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Drivers' Perception of Loss of Adherence in Bends: Influence of Motion Rendering

This paper investigated drivers' perception during situations of loss of adherence (LOA) in static and dynamic driving simulators. The intensity and duration of the LOA were manipulated. Results show that drivers were able to correctly discriminate the different conditions of LOA in both simulators. They also highlight the importance of nonvisual information, with steering wheel haptic cues predominating for the static simulator and both the steering wheel and motion platform predominating for the dynamic simulator. This study is a first step in developing an evaluation method for electronic stability control (ESC) handling in high-performance simulator experiments. [DOI: 10.1115/1.3622752]

Keywords: driving simulation, subjective assessment, sensorimotor cues

1 Introduction

Loss of adherence (LOA) can lead to loss of vehicle control, a major factor in many accidents. Electronic stability control (ESC) can limit the consequences of LOA by correcting vehicle trajectory, according to the driver's intentions and dynamics of lateral acceleration, yaw speed or drift of the vehicle [1,2]. The calibration and validation processes of ESC are time consuming and require the use of physical prototypes and expert drivers at specific test sites, especially for very low-adherence situations. Consequently, driving simulators are being used to study LOA episodes and ESC performance [3,4]. Driving simulators are useful tools in vehicle design and perception studies. They allow the safe exploration of critical situations with naive drivers and without environmental bias [5]. The present study is the first stage of a research program, which is aimed at understanding how drivers perceive and react to trajectory perturbations and to the intervention of an ESC system. This could be useful for using driving simulators to develop the engineering specifications of ESC and to evaluate how actual drivers perceive different system configurations.

During the LOA episodes, when sudden changes in the vehicle trajectory are induced drivers must perform an appropriate steering response to maintain the vehicle in the lane and avoid road departure. Numerous sensorimotor models have been proposed to

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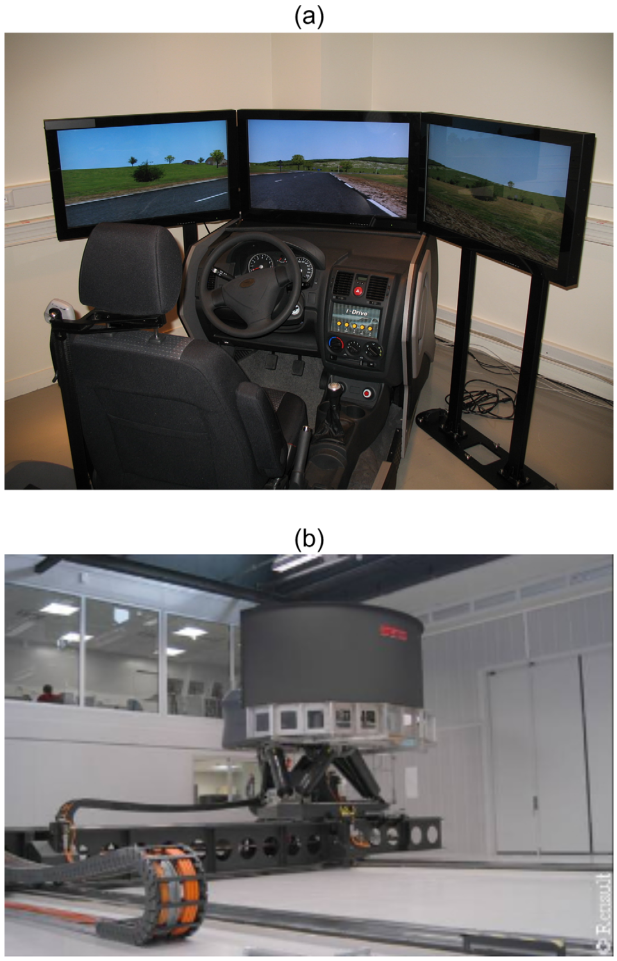

Fig. 1 (*a*) **IRCCyN driving simulator.** (*b*) **Ultimate Renault driving simulator**

Table 1 LOA conditions

Conditions	C1	C2	C3	C4	C5
Adherence coefficient	0.1	0.1	0.1	0.3	0.3
Duration (ms)	250	500	750	250	500
Conditions	C6	C7	C8	C9	–
Adherence coefficient	0.3	0.5	0.5	0.5	–
Duration (ms)	750	250	500	750	–

explain how drivers use visual, vestibular and haptic information to steer a vehicle in normal conditions [6–9]. However, little is known about sensory cues that are used by drivers to detect LOA episodes and the way in which steering responses are carried out. Hierarchical models of cognitive control applied to driving postulate that steering mainly relies on sensorimotor loops which operate below the level of consciousness [10,11]; emergence to consciousness arises when external disturbances occur [12]. We propose to investigate, how sensorimotor cues determine the conscious evaluation of driving incidents by assessing steering responses to LOA along with the associated subjective experience.

