Effect of Lateral Motion on Drivers' Performance in the MPI Motion Simulator

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Abstract

Motion restitution in driving simulators provides important inertial cues for perceiving the dynamics of the vehicle. In this study the effect of lateral motion was investigated in a slalom driving task by varying the amount of physical displacement with respect to the provided visual motion. The lateral shift of the vehicle was simulated by rotating the robotic arm of the MPI motion simulator along a curvilinear trajectory for the corresponding distance. Heading was directly mapped on the simulator motion and roll was linearly scaled according to the centrifugal acceleration. Four lateral motion gains (0.5, 0.75, 1, 1.25) were tested and the performances of the drivers were measured. Psychophysical scaling about the preferred motion gain and objective measures were used to analyze the driving behavior. The results showed that the amount of lateral motion at which the simulated vehicle is perceived as responding more appropriately to the driver's steering maneuver is around 60% of the real motion. A further increase of the lateral motion affects the driving style and introduces a significant delay in the car heading change.

Résumé

Introduction

When driving a car, it is typically assumed that visual information is the primary sensory feedback used by the driver to keep the car on the road (Kemeny & Panerai, 2003; Nobuyuki, Kazuyoshi, Naohiko, & Seiichi, 2005). However, inertial cues provide also important information about the vehicle dynamics when driving a curve (Reymond, Kemeny, Droulez, & Berthoz, 1999), especially when visual information is lacking (Macuga, Beall, Kelly, Smith, & Loomis, 2007). Consequently, high fidelity driving simulators integrate motion capabilities in order to provide acceleration and force feedback information (Reymond & Kemeny, 2000). Nevertheless, physical limitations and the restricted workspace of the simulators inhibit the full restitution of vehicle motion and the vestibular and somatosensory cues cannot be simulated to the full extent. The vehicle motion needs to be scaled and filtered in order to fit the mechanical constraints of the simulator while, at the same time, providing realistic sensory inputs to the drivers. Therefore, investigating the reliability of motion simulation is of great importance to the development of modern driving simulators.

In the framework of the European MOVES (MOtion cueing for VEhicle Simulators) Project (Eureka n° 3601) the MPI Motion Simulator has been introduced as a new type of driving simulator. In fact, one of the main purposes of the MOVES project is to evaluate and compare different motion simulators in their ability to simulate driving. The simulators involved in the project are based on different techniques and designs (e.g. centrifuge, robotic arm, linear sledges and customized Stewart platform) that affect the workspace and the motion capabilities in unique ways. As a consequence, individualized control algorithms need to be implemented for each of the simulators and their effectiveness can be measured by human behavioral testing methods (Colombet et al., 2008). Compared to the capability of standard Stewart-base driving simulators, the large motion range of the MPI motion simulator offers the possibility to provide realistic vehicle dynamics without requiring motion cueing algorithms, as it has been shown for simulated helicopter flight (Nusseck, Teufel, Nieuwenhuizen, & Bülthoff, 2008).

In the present study a typical slalom maneuver was established in order to assess the driving performance. The same task was also selected by the MOVES Project as the reference maneuver for measuring and comparing the effectiveness of motion restitution algorithms and architectures between the simulators. The gain of the simulator motion, i.e. the amount of lateral movement with respect to the visual displacement, was systematically varied during the experiment. Based on the assumption that a one-to-one motion gain may not be optimal with respect to simulation fidelity, four conditions were tested: (i) a normal driving experience where the physical motion resulted in exact amount of expected driver visual change; (ii-iii) two lower motion gains where the lateral motion was reduced with respect to the amount of visual displacement; (iv) a higher motion gain, allowed by the large workspace of the MPI simulator. The last condition was necessary to test the hypothesis that the optimal restitution gain may require the simulated motion to be higher than the real.

Behavioral recordings and subjective ratings were used to measure the performance of the drivers and the preferred amount of lateral motion. More specifically, the subjective measures were expected to show some preference peak for corresponding motion gains. This would mean that the judgments were based on the experienced physical gain rather than mere visually simulated motion. Overall, the behavioral and the subjective measures should indicate which gain values optimize the driving performance. These gain values can then be

compared to those obtained during the same task performed across different simulators. It is expected that the best gain values are the same across different simulators.

