The fun of engineering: a motion seat in a driving simulator

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Abstract

This study evaluates the use of a motion seat in a fixed-base driving simulator. Sixty subjects with driving experience participated in a braking experiment and a cornering experiment in a between-subjects design. In the braking experiment, motion seat cueing versus motion turned off was evaluated. In the cornering experiment, we evaluated motion cueing according to the engineering way, according to the ‘fun’ way, and motion turned off. When driving under the engineering way condition, the driver’s body is tilted outward in the corners, to simulate the forces acting on the body during driving in a qualitatively correct fashion. The fun way tilts the body in the opposite direction, into the corner, as is done in many amusement rides. As hypothesized, results of the braking experiment showed that the motion seat resulted in smaller vehicle decelerations, more consistent stopping positions at a stop line, and smoother braking onset as compared to motion off. Results of the cornering experiment did not show any significant differences in driving performance between the three conditions. Results of a questionnaire showed that subjects rated fun cueing as more realistic/satisfactory than motion off. Individual differences were large compared to the effects of the motion seat. Future research could evaluate whether the motion seat improves driver training results.

Résumé
Introduction

Depending on fidelity, drivers in a simulator may have difficulty with estimating distances, speeds and accelerations, which can result in control strategies that differ from reality (e.g., Boer et al., 2001). In this respect, the lack of motion cues in fixed-base simulators is suggested to contribute to unrealistic behavior (Greenberg et al., 2003). However, full motion-base simulators are often considered financially unattractive in the domain of commercial simulation-based driver training. Moreover, even with sophisticated simulators it is physically impossible to correctly simulate all the accelerations that affect the human body during driving (Von der Heyde and Riecke, 2001). A motion seat may act as a low-cost alternative for providing feedback. A previous study using a motion seat in a CAVE showed that subjects preferred motion to no-motion, however, subjective preference and driving behavior hardly differed between motion parameter sets (Mollenhauer et al., 2004). The present study aims to gain insight into the effects of a motion seat and potential motion cueing algorithms in a fixed-base driving simulator. Subjects (N=60) participated in a braking and a cornering experiment.

Braking experiment

In the braking experiment, a comparison was made between motion and no-motion. It was hypothesized that motion results in similar effects as those reported by Siegler et al. (2001), who compared a limited-amplitude dynamic simulator platform turned on and off. Siegler et al. found that the addition of motion resulted in more accurate stopping positions at a signpost, lower maximum decelerations, and lower jerk at the onset of braking. No differences were found for speed and distance to the target at braking onset.

Cornering experiment

In the cornering experiment, three fundamentally different conditions were compared: motion cueing according to the engineering way (Eng), the fun way (Fun), and no-motion (Off). When driving under the Eng condition, the driver’s body was tilted outwards in bends as is regularly done in motion driving simulators. Fun tilted the body in the opposite direction, into the corner. Evaluation of the engineering versus fun ways of motion cueing was proposed in a working paper of Von der Heyde and Riecke (2001).

The philosophy behind the engineering way is as follows: When driving through a bend in a real car, the centripetal forces from wheel-ground-contact point towards the inside of the bend. The driver observes a reactive centrifugal force that seems to move his/her body towards the outer edge of the car. The car generally rolls to the outside as well, as the suspension system generates a counteracting moment about the center of gravity. The roll angle in a real car, however, is different from the roll angle that would be required for substituting a centripetal force with a gravity force in a simulator. So, the engineering way can be considered a relatively realistic approach to motion cueing, as the steady-state forces are qualitatively correct. Yet, it is quantitatively incorrect.