This paper presents two driving simulator experiments in which episodes of LOA were triggered to produce significant modification of the vehicle's trajectory without loss of control and road departure. Intensity and duration of the LOA were manipulated. The first objective was to develop an evaluation method to describe LOA episodes by means of subjective indicators using a nonstructured-scaled questionnaire [13]. Objective indicators of the vehicle's dynamics and driver behavior were also analyzed. Another objective was to determine to what extent objective and subjective indicators were related [14].

A first experiment was conducted on a fixed-base simulator in order to develop the evaluation method with fewer technical constraints. Preliminary results have been presented in Ref. [15]. A second experiment was conducted on a high-performance dynamic simulator to improve the evaluation method and highlight the influence of motion rendering on driver's perception [16–19]. We also hypothesized that a dynamic high-performance driving simulator would improve the feeling of immersion and give rise to a more consistent and discriminating evaluation of the LOA characteristics.

2 Method

2.1 Participants. A total of 20 participants (4 female, 16 male) aged between 20 and 24 (mean age: 21.4) participated in the first experiment. They had held a driving licence for 3.4 yr on average and drove between 1000 and 25,000 km per year (mean: 6325 km).

A total of 20 participants (5 female, 15 male) aged between 19 and 58 years old (mean age: 36.8) participated in the second experiment. They had held a driving licence for 16.7 yr on average and drove between 1000 and 40,000 km per year (mean: 17,538 km).

2.2 Apparatus. The first experiment was conducted on a fixed-base simulator at the IRCCyN laboratory (Fig. 1(*a*)). It consists of a compact size passenger car with actual instrument panel, clutch, brake and accelerator pedals, handbrake, ignition key, and an adjustable seat with seat belt. It is equipped with a TRW© active steering system for realistic "scale one" force-feedback. Transmission was carried out using an automatic gearbox. Vibrators were installed underneath the driver seat and upper position of the steering column to render engine noise and vibrations. The

Table 2 Questionnaire

Item	Question
Perceived intensity	The LOA appeared to be weak/strong
Perceived duration	The LOA appeared to be short/long
Danger	I perceived a danger during the bend
Control feeling	I easily kept my vehicle in the lane
Visual perception	I visually perceived the LOA
Steering wheel perception	I perceived the LOA through the steering wheel
Physical movement feeling *(for static simulator)*	I had the impression of physically moving
Motion rendering *(for dynamic simulator)*	I perceived the LOA through physical motion
Perturbation perception	Did you feel a perturbation in the bend?
Realism	Driving the simulator was unrealistic/realistic
Comfort	I was at ease during the trial

Table 3 Experiment 1—Summary of the statistical analyzes performed on the effect of intensity and duration on all subjective variables

Subjective Items	IV	F	LoS
Perceived intensity	Intensity	(2,38) = 108.47	$p < 0.05$
	Duration	(2,38) = 1.97	n.s.
	Intensity*Duration	(4,76) = 5.35	$p < 0.05$
Perceived duration	Intensity	(2,38) = 34.78	$p < 0.05$
	Duration	(2,38) = 21	$p < 0.05$
	Intensity*Duration	(4,76) = 4.47	$p < 0.05$
Danger	Intensity	(2,38) = 63.04	$p < 0.05$
	Duration	(2,38) = 3.86	$p < 0.05$
	Intensity*Duration	(4,76) = 7.08	$p < 0.05$
Control feeling	Intensity	(2,38) = 89.58	$p < 0.05$
	Duration	(2,38) = 11.36	$p < 0.05$
	Intensity*Duration	(4,76) = 8.2	$p < 0.05$
Visual perception	Intensity	(2,38) = 62.53	$p < 0.05$
	Duration	(2,38) = 4.79	$p < 0.05$
	Intensity*Duration	(4,76) = 4.11	n.s
Steering wheel perception	Intensity	(2,38) = 89.58	n.s
	Duration	(2,38) = 11.36	n.s
	Intensity*Duration	(4,76) = 8.2	n.s
Physical movement feeling	Intensity	(2,38) = 63.04	$p < 0.05$
	Duration	(2,38) = 3.92	n.s
	Intensity*Duration	(4,76) = 3.84	n.s

audio system reproduces the audio environment for an interactive vehicle. It comprises an amplifier, four speakers, and a subwoofer.