Method

Setup

Apparatus

The experiment was performed using the MPI Motion Simulator (Teufel et al., 2007), which is based on a 3-2-1 serial robot (Kuka Roboter GmbH, Germany). A curved screen was mounted in front of the seat and provided the visual feedback to the driver (figure 1). A force feedback steering wheel was used to control the car. No foot pedals were present.
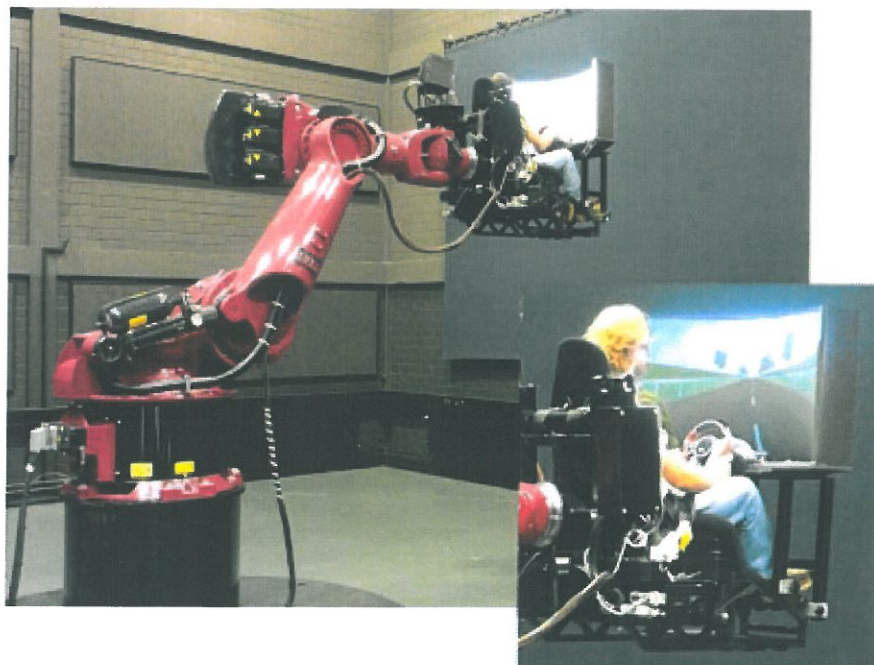

Figure 1. The MPI motion simulator as it was configured for the experiment.

For this experiment the movement of the robot was restricted to roll motion (Axis 6), to translation along an arc using the axis of rotation of the simulator base (Axis 1) and to simulation of heading using axis 5 of the robot arm (figure 2). Pitch remained zero over the entire experiment. A transport delay of 41 ms and the frequency response of the robot arm were measured during previous tests on the simulator (see for details Teufel et al., 2007).
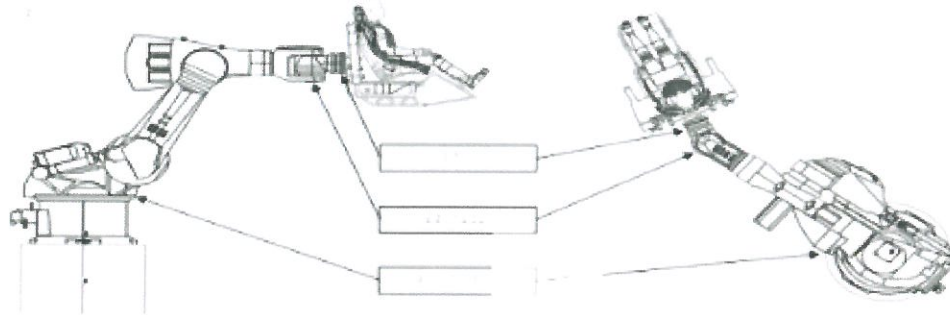
Figure 2. Mapping of the vehicle movements on the motion simulator: lateral (a) and top (b) view.

