VARIABLE ROLL-RATE PERCEPTION IN DRIVING SIMULATION

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Abstract – In driving simulation, simulator tilt is used to reproduce linear acceleration. In order to feel realistic, this tilt is performed at a rate below the tilt-rate detection threshold, which is usually assumed constant. However, it is known that many factors affect the threshold, like visual information, simulator motion in additional directions, or active vehicle control. Here we investigated the effect of these factors on roll-rate detection threshold during simulated curve driving.

Ten participants reported whether they detected roll in multiple trials on a driving simulator. Roll-rate detection thresholds were measured under four conditions. In the first condition, three participants were moved passively through a curve with: (i) roll only in darkness; (ii) combined roll/sway in darkness; (iii) combined roll/sway and visual information. In the fourth condition participants actively drove through the curve.

Results showed that roll-rate perception in vehicle simulation is affected by the presence of motion in additional directions. Moreover, an active control task seems to increase the detection threshold, i.e. impair motion sensitivity, but with large individual differences. We hypothesize that this is related to the level of immersion during the task.

Key words: Motion Cueing, Motion Perception, Tilt-coordination, Driving simulation

1. Introduction

In dynamic vehicle simulation, motion cueing algorithms (MCAs) aim to adapt the original vehicle motion to the limited capabilities of simulators, while preserving at the same time the perceptual realism of the simulation. The goal of MCAs is therefore to transform the linear and angular accelerations of the simulated vehicle into translations and rotations of the motion platform, such that perceptually equivalent specific forces and rotations are provided to the driver.

Most MCAs are based on washout filters, which split the input linear accelerations into high-frequency and low-frequency components. The high-frequency components are integrated to produce the translational motion of the platform, while the low-frequency components are reproduced by tilting the platform [Nah1]. The tilt of the platform is used by MCAs to simulate sustained accelerations (otherwise not reproducible) exploiting the so-called tilt-coordination technique [Ben1, Gro1]. This is one of the most used "perceptual tricks" in motion cueing, which relies on the tilt-translation ambiguity [Ang1]. Indeed, under certain conditions the simulator tilt can be perceived as linear acceleration, as the reorientation of the body with respect to gravity causes the sensation of being forced into (or away from) the seat. This illusion occurs because different combinations of linear accelerations and static body tilt result in similar gravito-inertial forces acting on the humans inertial sensory systems (primarily vestibular and somatosensory). This is particularly effective when concurrent translational motion is visually presented [Gro1]. The tilt-coordination technique exploits the inability of humans to resolve the tilt-translation ambiguity, and use simulator tilt to induce the illusory perception of sustained linear acceleration [Sta1].

However, the illusion is spoiled if the platform tilt is detected by the driver. This happens when the tilt velocity exceeds the perceptual threshold, inducing the sensation of rotational motion and resolving the ambiguity. Therefore, to preserve the realism of the simulation, a rate limiter saturates the platform tilt-rate below perceptual threshold. A commonly used saturation value is 3 deg/s [Gro1].

Tilt-rate detection threshold is usually measured in darkness [Soy1, Zai1]. Yet, it is known that motion perception thresholds can vary in the presence of visual information [Gro1, Val1], simulator motion in additional directions, i.e. increased motion complexity [Zai1], active vehicle control [Hos1, Dev1, Nes1], or even cognitive expectations [Wer1]. All these factors are actually present in a typical driving simulation. Still, most of current MCAs assume constant tilt rate thresholds, often derived from studies where simple motion stimuli were investigated. Therefore, a better understanding of how motion complexity, visual information and active control affect the perception of simulator motion may help in improving the efficiency of tilt-coordination techniques.

In this study, we investigated for the first time in the same experiment (using the same simulator and methodology for all experimental conditions), the effect of each of these factors on roll-rate detection threshold during simulated curve driving.

2. Method

2.1. Setup

The experiment was conducted on the CyberMotion Simulator (CMS) at the Max Planck Institute for Biological Cybernetics. The CMS was developed as an alternative to traditional dynamic simulators based on hexapod systems [Nie11]. It is a 8-dof serial robot, where a 6-axes industrial robot manipulator is mounted on a linear rail and equipped with a motorized cabin at the end effector (figure 1, top). The cabin is equipped with a stereo projection system and mounting possibilities for haptic control devices used for flight and driving simulation (figure 1, bottom). In the driving configuration it is equipped with force-feedback steering wheel (Sensodrive GmbH, Germany) and pedals, and a large projection screen (160 x 90 deg FoV) with two WUXGA (1920x1200 pixels) projectors. For this study, the motion was generated using a classical washout filter, adapted to the cylindrical workspace of the CMS [Rob1]. No linear rail was used and the lateral motion was mapped into a circular trajectory [Nes1]. The vehicle dynamics and the visualization environment were provided by the simulation software CarSim (Mechanical Simulation, Michigan, US). The visual scene resembled a flat skidpad, and no roll-motion was present other than the one originating from the car suspensions.