The SCANERII software package was used with the CALLAS dynamic vehicle model [20]. The visual environment was displayed on three 32-in. LCD monitors, each with a resolution of 1280 × 720. One monitor was positioned in front of the driver, with two laterals inclined at 45 deg from the front one, viewed from a distance of about 1 m and covering 115 deg of visual angle. A simple generic speed regulator was used, consisting of a Proportional-Integrator-Derivative (PID) corrector with a nominal speed of 75 km/h, using the automatic gearbox mode in order to reject intersubject velocity bias. This also allowed the subject to concentrate on the steering task.

The second experiment was conducted on the high-performance dynamic Ultimate simulator [21] at Renault Technical Center for Simulation (Fig. 1(*b*)). It consists of a compact size passenger car based on a real Laguna interior design. The cab is mounted on a large X-Y table and a hexapod motion system to render physical accelerations and rotations. Transmission is carried out using a manual gearbox. A system of sound synthesis is used to reproduce engine noise and the audio environment for an interactive vehicle. Active steering force feedback is computed by a proprietary model and reproduced by a TRW electric power steering system.

The SCANER Studio software package was used with a real-time version of the MADA (Advanced Modeling of Vehicle Dynamic) vehicle dynamic software, developed by RENAULT. The visual environment was displayed on a cylindrical screen (radius 1.9 m) by three single-chip DLP projectors, each with a resolution of 1024 × 768. The system covers a visual angle of 150 deg Speed regulation was unavailable for this experiment.

The same graphics database were used in both experiments. It reproduced an open countryside driving environment. Behavioural measures (lateral position, steering angle, lateral acceleration, etc.) were recorded during the trials at 20 Hz. All trials were performed on a short section of the driving environment which comprised a straight line followed by a bend (total distance: 700 m; mean radius in the bend: 111 m) without traffic.

2.3 Procedure. The LOA was simulated by modifying the adherence under the wheels when the vehicle reached a defined point in the bend. The intensity (adherence coefficient) and duration of the simulated LOA in the bend were manipulated as independent variables (IV). An adherence coefficient decrease corresponds to an increase in the intensity of LOA. These values of intensity and duration values were chosen to induce perceptible but controllable LOA simulated on four wheels (Table 1). The LOA situation induced a skid toward the outside of the bend. The environment did not give clues about a potential LOA (like snow, rain, or a mark on the road).

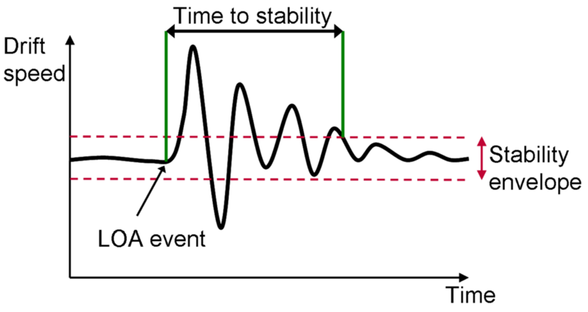

Fig. 2 Time to stability computation after LOA episode

Participants were asked to keep to their lane without cutting the corner, even if there was no oncoming traffic. After a 10-min practice session, they drove around the test bend at a predefined speed. Subjects in the first experiment were helped by the automatic gearbox and speed regulator. For the second experiment, the subjects received verbal assistance from the person conducting the experiment in order to maintain a constant speed and stay focused on steering control. Four trials without any LOA were performed in order to allow the subjects time to familiarize themselves with the task.

A control condition (no LOA) was inserted in the experimental design. A Williams Latin Squares design [22] was adopted to avoid rank and carry-over effects. Twenty trials were performed, preceded by four preliminary trials representing mild and strong LOA episodes. Those preliminary trials were conducted in order to familiarize the participants with the range of steering perturbations they would encounter during the experiment. They were not analyzed. Moreover, the experimental design was different for each type of LOA in order to maintain perceptible but controllable situations. A 3*3 factorial design was used (Intensity: 0.1, 0.3, and 0.5; Duration: 250, 500, and 750 ms). After each trial, a questionnaire about the subjects' perception of the event was displayed (Table 2). Answers to the questions were given by means of continuous horizontal scroll bars representing two ends of a continuous scale (0: totally disagree to 10: totally agree), with the exception of the question about event perception (Yes/No).

