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Evaluating sleep deprivation and time-of-day influences on crash avoidance maneuvers of young motorcyclists using a dynamic simulator

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Abstract

Introduction: Motorcyclists are particularly at risk of being injured when involved in a road traffic accident. To avoid such crashes, emergency braking and/or swerving maneuvers are frequently performed. The recent development of dynamic motorcycle simulators may allow to study the influences of various disturbance factors such as sleep deprivation (SD) and time-of-day (TOD) in safe conditions.

Methods: 12 young healthy males took part in 8 tests sessions at 06:00 h, 10:00 h, 14:00 h, 18:00 h after a night with or without sleep, in a random order. Participants had to perform an emergency braking and a swerving maneuver, both realized at 20 and 40 kph on a motorcycle dynamic simulator. For each task, the total distance/time necessary to perform the maneuver was recorded. Additional analysis was conducted on reaction and execution distance/time (considered as explanatory variables).

Results: Both crash avoidance maneuvers (emergency braking and swerving) were affected by increased speed, resulting in longer time and distance at 40 kph than at 20 kph. Emergency braking was mainly influenced by sleep deprivation, which significantly increased the total distance necessary to stop at 40 kph (+1.57 m; + 20%; $p < 0.01$). These impaired performances can be linked to an increase in reaction time (+21%; $p < 0.01$). Considering the swerving maneuver, TOD and SD influences remained limited. TOD only influenced the reaction time/distance measured at 40 kph with poorer performance in the early morning (+ 30% at 06:00 h vs 18:00 h; $p < 0.05$).

Discussion: Our results confirm that crash avoidance capabilities of young motorcyclists were influenced by the lack of sleep, mainly because of increased reaction times. More complex tasks (swerving maneuver) remained mostly unchanged in this paradigm.

Practical Applications: Prevention campaigns should focus on the dangers of motorcycling while sleepy. Motorcycling simulators can be used to sensitize safely with sleep deprivation and time-of-day influences.

Keywords: time-of-day, sleep deprivation, motorcycle dynamic simulator, emergency braking, swerving.

1. Introduction

Powered Two-Wheeler (PTW) riders are particularly at risk of being seriously injured or killed when involved in a road traffic accident. Although PTWs make up a small proportion of circulating vehicles in most countries (3-15%), PTW riders contribute to nearly 15-20% of all road deaths worldwide (European Commission, 2018; ONISR, 2019; NHTSA, 2019). The fatality rate (number of fatal accidents when accounting for per vehicle mile traveled) is significantly higher for PTW riders than for car drivers. This related increased risk is 27-fold in the United States (NHTSA, 2019), 20-fold in Europe (ONISR, 2019), and 29-fold in Australia (Haworth & Mulvihill, 2005). Even if PTW riding was considered a recreational activity in the last decades, Day et al. (2013) claimed that PTWs would be an integral part of the global transport future. The current trends confirm that PTWs are increasingly used for commuting (in particular to avoid traffic congestion in dense urban areas) and even for work purposes (e.g., taxi, delivery; de Rome et al., 2018; Wu et al., 2018; Möller et al., 2020). This may raise attention to their crash contributing factors.

Various studies based on epidemiological data have been conducted to identify associated risk factors in PTW safety. Regarding behavioral aspects, age (21-30 years), gender (male), experience (poor), absence of helmet and/or protective clothes, speeding, and blood alcohol concentration are highly related to crash occurrence and severity (Vlahogianni et al., 2012; de Rome et al., 2018; Wu et al., 2018; Wali et al., 2018, 2019). However, the results of these retrospective studies remained limited to the a posteriori available data. Other potential risk factors (such as fatigue and sleepiness) may thus be under-estimated since they are rarely taken into account in road accident reports, in particular regarding PTW crashes (Wu et al., 2018). For example, despite a lower traffic density at night, PTW riders are more at risk of being seriously injured or killed while riding in the dark (Möller et al., 2020; de Lapparent, 2006; Quddus et al., 2002). The severity of the accidents (number of fatalities/100 victims) is 1.5-fold higher at night than during the day (ONISR, 2019). Therefore, in France, 2005 road safety statistics reported that 35% of fatal accidents involving PTW riders and 26% of those with a serious injury happened at night (ONISR, 2007). Similarly, despite the fact that the riding experience itself is often considered as energizing, which would help offset feelings of fatigue, recent findings indicate the opposite. As previously observed for car drivers, international observations reported that fatigue and sleepiness are also associated with a higher risk for PTW riders of getting involved into a crash (Chen & Chen, 2016; Wali et al.,

2018; Lam et al., 2019; Santos et al., 2019; Zheng et al., 2019). More precisely, Chen and Chen (2016) showed that motorcyclists who had less than 6 hours sleep were more likely to reveal more risky riding behaviors, especially for speed. Wali et al. (2018) also indicated that the risk of getting involved in a crash increased by approximately 200% if the rider had 5 hours or less sleep (surrogate of drowsy-riding and/or fatigue).

Precrash maneuvers are associated with injury severity sustained by PTW riders involved in single-vehicle crashes (Wang et al., 2016). When a precrash maneuver is performed, the two most common maneuvers observed are braking and/or swerving (ACEM, 2009; Wang et al., 2016). Furthermore, emergency braking and swerving maneuvers performed on the left or on the right are also learned in PTW training programs and motorcycle license practice tests (Haworth et al., 1997), contributing to alleviate the crash risks and improve PTW safety (Wali et al., 2018). Emergency braking and/or swerving on a PTW require a high-level of perceptive and manipulative capabilities (Van Elslande et al., 2012). However, vigilance impairment, which can be induced by sleep deprivation (SD) and/or time-of-day (TOD), is recognized to negatively affect the different components of executive functioning implied in motorcycling (Bougard et al., 2016_{a,b}). Previous works from our laboratory have shown that motorcycling performance evaluated through a broad set of basic riding skills on a test track is sensitive to the effects of TOD, with an improvement of riding performance throughout the day following a normal night of sleep (Bougard et al., 2008; Bougard and Davenne, 2012). These riding performances evolved concomitantly to the rhythm of body temperature, considered as a good marker of the biological clock (Colquhoun, 1971). Considering SD effects, performance impairment depends on the ability under consideration (reaction time, motor coordination, balance, flexibility). More precisely regarding precrash avoidance maneuvers, Bougard et al. (2012) have shown that emergency braking was impaired in real motorcycling conditions by both disturbance factors, TOD and SD, mainly due to an impairment in the reaction time phase. Swerving capabilities were far less impacted. Nonetheless, for safety reasons due to the real motorcycling conditions of our experiment, the duration of the tests was limited (15 min) and the speed was reduced (20 to 40 kph), which may have limited the impacts of disturbance factors such as sleepiness. Nonetheless, to improve PTW safety, crash avoidance maneuvers deserve more research attention (Kuang et al., 2015) and evaluating the influence of fatigue and sleepiness on their execution is of particular interest.

