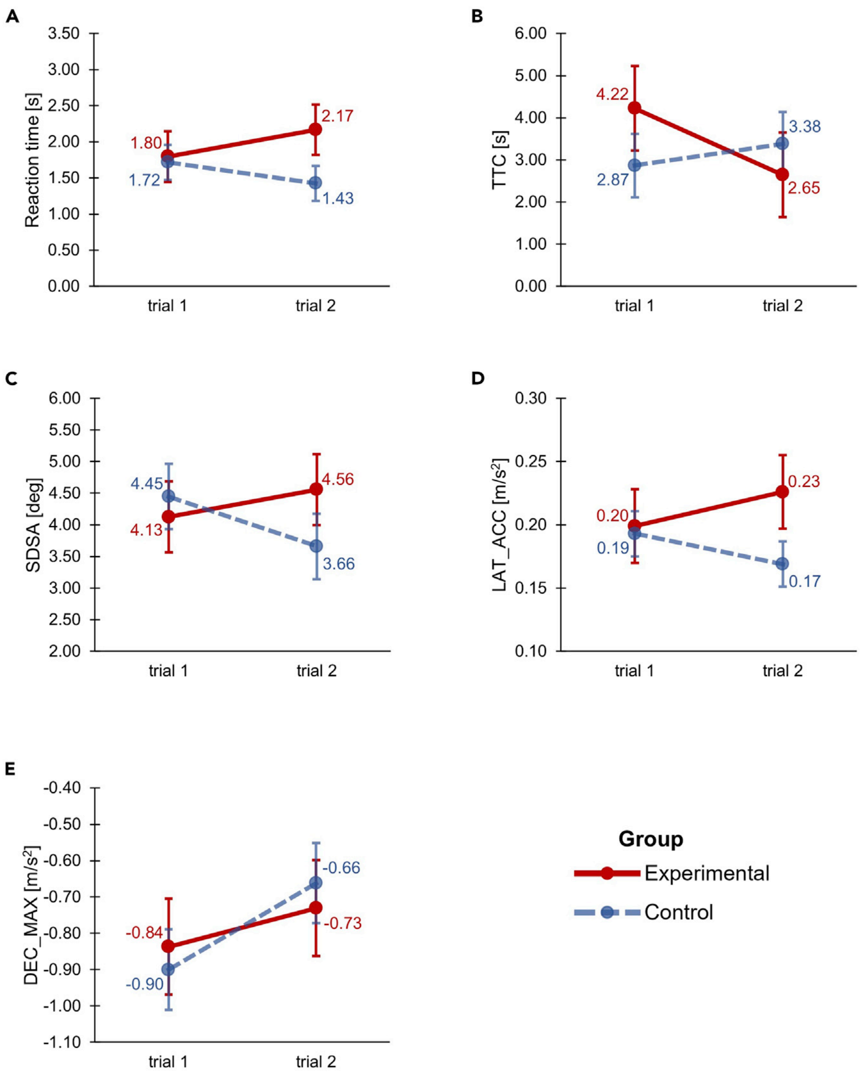

Figure 1. Visual representation of repeated measures ANOVA results

Dots: mean fitted values; bars: 95% confidence intervals. Effects of Trial and Group on: (A) reaction time at the signalized intersection; (B) time-to-collision during bicycle overtake (TTC); (C) standard deviation of steering angle during the freeway exit maneuver (SDSA); (D) mean lateral acceleration during the freeway exit maneuver (LAT_ACC); (E) maximum deceleration during the freeway exit maneuver (DEC_MAX).

and begin the overtaking maneuver later compared to their first trial, resulting in a lower minimum TTC to the cyclist.

Freeway exit

Toward the end of the route, drivers entered a 2.6 km two-lane freeway stretch, at the end of which they were required to perform an exit maneuver on a 300 m long deceleration lane with a parallel layout. Additional details are provided in Figure S1B.

Another set of repeated measures ANOVAs was carried out to investigate the exit maneuver. The variables chosen, again based on previous studies (Orsini et al., 2021), included speed, deceleration, trajectory, and lateral control indices.

