The Influence of Lateral, Roll and Yaw Motion Gains on Driving Performance on an Advanced Dynamic Simulator

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Abstract—**The present study investigates the respective roles of lateral acceleration, and lateral, roll and yaw motions for self-motion perception and cornering behavior on a dynamic driving simulator. A recent study advises the use of motion gains (in the range 0.4 to 0.75) on these three components in order to improve self-motion perception. However, the role of each component in self-motion perception has not been individually addressed and the same motion gain is proposed for all components, independently of the level of acceleration. The aim of the present study is to extend this previous result by systematically reassessing the motion gains for the three lateral motion components for several levels of acceleration. A slalom task was chosen (with the level of lateral acceleration modified by changing the distance between posts) so that cornering behavior and self-motion perception could be assessed for various settings of the three parameters. The main results suggest that 1/ lateral motion gain should be decreased when lateral acceleration is increased; 2/ roll motion gain should be set to 1 to improve and facilitate driving perception and performance and 3/ the yaw component has a more controversial role but it seems to facilitate driving control without influencing motion perception. In conclusion, this study shows that the three motion components generally used to simulate lateral acceleration should be set individually and that use of the same motion gain for all three is not the best solution for improving the realism of the simulator. Therefore, it is proposed that each parameter be dynamically set based on the driving conditions.**

Keywords-Lateral acceleration; motion gains; driving performance; tilt-coordination.

I. INTRODUCTION

On dynamic driving simulators, motion perception is produced by stimulating the vestibular and somatosensory systems in addition to the visual system [1]. However, the intricacy of the multisensory stimulations undergone when driving a car makes the optimization of motion based simulators quite complex. For instance, it has already been shown that the motion on a driving simulator is overestimated when simulated at 1-to-1 rate [2]–[4]. In order to avoid this overestimation, some technical tricks are used, like the scale factor, called gain, and/or a combination of tilt and translation, called tilt-coordination [3]. However, both the gain and tilt-coordination needed to reproduce a positive or negative acceleration (e.g., take-off or braking) are highly dependent on the level of the simulated acceleration [4][5].

For turning manoeuvers, the control of the simulator appears to be more complex than for longitudinal manoeuvers because, in addition to lateral acceleration, there are also the yaw and the roll motions of the car that have to be simulated. However, the main sensory information on which the driver depends in making the manoeuvers is lateral acceleration. Indeed, the driver controls the speed and the trajectory of the car to keep this acceleration in a comfortable range and to ensure a safety margin [6][7]. In most dynamic driving simulators, the simulation of lateral acceleration is produced by using the tilt-coordination technique (lateral translation and lateral tilt). However, during cornering, the car is subject not only to a lateral linear acceleration, but also to rotational motions, such as yaw and roll. These motion components are also taken into account for driving simulation and they are highly dependent on the steering behavior of the car during cornering. Therefore, Berthoz et al. (2013) [8] proposed that motion gains (for lateral and rotational acceleration) should be within the range 0.4-0.75. One limitation of this study is that the gain for linear translations, roll and yaw and their interactions were not systematically varied for different levels of acceleration.

To go further this limitation, the present study, conducted on PSA’s (Peugeot Society Automobile) dynamic driving simulator SHERPA² [9], is focused on cornering manoeuvers. It aims at systematically reassessing the motion gains for the three lateral motion components (lateral, yaw and roll motions) for several levels of lateral acceleration. In order to evaluate the individual effects of the three parameters on driving behavior, a slalom driving task was selected. Through subjective and objective analyses, we tried to identify and quantify the major sources of motion perception and driving performance in cornering, and to identify the best set of parameters for each level of acceleration to simulate. More precisely, the aim is to define a mapping of motion gain set-ups to improve the realism of the driving simulation for a wider range of lateral accelerations. It is hypothesized that the motion gains for the different parameters are not necessarily linked [10][11], and that they could be different depending on the level of lateral acceleration.

The paper will be structured as follows: in Section II “Methods”, the experiment is presented (participants, devices, scenario etc.). Section III “Results” gives the results of the study. Finally, Section IV “Discussion of Results and Conclusion” is a discussion of the results of the study and their applications.

