Perception of longitudinal acceleration on dynamic driving simulator

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Abstract – *Classical washout algorithm for driving simulators doesn't take into account the non-linearity of human sensory systems. Our previous work showed that the most realistic tilt/translation ratio for the simulation of braking during passive driving depends on the level of deceleration. However, the interpretation of previous results cannot be extended to acceleration. Therefore, a new experiment was developed in order to determine if the best tilt/translation ratios found for braking are also valid for acceleration. The present results suggest that the acceleration is generally overestimated directly proportional to the level of acceleration, but contrary to what was observed for deceleration, the variation of tilt/translation ratio doesn't seem to have an impact on the final perception of motion. As a conclusion, the simulation of deceleration and acceleration on a dynamic driving simulator should be considered separately.*

Key words: *dynamic driving simulator, motion perception, longitudinal acceleration, multisensory integration.*

Résumé - *L'algorithme Washout utilisé pour les simulateurs de conduite ne prend pas en compte la non-linéarité caractéristique des systèmes sensoriels humains. Nos travaux antérieurs montrent que le rapport basculement/translation le plus réaliste afin de simuler un freinage durant la conduite passive dépend du niveau de décélération à produire. Toutefois, ces résultats ne peuvent pas être appliqués stricto sensu au cas de l'accélération. Dans ce cadre, nous avons conduit une nouvelle expérimentation pour déterminer si le meilleur rapport basculement/translation trouvé pour freinage est également le meilleur pour restituer l'accélération. Nos résultats démontrent que l'accélération est généralement surestimée. Cette surestimation est directement proportionnelle au niveau d'accélération à produire. Mais contrairement à ce que nous avions pu montrer dans le cas de la décélération, les différents rapports basculement/translation proposés ne semblent pas produire des différences dans la perception finale de l'accélération. En conclusion, la simulation d'accélération et décélération sur simulateurs doivent être considérées séparément.*

Mots clés: *simulateur dynamique de conduite, perception du mouvement, accélération longitudinale, intégration multisensorielle.*

Introduction

Driving simulators have become an important tool in the automotive research. They bring great advantages in the upstream phases of the development of the car. Thanks to their complexity, they allow the exploration of certain areas of research that are difficult to reach in normal conditions, like the study of the interaction of multiple sensory cues during driving (visual, auditory, vestibular, somesthetic, etc.). However, the driving sensation on a dynamic simulator is sometimes reported by the subjects as unrealistic, especially for braking and turning situations. As a result, during the last decade, the driving simulation community started to concentrate their research on the motion perception and driver's behavior.

As showed by studies in driving simulation domain and in human motion perception, the addition of motion (basically tilt and translation) to static simulators may consistently improve the sensation of motion during driving simulation. From the motion point of view, it seems that using tilt extensively improves the perception of linear accelerations through the use of tilt-coordination technique (inclination of the simulator in order to orient the driver's head relative to gravity in a way similar to how the gravito-inertial acceleration (GIA) is oriented in the real vehicle during acceleration), even if the rotation of the simulator slightly exceeds the detection thresholds of the vestibular system (i.e. semicircular canals) [Gro; Ber]. Even so, this technique limits the maximum level of linear acceleration that can be simulated, due to the detection of rotation by the subject (beyond 3.7 deg/s of angular velocity [Ben] and 6 deg of inclination [Bri]). Therefore, new techniques were applied, like the addition of surge linear accelerations used at the beginning of the motion, which seems to support the visual simulation of larger motions. Unfortunately, small surge motions do not improve consistently the perception of the overall motion [Ber]. Still, many of the modern driving simulators possess motion-based platforms to produce longer translations to physically simulate stronger linear accelerations. These longer accelerations are commonly used in combination with tilt (tilt-coordination technique) in order to extend the range of "simulable" linear accelerations.