Recently, the development of PTW simulators allowed for the analysis of PTW rider behaviors in various situations. The advantage of such material is to propose different critical riding situations without inducing any risk of injuries (De Winter et al., 2012). Some studies used a fixed platform in a static vertical position in order to evaluate the influence of the level of expertise on hazard detection (Cheng et al., 2011; Hosking et al., 2010), or the effects of alcohol consumption on riding performance (Centola et al., 2020; Filtness et al., 2013). Others used a dynamic configuration that offers greater validity for PTW riding tests (Benedetto et al., 2014). In particular, this allows evaluating PTW rider behaviors in more realistic situations, such as lane position while negotiating a curve (Crundall et al., 2012), or gaze locations in bends (Lobjois and Mars, 2020). Lastly, Kováčsová et al. (2020) studied emergency braking at intersections using a motion-base simulator. They reported that the more dangerous the situation, the more likely riders were to initiate braking. Moreover, even if riders braked in an impending situation, they were often unsuccessful in avoiding a collision. For swerving maneuvers, although motion cueing algorithms are increasingly efficient regarding PTW dynamics, reproducing these maneuvers on a dynamic simulator still remains challenging. Nonetheless, and despite such sophisticated tools presenting numerous advantages, none has yet to evaluate the influences of TOD and SD on PTW riding behavior during precrash maneuvers using a moving platform.

The aim of this study was to evaluate the influences of time-of-day and sleep deprivation on two different crash avoidance maneuvers, namely emergency braking and swerving, performed on a dynamic motorcycle simulator. To do so, and to allow for possible comparisons, we choose to reproduce the experimental procedure used by Bougard et al. (2012), who were, to the best of our knowledge, the only ones to evaluate these effects in real motorcycling conditions. We hypothesized that similarly to real conditions, emergency braking performance on the simulator, which is a quite simple task, would improve during the day after a normal night of sleep (according to the diurnal fluctuations of body temperature) and that this improvement would be affected by SD. We also hypothesized that modifications of braking performance would essentially be paralleled by modifications in reaction time. In contrast, swerving (being a more complex maneuver) should remain constant throughout the day, regardless of the sleep condition.

2. Materials and methods

The study protocol complied with the tenets of the Declaration of Helsinki and was approved by the local ethics committee (Comité de Protection des Personnes Nord-Ouest III, France, n° 2007-A00581-52).

2.1. Participants

Twelve healthy young males (age: 22.9 ± 1.9 years old; height: 177.6 ± 7.5 cm; weight: 79.2 ± 13.2 kg) voluntarily signed an informed consent before being included in this study. To guarantee the homogeneity of the sample, particular attention was paid to motorcycling experience (participants held a motorcycling license for 3.8 ± 2.6 years) and to the participant's chronotype (person's circadian typology, reflecting morning and evening preferences) according to their answers to the Horne and Östberg (1976) questionnaire. All the participants were 'intermediate type' (score from 42 to 58), reflecting a mean bedtime between 22:30 h and 00:00 h; and a wake-up time between 07:00 h and 09:00 h. Moreover, all the participants had a score <11 on the Epworth sleepiness scale (Johns, 1991) in order to avoid excessive diurnal sleepiness.

2.2. Study design

As illustrated in Figure 1, each participant was evaluated during four test sessions, set up at 06:00 h, 10:00 h, 14:00 h, 18:00 h, following a night with or without sleep (corresponding to 24, 28, 32 and 36 waking hours in the SD condition) in a random order. The two days of testing were separated by a period of 1 week to allow for recovery from the night of sleep deprivation. For each of the two sleep conditions, the tests described in the following section were carried out once by each of the 12 participants at each time-of-day.

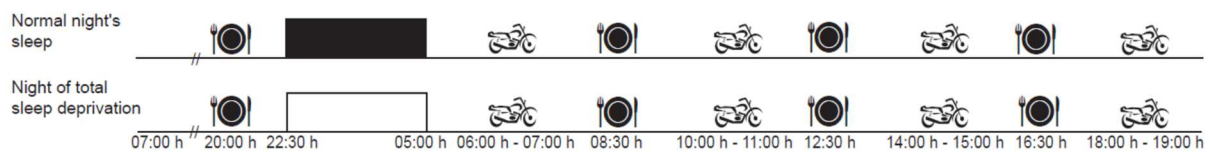


Figure 1. Experimental protocol. Each participant participated in two days of test sessions (🏍️), organized after either a normal night's sleep or a night of SD. During these days, standardized meals (🍴) were provided in between test sessions.

The day before the tests, participants were asked to wake up at 07:00 h (controlled by actimetry) before coming to the laboratory (which had room temperature of $21.6 \pm 0.8^{\circ}\text{C}$) at 19:00 h, and ate a standardized meal at 20:00 h. When the participants were evaluated following a night of normal sleep, they were asked to go to bed at 22:30 h in order to guarantee a minimum of 6 hours in bed. An experimenter woke them up at 05:00 h. Under these conditions, sleep duration conformed to the participants' usual sleeping habits, since participants reported during the inclusion visit that their mean sleep duration was 7 hours. For the night of SD, the participants remained in the presence of an experimenter and were not allowed to lie down. During this night of SD, the participants were only allowed to take part in activities not involving any physical load or excitement (such as reading, watching a movie, and playing cards), and energizing and stimulant drinks (coffee, tea, etc.) were not allowed (Reilly & Bambaiechi, 2003). All these precautions were also applied during the day, in between the test sessions.

A standardized breakfast was provided at 08:30 h, after the experimental session at 06:00 h (Baxter & Reilly, 1983), in order to limit inter-individual variability of the results (Bougard et al., 2009). A standardized meal was also provided for lunch at 12:30 h, and a light snack at 16:30 h. To avoid any performance improvement during the experiment due to a practice effect (Millar, 1992), all the participants were trained during a pre-experimental session set up a week before at 13:00 h, to obtain stabilization of their performances. More precisely, they simulator sickness symptoms. After a 30 min break, they had to complete the same riding tests as for the experimental test sessions during two training blocks of 15 min each, separated by 30 min.

2.3. Measurements

2.3.1. Oral temperature

Before each riding session on the PTW dynamic simulator, the participants were asked to lie down on a bed for 15 min (Souissi et al. 2007). Then, oral temperature was measured by an experimenter using a digital clinical thermometer (Omron, accuracy: 0.05°C) inserted sublingually for at least 3 min.

