Sensorimotor integration in a driving simulator: contributions of motion cueing in elementary driving tasks

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Abstract

In the framework of the European CARDS Project (Eureka n°1924) several experiments were carried out on the Renault Dynamic Simulator. The objective was to assess the contribution of kinesthetic cues provided by the motion platform when executing elementary driving tasks: braking and cornering at intersections.

In the braking experiment, 11 standard drivers were asked to repeat 16 times the following sequence: reach a target velocity (80 km/h), maintain this velocity constant and decelerate in order to stop as close as possible to a specific signpost. Motion platform was activated for eight successive trials and inactivated for the remaining eight trials (or reverse). Results show that motion restitution prevents subjects from reaching too high and unrealistic decelerations, which are observed in a static simulator. Moreover, an adaptation of braking behavior appears in static mode, as drivers apply increasing braking force trial after trial, whereas braking strategy remained stable in the presence of motion cues. This result is discussed in particular by analysing the first seconds of braking behaviour and respective platform motion.

In the cornering experiment, drivers took 2 laps around a square city block in a simulated urban environment free of traffic, in each of four platform conditions. In these conditions, lateral cues (sway+roll alone), longitudinal cues (surge+pitch alone), both of them or none were restituted, respectively. A global effect of the presence of the motion cueing shows on the trajectory pattern of the driven vehicle inside each 90° curve.

These experiments are discussed in the context of sensorimotor integration while driving. Motion cues -when present even with limited amplitude- may be integrated in the driver control loop as additional inputs, providing they are relevant to the driving task considered.

Résumé

Dans le cadre du projet européen CARDS (Eureka n°1924), plusieurs expériences ont été menées sur le Simulateur Dynamique Renault. L’objectif était d’évaluer la contribution des stimuli kinésthésiques produits par la plate-forme mobile pendant l’exécution de tâches élémentaires de conduite : freinage et virage en intersection.

Dans l’expérience de freinage, 11 conducteurs standard ont réalisé 16 fois la séquence suivante : atteindre une vitesse de consigne (80 km/h), maintenir cette vitesse, puis décélérer de sorte à s’arrêter le plus près possible d’un poteau spécifique. La plate-forme mobile était activée pendant huit essais et désactivée pour les huit autres essais. Les résultats montrent que la restitution du mouvement empêche les conducteurs d’atteindre les décélérations trop fortes et non réalistes observées en conduite sans la restitution du mouvement (simulateur statique). De plus, une adaptation du comportement de freinage apparaît en mode statique, où les conducteurs augmentent le niveau de freinage au fur et à mesure des essais, alors que leur stratégie de freinage demeure stable en présence de stimuli de mouvement.

Dans l’expérience de virage en intersection, les conducteurs parcouraient 2 tours d’un pâté de maison dans un environnement urbain simulé dépourvu de circulation, avec quatre conditions de restitution du mouvement. Dans ces conditions, les mouvements latéraux, longitudinaux, leur combinaison ou aucun étaient restitués. Un effet global de la présence de la restitution du mouvement a été observé sur la forme des trajectoires du véhicule conduit dans chaque virage à angle droit.

Ces expériences sont analysées dans le contexte de l’intégration sensorimotrice lors de la conduite, et montrent que les informations de mouvement – même lorsqu’elles sont rendues avec une amplitude faible – peuvent être intégrées dans la boucle de contrôle du conducteur comme des entrées supplémentaires.

Dans le cadre du projet européen CARDS (Eureka n°1924), plusieurs expériences ont été menée sur le simulateur dynamique de conduite de RENAULT. L’objectif était de déterminer les contribution du rendu kinesthétique fourni par la plate-forme mobile à l’exécution de tâches élémentaires de conduite : le freinage et le virage à une intersection.

Introduction

Several experiments have been carried out on Renault's dynamic simulator to assess the contribution of kinesthetic cues provided by the motion platform when executing two elementary driving subtasks: braking and cornering. Deceleration to a stop and negociating a 90° turn in a city environment involve high acceleration amplitudes. These specific driving situations are known to be difficult for the simulator driver since veridical restitution of high decelerations is questionable, especially when the platform does not allow large ranges of motion. The question we tackled is whether a motion restitution of limited amplitude may nonetheless be helpful for the simulator driver.