The fun way acts oppositely and simulates motion by leaning inwards in bends; an approach that is used in many amusement rides. The fun way can be considered less realistic than the engineering way as the gravity force in the simulator has the wrong direction. Still, it is hard to conceive that millions of spectators per year in amusement
rides are ‘wrong’. The fun way could provide advantages, such as higher ratings of pleasure and lower ratings of simulator sickness. It has been suggested that the incidence of simulator sickness symptoms in amusement rides is far less than that of commercial engineered driving simulators (Von der Heyde and Riecke, 2001). The present study hypothesizes that the engineering way causes higher ratings of realism, higher incidence of simulator sickness, and lower ratings of pleasure, than the fun way and no-motion (see also Von der Heyde and Riecke, 2001). Second, it is hypothesized that the engineering way results in more realistic (objectively measured) driving performance than the fun way and no-motion. Here, performance measures of Siegler et al. (2001) will be used. These authors compared cornering behavior in 90-degree bends with a limited-amplitude motion platform turned on and turned off. Siegler et al. found that motion caused subjects to take wider bends. Second, motion resulted in lower, more realistic, cornering speeds than motion off.

Method

Experiments were conducted in a medium-fidelity fixed-base Dutch Driving Simulator (www.rijsimulatie.nl, 2007). The simulator was operated using an automatic gearbox. The motion seat was obtained from FrexGP (www.frex.com/gp, 2007). Longitudinal and lateral accelerations of the virtual vehicle served as proportional input for the angular position of the seat. A lateral acceleration of 8.3 m/s² corresponded to an inclination of 6.2 degrees. A longitudinal deceleration/acceleration of 7.7 m/s² corresponded to an forwards/backwards inclination of 4.7 degrees. We did not subtract seat orientation from the visual presentation. The decision to not use visual compensation was based on a study described in Mollenhauer (2001), where it was found that subjects preferred the condition where seat orientation was not subtracted from the visuals.

A between-subjects design was applied as illustrated in Table 1. Longitudinal cueing was always provided according to the engineering way (Eng), i.e. backward tilt for acceleration, and forward tilt for deceleration of the simulated vehicle. Trial experiments were conducted with longitudinal Fun-cueing but this was considered awkward.

All subjects were male, with at least one year of driving experience, and approximately equal ages (mean 21.9 years, SD 1.9), driver license possession (mean 3.5 years, SD 2.1), and self-rated driving ability on a scale from 1-10 (mean 7.7, SD .91) in the three groups.

Twenty-four subjects were selected to complete a repeated measurement of the braking experiment one week after they completed the first series of experiments, thereby allowing for within-subjects analyses. Twelve subjects drove without motion in the first experiment and with motion in the second experiment. Conver sely, twelve other subjects drove with motion in the first experiment and without motion in the second experiment.

Table 1. Longitudinal (Long) & lateral (Lat) cueing during between-subjects experiment.

<table>
<thead>
<tr>
<th></th>
<th>Group Fun (N=20)</th>
<th>Group Eng (N=20)</th>
<th>Group Off (N=20)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Braking experiment (10 mins)</td>
<td>Long: Eng</td>
<td>Long: Eng</td>
<td>Off</td>
</tr>
<tr>
<td>Cornering experiment (8 mins)</td>
<td>Lat: Fun, Long: Eng</td>
<td>Lat: Eng, Long: Eng</td>
<td>Off</td>
</tr>
</tbody>
</table>

The experiments were started after a five-minute learning period. All subjects drove the same route and no traffic was present. The braking experiment lasted 10 minutes, and
consisted of a straight road in an urban area. At intersections the driver had to stop the car at the white line. Alternating speed limits of 30, 50, and 80 km/h were in place in-between intersections. The cornering experiment lasted 8 minutes, and involved a two-lane rural closed track with an 80 km/h speed limit. Subjects were asked to complete both experiments with a reasonable driving style, respecting the speed limit, and their position in their right lane. Subjects were not informed about the purpose of the experiment.