2.4 Data Analysis. For each trial, a time to stability (TTS) was computed (Fig. 2): this corresponded to the time taken by the driver after the onset of LOA to bring the vehicle speed drift back into a stability envelope. The stability envelope is defined as the average standard deviation of the speed drift measured in the control condition for all the participants. The angular drift speed (φ_{drift}) was calculated from the longitudinal speed (V_x) and the lateral speed (V_y):

$$\varphi_{\text{drift}} = \frac{d}{dt}\left(\arctan\left(\frac{v_y}{v_x}\right)\right) \quad (1)$$

The maximum lateral deviation and maximum steering wheel angle were computed in the TTS interval.

Repeated measures analyzes of variance (ANOVA, $\alpha = 0.05$) with the intensity and the duration of the LOA as independent variables (IV) were performed on the data. Bonferroni tests were performed for post-hoc analyzes. A principal component analysis was also performed on the subjective indicators in order to determine if they could be summarized by one or several underlying factors.

3 Results

3.1 Experiment 1: Static Simulator

3.1.1 Subjective Data. The standardized principal component analysis performed on the averaged subjective data showed that all indicators can be represented by a single factor (F1: 98.7% of total variance), which means that all variables were highly correlated. The simulation was globally judged as realistic (mean score = 7.64) with no significant effect of intensity and duration.

Intensity and duration of the LOA had a significant effect on the duration of danger perception and feeling of control (Figs. 3(*b*)–3(*d*)) and (Table 3)). The interaction between both IV also had a significant effect on these items. The effect of intensity and the interaction between intensity and duration on perceived