In addition, we wanted to investigate sensorimotor integration (how different sensory signals are taken into account by the central nervous system during or for a motor task) when executing a difficult control task on the simulator, such as cornering at a sharp intersection, by dissociating motion restitution along the different degrees of freedom. Specific attention was given to « learning effects » throughout individual driving sessions.

Speed and lateral position on the road when driving along a countryside road have often been the main studied variables when investigating whether motion cues could contribute to driving performance. For example, Alm (1995) found that means of both variables were similar in the two situations, but that variability in lateral position was less when motion cues were present. Recently, Panerai et al. (2001) also found no significant difference in driving speed perception when motion cues were either turned on or turned off during the execution of car following driving tasks.

One of the first experiments designed to evaluate the role of motion cueing in driving a dynamic simulator was Repa's et al. (1982). They compared drivers' performance (car lateral position and orientation on the road) when disturbed by sudden crosswinds in four motion cueing conditions. There was either no motion cueing, roll only, roll and yaw, or finally roll, yaw and lateral acceleration. Experimenters found that drivers were better at stabilizing the vehicle on the road when motion cues where present in several axes. Orientation of the car with respect to the road was found to be more sensitive to the influence of motion cues than lateral position on the road.

Reymond et al. (1999) developed a new criteria based on the relationship between speed and maximum lateral acceleration in order to evaluate the contribution of motion restitution to driver's perception and behaviour. By asking subjects to drive the same test track on the RENAULT dynamic simulator with or without motion cueing, they showed that lateral acceleration rendering in a simulator has a significant and positive effect upon the speed choice strategy adopted unconsciously by the drivers when driving along curved roads.

The experiments which are presented here were performed on RENAULT's dynamic simulator, in the framework of the European CARDS Project (Eureka n°1924; pilot project

Renault and other partners: LPPA, Pons, SEOS, Infotron, TNO and Hydraudyne) and the collaboration between LPPA and Renault. CARDS is a driving simulator project using a head-mounted display, including motion platform and vibration seat. The project aims at providing a research and development tool addressing different automobile studies from vehicle design to human factors.

The Renault Dynamic Driving Simulator features a full-scale instrumented Renault Clio cockpit, with force feedback on the steering wheel, brake, clutch, and accelerator pedals. The simulator software package is SCANeR©. A 150°x40° front view of the road environment is generated in real-time (30-60 Hz) by a SGI Infinite Reality workstation (three 1024x768 channels), and three rear-view mirrors images are rendered by three Pentium PCs. The Clio cockpit is mounted on a Hydraudyne Electrical 6DOF-1000kg motion platform, allowing maximum displacements up to about ±22 cm (surge, sway, heave) and ±15°(yaw, pitch, roll). This platform renders the linear and angular accelerations of the simulated vehicle as computed by the software vehicle dynamics model, which are transformed into position commands by a specific motion cueing module. 'Transient' accelerations (i.e. 0.4 – 3.0 Hz) are rendered directly, whereas 'sustained' accelerations are simulated by motion platform tilt. This type of cueing strategy is implemented by a classical frequency filtering algorithm which:

- removes the low frequency component of accelerations by high-pass filtering, then integrate the signal twice to output a position command,
- extracts the low frequency horizontal accelerations by low-pass filtering, then computes a 'tilt coordination' angles which is added to the output command,
- brings the platform back to its neutral position ('motion washout') by high-pass filtering of the resulting position commands.

In addition, some high-pass filtering artefacts are reduced by a specific adaptive output gain control algorithm (Reymond et al., 1999, 2000). Gains and time constants of the respective filters are configured for optimal use of the platform performance is general driving conditions. Modification of individual gains is used in the cornering experiment described below to disable some axes of motion cueing.

Braking experiment

Motivation in studying braking

Braking to a complete stop often involves high deceleration amplitudes of the order of 0.3-0.4 g, and 0.6 g or more when it is an emergency braking. The driver feels these decelerations through the vestibular system, but also by the neck and torso proprioception. When braking on a static simulator, these forces are missing and a visuo-vestibular conflict arises. This conflict is thought to be one of the main causes of simulator sickness. Furthermore, whether visual cues alone enable the central nervous system to compute self-deceleration is much debated. Visual presentation in a simulator is monoscopic with limited depth cues and perception of distance and/or velocity is often reported to be biased (Panerai et al. 2001).

At the same time, kinesthetic restitution of deceleration by a motion platform is difficult to set up because of the high deceleration amplitudes. When the motion platform surge is limited to a few tens of centimetres, constant components of deceleration need to be simulated by tilt-coordination. A trade-off needs to be found so that drivers do not have the impression to dive when braking.

