REAL VS VIRTUAL DRIVING OR HOW TO IMPROVE THE REALISM OF A DYNAMIC DRIVING SIMULATOR

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Abstract

Most of the dynamic driving simulators are using a constant under-unit scale factor, which is recommended between 0.4 and 0.75 depending on the studies, to produce realistic driving perception. However, other studies on passive driving showed that the scale factor should depend on the level of acceleration, suggesting that a constant scale factor would be less efficient. But none of these studies have validated their results obtained on simulators by comparing them to real driving situations. In our study, we aimed to determine 1/ the best value of the scale factor for the perception of a realistic acceleration, 2/ if this scale factor should be constant or not (evolving with the level of acceleration) by comparing driving behaviours recorded in real and comparable simulated situations. The results show a very small behavioural variability between the real and the virtual driving tasks. The most realistic combination of scale factor and tilt/translation is influenced by the tilt/translation ratio, especially when less tilt is used.

Key words: perceptual validity, longitudinal acceleration, self-motion perception, scale factor, tilt-coordination.

1. Introduction

It is generally accepted that the validity of a driving simulator is based on several aspects: physical, perceptual, relative behavioural and absolute behavioural validity [Rey1]. Still, a motion based driving simulator has a limited physical validity due to its mechanical limits. Therefore, the optimization of the driving simulators should mostly be based on perceptual validity, which should consist in comparing the driver's multisensory perception of self-motion to a real situation. Yet, most of the studies carried out until now were concentrating only on the motion perception in virtual environment, weakening the conclusions on perceptual validity. Nevertheless, it is known that, on dynamic driving simulators, the vehicle motion is overestimated and therefore, a constant under-unit scale factor must be used for the motion cueing algorithms [Gro1]. The paper of Berthoz and colleagues [Ber2] showed that this scale factor should be between 0.4 and 0.75 depending on the studies. However, our previous study on motion perception in driving simulators suggested that this scale factor should not be constant, but adapted to the level of acceleration induced by the driving task [Str2]. Still, scale factor is not the only useful parameter for the simulation of linear accelerations. The tilt-coordination technique, which is used on almost all driving simulators, brings an important benefit for the simulation of strong accelerations. However, there are still some questions regarding the quantity of tilt and translation that should be used in order to produce a realistic acceleration [Gro2, Ber1]. This is due to the fact that the perception of linear acceleration in passive driving seems to be directly influenced by the tilt/translation ratio [Str1]. Nonetheless, there is a perceptual difference between passive and active driving, given the cognitive involvement in the task of the driver during the latter (man-in-the-loop) and the fact that the acceleration is produced by the driver himself, while he's submitted to a predefined profile of acceleration during passive driving. Then, these previous contradictory results concerning the scale factor as well the effect of the tilt/translation ratio have to be accurately questioned in a more systematic way. As a result, we propose to implement a study on active driving that allows us to a/ evaluate the value of the most adapted scale factor b/ determine if the scale factor should be constant or not (evolving with the level of acceleration), c/ evaluate the best tilt/translation ratio for active driving and last, but not least, d/ to compare the induced perceptions of simulated longitudinal accelerations to a similar real car driving task and e/ to validate an experimental design adapted for driving simulation studies. This will allow us not only to answer to the previous questions, but also to define a setting of parameters for the motion cueing algorithm that will improve the realism of our simulator and therefore to reach a perceptual validity.

This study is included in an OpenLab research program, developed in collaboration with the Institute of Movement Sciences of Marseille.

2. Background

Our dynamic driving simulator, Sherpa² [Str1, Str2], like all dynamic driving simulators, needs to use technical artifices in order to simulate a linear acceleration. The first used artifice is a physical one, called scale factor: the real value of the acceleration is reduced by an **under-unit scale factor** (the choice of the scale factor is due to the overestimation of accelerations on dynamic driving simulators [Gro1]):

$$\underbrace{\ddot{x}_t^{Sherpa}}_{\substack{Simulated\ acceleration\\ on\ Sherpa}} = \underbrace{f(\ddot{x}_t^{MDV})}_{Scale\ factor} \times \underbrace{\ddot{x}_t^{MDV}}_{\substack{Real\ acceleration\\ output\ of\ véhicle\,dynamics\,\mathrm{mod}el}} \quad (1)$$

The second artifice is of psychophysical order and is called tilt-coordination. It uses the tilt of the cabin (and therefore of the subjects) to partly simulate linear accelerations [Gro2]. In order to determine the tilt/translation ratio, we use a parameter called **cut-off frequency**, which defines the limit between the tilt and the translation. From a perceptive point of view, a constant tilt could be perceived as a constant acceleration [Hol1]. The tilt is then produced with an under vestibular threshold angular velocity with the rotation point referred to the head of the driver.

