Driver Behavior Comparison Between Static and Dynamic Simulation for Advanced Driving Maneuvers

Abstract

In advanced driving maneuvers, such as a slalom maneuver, it is assumed that drivers use all the available cues to optimize their driving performance. For example, in curve driving, drivers use lateral acceleration to adjust car velocity. The same result can be found in driving simulation. However, for comparable curves, drivers drove faster in fixed-base simulators than when actually driving a car. This difference in driving behavior decreases with the use of inertial motion feedback in simulators. The literature suggests that the beneficial effect of inertial cues in driving behavior increases with the difficulty of the maneuver. Therefore, for an extreme maneuver such as a fast slalom, a change in driving behavior is expected when a fixed-base condition is compared to a condition with inertial motion. It is hypothesized that driving behavior in a simulator changes when motion cues are present in extreme maneuvers. To test the hypothesis, a comparison between No-Motion and Motion car driving simulation was done, by measuring driving behavior in a fast slalom. A within-subjects design was used, with 20 subjects driving the fast slalom in both conditions. The average speed during the Motion condition was significantly lower than the average speed during the No-Motion condition. The same was found for the peak lateral acceleration generated by the car model. A power spectral density analysis performed on the steering wheel angle signal showed different control input behavior between the two experimental conditions. In addition, the results from a paired comparison showed that subjects preferred driving with motion feedback. From the lower driving speed and different control input on the steering wheel, we concluded that motion feedback led to a significant change in driving behavior.

1 Introduction

In driving simulation, visual cues are assumed to be the primary source of information (Kemeny & Panerai, 2003). Therefore, fixed-base simulators are widely used to study driving behavior for different driving conditions (Snowden, Stimpson, & Ruddle, 1998; Farber et al., 2000). However, the role of motion feedback during driving maneuvers was found to be important (Fortmüller & Meywerk, 2005; Fortmüller, Tomaske, & Meywerk, 2008) for (subjects’ motion perception and driving behavior. This means that the results obtained in studies where fixed-base or motion-based simulators with limited capabilities are used can yield conclusions that may not be transferable to real
driving. For example, Greenberg, Artz, and Cathey (2003) found that motion cues have a significant effect on driving behavior when wind disturbances are present. They also observed that control errors are largest when motion cues are not present. This leads to the question of when exactly motion cues influence driving behavior. Reymond, Kemeny, Droulez, and Berthoz (2001) state that in simple driving maneuvers such as lane changes or following a lead car, the car is mainly controlled based on visual cues. However, they argued that in more demanding tasks such as curve driving, motion cues affect driving behavior. In their experiment, they compared a dynamic simulator with a fixed-base simulator during curve driving. The results showed that the motion cues significantly reduced driving speed when compared to the static condition. The lower driving speed found in the dynamic condition is more similar to what they found in actual driving. This suggests that motion cues have a strong influence on the perception of speed, which might be related to the fact that humans have limited ability to detect speed changes (i.e., acceleration) when using only visual inputs (Moen & Brenner, 1994). The relation between motion cues and the driving task was also discussed in other driving simulation studies (McLane & Wierwille, 1975; Repa, Leucht, & Wierwille, 1982). For example, Repa et al. (1982) stated that the role of motion cues increased when driving maneuvers became more extreme. The Motion/No-Motion discussion is not exclusive to the driving simulation domain. In flight simulation, the addition of motion feedback was shown to have a beneficial effect on pilot control performance (Hosman, 1996). Longridge, Bürgi-Cohen, Go, and Kendra (2001) raised the question of whether training performed in a full motion simulator is significantly better than training performed in a fixed-base simulator with a wide field of view (FOV). In our view, previous research converges to the fact that the importance of motion cues in a simulation environment is dependent on the complexity of the maneuver or task one wants to simulate. However, studies involving extreme driving maneuvers require a motion platform capable of generating accelerations with large amplitudes, which makes these studies difficult to conduct. To introduce motion feedback in advanced driving simulation, one needs a motion platform that is able to deliver accelerations of the same order of magnitude as those felt in a real car. We intend to contribute to this gap in the literature by using the large motion space of the Desdemona simulator to study extreme driving. Our goal is to study the change in driving behavior due to motion cues in an extreme maneuver where the vehicle is driven near the traction limits of the tires. In this study, we hypothesize that driving behavior in a simulator changes when motion cues are present in an extreme maneuver. Any changes in driving behavior that we find are compared to changes in real car driving as they are described in the literature (Ritchie, McCoy, & Welde, 1968; Reymond et al., 2001; Brünger-Koch, Briest, & Vollrath, 2006). Differences in driving behavior are associated with differences in the vehicle control inputs induced by motion feedback, the vehicle model or control input dynamics among others. We deduce driving behavior differences from performance measures such as average speed or steering wheel angle. See Brünger-Koch et al. (2006) for a review of examples of performance measures used to study differences in driving behavior. A direct comparison with real driving in a fast slalom was not performed in this study due to the risks that such extreme maneuvers may have on driver safety.

The driving task we used for this study was a slalom with nine different sections. The task difficulty increased from one section to the next. For a fast maneuver, velocity perception is crucial since a wrong velocity percept can lead to loss of control over the car. To study the effect of the motion cues on driving behavior, we used two different experimental conditions, one with visual and inertial information (Motion) and one with only visual information (No Motion). An Appendix is included with design details of the motion cueing algorithm used in this study.