Considering the fact that braking is difficult on a static simulator and that large motion restitution is impossible with an hexapod platform, we wondered whether limited restitution may nonetheless contribute to braking performance in a driving simulator.

Methods

Subjects were asked to drive the simulator on a country road, on the side of which signposts were positioned. During each trial, subjects were asked to make eight consecutive brakings, in order to stop as precisely as possible next to indicated signposts. For the first four brakings, they were free to initiate deceleration when they estimated it best to do so. For the next four brakings, they had to initiate deceleration at specific signposts. We will consider here results concerning only the self-initiated brakings. Subjects were asked to reach a 80 km/h speed before braking. Subjects were told that once they had started braking, they had to keep on decelerating even if they realised that they had initiated deceleration too far away from the signpost.

Eleven subjects participated in this experiment (3 females, 8 males). After a 10 minute training session, subjects were asked to drive the scenario twice. Once the simulator was in a dynamic configuration (condition "ON") and once in a static configuration (condition "OFF"). Six subjects started with the condition ON and five with the condition OFF.

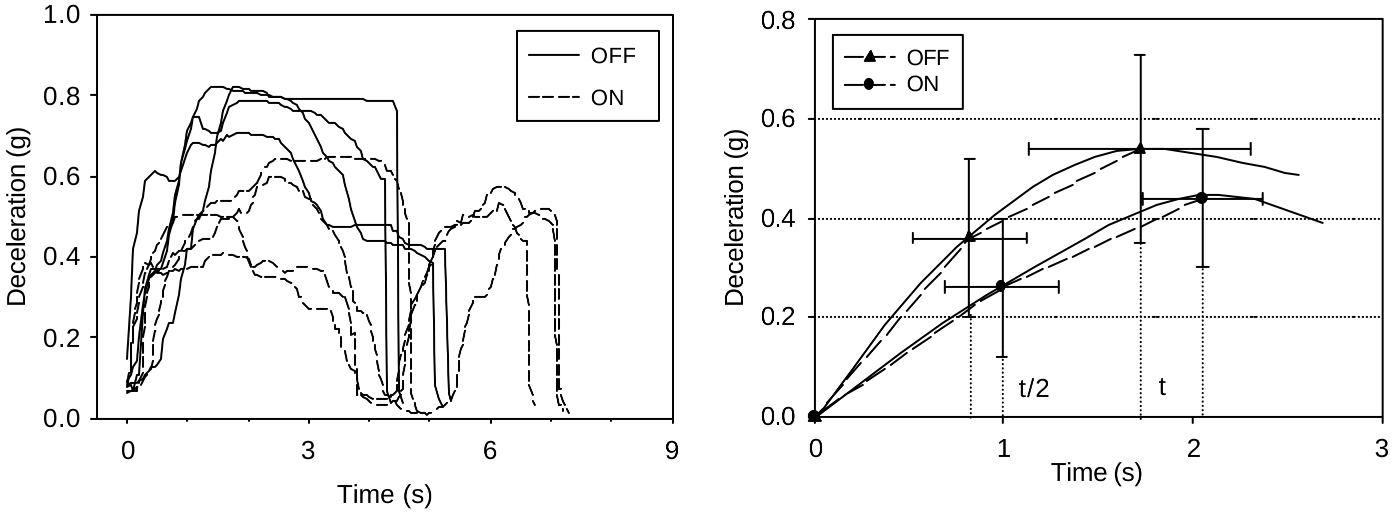

Figure 1: Left, deceleration profiles performed by one subject in both platform conditions. Right, analysing methods for the three first seconds of deceleration profiles

We concentrated the analysis of braking behaviour dynamics on the three first seconds of the driver’s action on the brake pedal. Indeed, this very first action on the brake pedal was thought to reflect the driver’s internal model of the car response dynamics, since this “knowledge” had to be taken into account to program when and how to press the brake pedal.

Maximal deceleration and instant *t* at which it has occurred were retrieved from deceleration profiles. Mean jerk between 0 ant *t/2* was also computed (Figure 1).