II. METHODS

A. Participants

27 volunteers (2 women and 25 men), aged between 22 and 49 (mean age: 28) participated in the study. All were PSA (Peugeot Society Automobile) employees who volunteered for the study, and none had significant experience of the simulator (average dynamic driving simulator experience less than 1.5 hours).

B. Experimental Devices

SHERPA² is a dynamic driving simulator equipped with a hexapod and an X-Y platform. The cell placed on the hexapod contains a fully-equipped half-cab Citroen C1 (2 front adjustable seats, seat belts, steering wheel, pedals, gearbox, rearview mirror and side-view mirrors) where the driver sits. The motion limits of the hexapod are ±30 cm, ±26.5 cm and ±20 cm, on X, Y and Z respectively [11]. 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 longitudinal and lateral acceleration is 5 m/s², and is actually produced by a combination of tilt and translation (in this paper, lateral tilt/translation is called “lateral motion”).

C. Experimental Scenario

The vehicle dynamics model (car dynamics and audio) selected for the present experiment was a Peugeot 208 1.4 HDi. The visual scene consisted of a straight two-lane road (road width: 8m). Guardrails were placed at both sides of the road to delimit the allowed maximum excursion of the car. The slalom driving scenario consisted of a series of 8 posts a constant distance apart (for a given level of acceleration). In addition, multiple mini-cones were used to represent the optimal sinusoidal pathway and help the subjects to perform the task [9]. The posts were alternately placed 0.9 m to the right and left side of the road centerline. The velocity of the car was set at 70 km/h. Then, by adjusting the distance separating two posts, various theoretical lateral accelerations were imposed. Hence, this gave three different slalom scenarios leading to three theoretical lateral accelerations, of 1, 2 and 4 m/s², corresponding to post spacings of 86.39, 61.09 and 43.19 meters, respectively. The equation enabling calculation of the theoretical lateral acceleration was borrowed from Grácio, Wentik and Païs (2011) [12].

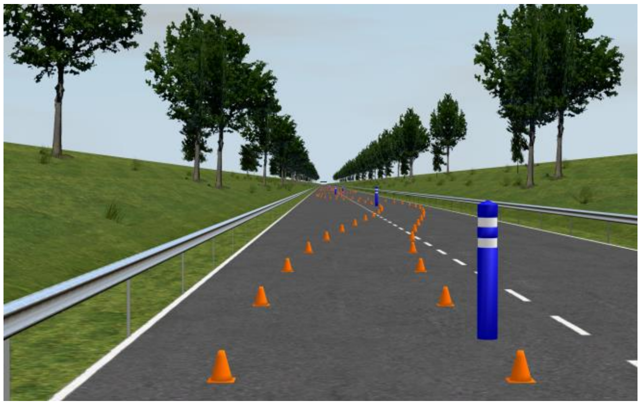

Figure 1. Visual environment of slalom task.

D. Task

Drivers were asked to perform a slalom course on the dynamic driving simulator by following the mini-cone path, without touching any posts or leaving the road. The run was performed in cruise control at a constant speed of 70 km/h.

E. Experimental Design

For each level of lateral acceleration (1, 2 and 4 m/s²), the motion gains of the 3 motion components (lateral motion; yaw and roll) were individually varied, leading to a total of 25 different conditions (see TABLE I).

The motion conditions varied according to different gains applied to the three simulator motion components. Slaloms 1, 2 & 3 respectively correspond to 1, 2 and 4 m/s² acceleration levels. Condition 20 corresponds to the current SHERPA² configuration. Each participant performed 3 repetitions per condition for a total of 75 trials divided into two sessions to avoid fatigue. The trials were organized using a central composite experimental design [13]. The choices of motion gains were made taking into account the physical limitations of the simulator (position, speed, linear and angular acceleration).

TABLE I. THE LIST OF THE 25 MOTION CONDITIONS TESTED FOR EACH SPECIFIC SLALOM.