2.3.2. Simulated riding tests

As proposed in Bougard et al. (2012), who studied the influences of time-of-day and sleep deprivation on real motorcycling capabilities, participants had to perform an emergency braking and a swerving maneuver, both realized at 20 and 40 kph in a random order, on a motorcycle dynamic simulator (Figure 2A). The same environment, an underground private parking area (Figure 2B), was reproduced on the simulator (Figure 2C). This simulator is based on the framework of a real motorcycle (125 YBR, Yamaha®), fixed on a mobile platform including 5DDL (roll, yaw, pitch, handlebar rotation, force feedback on the handlebar). It allows the reproduction of intensive braking, acceleration, and taking curves by tilting the PTW at $\pm 10^\circ$. All the commands from a real PTW were conserved and encoded via various sensors, allowing to ride in the virtual environment. A speedometer with LEDs on each side was reproduced on the lower screen so that the rider did not need to switch his gaze and attention between the real and simulated environment. In order to cover a wide field of view (60°) a video projection screen (height: 128 cm; width: 177 cm) was placed at 120 cm from the simulator with the horizon line at the participant's eye level.

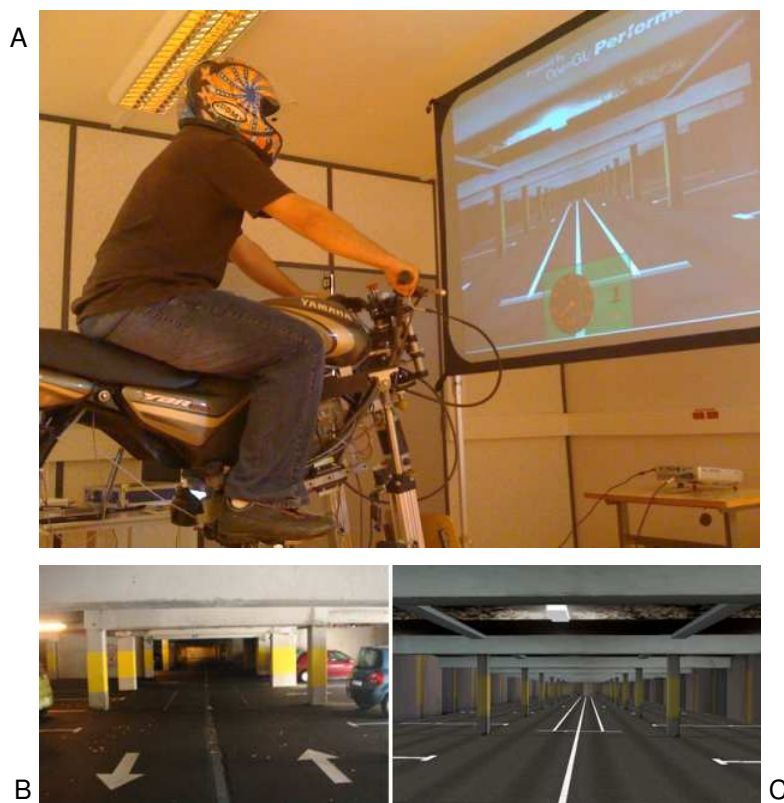


Figure 2. A. Participant on the dynamic simulator during the riding test; B. Real underground private parking area (Bougard et al., 2012); C. Simulated underground private parking area.

The test course comprised two different zones: a preparation zone (40 m) in which PTW riders had to achieve the required speed; an exercise zone (40 m) in which riders had to perform the required maneuver. At each extremity, an empty zone of 10m was respected for visual comfort and fidelity with the real underground parking area.

The emergency braking test was carried out at either 20 kph (12.43 mph) or 40 kph (24.86 mph) with the brake lever and pedal in a “ready-to-brake” position (foot just above the rear wheel brake pedal and fingers beyond the front wheel brake lever). Participants had to achieve the required speed before entering the exercise zone. From the entrance of the exercise zone, one LED was switched on in a random way. At this signal, the participant had to brake in order to stop the PTW as soon as possible (Figure 3). To better analyze the effects of TOD and SD on emergency braking, the combination of the different encoders allowed for the calculation of the following measures, retained as performance indices:

- Stopping time/distance: these measures describe the time/distance necessary for the rider to stop the PTW, once the LED was turned on.
- Reaction time/distance: these measures describe the time/distance between the LED turn-on and the rider pressed the brakes.
- Braking time/distance: these measures represent the time/distance during which the brakes were activated.

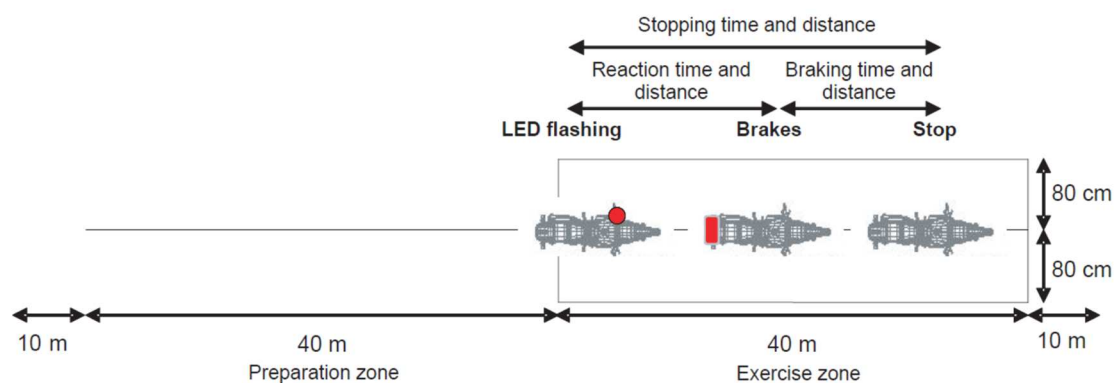


Figure 3. Emergency braking test and recorded measurements.

As for the swerving maneuver, the expected speed also had to be attained before entering the exercise zone. At the beginning of that zone, participants had to adjust the path of the PTW to the median line. Then, one of the two LEDs was switched on and the participant had to adjust

the path of the PTW to the line on the same side as the LED, as soon as possible. The order in which participants had to perform the maneuver on the left or the right were randomly chosen. The following measures were retained as performance indices:

- Total time/distance for the avoidance: these measures correspond to the time/distance separating the LED turn-on and the stabilization of the PTW path on the designated line according to the LED side (left/right) (Figure 4). To determine when the path was stabilized on the line, the recorded data were analyzed backward from the end of the trial. Once the handlebar position exceeded three standard deviations from the mean value calculated in the preparation zone, the path of the PTW was considered as stabilized.
- Reaction time/distance: these measures represent the time/distance separating the LED turn-on from the initiation of the turn. To determine the initiation of the turn, the mean position of the handlebar in the preparation zone was calculated. Then, once in the exercise zone, the first time the handlebar position exceeded three standard deviations from the mean value previously calculated was considered as the initiation of the turn.
- Swerving time/distance: these measures correspond to the time/distance necessary for the rider to stabilize the path of the PTW on the appropriated line once he had initiated the turn.

