ANALYSIS OF THE VISUAL COMPENSATION IN THE RENAULT DRIVING SIMULATOR

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Abstract

Renault has developed a dynamic driving simulator based on a 6-dof Stewart platform for vehicle design, ergonomics and human factors. This motion platform is designed to give sensations of acceleration. Since a fixed-based display system is used, the movement of the platform can only produce those sensations if the virtual environment appears stable to the driver in the cockpit reference frame. This is currently performed at the IG level by a “visual compensation”, based at present on the platform positions issued by the motion system. There is thus a delay between the actual platform movement and the display of the corresponding simulated images.

This paper aims at analysing the impact of the visual compensation delay on the driver’s behaviour during an overtaking maneuver. Prediction algorithms aiming at reducing the apparent delay of the visual compensation are also evaluated. A new measurement system was designed to measure accurately this delay.

Although the measured transport delay can effectively be reduced by prediction algorithms from 115 to 30 ms, driving experiments suggest that drivers seem unaware of such delays in a typical highway manoeuvre. The adaptation mechanisms occurring when driving a vehicle may be the cause of this apparent insensibility to such discrepancies in visuo-inertial cues.

Résumé

Renault a développé un simulateur de conduite dynamique utilisant une plate-forme type Stewart à 6-ddl pour la conception d’automobile, et d’études ergonomique et de facteurs humains. La plate-forme mobile est conçue pour procurer des sensations d’accélération. Dans la mesure où un écran fixe est utilisé, les mouvements de la plate-forme ne peuvent donner cette illusion que si l’environnement visuel paraît stable dans le cadre de référence visuel du conducteur lié au cockpit. Ceci est réalisé actuellement au niveau du générateur d’images par une « compensation visuelle », calculée à partir d’informations de position du cockpit fournies par le système de mouvement. Il y a donc un délai entre la position réelle de la plate-forme et la correction des images simulées.

Cet article étudie l’impact de ce délai de compensation visuelle sur le comportement du conducteur lors d’une tâche de dépassement sur autoroute. Des méthodes de prédiction destinées à réduire le délai apparent sont aussi évaluées. Un système de mesure innovant a été développé pour mesurer ce délai de façon précise.

Bien que le délai ainsi mesuré puisse être réduit par les méthodes de prédiction de 115 à 30 ms, les expériences en conduite suggèrent que les conducteurs ne perçoivent pas ces délais lors de la tâche de conduite. Des mécanismes d’adaptation présents dans la conduite d’un véhicule pourraient être la cause de cette insensibilité apparente à des discordances entre stimuli visio-inertiels.

As discussed in [Kemeny 2001], the influence of transport delays on driving simulator fidelity is not sufficiently known yet. It would seem that its role is more important than that of the amplitudes of the produced sensorimotor cues themselves.

In particular, the co-ordination of visual and vestibular stimuli during self-motion seems an imperative requirement for driving simulators. However, due to technical limitations (computation time, communication delays, actuator performance limits, etc.), perfect synchronisation is not possible. Transport delay represents the time elapsed between a movement initiated by the driver and the restitution of the corresponding cues. Typical acceptable values for simulator transport delays are 150 ms for civil flight simulators [FAA 1991], 50 ms for conventional driving simulators [Park 1992], up to 20 ms for head-mounted display applications [Bloche et al. 1997].

Experiments in visuo-vestibular co-ordination have shown that observers may be unaware of fairly large discrepancies between physical and visual motion stimuli [Van der Steen 1998]. For instance, some authors are suggesting that the use of scale factors in the restitution of vestibular cues is realistic in dynamic simulators [Groen et al 1999].

Nevertheless, a satisfactory knowledge of the necessary co-ordination between visual and inertial cues is still to be investigated, according to the different particular driving simulator configurations.

Here, we take into consideration the synchronisation of visual and inertial cues in the Renault Dynamic Simulator, a moving-based dynamic driving simulator (Figure 1).