Vehicle model and simulation

The vehicle dynamics from the simulated car was directly mapped to the simulator motion; hence no motion cueing algorithms were needed to scale down the movement to fit within the simulator workspace.

The vehicle model consists of a simplified geometric model representing the classical Ackermann steering geometry (figure 3). The maximum ~~steering~~ steering angle of the virtual front wheel was restricted to 3 deg, corresponding to a steering wheel angle of 120 degrees, with a constant gear ratio of 40:1. Because velocity was set to a constant value of 70 km/h, the maximum centrifugal acceleration achievable at maximum steering angle was 0.72 g. The centrifugal acceleration was linearly scaled such that the maximum acceleration resulted in a roll angle of 10 degrees.
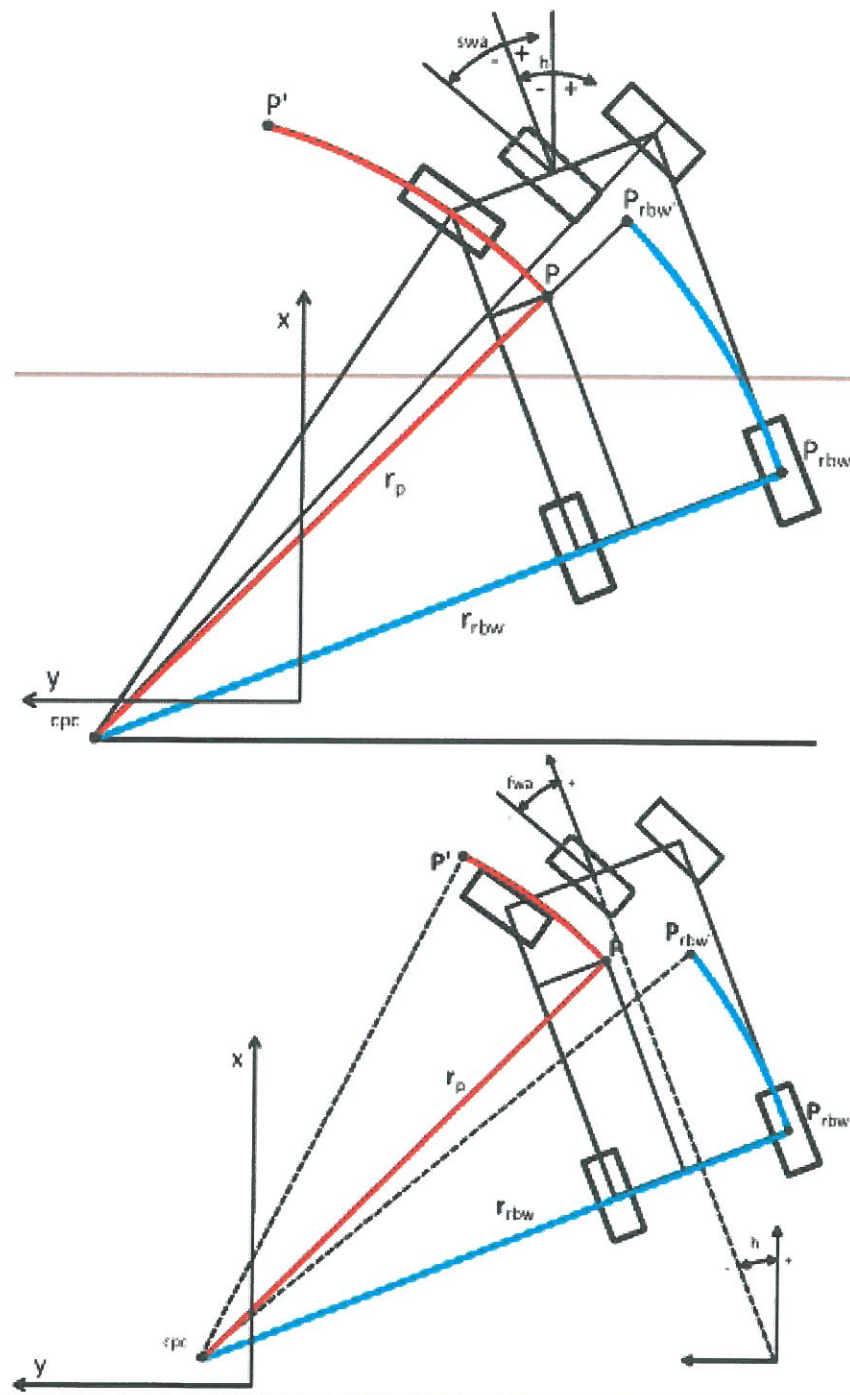
Figure 3. Vehicle model. All 4 axis of the wheels intersect at the center point of the curve (cpc). The vehicle model uses a virtual middle front wheel to simulate the different angles of turn of the two front wheels. The yaw angle of the virtual middle front wheel was controlled directly by the steering wheel angle (swa),. From the position of the driver (P), the current heading of the car (h) with respect to the base coordinate system and the virtual front steering wheel angle (fswa), the center point of the curve (cpc) may be computed by trigonometric calculus. By knowledge of cpc, the radius of the curve for the driver (r_p) can be computed. Because the car moves with constant velocity, the length of the circular segment driven within one time interval can also be estimated. Therefore the position of the driver moves from P to P′ by moving along the arc PP′ centered on cpc. All wheels move the same angular increment along circles around cpc with their specific radius, as shown in the figure for the right back wheel (rbw). The right back wheel moves from P_{rbw} to $P_{rbw'}$ with the angular increment on the circle around cpc and radius r_{rbw}. The centrifugal acceleration is calculated by the squared velocity divided by the radius of the curve r_p.