Background

In the framework of a collaborative project between PSA Peugeot-Citroën and the Institute of Movement Sciences of Marseille, we studied the processes underlying motion perception on PSA's dynamic simulator SHERPA². The first results of this collaborative work have shown that the combination of tilt and large translation determines the perception of acceleration in the case of passive braking [Str1; Str2]. In order to perceive the desired deceleration, the combination of tilt and translation must be adapted to the level of braking: for strong decelerations, more translation is needed, for weak decelerations, more tilt is needed [Str2]. Therefore, the best perceived tilt/translation ratio depends on the level of deceleration, suggesting that the motion cueing algorithms of the simulators should not only use gain factors, but also be adapted to this non-linearity. But on a dynamic driving simulator, the braking is simulated by forward tilt and backward translation, while the acceleration is simulated by backward tilt and forward translation. Studies on perception of acceleration/deceleration [Sch] or forward/backward motion [Bri] showed that, even if the two opposite motions are identical from the physical point of view (except direction), there are external factors that partly determine the final perception of motion, like speed (visual cues through optic flow), previous motion information, context or sense of familiarity [Hol1; Hol2; Hes].For example, Bringoux et al. [Bri] showed that the threshold for the perception of a body tilt is dependent on the direction of tilt. The thresholds were lower for forward tilt than for backward tilt. Moreover, Hess and Angelaki [Hes] observed a difference between eye movement latencies (translational VOR) during forward-backward displacement in rhesus monkeys. During forward movement, a shorter VOR latency was observed compared to backward motion. The authors considered that this difference could be due to the functional adaptation of vestibular system to forward movements, which are met more often compared to backward motions. This could also be related to Holly's works. Holly and colleagues have developed a theory on the construction of self-motion perception, in which the familiarity plays an important role [Hol1; Hol2]. The results of these studies suggest that perception of acceleration may be based on different signals and/or on different processes than the perception of deceleration.

As a consequence, the objective of the present study is to evaluate if the perception of acceleration also depends on the way tilt and translation are coordinated on a dynamic driving simulator. Therefore, we developed an experiment carried on the dynamic driving simulator SHERPA² that allows us to produce a large range of motions (up to 10 m on longitudinal translations).

Fig. 1. PSA Peugeot Citroën's dynamic driving simulator SHERPA².

Methods

SHERPA² is a dynamic driving simulator equipped with a hexapod and an X-Y platform (10 x 5 m) [Cha]. The cell placed on the hexapod contains a half-cab Citroen C1 fully-equipped (2 front adjustable seats, seat belts, steering wheel, pedals, gearbox, rearview mirror and side-view mirrors) where the driver is sitting. The motion limits of the hexapod are ±5 m, ±2.75 m and ±20 cm, on X, Y and Z respectively. The rotational movements are limited to ±18 deg, ±18 deg and ±23 degrees, on pitch, roll and yaw respectively. The X-Y motion platform can reproduce linear movements of 10 and 5 meters. The maximum acceleration is 5 m/s^2.

For this study, 26 volunteers (6 women and 20 men), aged between 21 and 47 were submitted to a passive acceleration (they did not control the motion of the car). The visual scene consisted in a straight two-lane road surrounded by an empty green field, with grass texture. The subject's car was advancing on the left lane, while a second car travelled a few meters forehead on the right lane of the road. Both cars were advancing towards a finish line at constant speed (50km/h). At a given distance from the finish line, the subject's car started to accelerate and the second car instantly disappeared. The acceleration lasted exactly 3 seconds, until the subject's car crosses the finish line. In order to evaluate perception of acceleration, we used a 2AFC paradigm. The moment the subject's car passed the finish line, the subject was asked to answer to the following question: "Who crossed the finish line first?", also using a certainty level from 1 to 6, where 6 was used to express a strong certainty of the answer, while 1 was used for uncertain answers.

The acceleration of the subject's car was precisely adjusted to pass the finish line in the same time than the other car. This was possible because the second car travelled at constant speed for all time, even after it has disappeared from the screen. The subject was informed about the constancy in speed of the second car, but not about the synchronous arrival of the cars. The dynamic stimulation, controlling the physical motion of the car, consisted in simulating the acceleration through tilt and translation. Three levels of acceleration were tested (1.0 m/s^2, 1.5 m/s^2 and 2.0 m/s^2). Each of the 3 accelerations was dynamically simulated on 5 combinations of tilt and translation (tilt/translation ratios). The ratios were composed of inverse-proportional percentages of tilt and translation (from 100 / 0 % tilt/translation to 0/100 % tilt/translation with a 25% step) presented in Table 1. The decelerations followed a cosine curve with the maximum peak corresponding to the 3 levels of acceleration.

The performance of the task was analyzed in terms of acceleration perception errors. Each time the subjects responded that they won the race (understand they thought to cross the finish line in first position), their answer was matched to a value of 1, corresponding to an overestimation of the acceleration. When they answered the other car won the race, the answer was matched to a value of -1, corresponding to an underestimation of acceleration. A repeated-measures analysis of variance (ANOVA) and a post-hoc Duncan test were conducted in order to determine the influence of the level of acceleration, tilt/translation ratio and the interaction between the two variables. The p-values calculated during ANOVA represent the probability of error that is involved in accepting our observed result as valid, that is, as "representative of the population" [Bro]. We chose $p=0.05$, indicating that there is a 5% probability that the relation between the variables found in our sample is a chance occurrence. Therefore, p-value should be smaller than 0.05 in order to observer a significant effect of the tested variable. The post-hoc Duncan test consists of looking at the data for patterns that were not specified a priori.