**Dependent measures**

Tables 2-4 show the measures that were calculated for each subject, adapted from Siegler et al. (2001). After the experiment, participants completed a questionnaire, consisting of ten questions related to realism and pleasure (see Table 4) which could be answered on an interval scale ranging from one to ten. Subjects also completed an adapted simulator sickness questionnaire (Kennedy et al., 1993). Our version did not distinguish between the nausea, oculomotor, and disorientation subscales. Moreover, the ‘fullness of the head’ symptom was removed\(^1\). For each symptom, subjects rated an interval scale from one to five (one meaning no problems and five meaning large problems). A total simulator sickness score was calculated by averaging over the symptoms.

**Table 2. Dependent measures for the braking experiment.**

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Unit</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>NrValidStops</td>
<td>[#]</td>
<td>Number of stops coming to standstill</td>
</tr>
<tr>
<td>Mean Vini</td>
<td>[m/s]</td>
<td>Mean speed at onset of braking (t=0 s)</td>
</tr>
<tr>
<td>Mean DTLini</td>
<td>[m]</td>
<td>Mean distance to the target line at onset of braking (t=0 s)</td>
</tr>
<tr>
<td>SD DTLfin</td>
<td>[m]</td>
<td>Standard deviation of distance to the target line when standing still (i.e. stopping consistency)</td>
</tr>
<tr>
<td>Mean max. dec.</td>
<td>[m/s^2]</td>
<td>Mean maximum deceleration (t=T s)</td>
</tr>
<tr>
<td>Mean onset jerk</td>
<td>[m/s^3]</td>
<td>Mean rate of change of deceleration for the first half of the stopping maneuver (Deceleration at t=T/2 divided by T/2).</td>
</tr>
</tbody>
</table>

The dependent measures were calculated for each subject by averaging over all stops. The first stop of each subject was removed from the analyses.

**Table 3. Dependent measures for the cornering experiment.**

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Unit</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>NrDepartures</td>
<td>[#]</td>
<td>Number of road departures</td>
</tr>
<tr>
<td>Mean LCE45deg</td>
<td>[m]</td>
<td>Lane centre error when halfway through the bend</td>
</tr>
<tr>
<td>Mean V45deg</td>
<td>[m/s]</td>
<td>Speed when halfway through the bend</td>
</tr>
</tbody>
</table>

The dependent measures were calculated for each subject by averaging over 90-degree bends with radii of 15-20m. A distinction will be made between 6 left bends and 8 right bends. For each subject, the first 7.35 km were selected, equaling one lap on the closed track. When a road departure had occurred, the car was automatically placed back on the road with zero speed. Data from 10 seconds prior to the departure to 20 seconds aft of each road departure were removed from further analyses.

1. We considered the original simulator sickness questionnaire (SSQ) not readily interpretable (e.g., how should subjects interpret ‘difficulty concentrating’ on the oculomotor scale?). Inspection of the work of Kennedy et al. (1993) showed that the three factors (nausea, oculomotor, and disorientation) were orthogonally rotated, and not obliquely to obtain simple patterns. A general simulator sickness factor was found to explain 50% of the variance in the orthogonal solution. State-of-the-art literature indicates that there is little justification to using orthogonal rotation when factors intercorrelate (Fabrigar et al., 1999). The present authors performed oblique rotation (oblimin) of the loadings shown in Kennedy et al. (1993, Table 2). Results indicated that the three factors indeed intercorrelate substantially (.28 to .40). The rotated pattern was considered better interpretable than the orthogonal loadings. We also calculated factor score coefficients (Bartlett procedure). It was found that some coefficients were very low, which may warrant consideration omitting items from the SSQ. Based on these findings, the present authors considered it theoretically and practically justified to use an adapted (i.e. simplified and more easily interpretable) SSQ.
Table 4. Questionnaire on realism/pleasure.