During the simulation, the actual displacement of the motion platform does not correspond exactly to that of the simulated vehicle, due to the limitations in actuator stroke. Motion control algorithms filter out low-frequency linear accelerations, which are rendered partly by tilting the cockpit. During such displacements, the visual environment surrounding the driver should remain stable in his/her visual reference frame, i.e. the cockpit. When the projection system is not physically coupled to the motion platform, a visual compensation has to be carried out by the image generator. With a fixed-based projection system, the virtual driver’s point of view has to be offset by the displacement of the motion system.

Practically, discrepancies may occur because of the inaccuracies in the real-time measurement of the actual displacement of the motion system, and the computation time needed to perform the visual compensation. The transport delay appearing between platform movement and corresponding images creates variations in the relative position of visual references, which may induce bias for the drivers in their perception of a stable outside world and the control of their vehicle in certain manoeuvres.

EXPERIMENTAL EQUIPMENT

Driving simulator

In the Renault Dynamic Simulator, a full scale instrumented Renault Clio cockpit is fixed on a 6-axis electromechanical platform for rendering vehicle accelerations/vibrations. Force feedback on the steering wheel, brake, clutch and accelerator pedals are provided on the simulator. A SGI Infinite Reality workstation generates in real time at 20-60 Hz a 150°×40° front view of the road environment. Three Barco CRT 808S projectors are used to display this view. Rear-view mirrors images are rendered by three Pentium PCs and LCD projectors. The simulator software package SCANeR© II runs the traffic, circuit scenarios, vehicle dynamics and images generation process [Kelada and Kemeny 1995, Reymond et al 2001].

The Rexroth Hydraudyne Electrical 6DOF-1000kg motion platform allows about ±22cm (surge, sway, heave) and ±15° (yaw, pitch, roll) maximum displacements. It is controlled in position at 100Hz to render linear and angular accelerations. A classical motion control strategy is implemented: transient part of the accelerations, selected by a high-pass filter, is integrated twice and rendered directly. The low frequency component of the accelerations is used to compute the tilt-coordination pitch angle. To bring the platform back to the neutral position ("wash-out"), a high-pass filter is used. An additional 'anti-backlash' filtering reduces high-pass filtering artefacts [Reymond and Kemeny 2000].

Figure 1: Renault Dynamic Simulator

Visual compensation

The visual compensation is performed by the simulation software using the platform position information sent by the motion system at 100 Hz through Ethernet communication.

The advantage of this method is that the visual compensation is based on the actual length of the platform actuators. Thus, nonlinearities in the platform response are taken into account in the computation of the images. However, the positions are received *a posteriori* due to the internal acquisition and processing time of the motion system. This method is therefore less favourable in terms of transport delay.

The data flow corresponding to this algorithm is represented in Figure 4. It corresponds to the data path going from A to D1.

Measurement of transport delay

The delay is estimated off-line from the cross-correlation between a measure of physical movement (i.e. movement of the platform in a dynamic simulator) and of visual scene movement (movement of the simulated images on the display screen). These signals are measured by a system completely separated from the simulator equipment.

The physical movement is measured with an analogue CrossBow inertial sensor fixed on the platform. Its bandwidth is [0-125Hz]. In this experiment, the input of this subsystem is a wave position trajectory along the lateral axis of the cockpit.

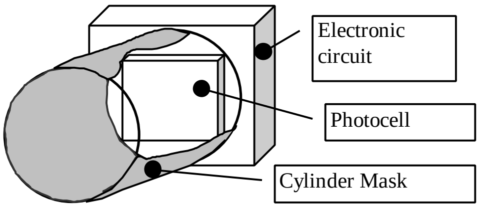

Figure 2 : Visual scene movement measurement system

The visual scene movement is measured with a system (VSMS) composed of a Burr-Brown OPT101 single supply photocell, its electronic circuit, and a black cylinder mask. The cylinder mask defines the illuminated surface to which the photocell is exposed to.

Signals from the accelerometer and the photocell are acquired at 500Hz by a signal processing system composed of a 12 bits ComputerCards acquisition card linked to PC (Pentium II).