2 Method

2.1 Subjects

Twenty-two participants (15 male and 7 female) participated in the experiment. The participants were all
TNO employees, and none had driving experience with advanced maneuvers. The average age of the participants was 38 years ($\sigma = \pm 11$ years); the average driving experience was 18 years ($\sigma = \pm 11$ years) with an average yearly driven distance of 18,000 km ($\sigma = \pm 16,000$ km). Data from two subjects had to be discarded since they did not complete the experiment due to motion sickness issues. The first subject stopped after the first experimental condition, which was a condition with inertial motion. He felt moderate nausea and was not able to continue. During the briefing he disclosed a possible predisposition to motion sickness. The second subject stopped during the third experimental condition, which was a condition without inertial motion. The participant felt severe nausea and retching and was not able to continue. A counterbalanced design was still possible with the remaining 20 participants.

2.2 Apparatus

2.2.1 Motion Platform. The present study uses the 6-DOF Desdemona simulator (see Figure 1). Desdemona has a cabin that is suspended in a gimballed 3-DOF system, which gives it the capability to rotate freely around any axis in space. These 3 DOFs are denominated by cabin roll ($\phi_{\text{cab}}$), cabin yaw ($\psi_{\text{cab}}$), and cabin pitch ($\theta_{\text{cab}}$). The gimballed system is mounted in a heave axis ($H$) that provides the simulator with vertical translation capabilities (2 m stroke). The system moves horizontally over an 8 m track. This DOF is denominated as radius ($R$). The 8 m track can rotate around its center to provide sustained centripetal acceleration. This rotational actuator is denominated as central yaw ($\psi_{\text{centr}}$). Details on the motion system can be found in Roza, Wentink, and Feenstra (2007).

2.2.2 Simulator Cabin. The Desdemona cabin contained a car mockup similar to the one used in Valente Pais, Wentink, van Paassen, and Mulder (2009). This mockup included a force feedback steering wheel (40 cm) and two pedals (gas and brake) with force feedback. The electric control loading system for the wheel was configured to simulate inertia, damping, and hysteresis with values of 0.1 kg $\cdot$ m$^2$, 0.025 Nm $\cdot$ s/deg, and 1.5 Nm, respectively. The steering wheel torque was calculated by the car model (Mechanical Simulation Corporation, 2010).

The outside visual scene was displayed using three projectors with a refresh rate of 60 Hz. Subjects were at approximately 1.5 m from the central screen with a field of view of 120$^\circ$ horizontal and 32$^\circ$ vertical. A sound system was used to reproduce the engine sound based on the car engine rpm.

In this study, we used Carsim 7.01b (Mechanical Simulation Corporation, 2010) to simulate car dynamics. The vehicle dynamics were similar to a Volkswagen Passat wagon. The car model had automatic transmission. The speed was limited to 70 km/hr.

2.3 Slalom Maneuver

The slalom designed for this study is based on that used in the MOVES (MOtion cueing for Vehicle Simulators) Eureka project (Feenstra, Wentink, Correia Grácio, & Bles, 2009). The maneuver was designed according to the theoretical sinusoidal path of Figure 2, where $a$ is the sinusoidal path amplitude, $d$ is the distance between pylons, and $v$ is the car velocity.

$$a_y = a \left(\frac{\pi}{d} v\right)^2$$

Figure 1. Desdemona research simulator.
Nine different pylon sections were created, each containing six pylons. Each pylon section was designed to generate a different theoretical lateral acceleration in the car, ranging from 1 to 5 m/s², with an increase of 0.5 m/s² from pylon section to pylon section. Figure 2 shows a pylon section example. To create the nine different sections, the sinusoidal path amplitude, \( a \), and the car velocity, \( v \), in Equation 1 were kept constant. Their values were 1.25 m and 70 km/hr, respectively. The distance between the pylons, \( d \), was the variable used to differentiate between the pylon sections.

The nine sections are each 200 m apart from each other to cancel any dynamic driving effects between sections. The pylons are at 0.5 m from the centerline of the road, as shown in Figure 2.

### 2.4 Motion Cueing Algorithm

In order to provide the appropriate limited motion cues in the simulator, a motion cueing algorithm (MCA) is used to limit, scale, and transform the linear and rotational accelerations calculated for the simulated vehicle into motions that can be implemented within the simulator’s motion space. For this experiment, two different conditions were used to test the influence of motion feedback in advanced driving maneuvers. The first condition, denoted as No Motion, only used Desdemona actuators when subjects drove over a pylon (an upward cue was triggered to notify the driver of the event). For the rest of the simulation, Desdemona behaved like a fixed base simulator. The second condition, denoted as Motion, used an MCA designed specifically for slalom driving. The new MCA used the 8 m sledge of the simulator to create lateral specific forces close to the ones generated by the car model (motion gain of 0.75). The MCA also guaranteed a yaw rate with the same signal shape as the vehicle model yaw rate (motion gain of 0.8). The design details of the MCA can be found in the Appendix at the end of this paper.

#### 2.4.1 Simulator Motion

![Figure 3](http://direct.mit.edu/pvar/article-pdf/20/2/143/1625150/pres_a_00040.pdf)

Figure 3 shows an example of lateral and vertical specific forces generated by the vehicle model versus the ones generated by the Desdemona simulator in the Motion condition. The figure shows pylon section 1 and pylon section 8 to indicate how the MCA handles the motion cues in a slow and in a fast pylon section.

It can be observed that the specific forces in the Desdemona simulator match the specific forces calculated from the car model fairly well. The two spikes in Figures 3(c) and 3(d) indicate where the car hit a pylon.