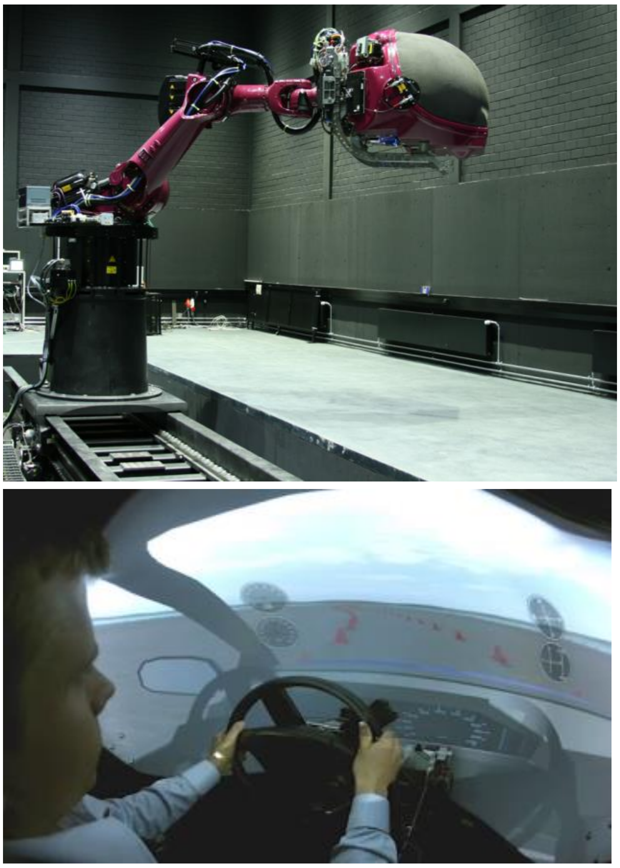

Fig. 1. The Max Planck Institute CyberMotion Simulator: exteriors (top) and cabin interior (bottom).

2.2. Experimental manipulations

The rate limiter of the tilt (roll) channel of the washout filter was manipulated during this experiment. Roll-rate detection thresholds were estimated under four conditions:

- "Roll": roll only in darkness;
- "+Sway": combined roll/sway in darkness;
- "+Visual": combined roll/sway and visual information whilst passively moved through a curve;
- "+Active": combined roll/sway and visual information whilst actively driving around a curve.

An overview of the experimental conditions is provided in Table 1.

Table 1. Experimental conditions

	"Roll"	"+Sway"	"+Visual"	"+Active"
Roll	present	present	present	present
Sway	absent	present	present	present
Visual	absent	absent	present	present
Active	absent	absent	absent	present

2.3. Procedure

Ten participants (three females), aged between 25 and 36 (mean = 29, SD = 3.5) took part in the experiment. All had a valid driving license for at least three years and self-reported regular car usage. The experiment was divided into four sessions, over different days. Each session started with three practice trials to familiarize the participant with the task. When the participant initiated a trial by button press, the car accelerated automatically on a straight road until a constant speed of 70 km/h was reached. The speed was maintained constant throughout the whole trajectory. During the acceleration phase, the surround scene and the layout of the curve were visible in all conditions (figure 1, bottom). Before entering the curve section, the screen turned to black in conditions "Roll" and "+Sway"; while in conditions "+Visual" and "+Active" the outside view remained visible. The car progressed through the curve automatically (conditions "Roll", "+Sway", and "+Visual") or with the heading actively controlled by the participant (condition "+Active"). At the end of the curve the road was straight again (no active control required) and the following question appeared on the screen: "Did the car tilt (Y/N)?" The participant indicated the answer by pressing a button accordingly. When the answer was given the car decelerated and the simulator was brought back to the starting position for the next trial.

Thresholds were measured by iteratively adjusting roll-rate saturation value according to the Single Interval Adjustment Matrix (SIAM) procedure [Kae1, She1]. In 50% of the trials, the tilt coordination path of the MCA was active (roll motion present), while in the other 50% tilt coordination was disabled (roll motion absent). Additional roll-motion of the car (e.g. suspensions) was not cued. The trials were randomly interleaved. The participants had to correctly identify whether the roll was present by answering the question above. The adjustment matrix of the four possible outcomes was set up to induce a neutral response criterion: the answer "yes" in presence of roll (hit) decreased the roll-rate saturation value for the next trial of one step size; the answer "no" in absence of roll (correct rejection) left the roll value unaltered; the answer "yes" in absence of roll (false alarm) increased the next roll value of two step size; the answer "no" in presence of roll (miss) decreased the roll rate of one step size for the next trial. The SIAM is given in short form in Table 2.