The signal from the VSMS respects the Shannon condition if the upper frequency of the lateral displacement of the platform is inferior to 20/2=10 Hz (for an image refresh rate of 20 Hz). In this experiment, displacements of the platform are sinusoidal movements at a frequency inferior to 10 Hz in order to respect this condition. The Shannon condition is also respected for the accelerometer signal.

Figure 3 shows typical measures from the sensors and their cross-correlation.

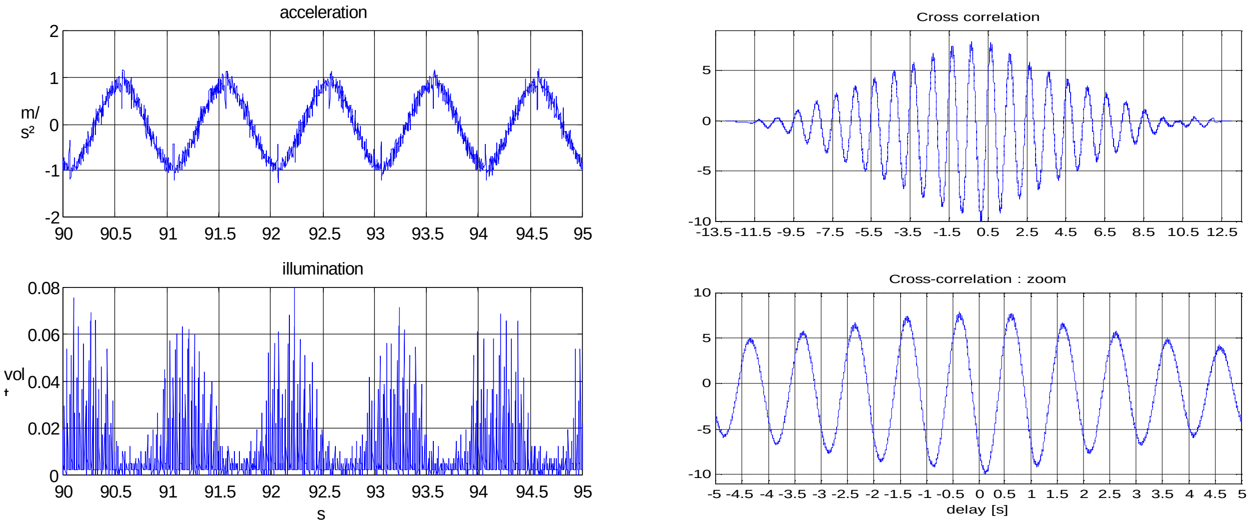

Figure 3 : Typical measures for the determination of transport delay

With the current set-up of the simulator, the transport delay of the visual compensation was measured with this equipment at different frequencies and amplitudes of platform motion. Results show that this delay is independent of the frequency of the motion input, and is variable from one measurement to an other with a distribution centred around 115 ms.

Transport Delay reduction techniques

Several techniques were implemented to reduce this transport delay. The principle is to directly sent position offset commands to the image generator in real-time, without waiting for the position information sent by the motion system. The commands are therefore less accurate spatially, but are more 'in-time' than with the previous method. Furthermore, prediction algorithms are used to further reduce the apparent delay of this information in the data flow.

The following techniques were implemented:

- direct feedthrough of position commands (referenced as technique 1)
- direct feedthrough of online-predicted platform position commands (technique 2)
- direct feedthrough of model-predicted platform position commands (technique 3)