In the literature, the scale factor is traditionally reported as being the most efficient between 0.4 and 0.75. However, multiple driving tests conducted on our simulator show that this value is not adapted to our device, being considered too high. Therefore, in the present study, we try to determine the scale factor and the cut-off frequency that produce a motion perception close to the one perceived during a real driving (baseline condition). The cut-off frequency represents a constant value, but the scale-factor can evolve with the level of acceleration, therefore it is defined as below:

$$f(\ddot{x}_t^{MDV}) = a - b \times \ddot{x}_t^{MDV} \quad (2)$$

, with $f(\ddot{x}_t^{MDV}) \in \Re_+$.

3. Methods

3.1. Subjects

30 persons participated to our study. All subjects were PSA's employees who volunteered for the study.

3.2. Experimental devices

The experimental devices used in the study were the Sherpa² driving simulator [Str1, Str2] and a real vehicle, a Citroën C3 HDI 70CH. The chosen driving situation was the take-off, meaning an acceleration from 0 to 30km/h on a straight road (in-situ of PSA's Velizy Technical Center). The virtual environment used on the dynamic driving simulator was identical to the real driving environment from visual, auditory and vehicle's dynamics point of view.

3.3. Task

The task of the participants was to accelerate from 0 to 30 km/h on straight line (speed limitation to 30km/h), without changing the gear. Once the speed of 30 km/h reached, they had to maintain the speed for 1-2 seconds and then to slowly brake until full stop. No acceleration profile was imposed; the participants were advised to drive in their own "driving style".

Each participant started the test by driving the real vehicle, producing up to 40 accelerations in order to be able to reproduce this acceleration on the dynamic driving simulator. Once they were confident in their repeatability, the subjects were taken on the driving simulator to reproduce the same task, by pairs, using the experimental design described below. At the end of each pair of accelerations, they had to answer to 2 questions: 1/ which acceleration seemed to be more realistic (closer to the real vehicle acceleration)? 2/ which acceleration was stronger?

Before starting to drive the real vehicle or the driving simulator, the participants were submitted to a familiarization phase of about 10 minutes on each device.

3.4. Experimental design

Once arrived on the dynamic driving simulator and after the familiarisation phase, the participants were asked to reproduce the acceleration memorized during the real car driving situation. Each reproduced acceleration was considered to be a test condition, the motion cueing parameters being changed from one condition to another.

The tested conditions were defined by taking into account the cut-off frequency and the parameters *a* and *b* of the linear scale factor (see equation 2). Therefore, the triplet (*a,b,Fc*) represents a test condition. For each variable of the triplet, we chose 2 values:

$$\begin{array}{c} a \in (0.4; 0.5) \\ b \in (0; 0.05) \\ Fc \in (0.6; 1.5) \end{array} \qquad (3)$$

These choices were made by taking into account the physical limitations of the simulator (position, speed, linear and angular acceleration) and on-the-table simulations that were made to verify the correlations of driver's sensations (analysis of acceleration's profile).

The experimental design was a complete-crossed factorial design. The factors are the parameters (*a,b,Fc*) with 2 values for each, meaning 8 test conditions (see table 1).

Table 1. The 8 test conditions.

Condition	a	b	Fc
1	0.4	0.05	0.6
2	0.4	0	0.6
3	0.4	0.05	1.5
4	0.4	0	1.5
5	0.5	0.05	0.6
6	0.5	0	0.6
7	0.5	0.05	1.5
8	0.5	0	1.5

The 8 test conditions were presented in pairs using William's Latin Square, which allowed balancing the order and report effects. The pairs A/B and B/A were balanced over the total panel of subjects. Each participant had $\frac{8\times7}{2}=28$ pairs to test. These pairs were presented to the participants in a pseudo-random order. This experimental design was repeated 3 times by each subject, meaning 84 trials per person.

For the real vehicle, there were 30 subjects x 20 profiles x 3 repetitions = 1800 acceleration profiles. For the driving simulator, there were 30 subjects x 56 profiles x 3 repetitions = 5040 acceleration profiles.

3.5. Data analysis

During each acceleration, on real vehicle and on driving simulator, some objectives measures were recorded: throttle pressure, vehicle speed, displacement time, acceleration profile.