Significant effects of the interaction Trial*Group were observed for the lateral control variables calculated in the deceleration lane: the SD of the steering angle (SDSA), [$F(1,42) = 6.3$, $p = 0.016$, $\eta_p^2 = 0.13$], and the mean lateral acceleration (LAT_ACC) [$F(1,42) = 4.2$, $p = 0.047$, $\eta_p^2 = 0.09$], with opposite tendencies in the two groups (Figures 1C and 1D). As the two dependent variables were significantly correlated [$r(88) = 0.86$, $p < 0.001$], the consistent trend observed was expected and it strengthens the findings on lateral control. In further detail, the EG drivers exhibited a decrease in their driving safety performance in trial 2, executing more abrupt exit maneuvers. In trial 2, SDSA in EG drivers was about 25% higher compared to CG drivers, which is a difference in performance comparable to that between individuals driving under the influence of alcohol (blood alcohol concentration = 0.08%) and their control trial (Yadav and Velaga, 2021).

A borderline significant effect of the interaction was observed for the maximum deceleration during the exit maneuver (DEC_MAX) [$F(1,42) = 3.7$, $p = 0.063$, $\eta_p^2 = 0.08$], again indicating a worse safety performance in trial 2 for the EG (Figure 1E).

Speed and trajectory during the exit maneuver were not statistically different in the two groups. However, the EG tended to be more abrupt, both in the change of direction and in the deceleration. As for the bicycle overtaking, this could be related to a reduced situation awareness after the DST transition, with the driver realizing the need to exit the freeway later, and thus operating in a more abrupt fashion in order to keep the desired exit speed and trajectory. Alternatively, this could be also due to an increased risk-taking attitude, with increased lateral and longitudinal acceleration thresholds being considered appropriate for the maneuver. Finally, and as observed for the reaction time at the signalized intersection, CG drivers improved their safety performance in trial 2, most likely in relation to previous experience (trial 1), and were therefore able to adopt a gentler driving style in their exit maneuver.

Conclusion

This study investigated the effect of the Spring transition to DST on driving behavior, by use of a driving simulator experiment including a comprehensive set of driving situations. This allowed us to assess the impact of the transition to DST on road safety in a situation-based, extremely detailed and precise fashion.

Several driving variables were negatively affected, with safety being compromised in the post-DST simulation: more overtaking violations, longer reaction times at a signalized intersection, lower TTC on overtaking a cyclist, worse lateral control and greater deceleration during the exit maneuver from a freeway. Since the experimental procedure was carried out over multiple days, the findings confirm that the effects of the transition to DST persist over several days, as observed in other studies (Alencar et al., 2017; Ferrazzi et al., 2018; Roenneberg et al., 2019a, 2019b).

DST-related sleep deprivation/circadian desynchrony is likely to result in this impairment in driving performance by favoring riskier behavior, impinging on reaction times and situation awareness, and on the ability to modify behavior based on recently acquired information.

Limitations of the study

Our study has some limitations, which will be addressed in future research. Firstly, because of the strict time constraints of the experimental design, the study involved only young male Italian drivers, not allowing investigation of potentially relevant factors such as age, sex, culture and location, together with pertinent weather conditions. In addition, more sophisticated dynamic analyses could be performed on some of the driving situations presented, possibly shedding additional light on the microscopic impact of DST on driving performance. It would also be interesting to compare objective driving indicators with subjective performance perception, to understand whether drivers are actually aware of any driving difficulties after DST, and their potential safety implications. Besides, our experiment had a relatively short duration, preventing the analysis of the effect of the Spring transition to DST on driving fatigue, which is also relevant to road safety and worthy of further study. Finally, the acquisition of daily sleep-wake diaries and/or actigraphic recordings may also be worthy to assess the direct impact of sleep duration and sleep quality on post-DST driving performance impairment.

STAR★METHODS

Detailed methods are provided in the online version of this paper and include the following:

- KEY RESOURCES TABLE
- RESOURCE AVAILABILITY

- Lead contact
- Materials availability
- Data and code availability
- EXPERIMENTAL MODEL AND SUBJECT DETAILS
  - Participants
- METHOD DETAILS
  - Apparatus
  - Experimental design and procedure
  - Baseline sleep-wake assessment
  - Driving scenario
- QUANTIFICATION AND STATISTICAL ANALYSIS
  - Robustness analysis

SUPPLEMENTAL INFORMATION

Supplemental information can be found online at https://doi.org/10.1016/j.isci.2022.104666.