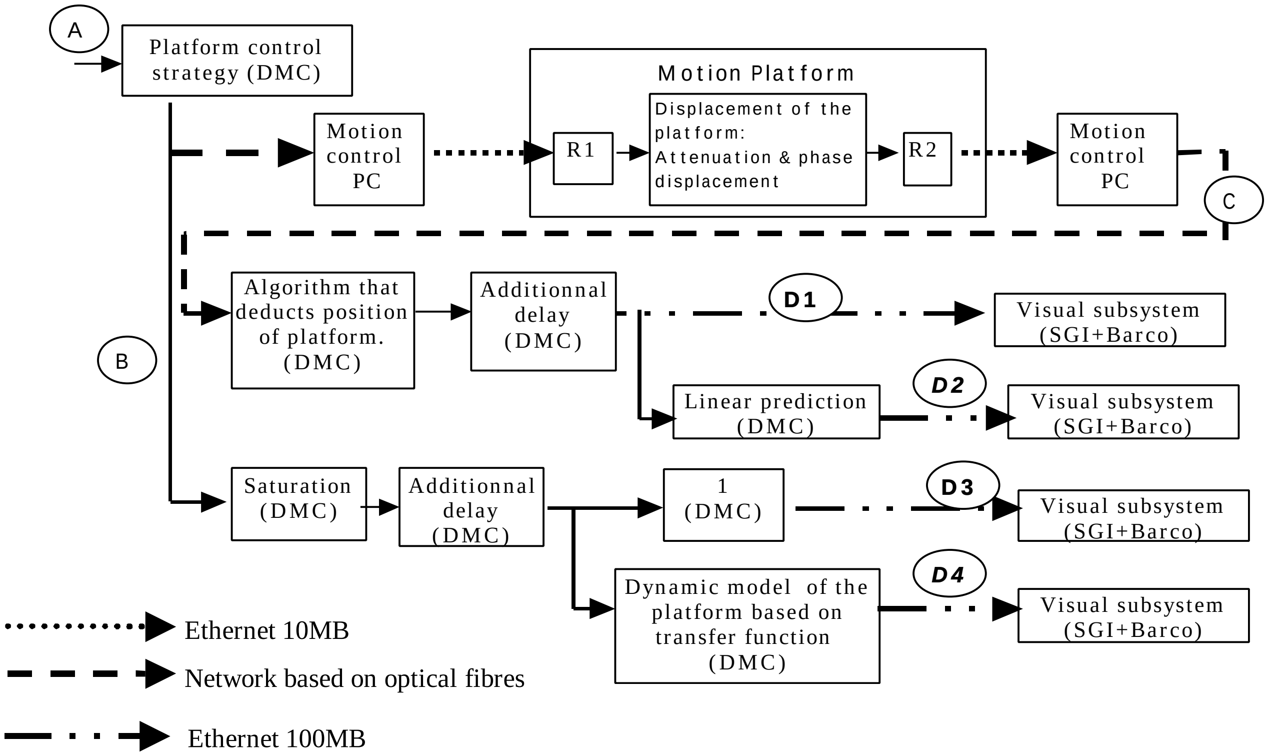

Figure 4 : data flow

Technique 1: direct feedthrough
The principle of the first algorithm is to suppose that the platform is a system with no delay and that it has unity gain. The data flow corresponding to this algorithm is represented in the figure 4, it goes from A to D3. The positions thus sent to the visual subsystem are not the exact positions of the platform: there is thus some geometric error in the computation of the visual compensation.

The delay of the visual compensation measured with the system described above shows decreasing values when the frequency of the input movement increases. This is due to the fact that this algorithm doesn't model the phase displacement of the platform. For a sinusoidal movement at 1 Hz, the delay is 40ms (average).

Technique 2: feedthrough with online prediction
The principle of this algorithm is to *predict* the actual positions of the platform from the positions sent by the motion platform. The data flow corresponding to this algorithm is represented in the figure 4, it goes from A to D2.

The evolution of the positions of the platform has been supposed autoregressive (AR): forecast values of the positions are dependent on past values. This AR model is obtained from a linear prediction algorithm based on a Levinson recursion [Bellanger 1989]. The performance of this algorithm has been studied for two couples of parameters: order 15 and step 8, and order 10 and step 8. In both cases, the apparent movement of the visual scene was slightly jerky, due to the error of prediction. The transport delay measured with this algorithm fluctuated around 50 ms.

Technique 3: feedthrough with online prediction
The principle of this algorithm is the same with the first one: we suppose the platform is a system with no delay. A model of the dynamic of the platform based on a previously measured transfer function is used to reduce the position estimation error. The data flow corresponding to this algorithm is represented in the figure 4, it goes from A to D4.

In this case, since the used model of the dynamic of the platform take into account the phase displacement, the delay is not linked to the frequency of the movement. The transport delay measured with this algorithm fluctuates around 30 ms.