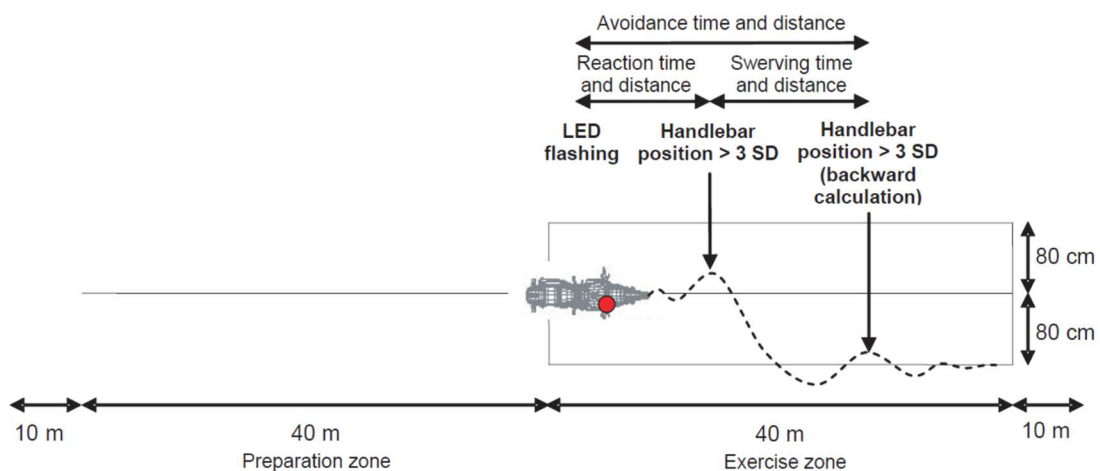


Figure 4. Swerving maneuver and recorded measurements.

Emergency braking and swerving are difficult and dangerous maneuvers on a motorcycle. In real-life conditions, riders can easily drop the bike or lose control. To improve realism and

better capture the real-life experience of riding a motorcycle, a ‘virtual’ fall occurred (reproduced by the simulation model in the visual scene and also by little vibrations in the motorcycle seat) when a rider failed to perform safely (braked too hard or overturned the bike).

We analyzed first the effects of TOD and SD on the time/distance necessary to perform the whole maneuver. Then, we further analyzed the reaction and execution part (braking/swerving) of the maneuver, considered as explanatory variables.

2.4. Statistical analysis

Since, in this experiment, participants took part in several test sessions throughout the day following both a normal night’s sleep and a night of sleep deprivation, they were considered as their own control. The repeated-measures ANOVA allow for comparing the effects of each disturbance factor separately (sleep condition or time-of-day) and also their possible interactions. In addition, with the motorcycling tests being performed at different speeds (20 kph and 40 kph) and according to instructions regarding the side of the maneuver (swerving maneuver), these factors were considered as categorical factors to identify their respective influence on participants performance.

The data recorded in temperature measurements during the eight test sessions were analyzed by a 2 (sleep condition: normal night; sleep deprivation) \times 4 (time-of-day: 06:00 h, 10:00 h, 14:00 h and 18:00 h) repeated-measures analysis of variance (ANOVA). For the motorcycling tests, both maneuvers were evaluated at two different speeds. Consequently, emergency braking data were analyzed by a 2 (sleep condition: normal night; sleep deprivation) \times 4 (time-of-day: 06:00 h, 10:00 h, 14:00 h, 18:00 h) repeated-measures analysis of variance (ANOVA) with a categorical factor (speed: 20 and 40 kph). For the swerving test, riders also had to perform the maneuver on both sides. The data was thus analyzed by a 2 (sleep condition: normal night; sleep deprivation) \times 4 (time-of-day: 06:00 h, 10:00 h, 14:00 h, 18:00 h) repeated-measures analysis of variance (ANOVA) with two categorical factors (speed: 20 and 40 kph; side: left and right). To maintain clarity and a full understanding of the results, only the main effects and those of interaction limited to 2-levels are presented further.

For all the collected data, the condition of sphericity was tested (Mauchly's test). The p -value levels were corrected for possible deviations from sphericity by means of the Huynh–Feldt epsilon (ϵ). We report the uncorrected degrees of freedom, the ϵ value, and the p -value according to the corrected degrees of freedom. When significant differences were observed, a post hoc analysis was then performed with a Bonferroni test.

All differences were considered as significant for p -value < 0.05 . For each significant effect, we estimated the size effect using the partial eta squared (partial η^2). All statistical analysis results are presented in detail in the Appendices (Table 1 for Emergency braking and Table 2 for Swerving).

3. Results

3.1. Oral temperature

A significant interaction effect between 'sleep condition' and 'time-of-day' ($F_{(3,33)} = 5.72$; $\epsilon = 1.00$; $p < 0.01$; partial $\eta^2 = 0.34$) was observed on oral temperature measurements. The post-hoc analysis indicated lower levels of temperature at 06:00 h after the normal night's sleep than after SD ($35.81 \pm 0.28^\circ\text{C}$ vs $35.99 \pm 0.24^\circ\text{C}$). In contrast, measurements realized at 10:00 h, 14:00 h and at 18:00 h did not depend on the previous sleep condition [$(36.16 \pm 0.31^\circ\text{C}$ vs $36.23 \pm 0.12^\circ\text{C}$), $(36.44 \pm 0.25^\circ\text{C}$ vs $36.36 \pm 0.17^\circ\text{C}$), $(36.55 \pm 0.24^\circ\text{C}$ vs $36.48 \pm 0.20^\circ\text{C}$), respectively].

3.2. Emergency braking

Before any analysis of emergency braking performance, it was necessary to check whether the participants rode at the correct speed. They respected speed instructions while riding at 20.86 ± 1.11 kph and 39.85 ± 3.81 kph at the beginning of the exercise zone ($F_{(1,22)} = 1582.38$; $p < 0.001$; partial $\eta^2 = 0.99$). Regarding the whole maneuver, a significant interaction effect between 'speed' and 'sleep condition' was observed on both the stopping distance ($F_{(1,22)} = 8.54$; $\epsilon = 1.00$; $p < 0.01$; partial $\eta^2 = 0.28$) and time ($F_{(1,22)} = 7.76$; $\epsilon = 1.00$; $p < 0.05$; partial $\eta^2 = 0.26$). At 20 kph, the participants stopped in a shorter distance (3.28 ± 0.26 m) and faster (0.63 ± 0.03 s) than at 40 kph (Figure 5A). At 40 kph, the distance necessary to stop the PTW (normal night: 7.58 ± 0.20 m vs SD: 9.16 ± 0.39 m; +21%), and also the stopping time significantly increased with SD (normal night: 0.85 ± 0.02 s vs 1.01 ± 0.22 s after SD; +19%).

To have further information, it would be of interest to determine whether the effects observed on the stopping distance/time were induced by changes in the ‘reaction’ and/or ‘braking’ part of the maneuver.