ACKNOWLEDGMENTS

L.Z. was supported by a Supporting TAlent in ReSearch @University of Padova (STARS - Call 2019) to S.M. The authors are grateful to the study participants for their collaboration.

AUTHOR CONTRIBUTIONS

Conceptualization, S.M., R.R., R.C., F.O., and L.Z.; Methodology, S.M., R.R., R.C., F.O., and L.Z.; Software, F.O.; Formal Analysis, F.O.; Validation, R.R.; Investigation, F.O., L.Z.; Resources, S.M., R.R.; Data Curation, F.O. and L.Z.; Writing – Original Draft, F.O., S.M., and R.C.; Writing – Review & Editing, S.M., R.R., R.C., L.Z., and F.O.; Visualization, F.O.; Supervision, S.M., R.R., and R.C.; Funding Acquisition, S.M. and R.R.

DECLARATION OF INTERESTS

The authors declare no competing interests.

Received: February 23, 2022
Revised: June 10, 2022
Accepted: June 19, 2022
Published: July 15, 2022

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STAR★METHODS

KEY RESOURCES TABLE

REAGENT or RESOURCE	SOURCE	IDENTIFIER
Software and alghorithms		
MATLAB (version R2021a)	Mathworks	https://www.mathworks.com/products/matlab/RRID:SCR_001622
JASP (version 0.14)	JASP Team	https://jasp-stats.org/RRID: SCR_015823
R (version 4.0.4)	R Development Core Team	http://www.r-project.org/RRID: SCR_001905

RESOURCE AVAILABILITY

Lead contact

Further information and requests for resources, data and materials should be directed to and will be fulfilled by the lead contact, Sara Montagnese.

Materials availability

This study did not generate new unique reagents.

Data and code availability

- Driving simulator data reported in this paper will be shared by the lead contact upon request.
- This paper does not report original code.
- Any additional information required to reanalyze the data reported in this paper is available from the lead contact upon request.

EXPERIMENTAL MODEL AND SUBJECT DETAILS

Participants

Forty-eight active drivers, all young males (24.1 ± 3.6 yrs, range 19–31) were recruited; half of them were included in the experimental group (EG), the other half in the control group (CG). Three of them (one from the EG, two from the CG) dropped out of the experiment prior to completing both trials. None of the participants had previous experience with driving simulators. Additional inclusion criteria were normal or corrected to normal vision, at least 1 year of driving experience with a full license, and average annual mileage of at least 1,000. We expressly selected young male drivers because, even if minimal, previous studies have shown different effects of sleep deprivation on cognitive performance in males compared to females (Alhola and Polo-Kantola, 2007; Alvaro et al., 2018).

Participants had no significant diseases, no diagnosed sleep disorders and were not on psychoactive medication or medication known to affect sleep and/or reaction times.

All participants were naïve to the aim of the experiment and received monetary compensation for completing the experiment. The study was conducted in compliance with the Code of Ethics of the World Medical Association (Declaration of Helsinki) (World Medical Association, 2013). The experimental protocol was approved by the Ethics Committee for the Psychological Research of the University of Padova (amendment to IRB N 3024 06/06/2019); written, informed consent was obtained from all participants prior to the study.

The demographic features of the participants are reported in Table S1.

METHOD DETAILS

Apparatus

The 2 degrees-of-freedom dynamic driving simulator at the Mobility & Behavior Research Center (MoBe) of the University of Padova was used for this experiment. The simulation system has been previously used and validated in a wide range of studies on traffic safety (Gastaldi et al., 2021; Orsini et al., 2019; Rossi et al., 2014, 2020). The simulator (Jentig 60, STSoftware®, Groningen, the Netherlands) encompasses a cockpit, an adjustable car seat, a dynamic force-feedback steering wheel, three pedals, and a manual gearbox. The virtual scenario was displayed on five 60-inch full-HD screens, creating a 330° by 45° field of view. The sound system consisted of three front speakers, two rear speakers, and a subwoofer. Thirty-one vehicle kinematic variables were collected by the simulator at a 50Hz sampling frequency.