	Lateral Motion Acceleration Gain			Roll Angle Gain	Yaw Acceleration Gain
Slalom	**1**	**2**	**3**	**1, 2 & 3**	**1, 2 & 3**
Condition					
1	**0.2**	**0.2**	**0.2**	**0.2**	**0.2**
2	**0.8**	**0.8**	**0.6**	**0.2**	**0.2**
3	**0.2**	**0.2**	**0.2**	**0.8**	**0.8**
4	**0.8**	**0.8**	**0.6**	**0.8**	**0.8**
5	**0.2**	**0.2**	**0.2**	**0.2**	**0.2**
6	**0.8**	**0.8**	**0.6**	**0.2**	**0.8**
7	**0.2**	**0.2**	**0.2**	**0.8**	**0.8**
8	**0.8**	**0.8**	**0.6**	**0.8**	**0.8**
9	**0**	**0**	**0**	**0.5**	**0.5**
10	**1**	**1**	**0.8**	**0.5**	**0.5**
11	**0.5**	**0.5**	**0.4**	**0**	**0.5**
12	**0.5**	**0.5**	**0.4**	**1**	**0.5**
13	**0.5**	**0.5**	**0.4**	**0.5**	**0**
14	**0.5**	**0.5**	**0.4**	**0.5**	**1**
15	**0.5**	**0.5**	**0.4**	**0.5**	**0.5**
16	**0.5**	**0.5**	**0.4**	**0.5**	**0.5**
17	**0.5**	**0.5**	**0.4**	**0.5**	**0.5**
18	**0.5**	**0.5**	**0.4**	**0.5**	**0.5**
19	**0.5**	**0.5**	**0.4**	**0.5**	**0.5**
20	**-1**	**-1**	**-1**	**-1**	**-1**
21	**0**	**0**	**0**	**0**	**0**
22	**1**	**1**	**0.8**	**1**	**1**
23	**1**	**1**	**0.8**	**0**	**0**
24	**0**	**0**	**0**	**1**	**0**
25	**0**	**0**	**0**	**0**	**1**

During the first session, the participants started with a simulator familiarization phase (10 min of rural driving) and a slalom learning phase (one trial for each slalom without motion of the simulator). This first session was followed by twenty-five trials of one slalom (same level of acceleration). The second session, performed four hours later, included another slalom learning phase along with the 50 remaining trials. The order of presentation of the three different slaloms was balanced over the total panel of participants. The order of the conditions was chosen using a Williams Latin Square, to balance the effect of the position and carryover effect between samples. The use of a central composite experimental design meant that the maximum information could be obtained in a minimum duration, and a model estimating nonlinear effects constructed. Furthermore, at the end of each trial, the participants answered a couple of questions to provide information about their subjective perception of the realism of the vehicle's behavior and the facility of the task. Two 11-point qualitative scales were used, ranging from 0 ("Not Realistic" or "Not Easy) to 10 ("Very Realistic" or "Very Easy"). In addition, motion sickness level was monitored throughout the experiment via a Motion Sickness Susceptibility Questionnaire (MSSQ) [10].

F. Data Analysis

During the driving task, some dynamic variables were recorded from the vehicle and simulator (e.g., lateral acceleration, steering wheel angle, lateral position). All these measurements were used to conduct an objective analysis of driver behavior. The Steering Wheel Reversal Rate (SWRR) was calculated from steering wheel angle. SWRR is a performance indicator that quantifies the amount of steering correction, and means that the effort required to accomplish a certain task can be determined [14]. This metric measures the frequency of steering wheel reversals larger than a finite angle, or gap. The magnitude of this gap, the gap size, is thus a key parameter for this metric [15]. In the present study, the number of reversals per slalom was counted. The steering signal was filtered using a second-order low-pass Butterworth filter with a cutoff frequency depending on the slalom level, specifically, 0.6, 2 and 5 Hz for the 1, 2 and 4 m/s^2 acceleration levels respectively. The algorithm for detecting the reversal was extracted from "Reversal Rate 2" in Östlund's study (2005) [15], and a difference greater than or equal to 2° (gap size) indicates one reversal.

Driving accuracy was quantified as lateral deviation from the reference trajectory (center of the mini-cone path) and computed as Root Mean Squared Error (RMSE) of the vehicle path.