Table 2. Single Interval Adjustment Matrix

Motion Stimulus	Answer: "Yes"	Answer: "No"
Roll	Hit [-1]	Miss [+1]
No Roll	False Alarm [+2]	Correct Rejection [0]

Since in the "Roll" condition the thresholds were expected to be the lowest, the initial roll rate was 6 deg/s, with an initial step size of 1 deg/s. For all other conditions the initial rate was 12 deg/s and the step size was 2 deg/s. The step size was halved every 4 reversals of the resulting staircase (figure 2). The session was terminated after 12 reversals, where a reversal is a change in the staircase direction from decrease to increase or vice versa. The threshold was then computed as the average roll rate over the last 5 reversals. An example of the resulting staircase profile is shown in figure 2.

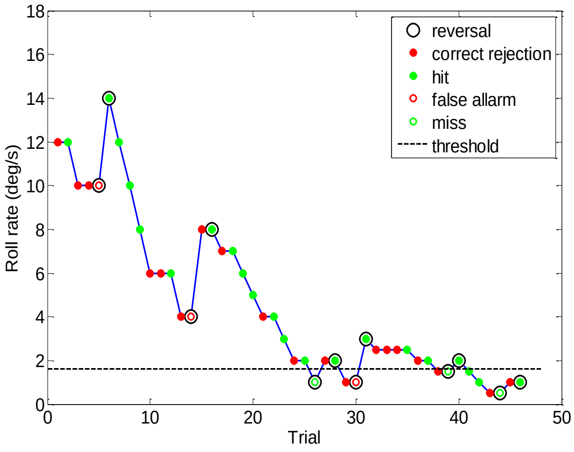

Fig. 2. An example of staircase from the study (condition "+Sway"). The initial roll rate was 12 deg/s, with initial step size 2 deg/s, which was halved to 1 deg/s after four reversals and to 0.5 deg/s after 8 reversals. The staircase was terminated after 12 reversals and the last five were averaged to compute the threshold (dashed line).

After each session, participants filled out a questionnaire to indicate their subjective ratings about mental demand, level of concentration, ability to maintain a constant level of attention, level of frustration, physical comfort and simulation realism on a 9-point rating scale (Table 3).

Motion sickness questionnaires were also collected for all participants after each experimental session [Ken1]. In every session, the level of sickness was monitored every 10 minutes using a numerical score, based on the scale used by Golding and colleagues [Gol1]. A typical session lasted about one hour.

Table 3. Rating Scale

Item #	Question
1	"Overall mental demand"
2	"Average level of concentration"
3	"Ability to keep concentration"
4	"Level of frustration"
5	"Physical comfort"
6	"Feeling of being in a car"
7	"Quality of lateral motion: strength"
8	"Quality of lateral motion: timing"

3. Results

In the following sections we report the results of the three types of measures that were collected during the experiment: perceptual thresholds for roll-rate, objective measures of the driving behavior, and subjective ratings of the task attentional demand and the level of immersion in the simulation.

One participant did not complete condition "+Visual" due to mild symptoms of motion sickness. Therefore, the corresponding staircase stopped after 7 reversals (31 trials), of which the last five were used to calculate the threshold. Two participants did not fill out the questionnaire at the end of a session. The missing values were replaced by the average score of the other participants in the same condition, and included in the analysis of subjective ratings.

3.1. Perceptual thresholds

Mean detection threshold for roll-rate increased from 0.7 deg/s with roll only (condition "Roll") to 6.3 deg/s in active driving (condition "+Active"), while mean threshold was 3.9 deg/s and 3.3 deg/s in conditions "+Sway" and "+Visual" respectively (figure 3, blue line). A repeated-measures analysis of variance (ANOVA) indicated a significant effect of the four conditions on the roll-rate detection threshold ($F(3,27) = 5.49$, $p < 0.05$). Post hoc test with Bonferroni adjustment for multiple comparisons revealed a significant difference between condition "Roll" and conditions "+Sway" and "+Visual", which did not differ from each other. For condition "+Active", large differences between participants were observed: for some the threshold did not increase from passive to active driving, while for others about 3 times higher threshold was measured. A cluster analysis (k-means clustering) of the thresholds distribution in condition "+Active" revealed that thresholds values could be divided into two clusters: "High Threshold Cluster" and "Low Threshold Cluster", respectively indicated by black and red lines in figure 3.