By analysing the acceleration profiles on real and virtual driving, we tried to determine:

- if drivers are able to reproduce the same acceleration profile in time and intensity, from one trial to another, and for both real and virtual driving,
- if drivers are able to reproduce a real acceleration profile on a dynamic driving simulator, independent of the MCA's parameters (triplet (a,b,Fc)),
- if there are several classes of acceleration profiles and therefore several classes of drivers,
- the relationship between the real car and the driving simulator.

Given the non-linearity of an acceleration profile (see fig.1), we calculated a 4-order polynomial trendline for each recorded profile and analysed the maximum point x_m, the corresponded time t_m and the total time t_t (see fig. 1). A phase 1 analysis of these factors was realized in order to underline the abnormal data. A phase 2 analysis was realised in order to define a profile-band that will allow determining the type of a subject for future experiments.

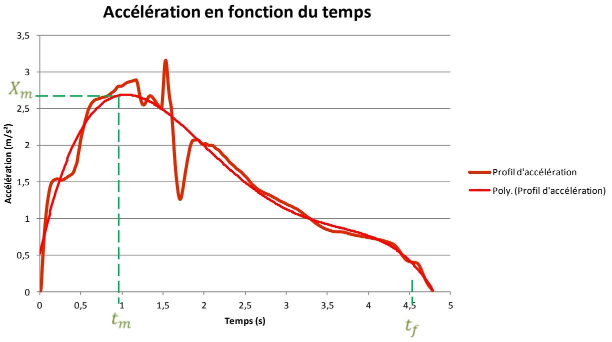

Fig. 1. Example of an acceleration profile.

In parallel, a subjective analysis of participants' responses on driving simulator was realised by using a Bradley-Terry-Luce model [Bra1, Luc1]. The responses for the two questions were analysed separately. For each subject and each pair, we computed a Bradley score that allowed us to determine the discriminant participants. Once the non-discriminant subjects were removed from the panel, a PCA (principal component analysis) was realised in order to evaluate the consensus of the panel and to determine the groups of homogeneous subjects. In the end, ANOVA and Duncan test were realised to determine the test configurations that differentiate from the others, and to determine the influential test factors. A partial eta² was also calculated, which allows determining the influence of one factor when the other factors are controlled. If eta² is around 0.01, there is a small effect of the factor. If eta² is around 0.06, there is a moderate effect of the factor. If eta² is around 0.14 or higher, there is a large effect of the factor.

4. Results

4.1. Descriptive analysis of acceleration profiles on real car and driving simulator

The analysis of the driving simulator's profiles highlighted exploitable and non-abnormal data for 21 subjects (fig.2). The corresponding data were also analysed on the real vehicle, which allowed the comparison between both devices.

By analysing the maximum point of the profile (x_m) and its correspondent time (t_m) (fig.2), 2 main groups of profiles were determined (Group A and Group B) and 3 secondary groups (see fig.3). For each group, a profile-band was computed.

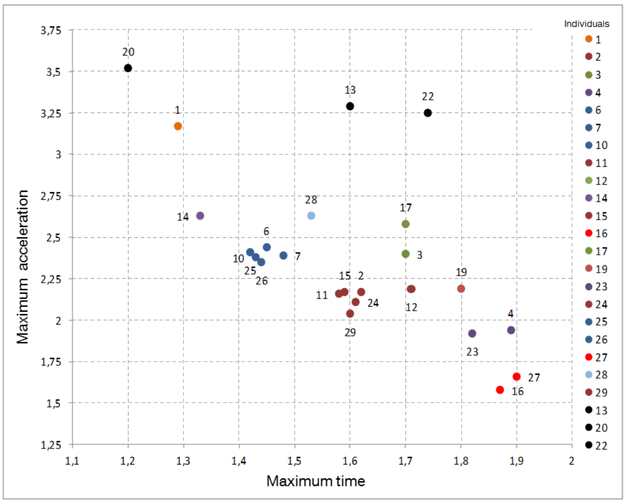

Fig. 2. The mean value of maximum accelerations and their correspondent time for each exploitable subject on driving simulator.

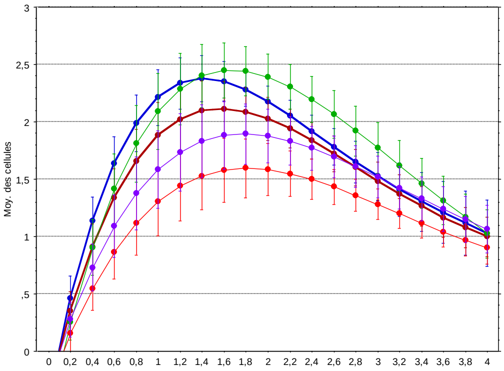

Fig. 3. The groups of acceleration profiles determined on dynamic driving simulator.