The third method seems to be most effective technically in reducing the apparent delay. In the following, the efficiency of these different techniques is assessed experimentally from the driver's point of view.

VALIDATION EXPERIMENTS

Seven participants, aged 25 to 35 carried out static perceptual and driving task experiments. All the subjects were familiar with virtual applications and in particular with this driving simulator.

Experiment 1 : Estimation of spatial stability

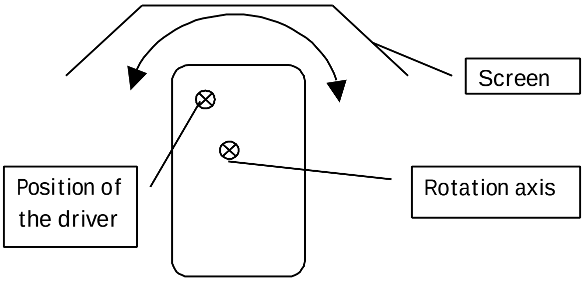

Figure 5 : set-up of Experiment 1

In this experiment, the impact of the visual compensation delay in passive situation is evaluated. Motion stimuli in yaw were generated artificially by the simulator, while the car was kept stopped on the road. The task of the participants was to concentrate their attention to the variations of position of the car relative to the road surface.

The experiment was composed of 14 sessions. A session consisted of: 1) generating a yaw motion wave (frequency of 1 Hz, amplitude of 1.15°) 2) using one of the three different visual compensation algorithms 3) adding an artificial delay (0 ms, 80ms, 150ms, 200ms). At the end of each session, we asked to the participants if they had the impression that the car moved on the surface of the road.

The following Figure represents the results of this experiment. The initial simulator configuration used at the present time is referenced 0.

Experiment 1				Impression that the car moves on the surface Of the road				
Sessions	Used algorithm	Additional delay	Parameter	Yes, a lot	Significantly	Slightly	Practically not	Not at all
1	0	0 ms		░	⬛	░		
2	0	80ms		░	⬛			
3	0	150 ms		▓	⬛			
4	0	200 ms		▓	▓	░		
5	1	0 ms					▓	⬛
6	1	80 ms			⬛	▓		
7	1	150 ms		▓	⬛			
8	1	200 ms		⬛				
9	2	0 ms	Order: 15, step: 8		░	⬛		
10	2	0 ms	Order: 10, step: 8		▓	▓		
11	3	0 ms				▓	⬛	
12	3	80 ms		░	▓	▓		
13	3	150 ms		▓	▓	░		
14	3	200ms		⬛	░		░	

Number of participants

⬛	5 or more
▓	3 to 4
░	1 to 2
	0

Figure 6: results of the experiment 1

With the initial simulator configuration, 85% of the participants had the sensation that the car was “floating” on the road (yes, a lot/significantly). With the three proposed prediction techniques (sessions 5, 9-10 & 11), the majority of drivers observed a stable car position (slightly/practically not/not at all). When the transport delay of the visual compensation was over 100ms (average), all the participants had clearly the impression that the visual scene was not stable: it was as the car was “gliding over from the right to the left and from the left to the right” or “doing a yawing movement”.

Sessions 9 & 10 were the only experiments during which drivers reported to be disturbed. They estimated the origin of this perturbation was the jerky movement of the visual scene. Nevertheless they considered (in average) that the car was not moving.

However, this method could not be used in a driving simulator to reduce the visual compensation delay because it reduces definitively the realism of a simulation.

A limitation of this experiment is that participants were faced to a visio-vestibular conflict: the visual scene produced movement stimuli physically incoherent with the motion stimuli produced by the platform. Therefore, their judgement concerning the visual stability could be biased.

Experiment 2: Overtaking manoeuvre

The goal of this experiment is to analyse the impact of the transport delay and the defined algorithms on the driver’s behaviour. More precisely, the behaviour of the driver is analysed through a defined task in which the driver has to change lanes on a straight highway inside a sparse traffic. The circuit reproduced in simulation was a section of a direct two-way highway. There were eleven cars on the road. Their speed was fixed to 90 km/h and they stayed on their way. Figure 7 represents schematically the traffic on the road.