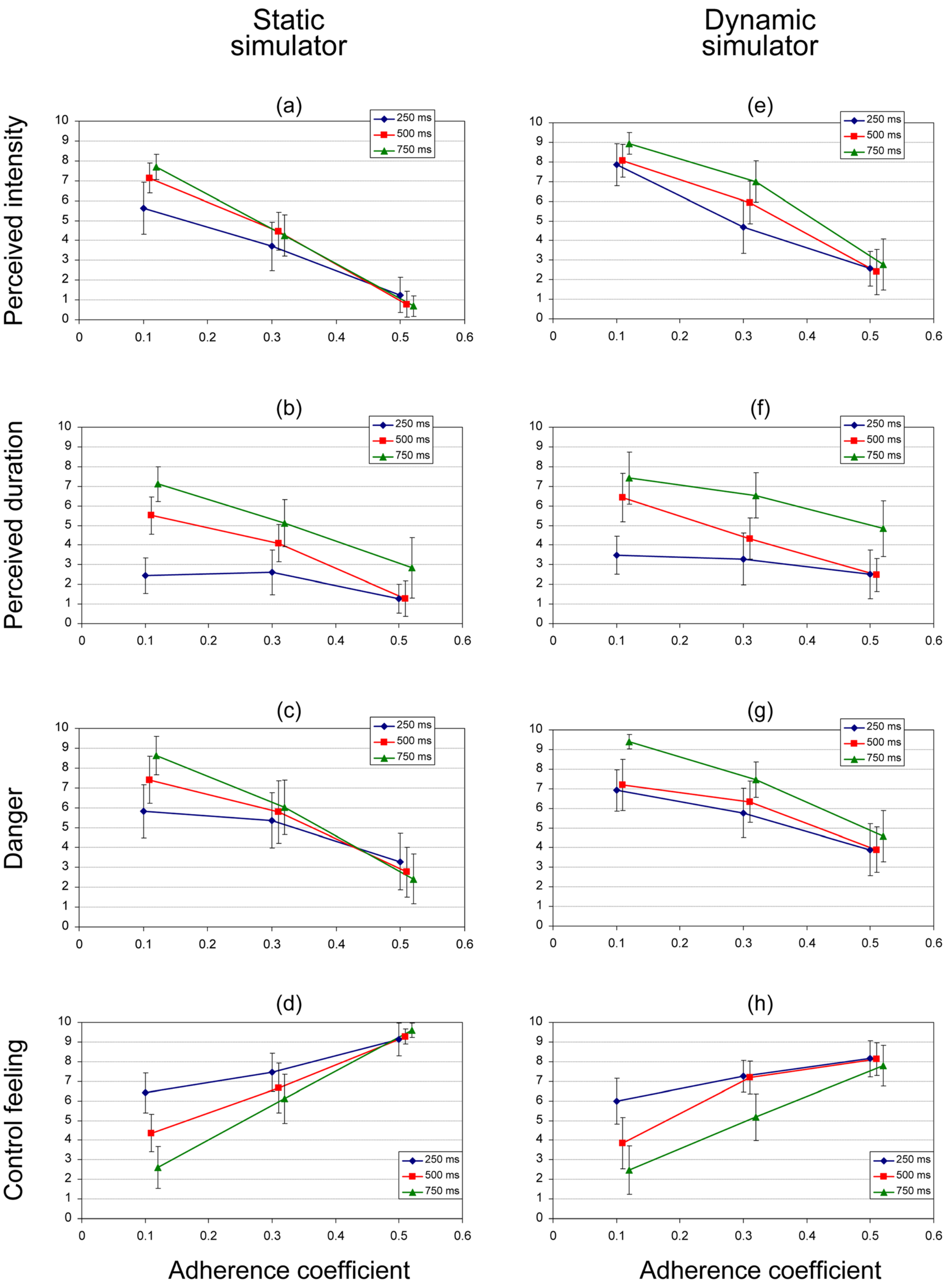

Fig. 3 Subjective answers about intensity and duration perceived, danger and control feeling for Experiment 1 (*a*)–(*d*) and for Experiment 2 (*e*)–(*h*)