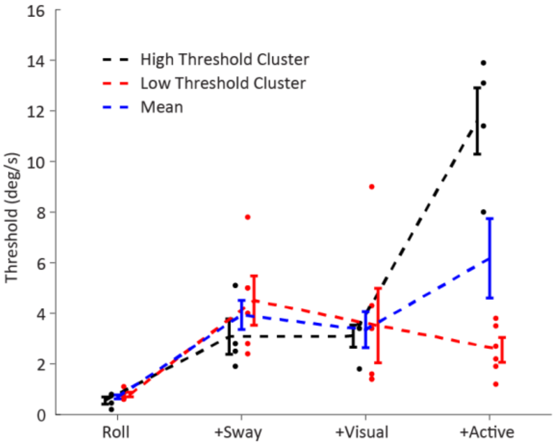

Fig. 3. Roll rate detection thresholds. Global mean (blue line); mean thresholds for participants who showed increment in condition "+Active" (black line); mean thresholds for participants who showed no increment in condition "+Active" (red line). Error bars indicate ±1 SEM.

3.2. Behavioral measures

During the trials of condition "+Active", steering wheel commands and car position were continuously recorded. These data where analysed to find evidence of the above reported differences in motion sensitivity.

Neither steering wheel angle and associated variance over time, nor the car position on the track and associated variance over time showed significant differences between the two clusters of participants. An inspection of the power spectral density (PSD) of the steering wheel commands also indicated no qualitative differences in driving behaviour between the two clusters.

We did not find any significant differences in driving behaviour for all the considered objective measures. This clearly indicates that the differences in roll-rate detection thresholds between the two clusters cannot be related to different driving styles, or to different motion profiles experienced by the participants.

3.3. Subjective ratings

In the active driving condition ("+Active"), participants with high thresholds (low sensitivity) reported a lower level of immersion (question 6 "Feeling of being in a car") than participants with low thresholds (better sensitivity), as shown in figure 4.

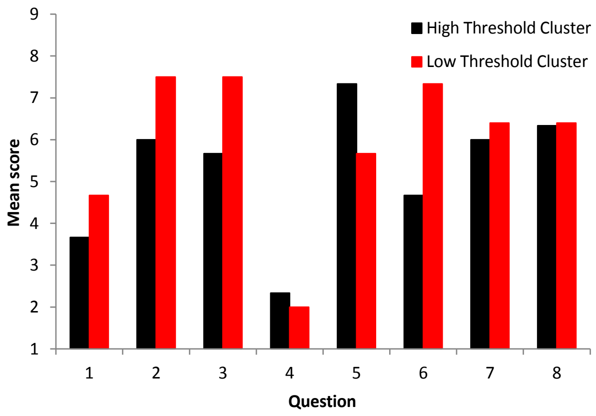

Fig. 4. Mean rating scores.

The Pearson's correlation coefficient calculated on the rating scores resulted in a significant negative correlation between the "Feeling of being in a car" (question 6) and the roll-rate thresholds ($r = -0.72$, $n = 10$, $p < 0.05$). This indicates that participants who experienced a lower feeling of immersion in the simulation also showed a lower sensitivity for roll rate, and were unable to notice the rotation of the platform up to 12 deg/s on average (figure 3). All other questions did not show any significant correlation with the threshold clusters.

Overall, the feeling of being in a car increased significantly ($F(3,27) = 6.58$, $p < 0.01$) from the condition in which roll motion was presented in darkness ("Roll") to the conditions where active control was available ("+Active"), as shown in figure 5.

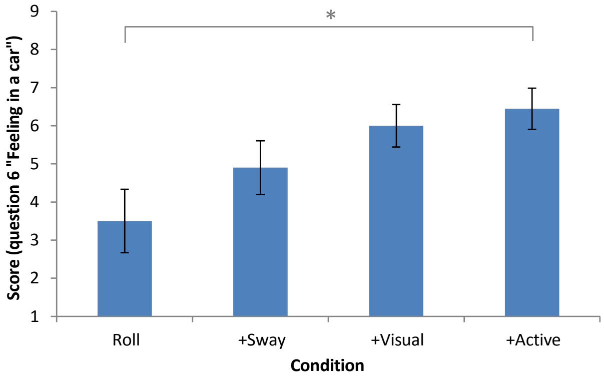

Figure 5. Mean score at question 6 "Feeling of being in a car" for different conditions. Error bars indicate ±1 SEM.