Figure 4 shows the roll and yaw rates of the vehicle model versus the ones rendered by Desdemona. The roll rate of the MCA was scaled with a factor of two in order to generate higher lateral specific forces to compensate for the lack of tilt coordination. This can be seen in Figure 4(b) where the simulator roll rates had clearly higher amplitude than the vehicle model roll rates. Details on this can be found in the Appendix. In Figures 4(a) and 4(b) a small delay of the simulator signal in comparison to the one of the vehicle model can be noticed. This delay was created by the MCA limiters.

The simulator yaw rate of pylon section 1 (Figure 3[c]) correctly follows the amplitude and frequency generated by the vehicle model. For pylon section 8 a small delay is noticeable due to the MCA limiters.

### 2.5 Experimental Design

The experiment had a repeated measures design. Two different experimental conditions were measured,
Figure 3. Specific forces of the vehicle model (dashed line) versus the specific forces generated by Desdemona simulator (solid line) for sections 1 and 8 of the slalom maneuver.

a Motion condition where visual and inertial cues were presented to the driver while driving through the pylon sections, and a No-Motion condition where inertial cues were presented only to indicate a cone was hit. The conditions were repeated two times which makes a total of four simulator runs for each subject. For simplicity, we denominated the first two runs as Trial 1 and the last two runs as Trial 2. Participants were not aware of this division nor that only two different experimental conditions were to be performed. The instructions just informed participants that four simulator runs would be performed without revealing any information regarding the inertial cues of the experimental conditions. To cancel order effects, we divided the subjects into two different groups as shown in Table 1. Subsequently, half of the subjects started with the Motion condition while the other half started with the No-Motion condition.

2.6 Procedure

The experiment started with a practice run. For this practice trial, only the first section of the slalom maneuver was driven. Subjects could repeat the practice run until they felt familiar with the task. After the practice run, each subject performed the four simulator runs. For each run, all nine slalom sections were driven, in increasing order of difficulty. Participants were instructed to drive through the slalom as fast as
possible; however, the velocity was limited to a maximum speed of 70 km/hr. They were told only to reduce the car velocity (using the brake pedal or releasing the gas pedal) when the car was near hitting the guard rail or if they felt they were losing the control over the car.

### Table 1. Motion Condition Order by Group Number

<table>
<thead>
<tr>
<th>Trial 1</th>
<th>Trial 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>First run</td>
<td>Second run</td>
</tr>
<tr>
<td>1</td>
<td>No Motion</td>
</tr>
<tr>
<td>2</td>
<td>Motion</td>
</tr>
</tbody>
</table>

#### 2.7 Data Analysis

#### 2.7.1 Objective Measures. Several simulation variables were recorded for each run. From the recordings, four objective measures were calculated. These were the average car speed, the average peak lateral acceleration, the power spectral density (PSD) of the steering wheel angle, and the number of pylon sections successfully completed.

#### 2.7.1.1 Number of Pylon Sections Accomplished. The number of pylon sections successfully completed consists of the number of participants who were able to drive through the nine pylon sections without ever
having an accident. Data of the number of accidents occurring per pylon section will also be presented.

2.7.1.2 Average Car Speed. The average car speed was obtained for each pylon section by calculating the mean speed for every subject and then averaging this value between subjects. Some participants lost control over the car before driving through the nine pylon sections, therefore the average speeds for the last pylon sections were calculated with a smaller number of participants. The average speed for each pylon section was obtained using participants who did not crash during both experimental conditions in that section, so that a proper statistical comparison between the two experimental conditions could be made.

2.7.1.3 Average Peak Lateral Acceleration. The average lateral peak acceleration was obtained for each pylon section by calculating the mean peak acceleration obtained from the car model for every subject and then averaging this value between subjects. Note that this acceleration is an output from the car model and not the acceleration being perceived by subjects during the Motion condition. The number of participants in the last pylon sections is smaller due to the number of crashes. Again, the average results were calculated using participants who did not crash during either experimental condition.

2.7.1.4 Power Spectral Density. The PSD of the steering wheel angle was obtained to examine differences in control inputs between the two different experimental conditions. The PSD was calculated for every subject and then averaged.

2.7.2 Subjective Measures.

2.7.2.1 Paired Comparison. A paired comparison technique was used to measure the subjective preference. This technique was already used in several driving simulation studies (Grant, Artz, Blommer, Cathey, & Greenberg, 2002; Grant, Blommer, Cathey, Artz, & Greenberg, 2003). In a technique like this, two stimuli are presented to the subject with a short time interval between them. In our case, the stimuli were the simulator runs. Then, subjects have to decide between the two runs, which condition felt more natural when compared to real car driving. After each comparison the preferred experimental condition would get a score of one. The total score used in the analysis is then the number of times that an experimental condition was preferred over the other condition. The paired comparison was made between the first/second, second/third, and third/fourth simulator runs.

2.7.2.2 Motion Sickness Scale. Motion sickness was scored with a six-point sickness scale (Golding, 1998; Mert, Bles, & Nooij, 2007), after each run. The scale is shown in Table 2. Subjects were asked to indicate their level of comfort after each run through the intercom. If their level was equal to or higher than four, the experiment stopped.