The analysis of real vehicle profiles showed a faint influence of the first repetition, which was not observed on the simulator. However, the participants presented a good reproducibility of the individual profiles. On the simulator, there were some atypical individuals, but most of the participants presented a good reproducibility of their profiles. The comparison between the real vehicle and the driving simulator showed that the subjects are able to reproduce their acceleration from real to virtual environment.

4.2. Analysis of subjective responses on driving simulator

4.2.1. Analysis of the realism of the acceleration

The analysis of the individual Bradley score for question 1 (realism of the acceleration) determined 75% of discriminant subjects. The PCA determined 1 group of subjects. The ANOVA and a Duncan test determined a significant influence of the test conditions (p=0.000, F=26.034), but no influence of the individuals (p=0.601). For the test conditions, an influence of the 3 variables (a,b,Fc) was observed, the most influential being the cut-off frequency (Fc) with a partial eta²=0.550. However, an interaction between *a* and *b* was also observed (p=0.000, F=2.769): the influence of a when b≠0 is weak, while its influence is stronger when b=0. There was no interaction between the cut-off frequency (Fc) and the scale factor (a,b) (p=0.142 and p=0.557). The most realistic conditions were considered to be conditions 1, 5, 2 and 6, for which Fc=0.6 (see fig. 4).

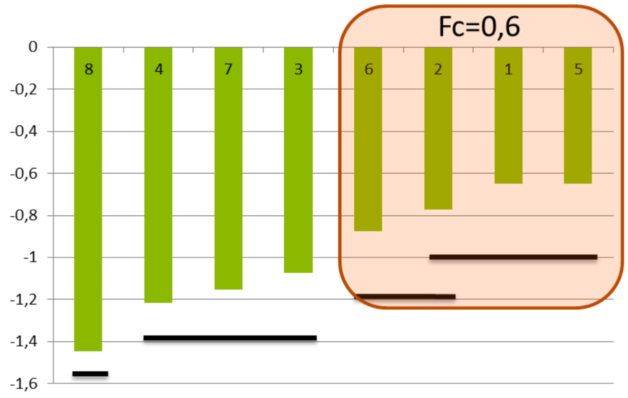

Fig. 4. The classification of test conditions by their realism, from non-realistic (left) to the most realistic (right).

4.2.2. Analysis of the realism of the acceleration

The analysis of the individual Bradley score for question 2 (intensity of the acceleration) determined only 50% of discriminant subjects. The PCA determined 1 group of subjects. The ANOVA and a Duncan test determined a significant influence of the test conditions ($p=0.000$, $F=11.410$), but no influence of the individuals ($p=0.888$). For the test conditions, an influence of the 3 variables (a,b,Fc) was observed, the most influential being b with a partial $eta^2=0.415$. No significant interaction between the 3 variables *a*, *b* and Fc was observed ($p=0.429$ for (a,b), $p=0.273$ for (a,Fc), $p=0.748$ for (b,Fc)). The conditions for which the acceleration was perceived as intensive were the conditions 8, 6 and 4, for which b=0 (see fig. 5).

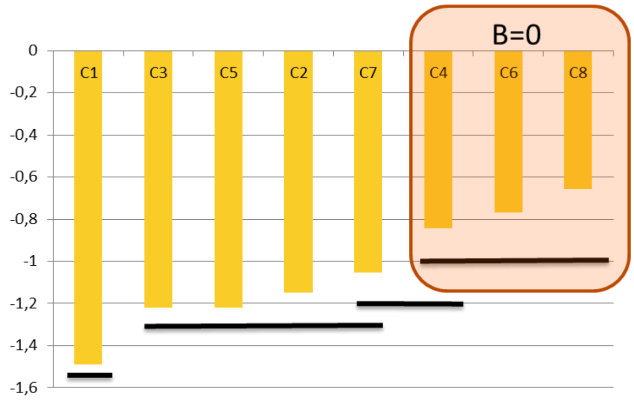

Fig. 5. The classification of the test condition by the perceived intensity of the acceleration: from the less intense (left) to the most intense (right).

5. Discussion

Dynamic driving simulators need to be validated from a perceptual point of view. Through this experiment, we tried to go beyond the previous studies and to compare the perception of acceleration on the simulator with the perception of acceleration on a real vehicle.

Moreover, our study had helped us to validate an experimental design adapted to our driving simulator, but also to validate our Motion Cueing Algorithm.