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Question on questionnaire</th>
</tr>
</thead>
<tbody>
<tr>
<td>RealDriving</td>
<td>How realistic did you find driving in the simulator?</td>
</tr>
<tr>
<td>RealBrake</td>
<td>How realistic did you find the braking?</td>
</tr>
<tr>
<td>RealAccelerate</td>
<td>How realistic did you find the accelerating?</td>
</tr>
<tr>
<td>JudgeSpeed</td>
<td>Could you well judge the speed of the car?</td>
</tr>
<tr>
<td>JudgeDistance</td>
<td>Could you well judge the distance to the signs in the braking experiment?</td>
</tr>
<tr>
<td>RealBends</td>
<td>How realistic did you find driving through bends?</td>
</tr>
<tr>
<td>JudgeSpeedB</td>
<td>How well could you judge the cornering speed?</td>
</tr>
<tr>
<td>RealSeat</td>
<td>Did the moving seat add to the feeling of realism?</td>
</tr>
<tr>
<td>Benefit</td>
<td>Do you think your driving performance benefited from the moving seat?</td>
</tr>
<tr>
<td>Pleasure</td>
<td>Did you enjoy the fact that the seat was moving?</td>
</tr>
</tbody>
</table>

Results

Results of the braking experiments are shown in Table 5. Subjects completed on average about 13 stops. As expected, maximum decelerations (Mean max. dec.) were lower, stopping consistency (SD DTLfin) was better and braking onset (Mean onset jerk) was lower for motion cueing (Eng&Fun groups aggregated) compared to Off. No significant differences were found for speeds and distances to the stopping line at onset of braking (Vini, DTLini). To confirm the results, the dependent measures were calculated for the cornering experiment as well, the results of which are shown in Table 6. It can be seen that motion again resulted in lower decelerations and lower jerk, while subjects also pressed the brake at a significantly greater distance to the bend.

Results of the cornering experiment are presented in Table 7. No significant differences were found between any of the conditions. Interestingly, the standard deviation (SD) of the lane centre error halfway through the left bend was considerably lower for Eng compared to Fun and Off. Closer examination was done by plotting the mean trajectories of each subject (see Figs. 1 and 2). It appears from Fig. 1 that the increased SDs of Fun and Off were caused by two subjects who had not respected the instruction to remain on their right lane by consistently shortcutting on the left lane. As only two subjects were involved, the larger SDs of the cornering paths cannot be attributed to the motion cueing conditions. Figures 3 and 4 show the mean speeds through the left and right bends. From Figs. 1-4 it can be seen that any differences in mean trajectories/speeds were negligibly small compared to the magnitude of individual differences.

Results of the questionnaire are shown in Table 8. It was hypothesized that Fun would result in a higher pleasure rating than Eng. In this study we found a pleasure rating of 6.4 for Fun, and a pleasure rating of 5.9 for Eng. These numbers were not significantly different (p=.4). To prevent committing type-I-errors, a multivariate approach was used on the questionnaire data. A Pearson correlation matrix was submitted to a principal axis factoring to extract one common factor explaining 39% of the variance. The decision to extract one factor was supported by the Scree plot, and the interpretability of the loadings compared to extracting two or more factors. Bartlett factor scores, representing total satisfactory/realism level, are shown in Table 8. A Kruskal-Wallis test indicated that the median factor scores for the three conditions were significantly different (p=.027). According to a Tukey-Kramer multiple comparison the satisfaction/realism-score was significantly higher for Fun compared to Off.
The results of the questionnaire on simulator sickness are shown in Table 9. There were no significant differences in sickness scores between the conditions. There were indications that Fun and Eng caused higher ratings on the following symptoms: general discomfort, fatigue, and eyestrain, compared to Off. After applying Bonferroni corrections these differences were not large enough to reach a critical significance level.

**Discussion**

The motion seat resulted in lower decelerations, more consistent stopping distances, and smoother braking onset than Off. As expected, the results are qualitatively congruent with the effects of a limited-amplitude motion platform (see Siegler et al., 2001). It was found as well that subjects pressed the brake at a greater distance towards the target for motion compared to Off, while Siegler et al. found no effect. The motion seat did not reduce peak decelerations to 3-4 m/s², which can be considered representative values for driving in a real car (Siegler et al., 2001). Previous experiments conducted at Delft University of Technology found comparable or larger reductions in decelerations as a result of motion cueing through a tensioning seatbelt and increasing the stiffness of the brake pedal (unpublished studies).