### Table 2. Six-Point Motion Sickness Scale

<table>
<thead>
<tr>
<th>Score</th>
<th>Symptom</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Feeling OK, no symptoms</td>
</tr>
<tr>
<td>2</td>
<td>Initial symptoms, such as stomach awareness, but no nausea</td>
</tr>
<tr>
<td>3</td>
<td>Mild nausea</td>
</tr>
<tr>
<td>4</td>
<td>Moderate nausea</td>
</tr>
<tr>
<td>5</td>
<td>Severe nausea and/or retching</td>
</tr>
<tr>
<td>6</td>
<td>Vomiting</td>
</tr>
</tbody>
</table>

3 Results

3.1 Number of Pylon Sections Accomplished

The slalom got increasingly more difficult with each pylon section. Table 3 shows the number of participants (out of 20) who were able to drive through the nine slalom sections without crashing the car. The runs were again divided in two groups, to show the difference between the first time a motion condition was driven (Trial 1) and its repetition (Trial 2). For the first trial, 55% of the participants were able to finish the slalom.
Table 3. Number of Participants out of 20 who Finished the Nine Pylon Sections

<table>
<thead>
<tr>
<th></th>
<th>Trial 1</th>
<th>Trial 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Motion</td>
<td>13</td>
<td>16</td>
</tr>
<tr>
<td>No motion</td>
<td>9</td>
<td>15</td>
</tr>
</tbody>
</table>

Table 4. Number of Accidents per Total Participants in Each Pylon Section

<table>
<thead>
<tr>
<th>Pylon section</th>
<th>Trial 1</th>
<th>Trial 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0/20</td>
<td>0/20</td>
</tr>
<tr>
<td>2</td>
<td>0/20</td>
<td>0/20</td>
</tr>
<tr>
<td>3</td>
<td>0/20</td>
<td>0/20</td>
</tr>
<tr>
<td>4</td>
<td>0/20</td>
<td>0/20</td>
</tr>
<tr>
<td>5</td>
<td>0/20</td>
<td>0/20</td>
</tr>
<tr>
<td>6</td>
<td>1/20</td>
<td>2/20</td>
</tr>
<tr>
<td>7</td>
<td>2/19</td>
<td>5/18</td>
</tr>
<tr>
<td>8</td>
<td>4/17</td>
<td>1/13</td>
</tr>
<tr>
<td>9</td>
<td>0/13</td>
<td>3/12</td>
</tr>
</tbody>
</table>

For Trial 2, subjects were more consistent and 75% were able to finish the slalom. Differences between Motion and No Motion were only considerable for Trial 1. In this trial, 65% of the participants in the motion condition were able to finish the slalom against 45% in the condition without motion feedback.

Table 4 shows the number of accidents per pylon section. It also shows the number of participants who were still driving at the beginning of each pylon section. One can observe that accidents start occurring mainly after the sixth pylon section. Note in Table 4 the higher number of accidents in Trial 1 compared to Trial 2.

### 3.2 Average Speed

The average speeds were analyzed to check differences in driving strategy between the two motion conditions. Note that the car velocity could be changed by pressing the brake pedal or by releasing the gas pedal. Subjects had a more constant driving behavior in Trial 2 than in Trial 1. For Trial 1, the total number of accidents was higher than for Trial 2. This was shown before with the number of pylon sections accomplished. The SD of the average speeds were also higher for Trial 1. For example, in pylon section 9, the SD of the average speed in the Motion condition is 4.84 for Trial 1 versus 1.33 for Trial 2. This means that the practice run was not enough for subjects to develop a constant driving behavior in that trial. Therefore we only considered Trial 2 for the speed analysis due to the more constant driving behavior and smaller number of accidents. In Figure 5, the average speed decreased for the more difficult pylon sections, and the speed in the Motion conditions is lower than the speed in the No-Motion conditions.

A repeated measures ANOVA was performed with the intent of studying the effect of motion on the car’s average speed (Table 5). Significant main effects were found to start on pylon section 5.

### 3.3 Average Lateral Acceleration Peak

For the analysis of the lateral acceleration, only Trial 2 was considered for the same reasons as presented in the average speed section. Figure 6 shows that the peak lateral acceleration is higher for the more difficult pylon sections. For the Motion condition, the peak lateral acceleration seems to maintain the same level
Table 5. Repeated-Measures ANOVA Results for the Effect of the Motion Condition on the Average Speed (* = p < .05)

<table>
<thead>
<tr>
<th>Section</th>
<th>F</th>
<th>p</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>F(1,18) = 8.697</td>
<td>0.009</td>
<td>*</td>
</tr>
<tr>
<td>6</td>
<td>F(1,18) = 19.278</td>
<td>0.000</td>
<td>*</td>
</tr>
<tr>
<td>7</td>
<td>F(1,17) = 25.306</td>
<td>0.000</td>
<td>*</td>
</tr>
<tr>
<td>8</td>
<td>F(1,14) = 5.940</td>
<td>0.029</td>
<td>*</td>
</tr>
<tr>
<td>9</td>
<td>F(1,11) = 5.352</td>
<td>0.041</td>
<td>*</td>
</tr>
</tbody>
</table>

Table 6. Repeated-Measures ANOVA Results for the Effect of the Motion Condition on the Average Lateral Acceleration Peak (* = p < .05)

<table>
<thead>
<tr>
<th>Section</th>
<th>F</th>
<th>p</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>F(1,18) = 4.294</td>
<td>0.053</td>
<td>—</td>
</tr>
<tr>
<td>6</td>
<td>F(1,18) = 7.229</td>
<td>0.015</td>
<td>*</td>
</tr>
<tr>
<td>7</td>
<td>F(1,17) = 5.510</td>
<td>0.031</td>
<td>*</td>
</tr>
<tr>
<td>8</td>
<td>F(1,14) = 33.067</td>
<td>0.000</td>
<td>*</td>
</tr>
<tr>
<td>9</td>
<td>F(1,11) = 4.986</td>
<td>0.047</td>
<td>*</td>
</tr>
</tbody>
</table>

Figure 6. Average lateral acceleration peak and 95% confidence interval for all pylon sections in Trial 2.

after pylon section 6. The same does not hold for the No-Motion condition, where the peak lateral acceleration increases until pylon section 8. For the later pylon sections, note that the No-Motion condition generates higher peak lateral accelerations than the Motion condition. A repeated-measures ANOVA was used to test whether the peak lateral accelerations found for the No-Motion conditions were significantly higher than the ones found for the Motion condition. The statistical analysis (see Table 6) showed that these differences are significant starting on pylon section 6.