Table 1 - Dynamic simulation of three levels of acceleration through 5 different combinations of tilt and translation.

Acceleration 1.0 m/s²				
Distance between cars: 6.11 m				
Acceleration distance: 34.14 m				
Condition	Translation	Tilt		
	m/s²	m/s²	deg/s	deg
1	0	1	6.12	5.85
2	0.25	0.75	4.6	4.38
3	0.5	0.5	3.06	2.92
4	0.75	0.25	1.53	1.46
5	1	0	0	0

Acceleration 1.5 m/s²				
Distance between cars: 7.24 m				
Acceleration distance: 34.84 m				
Condition	Translation	Tilt		
	m/s²	m/s²	deg/s	deg
1	0	1.5	9.2	8.8
2	0.375	1.125	6.9	6.58
3	0.75	0.75	4.6	4.38
4	1.125	0.375	2.3	2.2
5	1.5	0	0	0

Acceleration 2.0 m/s²				
Distance between cars: 8.37 m				
Acceleration distance: 35.54 m				
Condition	Translation	Tilt		
	m/s²	m/s²	deg/s	deg
1	0	2	12.3	11.76
2	0.5	1.5	9.2	8.8
3	1	1	6.12	5.85
4	1.5	0.5	3.06	2.92
5	2	0	0	0

Results

At the end of the test, all participants reported that they were exposed to different levels of acceleration and that there were different distances between the two cars and different distances to the finish line. Interestingly, none of the subjects reported the use of different tilt/translation ratios, even if, for the pure tilt simulations, they did felt the tilt and considered it as unnatural, especially for high values of acceleration. Moreover, for all trials, they were not aware to cross the line in the same time as the other car.

The responses of the subjects represented an overestimation (passing the finish line before the other car) or an underestimation (passing the finish line after the other car) of the perceived acceleration. The levels of certainty (from 1 to 6) used to evaluate their perception of motion describes their level of overestimation/underestimation or error perception. The variation of this level of certainty for each of the 5 tilt/translation ratios and for each of the level of acceleration is presented in figure 2.

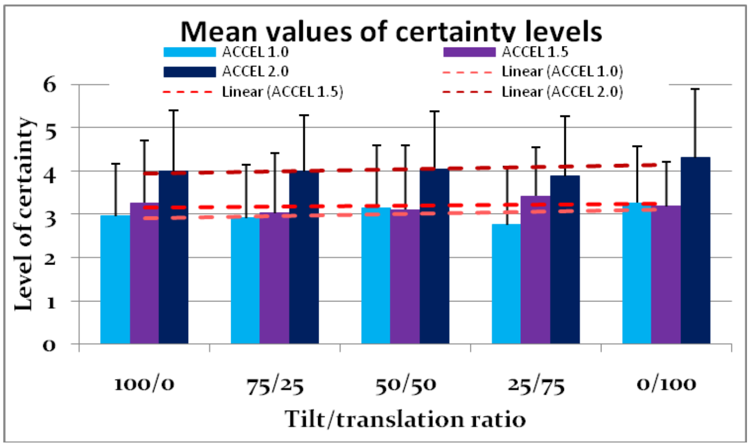

Fig. 2. Mean values of certainty level depending on the level of acceleration and on the tilt/translation ratios. The maximum value (6) represents a 100% certainty, while the minimum value (1) represents a 0% certainty. The dashed lines represent the linear tendencies for the 3 levels of acceleration.