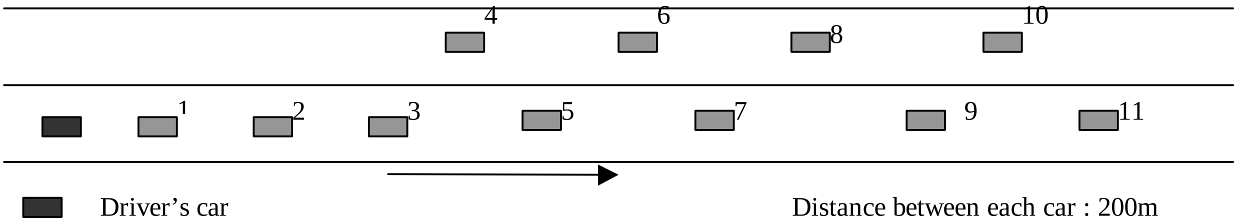

Figure 7 : traffic set-up of Experiment 2

Drivers were asked to drive at 130 km/h in their lane, to overtake incoming cars one at a time, and to concentrate their attention to the stability of the visual scene. This experiment was composed of 5 sessions, using one of the different delay compensation techniques and also artificially adding a delay (0 ms, 600ms, 1200ms). The influence of the algorithm based on feedthrough with online prediction was not tested because of the negative results of the first experiment.

In this experiment, to analyse the impact of those methods on the behaviour of the drivers, we investigated the role of the following parameters recorded at 20 Hz: steering wheel angle, lateral position of the car in the virtual world.

At the end of each session, the participants were asked to describe motion of the car relative to the road. The following chart represents the results of this experiment.

Experiment 2			Behaviour of the car with the road: the car		
Sessions	Used algorithm	Added delay	Had a vertical movement	Skidded on the road	was fixed to the road
1	1	0	□	□	■
2	0	0ms	□	□	■
3	0	600 ms	□	▨	▨
4	3	0 ms	□	□	■
5	0	1200ms	▨	▨	░

Number of Participants	
■	5 or more
▨	3 to 4
░	1 to 2
□	0

Figure 8: results of the experiment 2

The majority of the drivers reported not to perceive a difference between sessions 1, 2, 3 and 4. They had the impression to drive a real car (good control of the dynamic of the car, impression the car had a normal behaviour).

In session 4 and more particularly in session 5, some drivers verbally interpreted the delay of the visual compensation as if the car was skidding on the road. In session 5, 85% of them said they were significantly disrupted. They had the impression that the steering wheel was not correctly calibrated: the car moved too much compared to the steering wheel movement. There is also an impact on the tilt-coordination: on account of this delay, the relative position of the horizon fluctuates, giving the drivers the impression that the car has some unrealistic vertical motions.

To analyse objectively the impact of the delay on the behaviour of the driver, the number of steering wheel reversals was computed as well as the lateral position of the car. The following figure shows a typical evolution of the steering wheel angle and of the lateral displacement during the session 5.