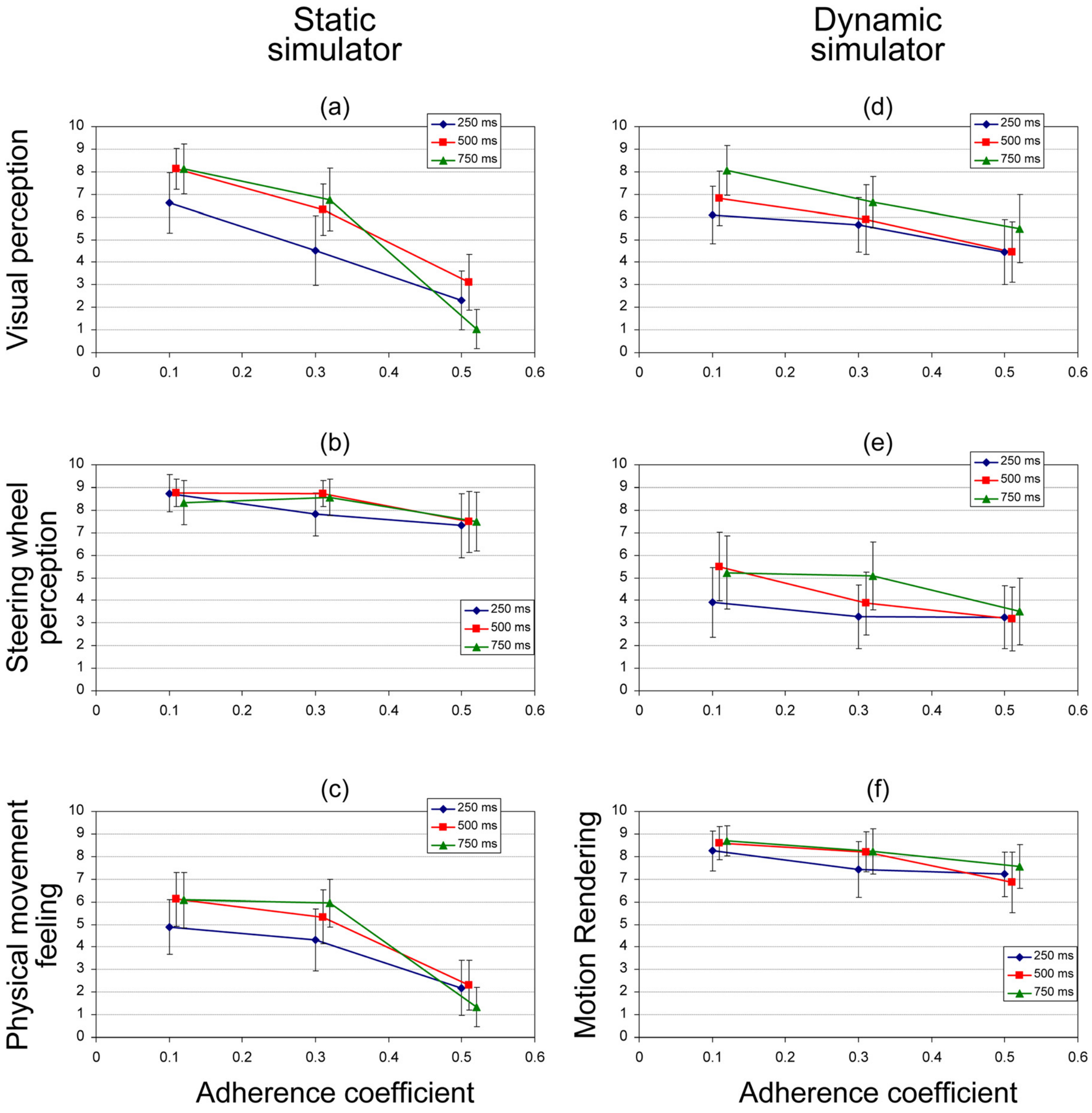

Fig. 4 Subjective answers of visual and steering wheel perception of the LOA for Experiment 1 (*a*,*b*) and for Experiment 2 (*d*,*e*). Physical movement feeling on static simulator (*c*) and motion perception of the LOA on dynamic simulator

intensity was significant; however, the effect of duration was not (Figs. 3(*a*)). Post-hoc tests confirmed that the effect of intensity on duration perceived, danger, intensity perceived and control feeling was significantly higher for longer LOA.

All the LOA situations were strongly perceived through the steering wheel in all conditions (mean value: 8.13, SD: 2.35), with no significant effect of intensity and duration (Fig. 4(*b*)). Conversely, the stronger the LOA, the more it was visually perceived, as shown by the significant effect of intensity and duration (Fig. 4(*a*)).

Although the experiment was conducted on a fixed-base simulator, a sensation of physical motion was reported, with a significant effect of intensity and no effect of duration (Fig. 4(*c*)).

3.1.2 Objective Data. Intensity (F(2,38) = 200.97, $p < 0.05$) and duration (F(2,38) = 57.65, $p < 0.05$) had significant effects on the TTS (Fig. 5(*a*)). The interaction between both IV was also significant (F(4,76) = 13.14, $p < 0.05$). Post-hoc tests confirmed that the effect of intensity on TTS was significantly higher for long duration and that there was no significant effect of duration for a lower level of intensity.

Tests performed on the maximum steering wheel angle showed a significant effect of intensity (F(2,38) = 136.7, $p < 0.05$) and duration (F(2,38) = 47.21, $p < 0.05$), with a significant interaction between both IV (F(4,76) = 23.08, $p < 0.05$). Similar results were observed on the maximum lateral deviation (intensity: F(2,38) = 125.48, $p < 0.05$, duration: F(2,38) = 97.08, $p < 0.05$; interaction: F(4,76) = 30.08, $p < 0.05$).

3.2 Experiment 2: Dynamic Simulator

3.2.1 Subjective Data. The standardized principal component analysis performed on the average subjective data showed that all indicators can be represented by a couple of factors (F1: 77.1%, F2: 21,2% of total variance). The feeling of control is the major contributor to the second factor (94%), which means that all other variables were highly correlated, except the feeling of control. The simulation was globally judged as realistic (mean score = 7.74) with no significant effect of intensity and duration.

There was a significant effect of intensity and duration of LOA and a significant interaction between both IV on the control feeling

(Fig. 3(*h*)) and Table 4. The effect of intensity and the interaction between both IV on intensity perceived was significant, but the effect of duration was not (Fig. 3(*e*)). The effect of intensity and duration was significant on perceived duration and the danger items but the effect of the interaction between both IV was not (Figs. 3(*f*) and 3(*g*)). Post-hoc tests confirmed that the effect of intensity on control feeling was significantly higher for longer LOA but revealed that the intensity effect on perceived duration was only significant for the intermediate level of LOA duration (500 ms) and could explain the global effect.

All the LOA situations were strongly perceived through motion rendering (mean value: 7.89, SD: 2.29), with a small but significant effect of intensity (Fig. 4(*f*)). LOA situations were not as clearly perceived through the steering wheel (mean value: 4.1, SD: 3.39) (Fig. 4(*e*)). As in the first experiment, the stronger the LOA, the more it was perceived through the visual channel, as shown by the significant effect of intensity and duration (Fig. 4(*d*)).