Results

	OFF	ON	p
V_{INI} (km/h)	80.2 ± 12.1	81.8 ± 7.0	0.5
DTT_{INI} (m)	-102.3 ± 33.6	-105.2 ± 32.0	0.7
DTT_{FIN} (m)	- 6.49 ± 5.81	-2.58 ± 3.5	**0.001***
Maximal deceleration (g) (at T s ∈[0-3s])	0.54 ± 0.19	0.44 ± 0.14	**0.003***
Mean onset jerk (g/s) ([0;T/2])	0.49 ± 0.28	0.29 ± 0.19	**0.0001***

Table 1: Results concerning self-initiated decelerations

Static and dynamic characteristics of braking

Main results are given in Table 1. There was no significant difference between both conditions in the velocity and distance to target at onset of braking. In both conditions, subjects stopped the vehicle on average before reaching the signpost. However, an ANOVA showed a significant difference in the final distance to target [F(1,70)=11.9, p=0.001]. Subjects got closer to the signpost in the ON condition (2.58 ± 3.5 m) than in the OFF condition (- 6.49 ± 5.81 m).

Differences in the dynamics of deceleration onset were also exhibited. Results are given in Table 1 and Figure 1. Subjects reached higher maximal decelerations in the OFF condition (0.54 ± 0.19 g) than in the ON condition (0.44 ± 0.14 g). A one-way braking ANOVA showed that this difference was significant [F(1,86)=9.3, p=0.003]. Mean jerk at onset of deceleration was also significantly higher in the OFF condition (0.49 ± 0.28 g/s) than in the ON condition (0.29 ± 0.19 g/s) [F(1,86)=15.4, p=0.0001].

Concerning brakings with trigger signposts, differences between both conditions were weaker. However, maximal deceleration remained significantly higher in the OFF condition (0.48 ± 0.10) than in the ON condition (0.43 ± 0.09) [F(1,86)=4.7, p=0.03].

Modification of braking behaviour in the course of a trial

In order to analyse the potential effects of learning, the population was divided into two groups depending on whether they had started with the OFF condition (Group 1) or the ON condition (Group 2). Results are given in Figure 2. On average, subjects from group 1 reached increasing levels of deceleration in the course of the first trial on the simulator (Figure 2, left): during the first deceleration, mean maximal deceleration was 0.44 g whereas it was 0.64 g during the fourth braking. Opposedly, subjects who started driving in the ON condition did not exhibit this learning bias : mean maximal deceleration remained below 0.44 g.

When driving in the ON condition, subjects from the group 1 reached on average a 0.52 g maximal deceleration at first braking and only 0.36 g during the fourth braking (Figure 2, right).

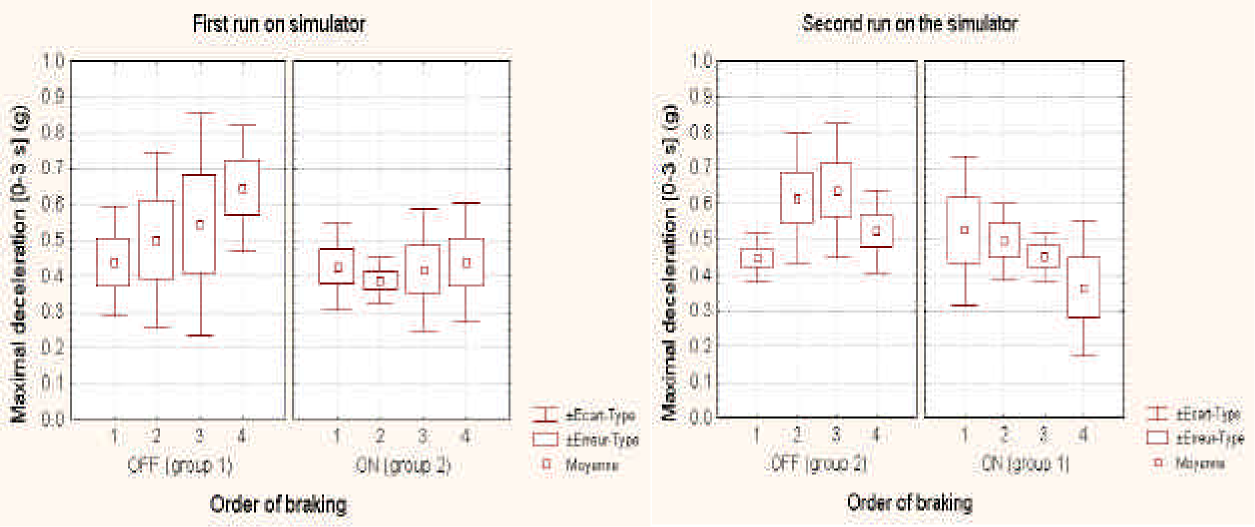

Figure 2: Maximal deceleration reached during the three first seconds of braking as a function of platform condition and order of trial in the experiment

Discussion

During our experiment, subjects reached maximal decelerations (0.4-0.6 g) that were much higher than during real driving. Malaterre & Fréchaux observed decelerations while braking on a static simulator that were even higher (0.75 g). Above 0.5-0.6 g, the braking is considered to be of emergency while driving a real vehicle.