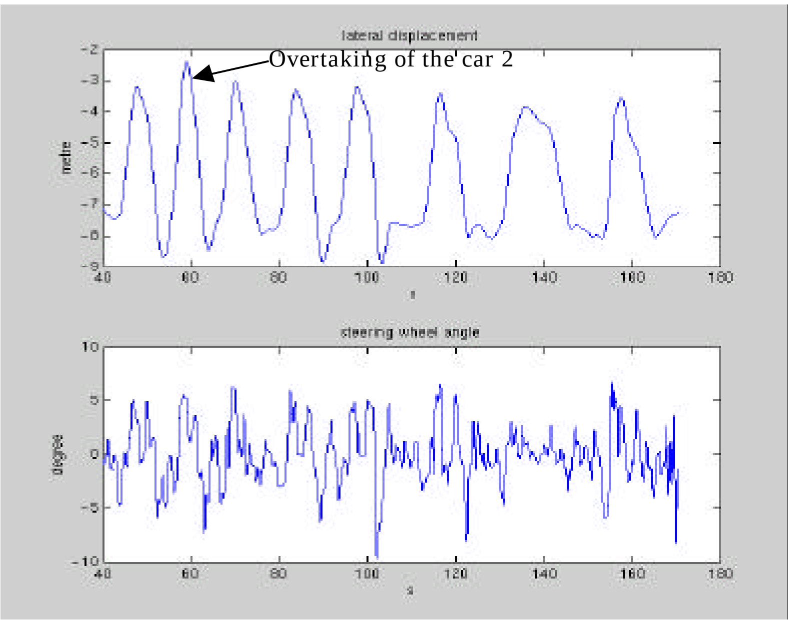

Figure 9: typical measure of the steering wheel position and the lateral displacement.

Note : a steering wheel reversal is detected if the derivative of the steering wheel angle changes signs and the amplitude of the variation of the steering wheel angle is higher than 1°.

The following chart shows that the number of steering wheel reversals and the lateral displacement during the overtaking of cars #2 to #5, and the overtaking of cars #7 to #11, average over all 7 participants.

Experiment 2		
Sessions	Used algorithm	Additional delay
1	1	0 ms
2	0	0 ms
3	0	600 ms
4	3	0 ms
5	0	1200ms

during the overtaking of the cars 2 to 5	
Number of steering wheel reversal during the overtaking	Min. and max. lateral displacement [m]
4.22	[1.38 ; 4.20]
4.16	[1.22 : 4.30]
4.42	[1.04 ; 4.41]
4.14	[1.10 ; 4.22]
4.71	[0.02 ; -4.61]

Sessions	Used algorithm	Additional delay
1	1	0 ms
2	0	0 ms
3	0	600 ms
4	3	0 ms
5	0	1200ms

during the overtaking of the cars 7 to 11	
Number of steering wheel reversal during the overtaking	Min. and max. lateral displacement [m]
4.15	[1.2 ; 4.34]
4.01	[1.12; 4.32]
4.35	[1.08; 4.48]
3.87	[1.20; 4.21]
4.60	[0.8; 4.52]

Note : Edge of the road : [0 5m]

Figure 10 : results of the experiment 2

In this experiment, drivers reach the edge of the road more often when the delay is higher than 1.2 s. They perform more steering wheel corrections not to go out of the road. This confirms their impression of a bad calibration of the steering wheel in session 5.

Nevertheless, during a session, the number of steering wheel reversals and the amplitude of the lateral displacement decrease. This suggests that drivers can integrate the dynamic of the simulated car and therefore anticipate its behaviour. They adapt their driving progressively to the perceived behaviour of the vehicle. However, due to high variability of the behaviour and to limited number of participants, the results of this experiment show a trend which has to be confirmed by further works.

In this driving task, the algorithm based on a model of the platform as a unitary gain, the one based on transfer functions of the platform and the actual one give to the drivers the impression that the visual scene is stable and that it is quite easy to control the dynamic of the car.

CONCLUSION

In dynamic driving simulators with fixed display systems, a visual compensation is necessary to maintain a visual stability for the driver. A delay in this process decreases the coherence between the visual and the inertial stimuli and could induce a bias in the driver’s behaviour. This study represents a step toward the comprehension of the impact of such a delay.

Seven drivers participated to two experiments. The main result of this work is that for long delays, drivers observed incoherence (bias) between their commands and the vehicle motion. For instance, some of them had the impression that the car was skidding or moving up and down while overtaking. Experiments also suggest that in passive situation (Experiment 1), this bias is perceptible for a delay of only 100ms yet while driving the simulator (Experiment 2), this delay is nor clearly perceived up to 700ms.

Though drivers are able to compensate delays and to maintain the control of the car, delays are to be reduced. Three visual compensation algorithms based on a model of the dynamic of the platform were proposed to reduce this delay. Their performance depends on the accuracy of the model and on the configuration of the simulator. A model simply based on a linear prediction was shown unsuitable. An algorithm based on transfer functions of the motion platform was shown to be more efficient to reduce this apparent delay.

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