Experimental design and procedure

Participants were randomly assigned to either the experimental (EG) or the control group (CG). Each subject participated in two trials, separated by exactly one week. The first trial of the EG took place in the week preceding the switch to DST (March 22nd – 25th, 2021), the second one in the week after it (March 29th – April 1st, 2021). The first trial of the CG took place three weeks before the switch to DST (March 8th – 11th, 2021) and the second one in the following week (March 15th – 18th, 2021). In both groups, the trials were performed in the morning, from Monday to Thursday. Six trials were carried out each day, the first starting at 08:00 a.m. and the last at 10:30 a.m.. The two trials of each participant took place at the same time on the same weekday. Due to the strict time constraints of such experimental design, the EG could encompass a maximum of 24 drivers.

In the days prior to the first trial, participants were asked to fill in questionnaires on their sociodemographic, sleep quality, sleep timing and chronotype features (*vide infra*).

On the day of the first trial, participants conducted a 5-minute training driving session to familiarize with the simulator. They then received the instructions for the experiment, which consisted of simply trying to drive as they would normally do in the real world, and following road signs for the city of Padova. The second trial was carried out with exactly the same procedure, except for the training session.

The duration of the driving test was approximately 15 minutes. An average temperature between 20 °C and 22 °C was maintained in the laboratory.

Baseline sleep-wake assessment

The following questionnaires were administered:

The Sleep Timing Sleep Quality Screening (STSQS) questionnaire (Montagnese et al., 2009). This provides an overall assessment of sleep quality rated on a 0–10 visual-analogue scale (0 = worst, 10 = best sleep ever) and allows collection of information on habitual sleep timing (i.e., bedtime, try to sleep time, sleep latency, wake up and get up time).

The Pittsburgh Sleep Quality Index (PSQI) (Buysse et al., 1989; Curcio et al., 2013). Responses to 19 questions are used to generate seven components, each of which is scored from zero (best) to three (worst). These component scores are then summated to provide the total PSQI score (range: 0–21); scores of >5 identify 'poor sleepers' (Buysse et al., 1989).

The Epworth Sleepiness Scale (ESS) (Johns, 1991; Vignatelli et al., 2003). Subjects rate their likelihood of 'dozing off' in eight different day-time situations, on a scale of zero (unlikely) to three (very likely). The component scores are summated to provide a total score (range: 0–24); scores of ≥11 indicate excessive daytime sleepiness (Johns, 1991).

The self-morningness/eveningness (Self-ME) questionnaire (Turco et al., 2015). This is a single-question assessment of chronotype through which participants qualify themselves as definitely morning, morning, evening or definitely evening types. For purposes of this study and for power reasons, participants were then grouped as definitely morning and morning (and qualified as morning) and evening and definitely evening (and qualified as evening).

The ultra-Short version of the Munich ChronoType Questionnaire (μMCTQ) (Ghotbi et al., 2020). This is an adaptation of the MCTQ (Roenneberg et al., 2003) from 17 to 6 essential questions, allowing for a quick assessment of midsleep (i.e. the midpoint, expressed as clock time, between sleep onset and sleep offset on free and work/study days), social jetlag (in this instance, the uncorrected difference between midsleep on free and work/study days) and sleep duration.

Driving scenario

The driving scenario consisted of a route of about 11,5 km, encompassing both rural and urban sections, and including signalized, unsignalized and roundabout intersections, and a freeway stretch, all in cloudy weather. The same route had been utilized in previous studies investigating the effect of in-vehicle visual and auditory cues on driving behavior (Orsini et al., 2021; Rossi et al., 2021a, 2021b). The route includes a wide range of driving situations, which are relevant to road safety, and have been extensively studied in the literature: car-following task (Ranney, 1999), braking on yellow onset at a signalized intersection (Zhang et al., 2014), bicycle overtaking (Dozza et al., 2016), freeway exit maneuver (Calvi et al., 2012).

The geometrical details of the urban road where the bicycle overtaking scenario took place are shown in Figure S1A, and those of the freeway exit maneuver in Figure S1B.

The route was identical in the two trials.

QUANTIFICATION AND STATISTICAL ANALYSIS

Continuous dependent variables were analyzed by repeated measures ANOVA, with Trial as a main factor, Group as a between factor and midsleep during free days as a covariate. Separate analyses were performed for each continuous dependent variable and included an estimation of the effect size (η_p^2). As a rule of thumb, η_p^2 indicates a small effect if it is between 0.01 and 0.06, a medium effect if it is between 0.06 and 0.14, and a large effect if it is greater than 0.14 (Cohen, 1988). Confidence intervals in Figure 1 were computed as in Morey (2008).