3.2.2 Objective Data. Intensity (F(2,38) = 32.65, $p < 0.05$) and duration (F(2,38) = 21.32, $p < 0.05$) had significant effects on the TTS (Fig. 5(*b*)), with no significant interaction. Post-hoc tests showed that the effect of intensity on TTS was significantly higher for long duration.

Tests performed on the maximum steering wheel angle showed a significant effect of intensity (F(2,38) = 46.9, $p < 0.05$) and duration (F(2,38) = 32.04, $p < 0.05$), with a significant interaction between both IV (F(4,76) = 12.16, $p < 0.05$). Similar results were observed on the maximum lateral deviation (intensity: F(2,38) = 60.24, $p < 0.05$, duration: F(2,38) = 48.86, $p < 0.05$; interaction: F(4,76) = 12.68, $p < 0.05$).

4 Discussion

The principal component analysis revealed that, in the first experiment, all subjective answers were correlated and could be described along one dimension, opposed to the adherence coefficient. The same analysis in the second experiment revealed a secondary dimension, mostly described by the feeling of control. The results suggest that subjective ratings were mainly determined by the intensity of the trajectory perturbation, highlighting a likely influence of motion rendering. It now remains to determine if the participants were able to discriminate the magnitude and duration of the manipulated LOA and whether motion rendering influenced the drivers' perception of this critical event.

In the first experiment, an effect of duration on the perceived intensity of the LOA was only observed for a higher intensity of LOA; this translated as a significant interaction between both variables with no main effect of duration. In the second experiment, the duration of LOA showed a main effect due to a slight increase of the level of intensity rating for longer LOA situations only. Interestingly, the perceived intensity was neither related to the maximum steering angle nor to the maximum lateral deviation. Since the maximum steering angle can be considered as a good indicator of the intensity of the steering correction, this suggests that subjects were able to evaluate how much adherence the vehicle lost, independently of how long it lasted and how much steering correction was needed. These results suggest that the duration of the perturbation moderately influenced the perception of LOA intensity. This was mainly determined by the actual intensity of the perturbation.

By contrast, the duration of the LOA was poorly perceived in the first experiment. The stronger the LOA, the longer it was perceived. It could be argued that the participants confused the duration of the LOA with the time needed to stabilize their vehicle: however, the clear instructions given prior to the experiment make this assumption hardly believable. A more plausible explanation is that LOA situations of high intensity were more stressful than milder ones, as confirmed by the danger ratings. Distortions of time have been observed under stress conditions, especially under life threatening conditions [23] or during specific critical tasks by paramedics [24]. This may be due to the attentional processes. Indeed, Tse et al. [25] proposed that novel or important events run in "slow motion" so that the information may be processed in greater depth per unit of objective time than for casual events.

Considering that the Ultimate high-performance simulator provided a stronger immersion within the driving environment, we could have expected an increase in the feeling of danger and the level of stress during the LOA situations. This would have resulted in an even stronger interaction between the duration and intensity on the perceived duration. This was not observed. The interaction between intensity and duration on the perception of LOA duration disappeared and the main effect of LOA intensity

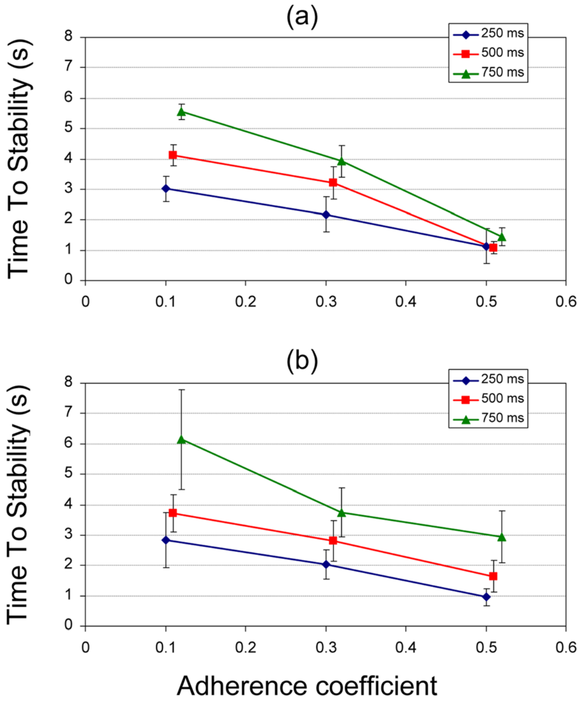

Fig. 5 TTS indicator for static (*a*) and dynamic simulator (*b*)