Published data concerning braking on real vehicle are scarce and generally concern automatic gearbox vehicles. The first main reference is Newcomb's description of driving behaviour (1981). He observed a high inter-individual variability in braking behaviour when drivers were asked to stop at a specific location (as opposed to brakings without any constraint on stop position). Maximal deceleration ranged from 0.25 to 0.65 g when initial speed is 108 km/h. Recently, Boer et al. (2000) also published data concerning braking behaviour on real vehicle. From an initial velocity of 80 km/h, maximal decelerations during braking to a specified position ranged from 0.2 to 0.35 g, with a few values at approximately 0.4 g. Boer et al. (2000) also asked subjects to drive on the same road in a simulator.

We concentrated our analysis of the braking behaviour to the first 3 seconds of braking, correspondling to the first driver’s action on brake pedal and during which simulator motion cues are the most effective.

We observed a significant difference in the dynamics of braking between the two motion cueing conditions. Considering the data given by the aboce cited literature, we observed that amplitudes of decelerations were more realistic in the ON condition than in the OFF condition. Motion cueing prevented drivers to reach overly high decelerations. Moreover, subjects succeeded in getting closer to the signpost when the simulator was in the dynamic configuration. It is possible that feeling the action of braking enabled drivers to better control deceleration at low velocity when approaching the target position.

We also analysed the learning process that might take place in the course of a trial on the simulator. When the simulator is in the static configuration, drivers tend to adopt very rapidly the behaviour of an emergency braking although no dangerous situation was ever submitted to drivers. This was not the case in the dynamic configuration. Motion cues seem to have an influence on the control of the vehicle dynamics and even on the driver's internal model of the vehicle dynamics since the difference between the static and the dynamic configurations was exhibited at the very beginning of the braking action.

Cornering

Motivations in studying cornering

Cornering is most probably a driving task during which drivers make use of kinesthetic information. The first reason is that visual anticipation is very limited. When the cornering manœuvre is initiated, the final position and orientation of the car after the manoeuvre is completely hidden and adjustments in the control of the car need to be performed "on line". Furthermore cornering involves high lateral acceleration of the order of 0.4-0.5 g and high angular velocities. Cornering in a city environment while driving a simulator is a difficult task also because of the high displacement of visual objects (close building projected on close screens) during the turn. Subjects often complain of being "lost" after turning on a static simulator. For these reasons, it is expected that driving performance while negociating a turn at an intersection might benefit from proprioceptive cues.

Methods

In each run (trial), subjects were asked to drive twice around a square city block, in an urban environment, therefore executing eight consecutive 90° turns (Figure 4 left). The roads were free of traffic. No specific target speed was specified. For most of the subjects, it was the first time that they drove in a city environment. They were recommended to drive slowly at the beginning of the scenario before gaining confidence.

Figure 3: Snapshot of the city database

Twenty-three subjects participated in this experiment.

All subjects went through a training session on the dynamic simulator a few days before the experiment. They drove a countryside road with little traffic for 10 to 15 minutes. Some subjects also drove for two minutes in the urban environment. These subjects were chosen for this experiment if they had demonstrated easiness in driving simulator during the training session.

Experimental conditions

Subjects were asked to drive the scenario once in four platform conditions, which were called ON, LA, LO and OFF, respectively. These conditions differed in the amount of motion restitution (Table 2). The order of presentation was randomised across subjects. The order of condition runs (ON, LA, LO, OFF) was different for all subjects and chosen so that each condition was submitted first, second, third or fourth an equal number of times.