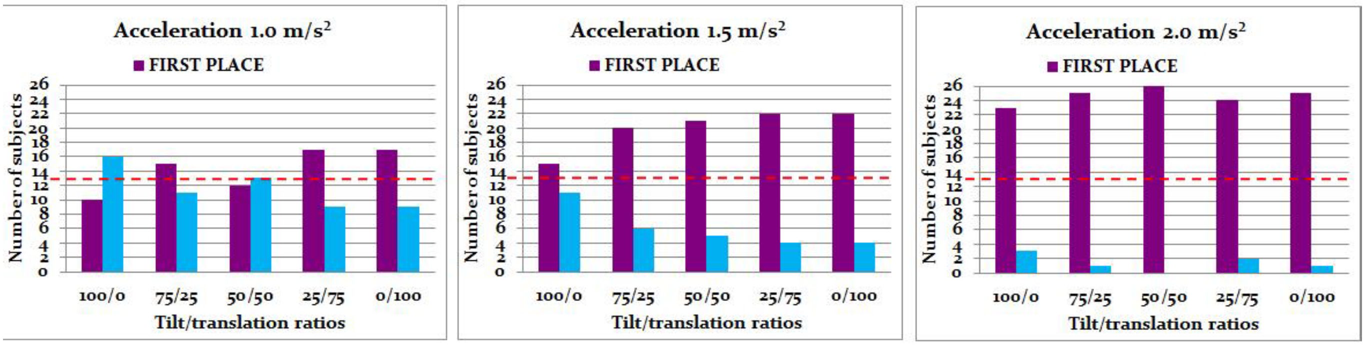

Fig.3. Number of subjects that overestimated (blue) or underestimated (purple) the acceleration, for each level of acceleration and for each tilt/translation ratio. The red line represents the case when 50% of the subjects overestimated the acceleration and 50% of them underestimated it. Under this line we talk about underestimation, over the line we talk about overestimation of the acceleration.

Interestingly, the results show no differences between the 5 tilt/translation conditions for the same level of acceleration, also confirmed by an ANOVA test (p=0.753). But the ANOVA yielded a significant effect of level of acceleration (p=0). The post-hoc Duncan showed a similarity between acceleration of 1.0 m/s² and 1.5 m/s², both different from acceleration of 2.0 m/s². Therefore, the error perception is higher in the case of 2.0 m/s² (the subjects are surer that they passed first the finish line).

If we compare the number of subjects overestimating/underestimating the acceleration, the results show an increased overestimation of the acceleration proportional to the level of acceleration (fig.3, ANOVA p=0). Moreover, as there is no significant difference between tilt/translation ratios for the same level of acceleration (ANOVA p=0.662).

Discussion

The experiment was designed to test the influence of the variation of tilt/translation ratio on the perception of positive longitudinal accelerations. The results showed no significant difference between the 5 tilt/translation ratios. This means that one level of acceleration can be simulated by any of the 5 tilt/translation ratios, without influencing the final perception of acceleration. Interestingly, these observations are in contrast with the results obtained for braking scenarios, where the perception of deceleration was greatly influenced by the use of tilt/translation ratios [Str1; Str2]. In addition, our results also showed that acceleration is mainly overestimated and the overestimation of acceleration seems to be direct proportional with level of acceleration (greater certainty levels for 2.0 m/s²). Nonetheless, given that the values of physical motion presented in this study are greater than the values used for braking situation, it is possible that the acceleration is underestimated for motions under 1.0 m/s².

However, as shown by the previous studies and the present study, there is a perceptual difference between acceleration and deceleration even on a driving simulator, which is in agreement with other previous studies [Sch; Bri]. This may be due to the fact that drivers are more used to forward motion [Hol2] or simply because the perceptual thresholds for tilt are lower for forward tilt than for backward tilt [Bri]. Nonetheless, it seems that, in our case, the tilt was detected by the subjects only for conditions with pure tilt (ratio 100/0%), even if most of the conditions that are including tilt have an angular velocity greater than the semi-circular canals' threshold of 3.7

degrees/s [Ben]. This suggest that the addition of translational motion to tilt could facilitate the perception of overall motion as linear acceleration, which is in correlation with other studies that used surge translations in combination with tilt [Ber]. This phenomenon may explain the linearity of acceleration perception throughout the 5 tilt/translation ratios, but it does not justify entirely the perceptual differences between acceleration and deceleration. In the case of our experiments, this difference may also be due to the presence or lack of visual cues: there were no visual cues during braking (no texture on the fields or the road, in order to avoid self-positioning in the space of the subjects), while they were present during latter. As a consequence, the presence of optic flow produced by the texture of the field and road may have produced, for one level of acceleration, constant visual information for all 5 tilt/translation ratios (the same displacement speed and traveled distances - even though there were no consecutively identical conditions). This may also explain the constancy of perceived linear acceleration along the tilt/translation ratios for the same level of acceleration. Therefore, even if physical motion represents an important cue in the simulation of linear accelerations on driving simulators, their weight in the process of motion perception could be influenced by non-vestibular cues. Viewed from the perspective of Bayesian framework [Zup], the non-inertial cues seems to change the reliability of the inertial cues (the semicircular canals' and otolith cues), giving more weight to the later, to the expense of semicircular canals.

As a result, motion cueing algorithms should use a gain factor that changes with the level of acceleration (for higher simulated accelerations we need smaller gain factors).However, which gain factors we need to use for each level of acceleration is still to be determined.

Conclusion

The perceptual differences between braking and acceleration during passive driving on a simulator suggest that the motion cueing algorithms should take into consideration the context of simulation (forward/backward motion), but also the influence of non-inertial cues (e.g. visual cues). Therefore, they must be adapted to the non-linearity of the human sensory systems in order to provide the tomorrow’s simulators.

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