The lateral position y was simulated by moving axis 1 of the robot arm in a way that the distance along the arc resembled the lateral distance y of the vehicle model (figure 3). The heading computed by the vehicle model was directly applied to axis 5 of the robot arm. ~~The centrifugal acceleration was linearly scaled to t~~The roll angle ~~which in turn~~ was simulated by moving axis 6 of the robot arm. <u>Because of the simple vehicle model, based on geometrical considerations, there was no time delay between the steering wheel rotation and the lateral acceleration and yaw velocity.</u>

Visual environment

The visual environment consisted of a straight road section, delimited on the sides by slanted planes and fences (figure 4).

Figure 4. Screenshot of the visual environment as it was displayed in the simulator.

The slalom path was outlined by a series of 8 gates placed every 62.5 m, alternatively 1 m to the right and 1 m to the left of the middle road marking. The ideal trajectory of the slalom was described by a sinus with 2 m amplitude and 125 m period.

Participants

Ten licensed drivers (4 males, 6 females) took part in the experiment. They were paid and naïve as to the purpose of the experiment. Only participants who declared a day-to-day car usage and had at least 3 years of driving experience were selected. The mean age of the sample was 26.8 ± 4.

Design and procedure

Participants were instructed to drive as smooth as possible by passing exactly in the middle of each gate. The written instructions explicitly mentioned that the driver seat was located at the centre of the virtual car.

The pairwise comparison method was used to present the experimental conditions (Thurstone, 1927). In each trial the participants were asked to execute two consecutive slaloms. The lateral motion gain was always different between the first and the second slalom. At the end

of each trial the participants had to answer to the following question: "~~indicated i~~In which of the two slaloms did you feel that the car was responding more appropriately to ~~the~~your steering maneuver~~s~~? (first/second)". The preference was recorded by a button press.

The combinations of the four tested gains (0.5, 0.75, 1.0, 1.25) were repeated twice, providing 24 pairs of slaloms split in 6 sessions of four trials each. A typical session lasted approximately 10 minutes, with 10 minutes break between two consecutive sessions.

The gain was applied only to the physical motion along the simulator arc (see figure 3), while the visual motion was always according to the rotation of the steering wheel. The speed of the vehicle was maintained at 70 km/h for the entire slalom. The simulation started 100 m before the first gate and was continued for 162.5 m after the last gate.

Measures

Both subjective and objective measures were recorded during the experiment.