	Surge (X)	Sway (Y)	Heave (Z)	Pitch (P)	Roll (R)	Yaw (H)
ON	✓	✓		✓	✓	✓
LA (lateral cues)		✓			✓	✓
LO (longitudinal cues)	✓			✓		
OFF						

Table 2 : Motion restitution along the degrees of freedom in each of the four conditions

Results

Mean trajectories

Mean trajectories were calculated for each condition for the entire population (Figure 4 right). Mean trajectories in ON and LA are almost superimposed, as well as mean trajectories in OF and LO. Drivers get closer to the side of the road in LO and OF than in LA and ON. In other words, lateral cueing seems to influence the driver in his/her control of the car trajectory. In order to verify this assertion statistically, distance to the side of the road was calculated on the bisecting line of the corner (A) in the four conditions (Figure 6D). An ANOVA showed that motion cueing had a significant influence on car trajectory ([F(3,507)=14.5, p<0.0001]).

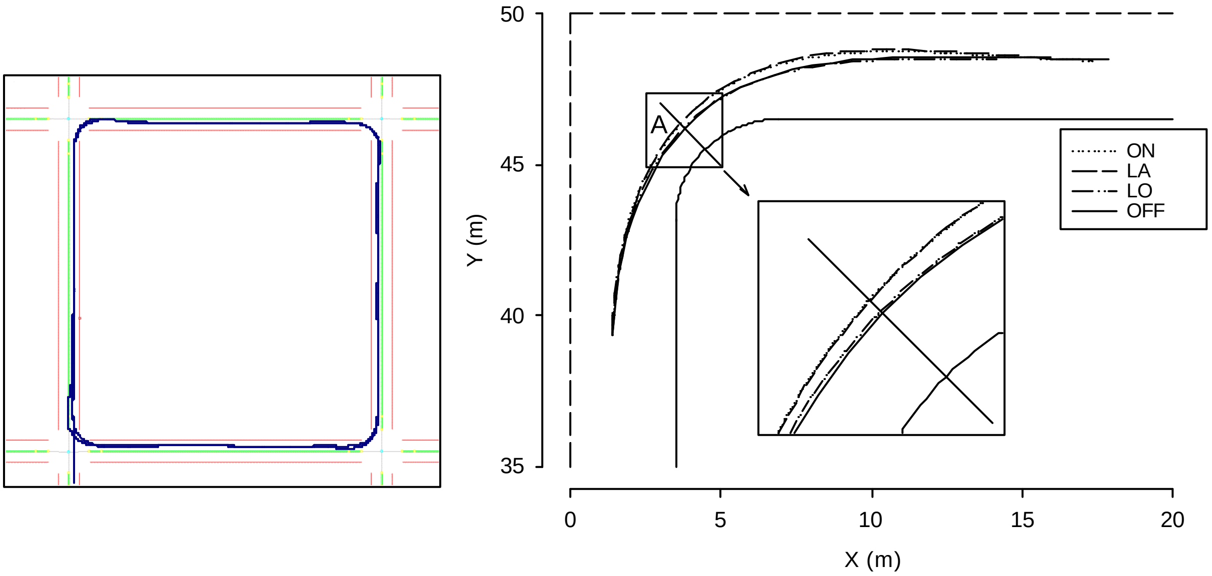

Figure 4: On the left, geometry of the road and superimposition of the car trajectory during one trial (two loops around the block). On the right, mean trajectories over all subjects and corners in the four platform conditions. A is the bisecting line of the corner.

Car dynamics on the bisecting line of the corner (point A)

Car linear velocity, angular velocity and lateral acceleration were calculated in point A (Figure 6). ANOVAs showed a significant influence of platform condition on linear velocity [F(3,507)=3.6, p=0.01] and angular velocity [F(3,507)=2.7, p=0.04]. Linear velocity was higher in conditions where longitudinal cues were absent, i.e. in LA (17.38±2.27 km/h) and OFF (17.61±2.10 km/h), than in the two other conditions, i.e. ON (16.91±2.20 km/h) and LO (16.89±1.99 km/h). Proprioceptive information relative to deceleration incited subjects to brake even more.

Car angular velocity depends both on driver's action on steering wheel and linear velocity. Supposedly, it is not a variable which is directly controlled by drivers and is highly dependent on road geometry. A significant difference between angular velocity in ON and in the three other conditions was found (lower in ON than in the others).

No significant influence of motion cueing on car lateral acceleration was exhibited (p=0.1). However, means of lateral acceleration were higher in conditions where linear velocity was higher (LA: 4.35±0.92, OF: 4.38±0.84, LO: 4.17±0.84, ON: 4.18±0.98 m/s^2).