For each continuous dependent variable, the assumption of normality was checked by QQ plot diagnostics and the Shapiro-Wilk test. Although ANOVA is generally considered robust to normality violations (Blanca et al., 2017), the sample size of each group was relatively small, therefore, a specific investigation on the robustness to outliers was carried out for all dependent variables that did not satisfy the assumption of normality. The details of such investigation, which confirmed robustness to outliers, are reported here below in the section "robustness analysis".

Since one of the dependent variables analyzed (overtaking decision during the car-following task) was categorical, contingency tables were built. When analyzing the effect of the factor Trial for a given Group (or sub-group, as in the case of evening type participants within the EG), data were treated as paired binomial values (please refer to Table 1 and Table 2), thus the McNemar test was utilised (McNemar, 1947). Since in our contingency tables the total number of values in the discordant cells was lower than 25, the mid-*p* version of the test was used. This is suggested as a compromise between overly conservative exact methods and the classical asymptotic method that violates the nominal level (Fagerland et al., 2013; Pembury Smith and Ruxton, 2020). When analyzing the effect of the factor Group for a given Trial, data were treated as independent binomial values; here the Fisher exact test was used as an alternative to the Chi-squared test for small samples (Bewick et al., 2004).

The procedure of pre-processing raw simulator data end extracting dependent variable values was performed with MATLAB. Subsequent statistical analyses were performed with the JASP statistical software (JASP Team, 2020; Love et al., 2019) and R. Significance level was set at $\alpha = 0.05$; p-values below 0.075 were qualified as borderline.

Robustness analysis

The assumption of normality for repeated measures ANOVAs was verified by QQ plot diagnostics and the Shapiro-Wilk test for each of the five continuous dependent variables analyzed (i.e. RT, TTC, SDSA, LAT_ACC, DEC_MAX).

The QQ plots (Figure S2) showed no macroscopic deviation from normality for any design cell. For the variables TTC, SDSA and LAT_ACC, a small number of outliers deviated from the diagonal line. Due to the relatively small sample size within each cell, the results of the Shapiro-Wilk test in some of these cells rejected the assumption of normality. In-depth analysis of such outliers showed that they were anomalous data only from a statistical standpoint. From a physical and practical perspective, they were plausible values, and thus not the result of aberrant/erratic driving or simulator malfunction.

To assess whether such outliers had any significant impact on the repeated measures ANOVAs, a robustness analysis was carried out, by removing them from the dataset and replicating the ANOVAs. For the TTC variable, 6 outliers (4 in the CG, 2 in the EG) were removed using the boxplot method (Tukey, 1977), with $k = 1.5$ (Figure S3B). After their removal, the Shapiro-Wilk test was non significant in all cells. The interaction Trial*Group was significant [$F(1,36) = 4.7$, $p = 0.037$, $\eta_p^2 = 0.12$]. For the SDSA variable, 5 outliers (3 in the CG, 2 in the EG) were removed using the boxplot method, with $k = 1.5$ (Figure S3C). After their removal, the Shapiro-Wilk test was non significant in all cells. The interaction Trial*Group was significant [$F(1,37) = 7.9$, $p = 0.008$, $\eta_p^2 = 0.18$]. For the LAT_ACC variable, 2 outliers (1 in the CG, 1 in the EG) were removed using the boxplot method, with $k = 1.5$ (Figure S3D). After their removal, the Shapiro-Wilk test was non significant in all cells. The interaction Trial*Group was borderline significant [$F(1,40) = 3.4$, $p = 0.074$, $\eta_p^2 = 0.08$]. None of the outliers was an "extreme" point (i.e. $k > 3$, Tukey, 1977). The outliers did not have any relevant impact on the SDSA variable; the removal of 6 outliers in the analysis of TTC changed the Trial*Group interaction from borderline significant to significant, and the removal of 2 outliers in the analysis of LAT_ACC changed the same interaction from significant to borderline significant. Thus all outliers were kept in the main analyses because:

- There were no physical grounds to justify their exclusion from the dataset;
- They did not impinge on the robustness of repeated measures ANOVAs, as their removal did not result in relevant changes to statistical significance.