For cornering, no significant differences in driving performance were observed between the fun way, engineering way, and no-motion. Contrary, Siegler et al. (2001) observed that subjects took a wider bend and adopted lower speeds when using a motion platform. Inspection of the results of Siegler et al., however, showed that their effects were very small, with a Cohen’s d between .2 and .3 for the speed halfway through the bend.

Subjects judged Fun as more realistic than Off. No significant differences were observed between Fun and Eng, i.e. two opposite forms of lateral motion cueing. Overall simulator sickness scores were low, and not significantly different between the three conditions.

In the present study, the seat was moving without compensation of the visual scene or the pedals/steering wheel, making it possible for the driver to be aware of his orientation while keeping his head upright. Seat inclinations could be noticed through tactile and proprioceptive feedback rather than the vestibular organs, like during real car driving.

Further research is recommended to evaluate whether a motion seat, possibly combined with other types of motion cueing, improves learning and transfer to the road. The seat has shown to be a successful means of improving the subjective realism of the simulator. Improved face validity may further improve students’ motivation to learn. It can be expected that more realistic braking behavior in the simulator (i.e. less abrupt braking, lower decelerations) transfers to the road, resulting in safer braking during the initial moments in real traffic. It is also recommended to further develop motion seat control algorithms. High-frequency cues may be beneficial to enhance speed and motion perception, and could be particularly suited to a (limited amplitude) motion seat. Finally, it seems worthwhile to investigate individual differences. For example, why is it that some subjects adopted much higher speeds than others? Understanding individual differences and their correlates might provide important insights for improving the effectiveness of simulation-based training.
Table 5. Results of the braking experiments.

<table>
<thead>
<tr>
<th>Measure</th>
<th>Between subjects experiment</th>
<th></th>
<th>Within subjects experiment</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean (SD)</td>
<td>p</td>
<td>Cohen d</td>
<td>Mean (SD)</td>
</tr>
<tr>
<td></td>
<td>Fun&amp;Eng (N=40)</td>
<td>Off (N=20)</td>
<td></td>
<td>Fun&amp;Eng (N=24)</td>
</tr>
<tr>
<td>NrValidStops</td>
<td>12.7 (3.8)</td>
<td>.8</td>
<td>.06</td>
<td>13.1 (1.8)</td>
</tr>
<tr>
<td>Mean Vini</td>
<td>15.9 (2.4)</td>
<td>.8</td>
<td>-.06</td>
<td>15.7 (1.4)</td>
</tr>
<tr>
<td>Mean DTLini</td>
<td>56.9 (19.6)</td>
<td>.1</td>
<td>.47</td>
<td>56.0 (13.8)</td>
</tr>
<tr>
<td>SD DTLfin</td>
<td>1.98 (1.15)</td>
<td>.015</td>
<td>-.65</td>
<td>1.78 (1.87)</td>
</tr>
<tr>
<td>Mean max. dec.</td>
<td>6.35 (1.41)</td>
<td>.4</td>
<td>-24</td>
<td>6.16 (1.37)</td>
</tr>
<tr>
<td>Mean onset jerk</td>
<td>2.62 (1.66)</td>
<td>.001</td>
<td>-.86</td>
<td>2.59 (1.58)</td>
</tr>
</tbody>
</table>

Significance levels and Cohen’s d effect sizes were calculated after z-transforming the results for each braking maneuver.

Table 6. Braking behaviour in the cornering experiment.

<table>
<thead>
<tr>
<th>Measure</th>
<th>Mean (SD)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Fun&amp;Eng (N=40)</td>
</tr>
<tr>
<td>Mean Vini</td>
<td>20.2 (1.7)</td>
</tr>
<tr>
<td>Mean DTLini</td>
<td>51.4 (10.0)</td>
</tr>
<tr>
<td>Mean max. dec.</td>
<td>5.24 (1.37)</td>
</tr>
<tr>
<td>Mean onset jerk</td>
<td>5.38 (3.57)</td>
</tr>
</tbody>
</table>

Measures were calculated for each subject over 15 straights on which subjects braked for the bends. Significance levels and Cohen’s d effect sizes were calculated after z-transforming the results for each braking maneuver.