The subjective and objective data were analyzed using the NEMRODW [9] software package. For each subjective and objective variable, data was collected from each participant and a principal component analysis (PCA) was performed, in order to determine if there was consensus among subjects; if no consensus was found, an ascending hierarchical classification was performed. Afterwards, a model was constructed (using NEMRODW) so that nonlinear effects and the best set of parameters could be estimated for a specific slalom level. The model contains first and second order coefficients on the three motion components. From these coefficients, statistical analyses were performed using multiple linear regressions in order to determine significant coefficients.

III. RESULTS

A. Subjective Analysis

1) Motion Sickness

During the experiment, four subjects felt motion sickness and were not able to finish all experimental conditions (Misery Score ≥ 6). Three of these participants felt motion sickness during the highest slalom level and with the highest lateral motion gains (Condition 10, 22 or 23 in TABLE I). The remaining twenty-three subjects were able to conduct the experiment without serious motion sickness (average Misery Score = 0.78 ± 1.2).

2) Realism of Vehicle Behavior

According to the PCA, no consensus was found among participants, so the data was centered, and a hierarchical clustering performed to identify homogeneous groups of subjects. The results of this analysis identified 2 groups (G1 and G2). The experimental results for the two groups were analyzed separately. The analyses of model's coefficients were performed to determine the optimal motion configuration. The coefficients are labeled as follows: "B0" is the model's constant, "B1" is the linear coefficient applied to lateral motion gain, "B2" is the linear coefficient applied to roll gain, and "B1-1" is the squared coefficient of lateral motion gain.

As shown in the TABLE II, for the first slalom (1 m/s²), lateral motion was a significant factor for both groups, while roll motion was a significant factor only for the second group. This means that changing their values should modify the perceived realism of the simulator. The model coefficients are presented in TABLE II for both groups.

TABLE II. THE MODEL'S COEFFICIENTS AND THEIR SIGNIFICANCE FOR GROUPS G1 AND G2, REGARDING REALISM OF VEHICLE BEHAVIOR FOR THE FIRST SLALOM (LATERAL ACCELERATION LEVEL OF 1 M/S²).

Name	G1 Coeff	Sign	G2 Coeff	Sign
B0	7.756	<0.01***	6.889	<0.01***
B1	-0.374	0.518***	1.174	<0.01***
B2	-0.081	48.5	0.405	2.13*
B1-1	-1.227	<0.01***	-4.5	0.05***

According to the answers of group 1 (G1), the experimental model assesses as more realistic a motion configuration with: lateral motion gain = 0.5, roll motion gain = 1, and yaw motion gain = 0.

According to the answers of group 2 (G2), the best set of parameters for realism is: lateral motion gain = 0.85, roll motion gain = 1, and yaw motion gain = 0. Figure 2 shows a 2D representation of the experimental model of Lateral and Roll motion gains for vehicle behavior realism in the first slalom and according to G2. In Figure 2, yaw motion gain is set at 0. As can be seen on this figure, the quality of realism grows with the amplitude of lateral motion gain, until a maximum at 0.85. This figure also shows the importance of roll motion gain (see TABLE II), which give the best result with a value of 1.

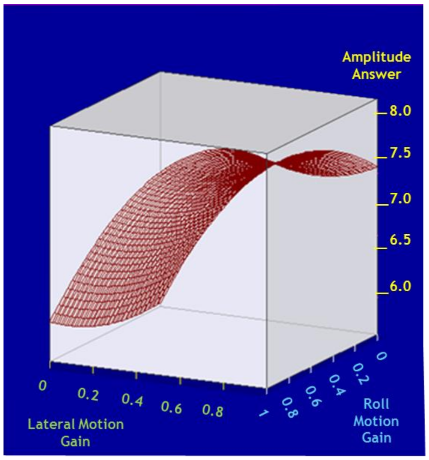

Figure 2. 3D representation of the experimental model for realism of vehicle behavior, for the first slalom and second group.

For the second slalom, the only significant factor for both groups was lateral motion (p<0.01). The lateral motion gain should be set to 0.4 and 0.7 for G1 and G2 respectively, to optimize the realism. In the third slalom, and for G1, the three motions were significant factors (p<0.01). For best realism, lateral, roll and yaw motion gain should be set to 0.25, 1 and 0 respectively. For G2, only lateral motion gain was a significant factor (p<0.01), and should be set to 0.5.