For the validation of the experimental design, we analysed the acceleration profiles realised on real vehicle and on driving simulator in order to determine if non-expert drivers were able to reproduce the same profile several times, but also if they were able to reproduce it on the simulator. We also wanted to see if there were several classes of drivers according to the acceleration profile and determine a relationship between driver's behaviour on the real vehicle and on simulator by comparing his acceleration profiles.

For the validation of our MCA, we tried to determine the influence and the interaction between the scale factor and the cut-off frequency on the perception of longitudinal acceleration for take-off, in order to obtain a more realistic driving simulator. The results clearly show that the two MCA parameters, scale factor and cut-off frequency, play an important role in the realism of the simulator's motion. However, it seems that the choice of these parameters is not so simple, because it depends on the goal of the simulation.

5.1. Validity of experimental design

The analysis of acceleration profiles determined that there are two main classes of drivers: the drivers that accelerate rapidly and reach a maximum acceleration of 2.5 m/s^2 (mean value) in about 1.4 sec and the drivers that accelerate slower (mean value of 2.1m/s^2) in more time (1.6 sec) (see fig.3). However, the two acceleration profiles are not so different. Moreover, these results showed that the non-expert drivers are able to reproduce the same acceleration profile on real vehicle and on dynamic driving simulator, at least for this specific driving situation, the take-off. This observation underlines the validity of the experimental design built for this study. However, further validations are required for other driving situations, like braking, before generalising the design for all simulations. Moreover, the obtained data represent the baseline for the implementation of a predictable model for driver's profile.

5.2. Realism of the acceleration

In this study, the perceptual validity of Sherpa² was questioned by comparing the real and the virtual driving. The results of this study show that the ratio tilt/translation plays an important role in the perception of a realistic acceleration during active driving. Our results mainly show that it is important to adjust the cut-off frequency so that the level of tilt remains lower than the level of translation, independently of the maximal level of acceleration (see the groups of profiles). Indeed, all of our participants complained of strong tilt during the conditions with Fc=1.5. It confirms the statistical analysis showing that the less realistic conditions were conditions 8, 4, 7 and 3, with Fc=1.5. These results are complementary to the results obtained on passive driving that showed that the tilt/translation ratio was less important than the scale factor, that should be adapted to the level of acceleration (non-constant scale factor) [Str2]. A striking result of our study is that, even in active driving, a non-constant scale factor has to be used in order to achieve a realistic acceleration. Therefore, it is also recommendable to increase b and to reduce a, which means that less jerk should be produced on the motion platform. Indeed, some previous studies showed that the detection of linear motion is based not only on the linear acceleration, but also on the change rate of this acceleration [Gun1, Ben1]. This may be due to the fact that the discrimination threshold of linear acceleration depends on signal's frequency [Nas1].

5.3. Intensity of the perceived acceleration

Our results showed that 50% of the subjects are discriminants for the second question concerning the perceived intensity of the acceleration. We could then conclude that this kind of evaluation is more difficult to achieve than a comparison with a real acceleration (question 1). This may be due to the fact that the subjects compared two virtual accelerations, which were produced in the same manner (same acceleration profile – see results), but simulated differently (different scale factor and different tilt/translation ratio). Therefore, the perception of acceleration's intensity could be influenced by the way this acceleration is simulated by the motion platform. The statistical analysis shows that the perception of the motion is mainly influenced by the scale factor, and more specifically, by the b variable. If the scale factor is constant (b=0), the acceleration is perceived as being stronger than in the case where the scale factor evolves with the level of acceleration. Therefore, if we are interested in producing stronger accelerations, it is recommended to reduce b, increase a and Fc, meaning that the scale factor is constant and at a higher value (0.5 in our case) and that we should use more tilt than translation (Fc=1.5). If we are interested in producing a softer acceleration, it is recommended to increase b and reduce a and Fc, meaning that we should use a non-constant scale factor and more translation than tilt (in our case Fc=0.6). This means that the tilt is the motion that induces the "impression" of intensity in the simulation of linear acceleration. This may be due to the fact that the driver perceives the rotation, but it integrates it as part of natural pitch of the car, which corresponds indeed to a stronger longitudinal acceleration.

6. Conclusion

This study showed that the Motion Cueing Algorithm used on Sherpa^2 could be well set-up, if some conditions are met, for realistic take-offs. Therefore, it is important to verify if these conditions are also adapted for other driving situations, for instance, the braking (from 30km/h to full stop). However, we should analyse more deeply the behaviour data collected during this study and make a crossed-analysis between the subjective answers and acceleration profile analysis.

7. References

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