Table 7. Results of the cornering experiment.

<table>
<thead>
<tr>
<th>Measure</th>
<th>Mean (SD)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Fun (N=20)</td>
</tr>
<tr>
<td>NrDepartures</td>
<td>.35 (.49)</td>
</tr>
<tr>
<td>Mean LCE45deg (left bends)</td>
<td>1.72 (.78)</td>
</tr>
<tr>
<td>Mean LCE45deg (right bends)</td>
<td>-.74 (.36)</td>
</tr>
<tr>
<td>Mean V45deg (left bends)</td>
<td>11.6 (1.21)</td>
</tr>
<tr>
<td>Mean V45deg (right bends)</td>
<td>10.0 (1.48)</td>
</tr>
</tbody>
</table>

Significance levels and Cohen’s d effect sizes were calculated after z-transforming the results for each bend.

Table 8. Questionnaire results.

<table>
<thead>
<tr>
<th>Measure</th>
<th>Mean (SD)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>RealDriving</td>
</tr>
<tr>
<td></td>
<td>RealBrake</td>
</tr>
<tr>
<td></td>
<td>RealAccelerate</td>
</tr>
<tr>
<td></td>
<td>JudgeSpeed</td>
</tr>
<tr>
<td></td>
<td>JudgeDistance</td>
</tr>
<tr>
<td></td>
<td>RealBends</td>
</tr>
<tr>
<td></td>
<td>JudgeSpeedB</td>
</tr>
<tr>
<td></td>
<td>RealSeat</td>
</tr>
<tr>
<td></td>
<td>Benefit</td>
</tr>
<tr>
<td></td>
<td>Pleasure</td>
</tr>
<tr>
<td>Factor-score</td>
<td>.29 (1.03)</td>
</tr>
</tbody>
</table>

Eigenvalue of the first factor was 4.46. Eigenvalue of the second, unretained factor was 1.38. A Kruskal-Wallis test indicated that the factor-scores are different (p=.027). A Tukey-Kramer multiple comparison indicated that Fun and Off are significantly different.

Table 9. Results of the questionnaire on simulator sickness.

<table>
<thead>
<tr>
<th>Measure</th>
<th>Mean (SD)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>RealDriving</td>
</tr>
<tr>
<td></td>
<td>RealBrake</td>
</tr>
<tr>
<td></td>
<td>RealAccelerate</td>
</tr>
<tr>
<td></td>
<td>JudgeSpeed</td>
</tr>
<tr>
<td></td>
<td>JudgeDistance</td>
</tr>
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<td></td>
<td>RealBends</td>
</tr>
<tr>
<td></td>
<td>JudgeSpeedB</td>
</tr>
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<td></td>
<td>RealSeat</td>
</tr>
<tr>
<td></td>
<td>Benefit</td>
</tr>
<tr>
<td></td>
<td>Pleasure</td>
</tr>
</tbody>
</table>

Note: A Kruskal-Wallis test indicated that the scores are not significantly different (p=.4).
Fig. 1. Mean LCE in left bends. Gray lines represent subjects’ mean LCE of 6 bends. Lines at LCE = 2.5 and LCE = -2.5 represent lane boundaries.

Fig. 2. Mean LCE in right bends. Gray lines represent subjects’ mean LCE of 8 bends. Lines at LCE = 2.5 and LCE = -2.5 represent lane boundaries.

Fig. 3. Mean speed in left bends. Gray lines represent subjects’ mean speed of 6 bends.
Fig. 4. Mean speed in right bends. Gray lines represent subjects’ mean speed of 8 bends.

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**References**