The participants' choices to the pairwise comparison task were used as a subjective measure for ordering the tested gain values along the preference dimension. This method allows the construction of a standardized interval-type scale (Torgeson, 1958) from which an optimal lateral motion gain can be derived. In this study, the optimal value corresponds to the gain that is perceived to provide the most appropriate behavior to the simulated vehicle.

The car position and orientation, the steering wheel angle and the motion of the simulator axes were updated and recorded every 12 ms for the whole duration of the experiment. Some of these parameters were used to analyze the drivers' behavior and performance.

Results

Subjective rating

A frequency matrix of the preference judgments was constructed and then converted into proportions. In turn the proportions were converted into standard scores and averaged for each tested gain. The resulting interval scale is presented in figure 5.
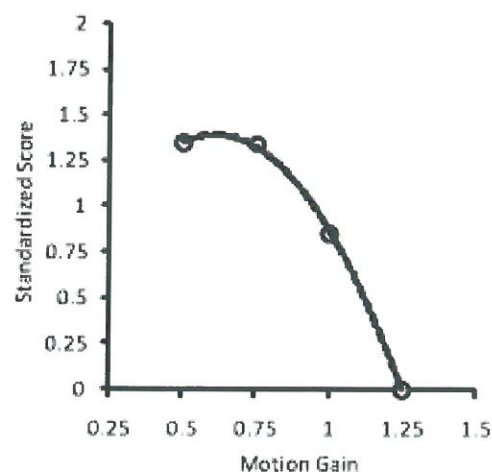

Figure 5. Scaling of preferred motion behavior for the simulated car. The interval scale for the preferred motion gain was computed under the following assumptions: (i) the discrimination process between two gain values may vary on repeated presentations according to a normal distribution; (ii) the distribution of the difference between the two gain values is also described by a normal distribution and it is a function of the proportion that one value is preferred to the other (Montag, 2006). The dashed line indicates the fitting of a quadratic regression model.

The data are well fitted by a quadratic regression model (R = 0.999), which shows a peak of preference at the gain value of 0.61. This result clearly suggests that in the current slalom simulation gains lower than 1 for lateral motion are preferred.