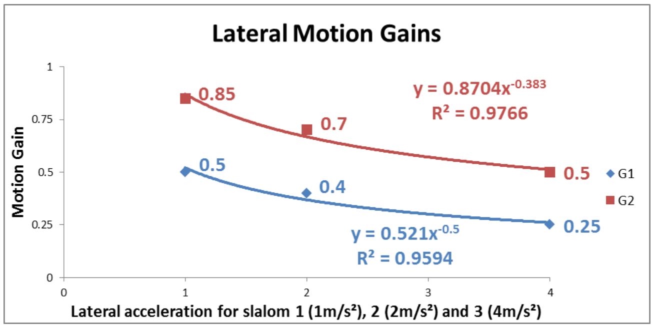

Figure 3. Best lateral motion gains for the two groups and the three slaloms.

Figure 3 presents the most realistic lateral motion gains, according to both groups. Lateral motion gains are digressive (reducing with increased acceleration) for both groups. Furthermore, for both groups, a roll motion gain of 1 always gives the best result in all slaloms.

3) *Facility of Achieving Slalom*

In the first slalom, no difference was found between all configurations. The first slalom was certainly very easy, and so drivers did not need external help to perform the task, and consequently, did not feel perturbed by the motion of the simulator.

For the second and the third slaloms, PCA analysis yielded a consensus between participants. Consequently, participants were included in the same group for subsequent analysis and computation of the model. The only significant factor in the second and the third slaloms was lateral motion ($p<0.01$). Contrary to the first slalom, participants found the second and the third slaloms less easy to perform, notably when lateral motion gain exceeded 0.2 in the second slalom and 0 in the third.

The best motion gains for perceived facility are presented in TABLE III.

TABLE III. BEST MOTION GAINS FOR ALL SLALOMS, REGARDING FACILITY OF ACHIEVING SLALOM.

	Lateral Motion Gain	Roll Gain	Yaw Gain
Slalom 1	**0 to 1**	**0 to 1**	**0 to 1**
Slalom 2	**0.2**	**0.3**	**0**
Slalom 3	**0**	**1**	**1**

Facility depends on slalom level, hence the motion gains, in particular lateral gain, should be adapted as a function of slalom level.

B. *Objective Analysis*

1) Steering-Wheel Reversal Rate

The PCA revealed a consensus among the participants, for all slalom levels. Hence, all 23 participants were analyzed together for the three slalom levels. For all slalom levels, the main significant factor was lateral motion gain.

For the first slalom level, the results showed that the number of reversals decreases with an increase in lateral motion gain, so that more steering corrections were required with low lateral motion gain. The analysis also suggests that roll motion gain has no effect on driving performance, although the best result was obtained for a roll motion gain of 0.

TABLE IV. BEST MOTION GAINS FOR THE SWRR VARIABLE FOR ALL SLALOMS.

	Lateral Motion Gain	Roll Gain	Yaw Gain
Slalom 1	**1**	**0**	**0**
Slalom 2	**0.5**	**1**	**1**
Slalom 3	**0.25**	**1**	**1**

Contrary to the first slalom, for the second and the third slaloms, the best model was obtained with a roll motion gain of 1. However, lateral motion gain has to be reduced when lateral acceleration to simulate increase. The yaw motion effect, although not significant in the model, seems to be best adjusted with a motion gain of 1 (see TABLE IV).

2) Path Root Mean Square Error

As for the previous variables, a single group was used for the model constructions. No difference was found between the motion configurations for the first and the second slalom. It is possible that the mini-cone path was helpful for accurate driving. Nonetheless, differences were found in the third slalom (4 m/s^2). Again, the significant factor was lateral motion gain.

The experimental model found two configuration settings that lead to the same performance (see TABLE V).

TABLE V. BEST MOTION GAINS FOR THE RMSE VARIABLE FOR ALL SLALOMS.