3.4 Power Spectral Density Analysis

The power spectral density (PSD) of the steering wheel angle was calculated and examined for differences in control input between the tested motion conditions. Similar inspections of the PSD signals were done for flight simulation studies (Guo, Cardullo, Telban, Houck, & Kelly, 2003; Gouverneur, Mulder, van Paassen, Stroosma, & Field, 2003; Telban, Cardullo, & Kelly, 2005; Soparkar & Reid, 2006).

Figure 7 shows the results obtained from the PSD analysis. Here, only the results of Trial 2 were used, and the PSD for pylon sections 2 and 9 is shown. The spectrum of the control input is largely determined by the steering wheel movements required to negotiate the pylons. These movements are reflected in the peaks in Figures 7(a) and 7(b) having similar frequency as the slalom. Figure 8 shows a detailed zone of Figure 7. It is possible to observe additional higher frequency power after the main frequency peak for the No-Motion condition. This behavior is evident in both pylon sections but in different frequency zones. For pylon section 2, this behavior is noticeable in the frequency band from 0.3 to 0.6 Hz, while for pylon section 9 the frequency band is from 0.6 to 1 Hz. Therefore, to determine the effect of motion on the control input, the average power in the frequency band from 0.3 to 0.6 Hz was computed for section 2, and for section 9 the power in the frequency band from 0.6 to 1.0 Hz. Control inputs in this frequency are not forced by the slalom, but indicate additional energy in the control input. The dependent t-test results can be found in Table 7. For pylon section 2, the results are significant. For pylon section 9, no significant differences were found.

3.5 Paired Comparison

Figure 9 shows the total scores for each of the paired comparisons. A chi-square test was used to verify
Figure 7. Average PSD of the steering wheel input for pylon sections 2 and 9.

Figure 8. Zoom of the average PSD for pylon sections 2 and 9.

Table 7. Dependent t-test Results for the Mean PSD in the Frequency Range of 0.3–0.6 Hz in Pylon Section 2 and 0.6–1 Hz in Pylon Section 9 (* = p < .05)

<table>
<thead>
<tr>
<th>Pylon section</th>
<th>Motion</th>
<th>No Motion</th>
<th>Standard error</th>
<th>t</th>
<th>p</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>0.0101</td>
<td>0.0341</td>
<td>0.0058</td>
<td>t(19) =</td>
<td>4.157</td>
<td>0.001 *</td>
</tr>
<tr>
<td>9</td>
<td>0.0267</td>
<td>0.0455</td>
<td>0.0122</td>
<td>t(13) =</td>
<td>1.536</td>
<td>0.149 —</td>
</tr>
</tbody>
</table>

the significance of the paired comparison analysis. In the first comparison (1 vs. 2 in Figure 9) there was no significant effect of the Motion condition in the subjects’ overall impression, χ²(1) = 3.2, p = .074. A total of 14 subjects preferred the condition with motion, while six subjects preferred the No-Motion condition. For the second and third comparisons, a significant effect of the Motion condition at the 5% level...
was found, \( \chi^2(1) = 5, p = .025 \) and \( \chi^2(1) = 9.8, p = .02 \), respectively. For the second comparison, 15 subjects preferred the Motion condition. For the third comparison, 17 subjects preferred the condition with motion.

When the scores of the paired comparisons are accumulated, the result is a total score of 46 for the Motion condition and a total score of 14 for the No-Motion condition. In this case, there is a significant effect of the Motion condition at the 1% level, \( \chi^2(1) = 17.067, p < .01 \).

### 3.6 Motion Sickness Scale

The motion sickness scale was used to observe the subjects’ sickness level during the experiment. Figure 10 shows the average sickness scores of all motion conditions for Trials 1 and 2. It can be observed that the No-Motion condition scored higher on the sickness scale than the Motion condition. A repeated-measures ANOVA was performed to check for significant effects of the Motion condition or the trial. The No-Motion condition had significantly higher scores than the Motion condition, \( F(1,19) = 5,444, p = .031 \). A significant main effect of the trial on the motion sickness scale was not found. However, note that the motion sickness average scores are low for all the conditions (below 2 on a scale of 1–6), which indicates that except for the two subjects who could not finish the simulator runs, motion sickness was not an issue during the experiment.

### 4 Discussion

#### 4.1 Driving Behavior

The performance, in terms of the number of slalom sections successfully completed by the subjects, was higher for the second trial than for the first trial. This indicates that, despite the practice sessions before the experimental runs, a learning effect was still present during the first trial. A contributing factor is that the practice section only contained the easiest pylon section. Therefore, subjects were not trained for the more difficult driving conditions encountered during the experimental runs. For Trial 2, the driving behavior in the two experimental conditions was more similar; for both conditions the number of participants who were able to successfully drive through the nine pylon sections was approximately equal.