Objective performance measures

The steering wheel angle (SWA), heading direction (HD) and lateral position (LP) when passing through the gates were averaged across subjects and are shown in figure 6.
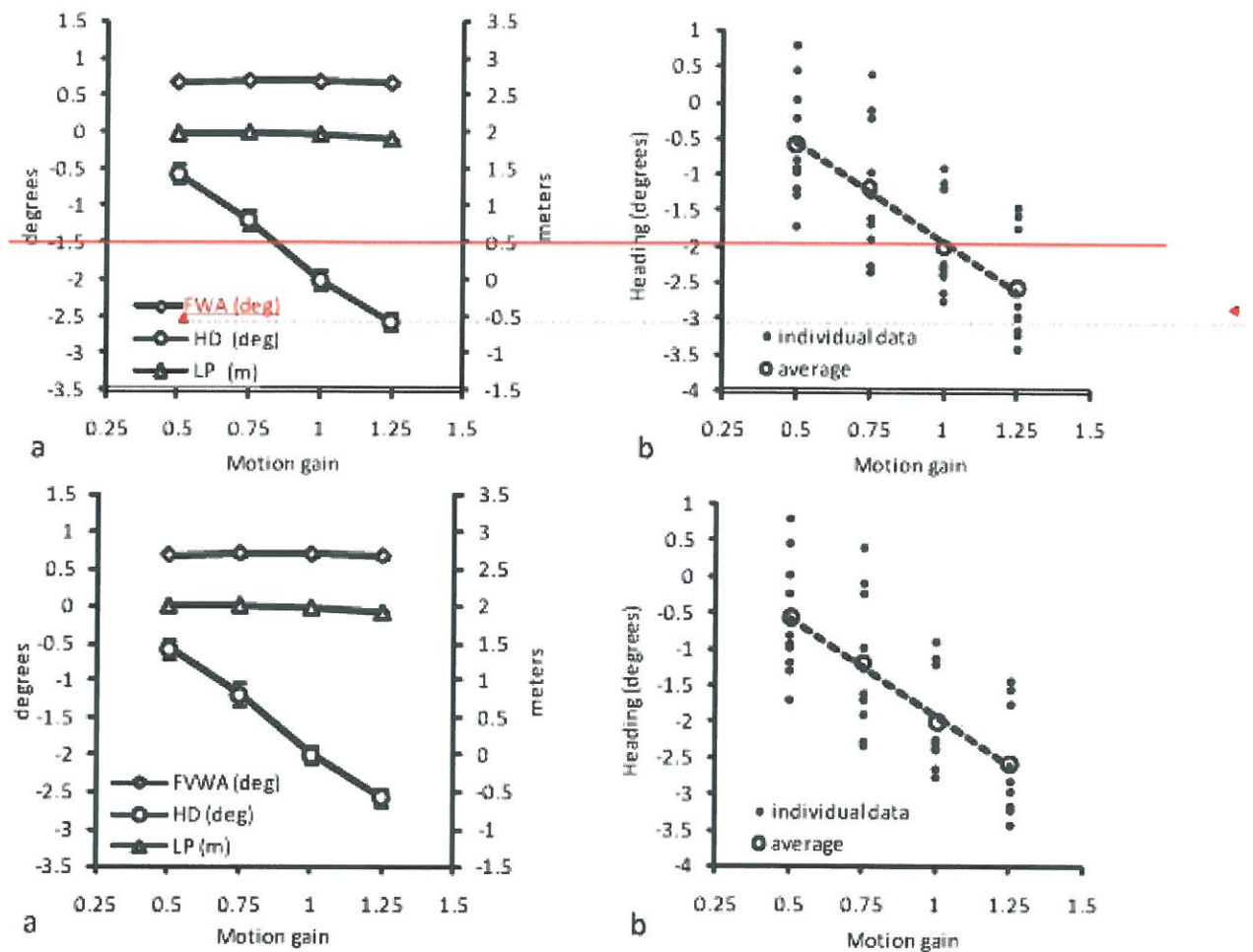

Figure 6. FrontSteering wheel angle (FSWA), heading direction (HD) and lateral position (LP) when passing through the gates as a function of the motion gain (a); individual and averaged data for the heading direction (b). Error bars in (a) indicate the Standard Error. Dashed line in (b) indicates the fitting of a linear regression model.

Only the heading direction showed a significant linear trend with regard to the lateral motion gains ($F1,38 = 38.86$; $p < .001$). The vehicle was directed towards the external side of the slalom (thus, deviating from the ideal path) with an increasing angle, according to the amount of lateral motion. The average lateral position was around 1.99 m, i.e. almost in the middle of the gates, and the average standard deviation of the lateral position was about 0.12 m. Neither the average nor the standard deviation of the lateral position showed significant differences between the tested gains. Similarly, the steering wheel was always rotated ~~steering wheel angle was constantly about 0.7~~28 degrees toward the inner pylon of the gates, corresponding to a front wheel angle of 0.7 degrees (see figure 6a).