	Lateral Motion Gain	Roll Gain	Yaw Gain
Slalom 1	**0 to 1**	**0 to 1**	**0 to 1**
Slalom 2	**0 to 1**	**0 to 1**	**0 to 1**
Slalom 3			
First configuration	**0.25**	**1**	**0**
Second configuration	**0.35**	**0 or 1**	**1**

Figure 4 shows the results for the second configuration (lateral motion gain of 0.35); it can been seen that the curve is mainly influenced by the amplitude of lateral motion gain. With low or high lateral motion gains, the drivers take wider trajectories; thus, extreme lateral motion gains decrease drive accuracy.

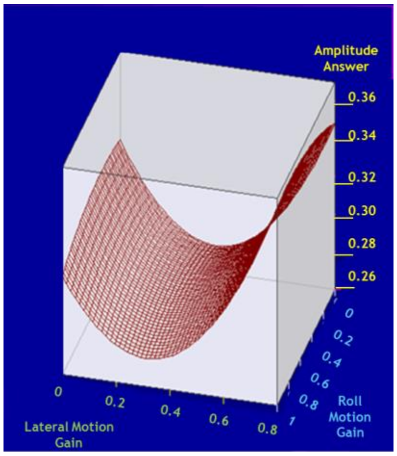

Figure 4. 3D representation of the experimental model for the RMSE variable, for the third slalom and the second configuration.

Thus, the results of objective variables seem to corroborate the results of subjective variable concerning the setting of lateral and roll motion gains, which is not the case for the yaw motion gain.

IV. DISCUSSION OF RESULTS AND CONCLUSION

The present research aims to reassess motion gains for the three lateral motion components (lateral, yaw and roll movements) for several levels of lateral acceleration. The slalom task has already been validated by several earlier studies. This research on dynamic driving simulators recommended use of unit motion gains in cornering, to improve motion perception and driving behavior [8][14].

However, these studies did not systematically investigate possible changes in the various motion gains depending on the levels of acceleration to be simulated. In fact, these studies only used equal motion gains for all three lateral components, and did not consider the effect of their decoupling on final performance and motion perception. In the present study, it was found that the three lateral motion components should not be set to the same gain, and should change as a function of lateral acceleration level.

A. *Motion Gains*

These results clearly show that, for all subjective and objective evaluations, lateral motion gain should be reduced as lateral acceleration increases. The equations from the Figure 3, which characterize lateral motion gain as function of lateral acceleration, could be used for simulator settings in order to improve realism. Nevertheless, these results seem to suggest there were two groups of drivers in the test population, preferring different lateral motion gains; it is possible that some of the participants assessed “comfort” instead of the realism. With regard to the subjective perception of task facility, a decrease in preferred lateral motion gain was observed as slalom level increased. Drivers found it more difficult to perform the second and the third slalom for configurations with lateral motion gains greater than 0.2 and 0 respectively. Greater physical fidelity (motions gains close to 1) and hence greater discomfort is probably the cause (large driver movements, lower facility of driving). Nonetheless, as showed by the objective analysis of steering-wheel corrections and lateral deviations, lateral motions gains below 0.2 are not recommended for maintaining accurate driving. Indeed, varying the amount of lateral motion in a simulated slalom affects driver performance. Except for the first slalom, where a lateral motion gain of 1 enabled optimal steering, driving accuracy for the two others slaloms was better with lower lateral motions gains. However, a lateral motion gain of 0 is not recommended for good driving performance and accuracy, as shown by the RMSE variable (see TABLE V).

With regard to roll motion gain, the experimental model showed that a roll motion gain equal to 1 is evaluated as being the most realistic situation, despite the fact that the two groups preferred different lateral motion gains. Although roll motion is not the most significant of the three lateral movements, it does enhance driving control for slaloms levels ≥2 m/s², notably with a gain of 1 (see TABLE IV).

Yaw motion was never a significant factor for vehicle behavior realism, except for G1 and the third slalom. Indeed, results on maneuverability show that drivers are sensitive to variations in yaw gains, and this motion can contribute to a change in the perceived maneuverability. However, as can been seen from the objective data from the second slalom, a better model is produced with a yaw motion gain of 1, probably because a very reactive car enables better handling (see TABLE IV).