As for the reaction part of the maneuver, a significant interaction effect between ‘speed’ and ‘sleep condition’ was observed on both the distance ($F_{(1,22)} = 9.96$; $\varepsilon = 1.00$; $p < 0.01$; partial $\eta^2 = 0.31$) and time ($F_{(1,22)} = 8.08$; $\varepsilon = 1.00$; $p < 0.01$; partial $\eta^2 = 0.27$). At 20 kph, participants reacted in a shorter distance (2.30 ± 0.25 m) and faster (0.39 ± 0.02 s) than at 40 kph. At 40 kph, the reaction distance (normal night: 6.53 ± 0.20 m vs SD: 8.05 ± 0.37 m; +23%) and time significantly increased with SD (normal night: 0.62 ± 0.02 s vs SD: 0.75 ± 0.03 s; +21%) (Figure 5B).

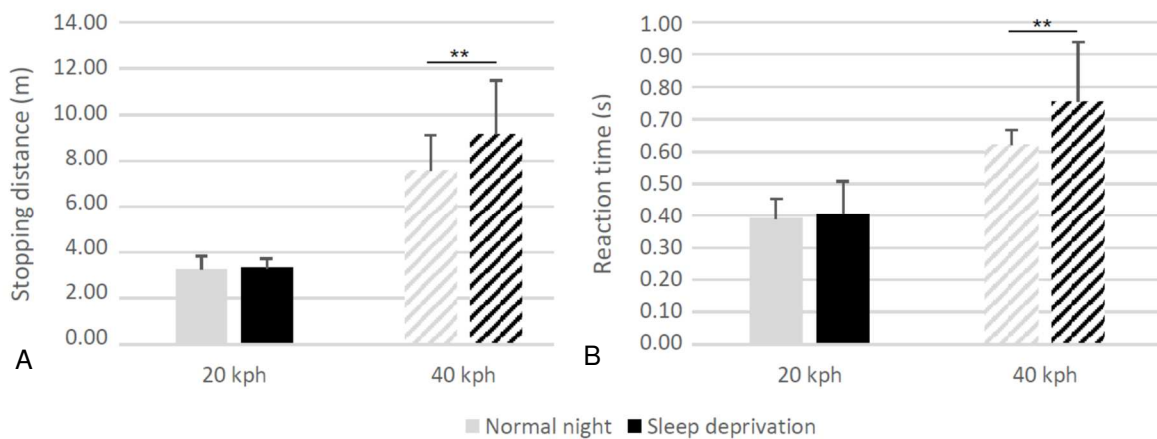


Figure 5. Stopping distance (A) and reaction time (B) recorded at 20 kph (on the left) and 40 kph (on the right) after the normal night’s sleep (grey) and sleep deprivation (black); ** $p < 0.01$.

Regarding the braking part of the maneuver, a significant effect of ‘speed’ was observed on the distance during which the brakes were activated ($F_{(1,22)} = 13.45$; $\varepsilon = 1.00$; $p < 0.001$; partial $\eta^2 = 0.38$). The participants pressed the brakes for shorter distances at 20 kph than at 40 kph (0.91 ± 0.20 m vs 1.08 ± 0.22 m; -16%). Surprisingly, the effect of ‘speed’ was not observed on braking times. In addition, an interaction effect between ‘sleep condition’ and ‘time-of-day’ was observed on braking distance ($F_{(3,66)} = 3.16$; $\varepsilon = 0.89$; $p < 0.05$; partial $\eta^2 = 0.13$) and time ($F_{(3,66)} = 3.21$; $\varepsilon = 0.83$; $p < 0.05$; partial $\eta^2 = 0.13$). The Bonferroni post-hoc analysis reported no significant differences regarding braking distances; while braking times measured after the normal night’s sleep were significantly shorter at 06:00 h than at 18:00 h (0.19 ± 0.01 s vs 0.22 ± 0.01 s; -16%).

3.3. Swerving

The target speed recorded at the beginning of the exercise zone conformed to the instructions since participants rode at 21.32 ± 0.68 kph and 40.31 ± 1.24 kph ($F_{(1,45)} = 1796.40$; $p < 0.001$; partial $\eta^2 = 0.98$). ‘Speed’ significantly influenced the total distance ($F_{(1,45)} = 15.12$; $p < 0.001$; partial $\eta^2 = 0.25$) and time ($F_{(1,11)} = 64.57$; $p < 0.001$; partial $\eta^2 = 0.59$) necessary to perform the avoidance maneuver while swerving. The participants needed shorter distance (27.95 ± 0.86 m vs 32.67 ± 0.54 m; -14%) but took longer (4.88 ± 0.13 s vs 3.52 ± 0.12 s; +38%) to change their path at 20 kph than at 40 kph.

To have further information, it would be of interest to determine whether the effects observed on the avoidance distance and time were induced by changes in reactions and/or changes in the movement part of the swerving maneuver.

Regarding the reaction part of the maneuver, a significant interaction effect between ‘speed’ and ‘time-of-day’ was observed on both the reaction distance ($F_{(3,135)} = 3.16$; $\epsilon = 1.00$; $p < 0.05$; partial $\eta^2 = 0.07$) and time ($F_{(3,135)} = 2.79$; $\epsilon = 1.00$; $p < 0.05$; partial $\eta^2 = 0.06$). At 20 kph, the participants travelled less distance before initiating their maneuver (1.87 ± 1.11 m) and reacted faster (0.32 ± 0.01 s) than at 40 kph. At 40 kph, reaction distance and time were increased at 06:00 h (4.44 ± 0.22 m; 0.42 ± 0.02 s, respectively) in comparison with measurements realized at 10:00 h (3.50 ± 0.20 m; 0.32 ± 0.02 s, respectively), 14:00 h (3.26 ± 0.20 m; 0.30 ± 0.02 s, respectively), and 18:00 h (3.40 ± 0.21 m; 0.30 ± 0.02 s, respectively).

As for the swerving part of the maneuver, a significant effect of ‘speed’ was observed on the distance ($F_{(1,45)} = 7.07$; $p < 0.05$; partial $\eta^2 = 0.14$) and time ($F_{(1,45)} = 58.48$; $p < 0.001$; partial $\eta^2 = 0.57$) necessary to adjust the trajectory of the PTW. More precisely, the participants needed shorter distance (27.14 ± 0.91 m vs 30.56 ± 1.44 m; -11%) but took longer to adjust their path (4.74 ± 0.14 s vs 3.36 ± 0.12 s; +41%) while riding at 20 kph than at 40 kph, respectively.

4. Discussion

This study aimed at determining whether motorcycling performances evaluated through crash avoidance maneuvers usually performed (namely emergency braking and swerving) evolved with sleep deprivation and time-of-day while evaluated on a dynamic simulator. Our major finding is that emergency braking performance was significantly affected by lack of sleep,

more particularly at 40 kph. The increase observed in stopping time and distance when riding at 40 kph could be directly connected to the reaction part of the maneuver (+0.13 s, +21.4%). In contrast, it seems that swerving performance remained unchanged according to TOD or SD in our experiment. At 40 kph, only the reaction part of the maneuver evolved throughout the day with slower reactions in the early morning, while these influences had no consequence on the whole maneuver.