In figure 7 two slalom trajectories are plotted in order to visualize the different driver's behavior induced by the lowest and the highest motion gains in the experiment.
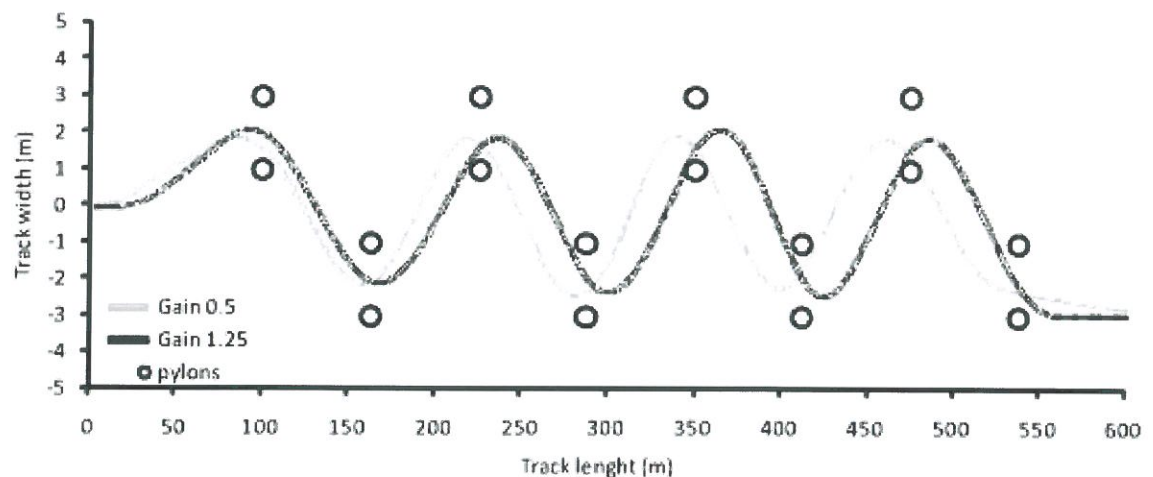

Figure 7. Example of two slalom trajectories with high and low motion gain. In the high gain condition (black line) the peaks of the sinusoidal trajectory are delayed.

The larger absolute car heading angle measured in the higher lateral motion conditions indicates that the point of maximal lateral displacement was reached after the gates, and later than in the lower motion gains (figure 7). This result may indicate that the implementation of higher inertial cues make the control of the vehicle more difficult.

Discussion and Conclusions

The results of the present experiment show that (i) the MPI motion simulator can effectively reproduce a realistic slalom maneuver, (ii) varying the amount of lateral motion in a simulated slalom affects the drivers' performance, (iii) different motion gains can be compared in a preference judgment, (iv) the preferred lateral motion gain is lower than 1, (v) increasing the amount of lateral motion induces a proportional heading change, and therefore a deviation from the optimal path.

Overall, it seems that the presence of lateral motion lateral motion increases the simulation fidelity and contributes to the diver's perception and control of motion. although the optimal motion gain is indicated around 0.6 of the expected physical motion. A previous study has shown that lateral motion can facilitate driver's ability to reject external disturbances (Greenberg, Artz, & Cathey, 2003). The authors of that study suggested that lateral motion gains of approximately 0.5 may be sufficient to minimize heading errors. In line with this, the present results indicate that the perceived optimal motion gain is around 0.6 of the expected physical motion. The heading error measured in the present experiment is indeed the lowest for a tested lateral motion gain of 0.5. It can be expected that when no or low lateral motion is produced the control of the vehicle requires more attentional demands and the heading errors increase (Greenberg et al., 2003). Moreover, the present results suggest that Wwhen the lateral motion is further increased, the drivers experience higher inertial cues and the control of the vehicle becomes more demanding. As a result, the driving style changes and the steering toward the internal side of the slalom is delayed. When passing through a slalom gate, the car heading is still directed towards the external pylon and the tangent point of the curve is postponed (ideally it should be at the gate). This result is also in agreement with previous

findings, which showed that in the presence of lateral motion the drivers take a wider turn on a cornering task (Siegler, Reymond, Kemeny, & Berthoz, 2001).

In a different study it was found that the standard deviation of the lateral displacement is significantly lower on the real road than in the fixed-base simulator (Blana & Golias, 2002). However, in the present experiment it was found that using a motion-based driving simulator the standard deviation of the lateral displacement is very low. Consequently, it seems advisable to have motion capabilities integrated in the driving simulation in order to elicit more realistic drivers' behavior.

Finally, the combination of subjective rating and objective behavioral measures seem a profitable method for assessing simulator fidelity and motion restitution effectiveness in the field of driving simulation.

In ongoing work, the authors are testing with the same methodology as described above lateral motion gains of 0 and 0.25 in order to evaluate the driving performance when no or low physical motion is produced. ~~It is expected that when only visual feedback is provided the car heading at the gates corresponds to the tangent point of the curve according to the optimal trajectory. Furthermore, the subjective rating is expected to drop for low motion gain.~~

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