The average speed at which the later, and more demanding, slalom sections were driven is significantly lower for the Motion condition than for the No-Motion condition. Also, the lateral acceleration peaks were higher for the No-Motion condition. This indicates that the subjects changed their driving strategy when motion feedback was present. Reymond et al. (2001) also reported a change in driving style when comparing a Motion/No-Motion situation during curve driving. Drivers would select a lower speed in conditions where lateral acceleration motion was present. In our case, the motion cues significantly changed the average driving speed, forcing drivers to drive slower. From the acceleration peak results, we observe that in the Motion condition, subjects kept a constant car lateral acceleration of approximately 5 m/s² from the sixth pylon section on. This acceleration level seems to be their threshold for normal driving. It seems that subjects used the lateral acceleration feedback to adjust their driving speed to a level that provides comfortable driving. During the No-Motion condition, the speed decrease was less, possibly because there was no lateral acceleration feedback to make them adjust the car velocity to a more comfortable level. This is also observed in the increased peak lateral acceleration, which increases except for at pylon section 9, where adaptation was needed to keep...
control over the car. The literature shows that for other driving maneuvers, the average car velocity is different when a static simulator is compared to a dynamic simulator (Reymond et al.; Siegler, Reymond, Kemeny, & Berthoz, 2001; Brünger-Koch et al., 2006). Similar results were also reported when comparing real and simulated driving (Reymond et al.; Brünger-Koch et al.). In this case, it was shown that participants drove faster in a simulated environment. Their results are congruent with what was found in actual curve driving, where drivers adapt their forward speed based on the lateral acceleration (Ritchie et al., 1968).

From the PSD results, we also observe different driving behavior between the two experimental conditions. In pylon sections with lower acceleration levels (see Figure 7[a]), additional energy at higher frequency is present in the control signal of the No-Motion condition. This high frequency energy in the control input is present possibly to correct for small errors in the car trajectory. In the Motion condition, this additional energy is not present probably because the lateral force feedback helps drivers to have a more precise control input. Similar effects in control behavior were also found in flight simulation studies (Zaal, Pool, Mulder, & van Paassen, 2009).

The observed differences in the dependent variables for the more demanding pylon sections are congruent with what was found in other studies that argued that motion feedback has an effect in extreme maneuvers (Repa et al., 1982; Reymond et al., 2001). In our case, we observed significant changes in driving behavior, measured by the average speed, the lateral acceleration peaks, and the control effort (PSD) for the more extreme sections of the slalom maneuver, while in the less extreme sections, changes between motion/no motion are small.

### 4.2 Motion/No-Motion Preference

In the experiment, subjects were asked to state their preference between different motion conditions. Subjects were not informed of the nature and number of different motion conditions that had to be compared. Although the No-Motion condition had no motion feedback—except in cases where a pylon was hit—some subjects indicated that they perceived vestibular motion in this condition.

From the paired comparison analysis, we see that the Motion condition was clearly preferred over the No-Motion condition. We also observe that with the progression of the experiment, preference for the Motion condition further increased. This occurred mainly with the subjects that started the experiment...
with the No-Motion condition. In the first paired comparison, four subjects of this group preferred the No-Motion condition, while in the last comparison, only two subjects continued to prefer this condition.

By accumulating the results from the three paired comparisons, the difference between the two motion conditions was more obvious, showing that, overall, subjects prefer the condition with motion feedback. It can be concluded that for advanced maneuvers like this slalom, subjects prefer to have a simulator with motion feedback, rather than a fixed-base simulator. Some of the participants commented that it was much easier to “get in tune with the cadence” (the sinusoid) of the slalom when motion was present. Similar preferences were found in other slalom driving studies, with less extreme conditions (Feenstra et al., 2009; Pretto, Nusseck, Teufel, & Bülthoff, 2009). These studies found that subjects prefer a simulation with motion rather than a simulation without motion. The slalom maneuver of these studies was composed of only one pylon section with pylons spaced 62.5 m apart, which is comparable with the second pylon section of our study.

4.3 Motion Sickness Scale

The sickness scores were very low for all the motion conditions. This is a desired result, since higher motion sickness scores could bias the other experimental measures.

The No-Motion condition was more sickening than the Motion condition. This would match the theory of Groen and Bos (2008), who state that simulator sickness arises from the difference between the simulator motion and the expected motion. In the No-Motion condition, there is no inertial stimulation. This creates an incongruency between the vestibular sensors and the information acquired from the visual path, while in the motion condition, the motion signals were largely congruent with the motion of the simulated vehicle. Subjects with driving experience are expected to be more sensitive to this discrepancy, which could produce high sickness scores in the No-Motion condition.

Although there is a slight increase of the sickness scores with the trials, a significant effect was not found from the statistical analysis.

5 Conclusion and Recommendations

In this study, an advanced driving task, namely slalom driving, was tested in a No-Motion and a Motion condition. The Desdemona simulator was used in this experiment, which allows the generation of motion profiles that strongly resemble the motion in the actual vehicle for such a driving task.

In response to the motion feedback in the task, the subjects adapted their driving behavior in the following way:

- A direct adaptation was apparent from changes in the PSD of the steering wheel control input. Apparently, subjects use motion feedback as one of the sources for determining their control response. For the less extreme sections of the slalom, the PSD of the No-Motion condition showed more energy in the control signal at frequencies above the ones imposed by the driving task. This suggests a noisier control input than the one of the Motion condition.

- An indirect adaptation or change in strategy occurred as well. In the more difficult slalom sections (starting with section 6), subjects adapted their speed in the Motion condition to maintain an approximately constant level of lateral acceleration. In the No-Motion condition, the level of lateral acceleration increased up until pylon section 8.