Oral temperature was measured in this study because it is considered as a major biomarker of circadian rhythmicity (Colquhoun, 1971). As classically observed in the literature, the measurements realized after the normal night's sleep fluctuated throughout the day, according to the circadian rhythm of core body temperature. The amplitude of this diurnal fluctuation (+0.7 °C) is classically reported in participants with intermediate chronotype and attests that the participants selected in this study presented a clear circadian rhythmicity (Reilly & Waterhouse, 2009). The diurnal fluctuation of temperature was preserved after the sleepless night with a decreased amplitude, induced by higher values recorded in the morning (Souissi et al., 2003). This also confirmed that the test sessions were set up at appropriate time schedules to evaluate marked diurnal fluctuations in motorcycling performances.

The results observed in the emergency braking test confirmed that stopping distance increases with speed (Corno et al., 2008). Our dynamic model induced a 5-m increase between maneuvers performed at 20 kph and 40 kph (+155%). Even if these results may seem intuitive, they reproduced previous measurements obtained in real riding conditions (Bougard et al., 2012; + 9 m, + 203%), confirming the pretty good generalizability of our results obtained on a dynamic simulator. While evolving at 20 kph faster, a 5 meters difference in stopping distance may have serious consequences if a rider has to brake suddenly. Consequently, PTW riders have to respect speed limitations in dense areas. The stopping distance and time at 40 kph were increased after SD. These worsening performances (distance: +1.58 m, +21%; time: +0.16 s, +19%) indicated that participants were not able to stop as quickly as they did after the normal night's sleep, even at quite low speeds. This can have fatal consequences in real-life riding, particularly in a city center where speed limitations are fixed at 50 kph, with a lot of pedestrian crossings. Further analyses indicated that these impaired performances after the sleepless night should be mainly related to increased reaction times. After the normal night's sleep, reaction times measured at 20 kph (0.39 s) and 40 kph (0.62 s) were in agreement with several studies in real motorcycling condition, using artificial

stimuli such as lights and road markings for safety reasons (Bougard et al., 2012; Davoodi et al., 2012; Ecker et al., 2001; Vavryn & Winkelbauer, 2004). At 40 kph, reaction times increased after SD, which is in agreement with previous findings obtained in laboratory conditions (Corsi-Cabrera et al., 1999; Doran et al., 2001). Nonetheless, most of these studies also reported that reaction time still fluctuates throughout the day, independent of the lack of sleep (Arnal et al., 2015; Basner et al., 2013; Bougard et al., 2016). This was not the case on the simulator. It can be assumed that, due to monotony on the simulator in this relatively simple task, the effect of sleep deprivation was so important that the influence of diurnal fluctuations remained limited. Another interesting aspect is that reaction times were faster at 20 kph than at 40 kph. It has to be noticed that to ride at 20 kph, the participants only needed to select the third gear, while the engine was idling. They did not need to turn the throttle. In contrast, to ride at 40 kph the participants also needed to maintain their speed by controlling the throttle, similar to a real motorcycle, which is a bit more complex. Finally, the braking part of the maneuver remained mostly unchanged in our study. Only a significant effect of 'speed' was observed on the braking distance, but no effect of TOD nor SD. It is particularly difficult to reproduce the tire ground contact on a motorcycling simulator, even on a dynamic simulator. It can be inferred that the lack of rendering was a measuring weakness of this parameter. Nonetheless, in case of emergency, riders might press the brakes heavily in order to stop the PTW as quick as possible, in peculiar with an ABS system. These observations confirm those of Kováčsová et al. (2020), reporting no differences between braking styles observed with motion and no-motion simulator configurations. These results are also in agreement with those of Humphrey et al. (1994), reporting that the deleterious effects of SD on reaction time are mainly induced by an alteration of the first stages of information processing, the perception, but not from the motor execution part.

As for the swerving maneuver, the total distance and time necessary to perform the maneuver increased with speed. Riding 20 kph faster (from 20 to 40 kph), increased the avoidance distance by 5 meters approximately. These results are in agreement with previous observations in real motorcycling conditions (+ 7 meters between 20 and 40 kph; Bougard et al., 2012). This tends to indicate a good reproducibility of motorcycling behavior, but also of motorcycle dynamics on the simulator. In addition, our results confirm that up to 40 kph, and without any distraction, emergency braking requires shorter distance than swerving (Shuman et al., 2006). Once again, in critical situations PTW riders must be aware of the impact of speed on their crash avoidance capabilities. Furthermore, analyzing the different components

of the maneuver indicated that reaction times and distances evolved throughout the day. At 40 kph, the participants reacted slower at 06:00 h than at other times of the day, which resulted in longer distances travelled before initiating the maneuver (+ 1 m). These observations confirm that the diurnal fluctuation of attention, with increased reaction times in the early morning, evolves closely to the body temperature rhythm (Bougard et al., 2016; Rabat et al., 2016). The swerving part of the maneuver only changed with 'speed.' According to PTW dynamics, the participants adjusted their trajectory faster, but while traveling more distance at 40 kph than at 20 kph (Shuman et al., 2006). As PTW riders use the right-hand side of the road in France, and usually need to avoid an obstacle by swerving on the left (e.g., door of a car parked could open, right of way violation), we believed that the swerving maneuver would be performed more efficiently on the left than on the right. However, the participants of our study, being quite young, may have lack of exposure to critical situations to develop such preference. Although the effects of SD are well-known, the swerving performances remained globally unchanged in our study. These observations are in agreement with those of Bougard et al. (2012). This maneuver was the more complex in our study, much more than the emergency braking. Indeed, the participants had to maintain speed and control their trajectory while entering the exercise zone, and then to react as quickly as possible to the light signal and perform the correct maneuver according to the side indicated by the LED. Previous studies have shown that compensatory mechanisms may be set up to mitigate SD effects in complex tasks (Drummond et al., 2005). Our results confirm that TOD and SD have different effects on the initial stages of information processing and those responsible for executive functions and motor execution (Humphrey et al., 1994; Kraemer et al., 2000; Frey et al., 2004). These last mechanisms seem to be more resistant to the effects of both disturbance factors and performances remain mostly unaffected.

Some limitations should be considered in our study. The limited sample size reduces generalization of our results, in particular to other age ranges, since riders were quite young in our study. Moreover, it should be assumed that even if there was some uncertainty related to the side on which the maneuver had to be performed, the participants knew that they had to do something when entering the exercise zone. As a consequence, they were already in an alert state, and waited for a LED signal. Therefore, the practical significance of these results must be interpreted in the context of the contrived experimental conditions. However, this methodological choice was guided by possible comparisons with previous studies conducted in real motorcycling conditions. The total sleep deprivation was rather severe in our study.