4. Discussion

The purpose of the study was to investigate the effect of different sensory and cognitive factors on motion sensitivity in a driving simulation. We measured detection thresholds for roll rate in darkness, with additional lateral motion, with available visual motion information, and in conditions that closely resemble an actual driving scenario, in which a driver actively controls the vehicle.

We found that thresholds significantly increase when translational motion (sway) is added to rotational motion (roll). This result essentially replicates what was previously reported by Zaichik et al. [Zai1]. Visually suppressing the roll did not increase the thresholds further, but led values comparable to those reported by Groen et al [Gro1]. Our study extends the validity of previous results by allowing a direct comparison of the measured thresholds, since all the conditions were tested here using the same participants, motion stimuli, platform and methodology.

Interestingly, the addition of incongruent visual information did not affect further the detection threshold. Indeed, the visual motion information during the experiment showed a lateral translation with no roll, which was actually present in the inertial motion stimulation due to tilt-coordination. We confirm again the results of previous literature [Gro1], which indicated in about 3 deg/s the pitch rate detection threshold for incongruent visual-inertial stimulation during passive motion.

Up to now, this value was widely adopted within the driving simulation community and used as a reference for the tilt rate limiter in the washout algorithms responsible for tilt-coordination. However, one should consider that this value was measured during passive motion. In other words, this value refers to the motion sensitivity of a passenger, not a driver. Since it is reasonable to expect a further decrease in sensitivity during an active task [Hos1], we measured the threshold during active driving, with the intent of providing the community with a more realistic value to be used in simulation. The result replicates our previous finding, indicating an average roll rate detection threshold of approximately 6 deg/s [Nes1]. However, here we found that two clusters better describe the thresholds for roll in active driving conditions. The "low threshold" cluster showed no difference in threshold between the passive and active driving simulation (approximately 3 deg/s), while the "high threshold" cluster showed a significant increment: roll rate of 12 deg/s was required to perceive a body rotation to the side while driving.

Despite the small size of the sample, we found also a significant negative correlation between the threshold clusters in condition "+Active" and the feeling of being in an actual car. Thus, lower sensitivity for roll rate correlates with a lower level of immersion in the simulation. Conversely, a better feeling of being in an actual car correlates with a higher sensitivity for rotational rates. We hypothesize that sensitive drivers (“low threshold”) take advantage of a better feeling of immersion, and can maintain their sensitivity even when their attention is diverted to the driving task, with complex and rich multisensory stimulation. This suggests that a realistic driving simulation, in which drivers have active control over the vehicle, helps the sensitive drivers to better understand the characteristic vehicle motion. As a consequence, drivers concentrate more on the relevant motion aspects, and maintain a high sensitivity. On the other side, one could be overwhelmed by the richness of the simulation and the effort required in controlling the vehicle. This would prevent the driver to reach a sufficient level of immersion. The consequence would be a distribution of the attentional resources over multiple cues, with a reduced level of attention to the relevant motion aspects, and an increased threshold.

The driving simulation community should carefully evaluate the importance of our findings when transferring the results from simulator studies to production cars. Indeed, recruiting simulator users with low motion sensitivity (high threshold) would increase the perceptual workspace of the simulator, as higher tilt rate saturation values would be accepted. However, our study shows that drivers with low sensitivity also report a lower feeling of immersion, with potential negative impact on the validity of the results for safety and training applications.

Future studies should address more specifically the cause of individual differences in motion sensitivity during active driving simulation. The relationship between subjective feeling of immersion and individual motion sensitivity should be also further investigated. For this, the development of novel and robust method for measuring immersion, perhaps based on perceptual judgments [Wal1], would be highly beneficial. This will improve our understanding of human motion perception and the reliability and validity of simulator studies for real world applications.

5. Conclusion

In this study we investigated how roll rate detection threshold during lateral motion is affected by motion in multiple directions, concurrent visual information, and active control task. Indeed, motion in different directions, multisensory visual-inertial stimulation and vehicle control activities are actual parts of a typical driving simulation. Thus, the question is particularly relevant for the development of efficient motion cueing techniques in driving simulation, in order to ensure the best use of the simulator workspace and provide the user with a realistic driving experience.

The main results indicate that roll rate perception is affected by the combination of different simulator motions. Furthermore, for some drivers an active control task seems to increase detection threshold for roll rate, i.e. impair motion sensitivity; while for others the threshold remain unaffected by the additional attentional load.

We hypothesize that an active control task may induce a better feeling of immersion and a better understanding of the vehicle relevant motion. If this does not occur, however, the overall complexity of the simulation may cause motion sensitivity to decrease.

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