B. *Lateral Motion*

As presented in Section 3, both subjective and objective variables show that lateral motion gain should be reduced when the lateral acceleration to simulate increases, so as to improve self-motion perception and driving performance. This very important result could be related to a previous result obtained in longitudinal acceleration, where the way the acceleration is produced (tilt/translation ratio) and the motion gain required to reproduce braking depend on the level of the acceleration [3]. In addition, previous research [8] has shown a decrease in steering corrections when lateral motion gain is increased. Nevertheless, they analyzed only one level of acceleration (1.2 m/s²). In the present study, it is shown that with increased lateral acceleration (i.e., slalom level), control of the vehicle demands more attention to accomplish the slalom with a unit or near a unit lateral motion gain.

The perception of simulated self-motion can tolerate significant discrepancies between the physical and visual motion cues [16]. Nevertheless, the tilt coordination technique was used to reproduce lateral acceleration; it is also possible than tilt is more easily perceived as lateral acceleration increases. A previous study [17] has shown that the limit of lateral tilt (perceived as a tilt and not as a lateral acceleration) is higher for active drivers than for passive passengers [2]. This research advised limiting tilt rate to 6°/s, twice the limit found for passive subjects. In our study, for the second and third slaloms and for the higher lateral motion gains, lateral tilt could reach 14° of inclination and an angular velocity of 12°/s (the limit set by our motion cueing algorithm or MCA). These magnitudes are higher than recommended by Nesti et al. [17], and higher than the threshold for roll tilt [18]; hence, the tilt of lateral motion is not perceived as lateral acceleration, but rather as a roll motion of higher amplitude than natural roll.

C. *Roll Motion*

A roll motion gain equal to 1 was perceived as the most realistic; moreover, the results from the RMSE and SWRR variables confirm this. Contrary to that for lateral motion gain, this result represents a new advance in the domain of simulation. It seems to confirm previous results obtained with expert drivers [11]. In the present study, this result has been extended to the wider population of “normal” drivers. A previous study [8] did not find this result. Indeed, as they used lateral motion gains of below 1, they never used a lateral motion gain of below 1 with a roll motion gain of 1. The driving simulator used in the present study reproduces exactly the roll angle and its derivates, and is temporally coherent with the visual roll. The absolute threshold of roll motion is around 2°/s [19]. Thus, a roll motion with a downscale factor is not necessarily felt by the driver. A roll motion supra-threshold has been shown to reduce latency of vection [20]. Hence, roll motion must remain at upper-thresholds to improve realism and driving performance. This means that a roll motion gain equal to 1 is advisable, regardless the level of lateral acceleration.

D. *Yaw Motion*

Surprisingly, yaw motion only slightly influences final perception, contrary to results obtained in a recent study showing that the presence of yaw motion in a curve affected driving behavior [21]. This different result could be explained by the fact that its intensity was probably not felt (yaw rate in slalom 1 (≤3°/s) or was masked by the two other components, i.e., the lateral and roll motion, unless visual yaw is sufficient in this slalom task (with low radius of curvature). In the previous study [21], the task was a corner negotiation (90° of rotation); the angle of curvature along with the total simulator velocity and angle were probably greater than in this slalom task. Thus, at higher velocity, drivers could probably more easily discern a configuration with and without yaw, which was not necessarily the case in the present study. Further work is required to elucidate this point, notably in a task requiring higher angular velocity, total angle, and lower linear speed.

In conclusion, the results of the present study clearly demonstrate that lateral motion gain should be adjusted as a function of the level of lateral acceleration to simulate. This seems to be mandatory for the settings of dynamic driving simulators and represents a new advance in the domain of simulation. However, tilt limit has to be considered. In addition, roll and notably yaw motions seem to have less influence on perception and driving performance. Surprisingly, it is therefore suggested that 1-to-1 gain could be the best setting for roll (as roll is not necessarily perceived by drivers with a lower gain). Although, the results from the subjective and objective variables with regard to yaw are not in agreement, yaw motion gain is never a factor significantly influencing the results in a positive way, at least in this slalom task. Thus, we cannot recommend using any specific yaw motion gain. Consequently, and in order to improve driver perception and control performance, the MCA should be changed by decreasing the lateral motion gain, while keeping the roll motion gain equal to 1. Yaw motion gain needs to be studied under different conditions.

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