It can be concluded that it is important to consider not only the direct effects of a difference in behavior caused by impoverished feedback (in this case a larger noise component in the control signal at higher frequencies), but also indirect effects, causing subjects to adopt different strategies because the reduced feedback hinders, as in this case, the perception of risks.

From a paired comparison between the Motion and No-Motion conditions, it was shown that subjects preferred the Motion over the No-Motion conditions.

The present experiment explored the two extremes possible for the slalom task in the Desdemona simulator; a No-Motion condition versus a Motion condition where the motion to a large extent matched the motion in a real vehicle. It would be interesting to explore to what degree lower fidelity motion can produce driving
behavior and strategy that are equivalent to the full-motion condition. In this study, it was found that the motion cues were used to adapt the car velocity to a comfortable level. The fact that subjects were not expert drivers can be an explanation for the use of the lateral acceleration in a more conservative driving style, that is, driving slower and with less steering wheel effort, instead of a more aggressive driving style. It is expected that expert drivers, for example, race car drivers, would use such inertial cues to estimate the saturation limits of the car tires, which would allow them to drive faster during the motion condition. This hypothesis would be interesting to test in a future study.

Acknowledgments

This work was conducted in the framework of the MOVES (MOtion cueing for VEhicle Simulators) Eureka #3601 European research project, which aims to increase scientific knowledge of human multisensory perception of motion in virtual environments, and to explicitly define the possibilities and limitations of several high-end European driving simulators. The MOVES consortium is composed of LPPA/CNRS, Renault, TNO Human Factors, MPI-Biological Cybernetics, AMST, and collaborates with DLR and SIMTEC.

References


Appendix

In this section, we describe in detail the MCAs used for the different experimental conditions.

A.1 No Motion

The MCA used in this motion condition was composed by a collision algorithm (that detects when subjects drive over a pylon) in series with a third order high-pass filter. Figure A1 shows a block diagram of the MCA used in the No-Motion condition. The inputs of the MCA were the car $x$ and $y$ positions in the virtual world, while the outputs were the position, velocity, and acceleration of Desdemona’s heave drive. The collision algorithms verified the car position and the pylon position and calculated the difference between them. When the car passed too close to a pylon, an acceleration impulse was generated by the algorithm and sent to the block HP Filter 3order represented in Figure A1. The HP Filter 3order block is defined by Equation 2, where $\omega$ is the second order high-pass filter natural frequency, $\xi$ is the second order high-pass filter damping, and $\omega_b$ is the first order high-pass filter natural frequency.

$$H(s) = \frac{s^2}{s^2 + 2\omega\xi s + \omega^2} \frac{s}{s + \omega_b}$$

The collision algorithm was implemented in both motion conditions, providing equal consequences for hitting a pylon, thereby forcing subjects to comparable behavior regarding the avoidance of pylons.

A.2 Motion

The Motion condition uses an MCA designed for advanced driving maneuvers. Previous solutions developed for Desdemona (Wentink, Valente Pais, Mayrhofer,
Figure A1. Block diagram of the motion cueing algorithm used in the No-Motion condition.

Figure A2. Desdemona frame of reference. Initially the participant is looking in the positive $x_d$ direction. During the motion profile, the simulator cabin can be misaligned, therefore changing the subject direction in relation to the $F_d$ (note that the simulator cabin is not represented in the schematic).

Figure A3 shows the block diagram of the MCA used in the Motion condition. The inputs for this motion filter were the car-specific forces ($f_x$, $f_y$, and $f_z$), the car positions ($x$ and $y$) and the car longitudinal velocity ($v_x$). The outputs are the position, velocity, and acceleration of all Desdemona’s six actuators. The filter is divided into two channels: a specific force channel and an angular rate channel.

A.2.1 Specific Force Channel. In this channel, the car-specific forces were first scaled using the Scaling Factor block and then were sent to the Car2Desdemona block. The Car2Desdemona block transformed the specific forces from the vehicle reference frame into the

Feenstra, & Bles, 2008; Valente Pais et al., 2009) were not able to deliver lateral specific forces with amplitudes higher than approximately $3 \text{ m/s}^2$. This is because these solutions were targeted at city driving, with a focus on low-speed curve driving.

For the advanced driving MCA, the motion filtering is applied in the Desdemona body reference frame ($F_d = x_d y_d z_d$) represented in Figure A2. The origin of the reference frame is in the middle of the heave sledge, meaning that when the sledge moves, the reference frame moves with it.

The specific forces calculated with the car model are scaled and then converted to the Desdemona reference frame ($F_d$), after which the motion filters are applied.
Desdemona reference frame. In this way, the specific forces were filtered at the actuator level. We transformed the specific forces coming from the Car2Desdemona block into accelerations by subtracting the gravitational component.

A.2.1.1 Heave Channel. The $z$ acceleration coming from the Car2Desdemona block is added with the acceleration from the Collision Algorithm block. The Collision Algorithm was equal to the one used in the No-Motion condition. The acceleration signals are filtered using a third-order high-pass filter (HP Filter 3order), defined by Equation 2. The Road Rumble block is used to create the oscillations generated by road irregularities. This algorithm was already used in a previous Desdemona study (Wentink et al., 2008; Valente Pais et al., 2009). The accelerations generated by the Road Rumble algorithm are added to the ones coming from the high-pass filter. The acceleration signals are sent to a Limiter block that keeps the signals within the Desdemona limits.