Table 4 Experiment 2 – Summary of the statistical analyzes performed on the effect of intensity and duration on all subjective variables

Subjective items	IV	F	LoS
Perceived intensity	Intensity	(2,38) = 85.18	$P < 0.05$
	Duration	(2,38) = 3.89	$P < 0.05$
	Intensity*Duration	(4,76) = 1.03	n.s
Perceived duration	Intensity	(2,38) = 12.93	$P < 0.05$
	Duration	(2,38) = 20.73	$P < 0.05$
	Intensity*Duration	(4,76) = 1.58	n.s
Danger	Intensity	(2,38) = 32.89	$P < 0.05$
	Duration	(2,38) = 6.94	$P < 0.05$
	Intensity*Duration	(4,76) = 0.77	n.s
Control feeling	Intensity	(2,38) = 41.02	$P < 0.05$
	Duration	(2,38) = 10.54	$P < 0.05$
	Intensity*Duration	(4,76) = 2.72	$p < 0.05$
Visual perception	Intensity	(2,38) = 8.09	$p < 0.05$
	Duration	(2,38) = 3.24	$P < 0.05$
	Intensity*Duration	(4,76) = 0.19	n.s
Steering wheel perception	Intensity	(2,38) = 3.27	n.s
	Duration	(2,38) = 1.72	n.s
	Intensity*Duration	(4,76) = 0.55	n.s
Motion rendering	Intensity	(2,38) = 5.1	$p < 0.05$
	Duration	(2,38) = 0.8	n.s
	Intensity*Duration	(4,76) = 0.3	n.s

was smaller than in the first experiment. A plausible explanation may reside in the nature of the event and the role of motion rendering. Indeed, the events started with a sudden LOA and ended with an equally sharp return to the normal coefficient of adherence. This created a sudden change in vehicle roll, which may have given an additional important cue to the subject regarding the beginning and the end of the event. Nevertheless, it should be noted that the participants were able to more clearly discriminate the shorter and longer LOAs than those of intermediate duration, in which a distortion of subjective time occurred in spite of additional sensory cues.

Although visual cues are a principal source of motion perception, only the strongest LOA were clearly reported to have been perceived through visual information, especially when using a static simulator. The higher ratings observed with the Ultimate simulator for the LOA of mild intensity probably reflect visuo-vestibular interactions that come into play in the perception of self-motion [19]. Ratings concerning nonvisual cues also suggest that, in this kind of sudden critical event, nonvisual information is crucial. Interestingly, those results strongly differ in both experiments. LOA situations induced high lateral acceleration and yaw speed variations. The rendering of these influenced drivers' subjective answers. The first, experiment clearly showed that the subjects perceived all the LOA situations mainly through the steering wheel, although some sensation of physical movement, supposed induced by visual vection, was often reported. Conversely, the LOA events in the second experiment were clearly perceived more through physical cues and less through the steering wheel. A plausible explanation is that subjects focused on the most salient and reliable cue in each simulator. Indeed, the moving base may have enhanced the perception of skidding through inertial cues, in particular through vestibular information. By contrast, steering wheel force feedback was probably the most useful cue to detect and evaluate LOA in the fixed-base simulator. Another explanation could be technical, highlighting the limitations of driving simulators to reproduce real vehicle motion and steering wheel force feedback. Even if physical cues appeared to override visual and haptic cues through the steering wheel in the Ultimate simulator, we cannot clearly say that this is the preeminent way to detect LOA. From a technical point of view, those results highlight the importance of motion and steering wheel torque feedback to increase the fidelity of driving simulators when drivers encounter critical situations with fast changes in vehicle dynamics.

5 Conclusion

Our work contributes to the enlargement of potential applications of driving simulators, allowing them to take into account human factors within the design process. This study demonstrated that drivers are able to discriminate and correctly rank different conditions of LOA along various dimensions, both in a fixed-base and a dynamic simulator. However, dynamic high-performance simulators may provide additional sensory cues to assess intensity and duration of LOA episodes with minimal misperception. The next step is to link subjective ratings with vehicle dynamics and to compare these perceptions with the action of a simulated ESC system. This would be a useful contribution to the development of engineering specifications of ESC systems and the evaluation of actual drivers' perception.

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