Nonetheless, previous studies using cumulative partial sleep deprivation, which are more comparable with what happens in everyday life, have shown that the performance decrement increased progressively with the accumulation of the sleep debt (Banks & Dinges, 2007; Van Dongen et al., 2003). It appeared that cumulative restriction of sleep to 6 h or less per night across 14 nights produced cognitive performance deficits equivalent to up to two nights of total sleep deprivation. Other studies also reported that 18, 21, and 28 waking hours had the same deleterious effect as a blood alcohol concentration of 0.05, 0.08, and 0.1%, respectively (Arnedt et al., 2001; Williamson et al., 2001). In addition, the short duration of the riding sessions may have allowed for compensatory mechanisms enabling limiting time-of-day or sleep deprivation influences (Bougard et al., 2008). Finally, in contrast with results observed in real motorcycling conditions (Bougard et al., 2012), the influence of time-of-day on the simulator remained limited. It is well-known that sleepiness influence on driving capabilities is increased in simulated conditions (Davenne et al., 2012). It can be assumed that the effects of sleep deprivation were strong enough in our paradigm to mask time-of-day influence. In addition, even if motorcycling performance obtained in our dynamic simulator does not precisely replicate real motorcycling conditions, different measurements such as reaction times and stopping distances evolved in the same range between simulated and real driving conditions (Bougard et al., 2012). This tends to confirm the ‘relative’ validity of riding behaviors in the present study (Godley et al., 2002).

5. Conclusion

This study is the first to demonstrate, on a dynamic PTW simulator, that motorcycling capabilities evolve with sleep deprivation and time-of-day, in reference to emergency braking and swerving maneuvers. The more complex tasks (swerving maneuver) used in this study were only weakly influenced, but the tests performed may have been too short. The PTW simulator, as it mimics the results obtained in real riding conditions at low speed, can be considered a useful tool to focus on more realistic scenarios. Further studies may focus on prolonged motorcycle riding sessions with various road environments (e.g., city, country, and highway) to better understand the impact of fatigue and sleepiness on riding behavior and crashes.

Practical Applications

Even during simple tasks at low speed, emergency braking and swerving maneuvers evolved with TOD alone or combined with SD. This suggests that, while riding for a longer duration and in a more complex environment (including numerous distractors), PTW riders should be aware of their limited capabilities at different TOD and/or when SD occurred.

Prevention campaigns for road safety should focus on the dangers of motorcycling while sleepy. As for sensitizing drivers to the dangers of alcohol intoxication using simple equipment (prismatic glasses), specific scenarios could be developed for low-cost PTW simulators such as the Honda Riding Trainer (HRT) which are, for example, already used in motorcycling schools in France.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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1 **Appendices**

1 **Table 1:** Repeated-measures analysis of variance (ANOVA) of Emergency braking. *Italic* : categorical factors. **Bold**: significant effect ($p < 0.05$). Speed (20; 40 kph), Sleep:
 2 sleep condition (normal night; sleep deprivation), TOD : time-of-day (06:00 h; 10:00 h; 14:00 h; 18:00 h).

	ddl	F	p-value	partial η^2		ddl	F	p-value	partial η^2		ddl	F	p-value	partial η^2
<u>Speed instruction</u>					<u>Reaction distance</u>					<u>Braking distance</u>				
<i>Speed</i>	(1,22)	1582.38	0.000	0.99	<i>Speed</i>	(1,22)	190.42	0.000	0.90	<i>Speed</i>	(1,22)	13.45	0.001	0.38
Sleep	(1,22)	0.00	0.951	0.00	Sleep	(1,22)	13.73	0.001	0.38	Sleep	(1,22)	0.25	0.620	0.01
Sleep x <i>Speed</i>	(1,22)	0.13	0.721	0.01	Sleep x <i>Speed</i>	(1,22)	9.96	0.005	0.31	Sleep x <i>Speed</i>	(1,22)	0.81	0.379	0.04
TOD	(3,66)	0.51	0.649	0.02	TOD	(3,66)	0.40	0.754	0.02	TOD	(3,66)	1.20	0.318	0.05
TOD x <i>Speed</i>	(3,66)	0.18	0.886	0.01	TOD x <i>Speed</i>	(3,66)	1.17	0.327	0.05	TOD x <i>Speed</i>	(3,66)	0.20	0.896	0.01
Sleep x TOD	(3,66)	2.30	0.086	0.09	Sleep x TOD	(3,66)	0.28	0.836	0.01	Sleep x TOD	(3,66)	3.16	0.030	0.13
Sleep x TOD x <i>Speed</i>	(3,66)	0.45	0.719	0.02	Sleep x TOD x <i>Speed</i>	(3,66)	0.92	0.437	0.04	Sleep x TOD x <i>Speed</i>	(3,66)	0.15	0.927	0.01
<u>Stopping distance</u>					<u>Reaction time</u>					<u>Braking time</u>				
<i>Speed</i>	(1,22)	195.43	0.000	0.90	<i>Speed</i>	(1,22)	190.42	0.000	0.90	<i>Speed</i>	(1,22)	0.16	0.691	0.01
Sleep	(1,22)	10.26	0.004	0.32	Sleep	(1,22)	12.65	0.002	0.37	Sleep	(1,22)	0.11	0.741	0.01
Sleep x <i>Speed</i>	(1,22)	8.54	0.008	0.28	Sleep x <i>Speed</i>	(1,22)	8.08	0.009	0.27	Sleep x <i>Speed</i>	(1,22)	0.00	0.976	0.00
TOD	(3,66)	0.34	0.796	0.02	TOD	(3,66)	0.08	0.923	0.00	TOD	(3,66)	1.54	0.212	0.07
TOD x <i>Speed</i>	(3,66)	0.37	0.775	0.02	TOD x <i>Speed</i>	(3,66)	0.79	0.465	0.03	TOD x <i>Speed</i>	(3,66)	0.50	0.686	0.02
Sleep x TOD	(3,66)	0.12	0.946	0.01	Sleep x TOD	(3,66)	0.19	0.880	0.01	Sleep x TOD	(3,66)	3.21	0.038	0.13
Sleep x TOD x <i>Speed</i>	(3,66)	0.83	0.480	0.04	Sleep x TOD x <i>Speed</i>	(3,66)	0.29	0.805	0.01	Sleep x TOD x <i>Speed</i>	(3,66)	1.95	0.142	0.08
<u>Stopping time</u>														
<i>Speed</i>	(1,22)	54.84	0.000	0.71										
Sleep	(1,22)	9.78	0.005	0.31										
Sleep x <i>Speed</i>	(1,22)	7.76	0.011	0.26										
TOD	(3,66)	0.29	0.805	0.01										
TOD x <i>Speed</i>	(3,66)	0.32	0.776	0.01										
Sleep x TOD	(3,66)	0.69	0.563	0.03										
Sleep x TOD x <i>Speed</i>	(3,66)	2.07	0.112	0.09										