A.2.1.2 Radius Channel. The $y$ specific force coming from the Car2Desdemona block is filtered using a second-order high-pass filter (HP Filter 2order) defined by:

$$H(s) = \frac{s^2}{s^2 + 2s\omega\xi + \omega^2} \quad (3)$$

Here $\omega$ is the second-order high-pass filter natural frequency and $\xi$ is the second-order high-pass filter natural damping ratio.

Figure A3. Block diagram of the MCA used in the Motion condition.
damping. The Limiter block was again used to limit the signal before sending it to the actuator.

A.2.1.3 Central Yaw Channel. The central yaw actuator is used to generate longitudinal acceleration. In contrast to the radius and heave actuators, the central yaw ($\psi_c$) is a rotation actuator instead of a translational actuator. Therefore, the simulation of longitudinal specific force is not so straightforward as for the other actuators. By rotating $\psi_c$, centripetal and tangential accelerations are generated. This can be seen in Figure A4, where $\vec{a}_c$ is the centripetal acceleration, $\vec{a}_t$ is the tangent acceleration, $\omega$ is the central yaw angular velocity, and $R$ is the current cabin radius.

The tangent acceleration will be used to cue the longitudinal acceleration coming from the Car2Desdemona block. The tangent acceleration is given by Equation 4, where $\vec{a}_t$ is the tangent acceleration, $\dot{\omega}$ is the angular acceleration of the central yaw, and $R$ is the current cabin radius.

$$\vec{a}_t = \dot{\omega} R$$  \hspace{1cm} (4)

Consider now that the longitudinal acceleration from the Car2Desdemona block ($\vec{a}_x$) equals $\vec{a}_t$ and that Equation 4 is resolved in order to yield the angular acceleration creating Equation 5. Equation 5 is then the needed angular acceleration of the central yaw to generate a longitudinal force equal to $\vec{a}_x$.

$$\dot{\omega} = \frac{\vec{a}_x}{R}$$  \hspace{1cm} (5)

The YawAcc block (Figure A3) uses Equation 5 to transform linear acceleration into angular acceleration. Note that this method will also generate centripetal acceleration (Figure A4). Because this technique is limited to generating onset cues, we expect low angular velocities and thus limited centripetal acceleration components. The angular acceleration is filtered by a second-order high-pass filter (HP Filter 2order) defined by Equation 3. The Limiter block was used at the end of the channel to guarantee that Desdemona limits were not violated.

A.2.2 Angular Rate Channel. The angular rates coming from the car model are scaled in the Scaling Factor block. The scaled angular rates are then transformed from body rates into Desdemona angular rates in the Body2Desdemona block. The Limiter block was used to guarantee that the signals sent to the simulator are within limits. The fact that filtering was not performed in this channel guarantees that the shape of the signal coming from the vehicle model is maintained.

A.2.3 Tuning the MCA for the Slalom Maneuver. Figure A5 shows a schematic of the simulator movement for a slalom left curve. While the virtual vehicle approached the pylon (1 in Figure A5), the Desdemona cabin remained at the neutral position. When the vehicle started turning to the right (2), Desdemona moved along the radius sledge to the right. The cabin rotated along its $z$ axis to follow the rotation of the virtual vehicle. With this movement, the cabin $y$ axis, which is in the car frame of reference, is no longer aligned with the Desdemona radius, which is in the Desdemona frame of reference. Therefore, the central yaw actuator moved to keep the lateral specific force generated by the simulator aligned with the one of the virtual vehicle. This change of reference frame is performed by the Car2Desdemona block in Figure A3. When the virtual vehicle turned to the left (3), the simulator changed its movement also to the left along the radius track. Note that it is not possible to cue longitudinal specific force with the cabin at the center of the radius track, accord-
Figure A5. Schematic of Desdemona cabin motion during a slalom left curve. (a) Desdemona movement. (b) Car movement in the virtual world.

Table A1. Motion Cueing Algorithm Scaling Factors

<table>
<thead>
<tr>
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<th>Scaling factor</th>
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</thead>
<tbody>
<tr>
<td>Lateral specific force</td>
<td>0.75</td>
</tr>
<tr>
<td>Vertical specific force</td>
<td>1</td>
</tr>
<tr>
<td>Roll rate</td>
<td>2</td>
</tr>
<tr>
<td>Pitch rate</td>
<td>0.8</td>
</tr>
<tr>
<td>Yaw rate</td>
<td>0.8</td>
</tr>
</tbody>
</table>

Table A2. Motion Cueing Algorithm Characteristics

<table>
<thead>
<tr>
<th>Desdemona actuators</th>
<th>$\omega$</th>
<th>$\xi$</th>
<th>$\omega_b$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Central yaw ($x$ direction in the cabin frame)</td>
<td>1 rad/s$^2$</td>
<td>1</td>
<td>—</td>
</tr>
<tr>
<td>Radius ($y$ direction in the cabin frame)</td>
<td>0.2 rad/s$^2$</td>
<td>1</td>
<td>—</td>
</tr>
<tr>
<td>Heave ($z$ direction in the cabin frame)</td>
<td>2 rad/s$^2$</td>
<td>1</td>
<td>2 rad/s$^2$</td>
</tr>
</tbody>
</table>

To Equation 5. For this reason, it was chosen not to include the vehicle longitudinal cues in the filter.

Table A1 shows the values of the scaling factors used in the Scaling Factor blocks of the MCA (Figure A3) while Table A2 shows the parameters used in the MCA high-pass filters. The vehicle roll rate was amplified in this block; this leads to higher roll angles when the car is in a curve, with a resulting lateral gravity component that provides additional lateral forces. The rotational false cue was not disturbing, as confirmed during initial tests.