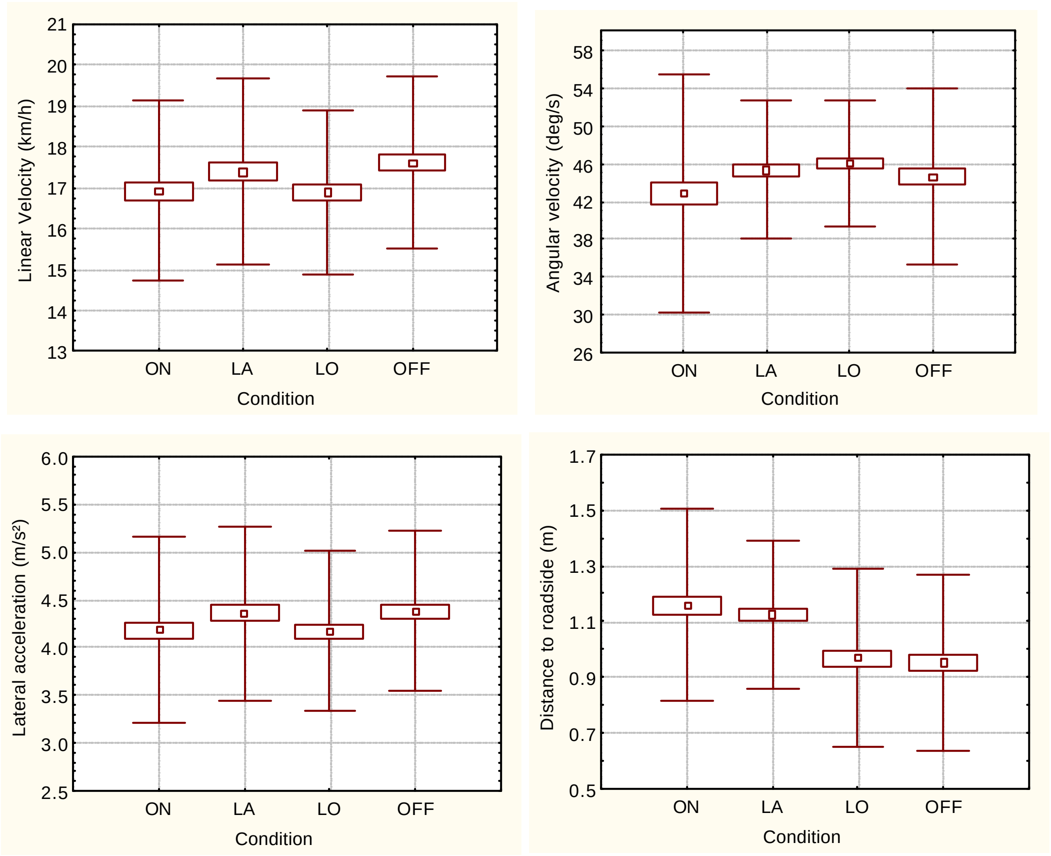

Figure 5 : Means (dots), standard error (rectangle) and standard deviation (bars) of linear velocity, angular velocity, lateral acceleration and distance to road side in the four conditions

Discussion

This experiment on cornering shows that lateral cues do have an influence on the driver's behaviour during this driving task. The most consistent effect is the fact that drivers take a wider turn when lateral cues are present (the car is more distant to the right side of the road). A significant difference between the means was found of the order of 20 cm. Further experimentation is needed to understand better underlying driving strategies for example efforts of subjects trying to minimise lateral acceleration during the turn. Another result is that longitudinal cues were shown to influence significantly linear velocity.

Conclusion

The experiment on braking revealed that motion restitution, although of limited amplitude, prevented subjects from performing too unrealistic decelerations. Indeed, when the motion platform was desactivated, subjects tend to reach increasing levels of decelerations from trial to trial. When the platform was activated, this bias in the behaviour was very much reduced although braking behaviour could not be qualified as being realistic. For applications implying vehicle control strategies these results show that the use of static simulator is not suitable while motion platform equipped simulators allow stable driving behaviour.

In the cornering experiment, an influence of motion cues on driving behaviour was also exhibited: lateral cues influenced the driver's control of the trajectory and longitudinal cues influenced linear velocity in the turn. Because of this double influence of longitudinal and lateral cues, the analysis of results is complex. Further work need to be carried out to understand what are the most useful degrees of freedom in a dynamic simulator, as well as determine what are the body/car motions that are efficiently involved in the sensorimotor control loop for car driving.

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