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Table 2: Repeated-measures analysis of variance (ANOVA) of Swerving. *Italic* : categorical factors. **Bold**: significant effect ($p < 0.05$). Speed (20; 40 kph), Side (left; right), Sleep: sleep condition (normal night; sleep deprivation), TOD : time-of-day (06:00 h; 10:00 h; 14:00 h; 18:00 h).

	ddl	F	p-value	partial η^2		ddl	F	p-value	partial η^2		ddl	F	p-value	partial η^2
<u>Speed instruction</u>					<u>Reaction distance</u>					<u>Adjustment distance</u>				
<i>Speed</i>	(1,45)	1796.40	0.00	0.98	<i>Speed</i>	(1,45)	113.00	0.00	0.72	<i>Speed</i>	(1,45)	7.07	0.01	0.14
<i>Side</i>	(1,45)	0.03	0.87	0.00	<i>Side</i>	(1,45)	0.28	0.60	0.01	<i>Side</i>	(1,45)	0.03	0.85	0.00
<i>Sleep</i>	(1,45)	1.24	0.27	0.03	<i>Sleep</i>	(1,45)	0.25	0.62	0.01	<i>Sleep</i>	(1,45)	0.62	0.43	0.01
<i>Sleep x Speed</i>	(1,45)	0.54	0.04	0.85	<i>Sleep x Speed</i>	(1,45)	0.02	0.89	0.00	<i>Sleep x Speed</i>	(1,45)	0.07	0.80	0.00
<i>Sleep x Side</i>	(1,45)	15.89	1.11	0.30	<i>Sleep x Side</i>	(1,45)	0.36	0.55	0.01	<i>Sleep x Side</i>	(1,45)	0.95	0.33	0.02
TOD	(3,135)	2.51	0.20	0.86	TOD	(3,135)	4.28	0.01	0.09	TOD	(3,135)	0.41	0.75	0.01
TOD x <i>Speed</i>	(3,135)	22.22	1.74	0.17	TOD x <i>Speed</i>	(3,135)	3.16	0.03	0.07	TOD x <i>Speed</i>	(3,135)	1.23	0.30	0.03
TOD x <i>Side</i>	(3,135)	23.36	1.82	0.16	TOD x <i>Side</i>	(3,135)	1.23	0.30	0.03	TOD x <i>Side</i>	(3,135)	0.02	0.99	0.00
<i>Sleep x TOD</i>	(3,135)	16.26	1.59	0.20	<i>Sleep x TOD</i>	(3,135)	0.68	0.57	0.01	<i>Sleep x TOD</i>	(3,135)	0.95	0.42	0.02
<i>Sleep x TOD x Speed</i>	(3,135)	6.77	0.66	0.57	<i>Sleep x TOD x Speed</i>	(3,135)	1.51	0.21	0.03	<i>Sleep x TOD x Speed</i>	(3,135)	0.67	0.57	0.01
<i>Sleep x TOD x Side</i>	(3,135)	34.59	3.38	0.02	<i>Sleep x TOD x Side</i>	(3,135)	0.41	0.75	0.01	<i>Sleep x TOD x Side</i>	(3,135)	0.51	0.68	0.01
<u>Swerving distance</u>					<u>Reaction time</u>					<u>Adjustment time</u>				
<i>Speed</i>	(1,45)	15.12	0.00	0.25	<i>Speed</i>	(1,45)	0.88	0.35	0.02	<i>Speed</i>	(1,45)	58.48	0.00	0.57
<i>Side</i>	(1,45)	0.06	0.81	0.00	<i>Side</i>	(1,45)	0.30	0.59	0.01	<i>Side</i>	(1,45)	0.00	0.96	0.00
<i>Sleep</i>	(1,45)	1.05	0.31	0.02	<i>Sleep</i>	(1,45)	0.02	0.89	0.00	<i>Sleep</i>	(1,45)	0.05	0.82	0.00
<i>Sleep x Speed</i>	(1,45)	0.15	0.70	0.00	<i>Sleep x Speed</i>	(1,45)	0.06	0.80	0.00	<i>Sleep x Speed</i>	(1,45)	0.64	0.43	0.01
<i>Sleep x Side</i>	(1,45)	0.41	0.52	0.01	<i>Sleep x Side</i>	(1,45)	0.41	0.52	0.01	<i>Sleep x Side</i>	(1,45)	1.87	0.18	0.04
TOD	(3,135)	0.34	0.80	0.01	TOD	(3,135)	4.08	0.01	0.08	TOD	(3,135)	0.03	0.99	0.00
TOD x <i>Speed</i>	(3,135)	1.03	0.38	0.02	TOD x <i>Speed</i>	(3,135)	2.79	0.04	0.06	TOD x <i>Speed</i>	(3,135)	0.76	0.50	0.02
TOD x <i>Side</i>	(3,135)	0.07	0.98	0.00	TOD x <i>Side</i>	(3,135)	1.38	0.25	0.03	TOD x <i>Side</i>	(3,135)	0.38	0.74	0.01
<i>Sleep x TOD</i>	(3,135)	1.28	0.28	0.03	<i>Sleep x TOD</i>	(3,135)	0.74	0.53	0.02	<i>Sleep x TOD</i>	(3,135)	1.11	0.34	0.02
<i>Sleep x TOD x Speed</i>	(3,135)	1.19	0.32	0.03	<i>Sleep x TOD x Speed</i>	(3,135)	1.70	0.17	0.04	<i>Sleep x TOD x Speed</i>	(3,135)	0.29	0.81	0.01
<i>Sleep x TOD x Side</i>	(3,135)	0.66	0.58	0.01	<i>Sleep x TOD x Side</i>	(3,135)	0.77	0.51	0.02	<i>Sleep x TOD x Side</i>	(3,135)	0.50	0.66	0.01
<u>Swerving time</u>														
<i>Speed</i>	(1,45)	64.57	0.00	0.59										
<i>Side</i>	(1,45)	0.04	0.84	0.00										
<i>Sleep</i>	(1,45)	0.02	0.88	0.00										
<i>Sleep x Speed</i>	(1,45)	0.60	0.44	0.01										
<i>Sleep x Side</i>	(1,45)	1.09	0.30	0.02										
TOD	(3,135)	0.02	0.99	0.00										
TOD x <i>Speed</i>	(3,135)	0.52	0.62	0.01										
TOD x <i>Side</i>	(3,135)	0.68	0.53	0.01										
<i>Sleep x TOD</i>	(3,135)	1.04	0.37	0.02										
<i>Sleep x TOD x Speed</i>	(3,135)	0.37	0.74	0.01										
<i>Sleep x TOD x Side</i>	(3,135)	0.59	0.59	0.01										