MOTION FEEDBACK IN ADVANCED DRIVING MANOEUVRES

B. J. Correia Grácio*, M. Wentink*,
P. Feenstra*, M. Mulder†
M. M. van Paassen†, W. Bles*

*TNO Defence, Security and Safety
Human Factors
3769 ZG Soesterberg, the Netherlands

†Control and Simulation Department,
Aerospace Engineering,
Delft University of Technology
P.O. Box 5058, 2600 GB Delft, the Netherlands

bruno.correiagracio@tno.nl

Abstract

During advanced driving manoeuvres, drivers can be hypothesized to use all the available cues to optimize their performance. Fixed-base simulators are commonly used for training of these advanced driving manoeuvres, despite the fact that motion cues are not present. In this experiment we hypothesize that motion feedback improves driver performance and affects the driving control strategy during advanced driving manoeuvres when compared to a situation without motion feedback. A comparison between no-motion car-driving simulation and motion-feedback car-driving simulation is done, by measuring driver performance and control behaviour in a fast slalom. In the fast slalom designed for this experiment, a car drives at 70 Km/h around pylons spaced quite closely at approximately 30 meters apart.

The advanced Desdemona motion platform was used in this study. Desdemona's unique motion system allowed us to create a motion simulation that was almost one-to-one regarding the specific forces and angular rates in the actual car. A new motion cueing algorithm was developed to handle advanced driving manoeuvres like this fast slalom.

Twenty subjects successfully drove the fast slalom in both conditions. The results from a paired comparison show that subjects prefer driving with motion feedback. Motion feedback also helped subjects conducting the driving task. The number of accidents was significantly lower in the motion condition, as compared to the no-motion condition. Significant differences in the maximum lateral specific force and in the average speed between the two motion conditions were found also. From the experimental results we conclude that there is a difference in driving advanced manoeuvres in a fixed based simulator as compared to a motion simulator. This difference influences driving behaviour with respect to keeping control over the car and also it is clear that the driver changes his control strategy.

Résumé

Introduction

The number of simulators with motion feedback has increased in the past few years. Due to their physical limitations, one-to-one motion is often not possible to render in current simulators. These motion limitations introduce false cues in the simulation, such as the motion responsible for bringing the simulator cabin back to the neutral position. False cues can be very disturbing [1], degrading the simulator fidelity. Clearly, within the constraints of the simulator motion space the negative effects on simulation fidelity must be minimized.

The goal of this study is to assess the effect of motion feedback on driver performance in advanced driving manoeuvres. Advanced driving manoeuvres are usually close to the car dynamic traction limits [2], like fast slaloms or fast curves (like those in racing circuits) that can induce under- and/or oversteer in the car. Fixed-base simulators or simulators with low motion capabilities are the most used in driving and advanced driving training [3]. With this experiment we want to investigate the difference of using a fixed based simulator or a simulator with motion feedback in advanced manoeuvres. The manoeuvre used will be a fast slalom for two reasons: to compare the results with other experiments in the MOVES (MOtion cueing for VEhicle Simulators) Eureka project [4], and because this type of manoeuvre is usually used in advanced driving courses.

This research aims to understand whether motion feedback is an advantage in advanced driving simulation. Our first hypothesis is that simulator motion cues improve driving performance during advanced driving manoeuvres. We expect that motion feedback will help the driver in controlling the car during an extreme manoeuvre. Secondly, we hypothesize that with motion cues available, drivers are better able to identify events like understeer and oversteer.

The paper will start with a brief description of the Desdemona simulator followed by the explanation of the experimental method. The motion cueing filter for Desdemona is explained here as well. Next the results are presented and discussed followed by conclusions.

Desdemona

The present study uses the 6 DoF Desdemona simulator at TNO Human Factors, The Netherlands [5]. The Desdemona motion platform, with its unlimited rotation and high specific force capabilities, can be used as a tool to assess how motion feedback influences drivers in advanced manoeuvres. A first driving simulation experiment was already carried out in Desdemona on the topic of cornering [5]. In the current study a motion cueing algorithm will be developed for slalom driving with the objective of providing realistic motion cues without violating Desdemona physical limits. In the development of the algorithm, an effort is made to guarantee that the necessary motion cues for advanced driving are present, like cues that indicate over- and understeer.

Method

Motion Cueing Algorithm

Two different motion conditions were used in this experiment. 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 a Desdemona motion cueing algorithm that was designed specifically for advanced driving simulation. The next sections explain in more detail the two motion conditions.

No Motion

This motion condition contains an algorithm that activates the Heave drive every time a subject hits a pylon, giving the subject a feeling of actually driving over the pylon. In this way, subjects had a better perception of their own performance. If no pylons were hit during the simulation, Desdemona behaved like a fixed base simulator.

Motion

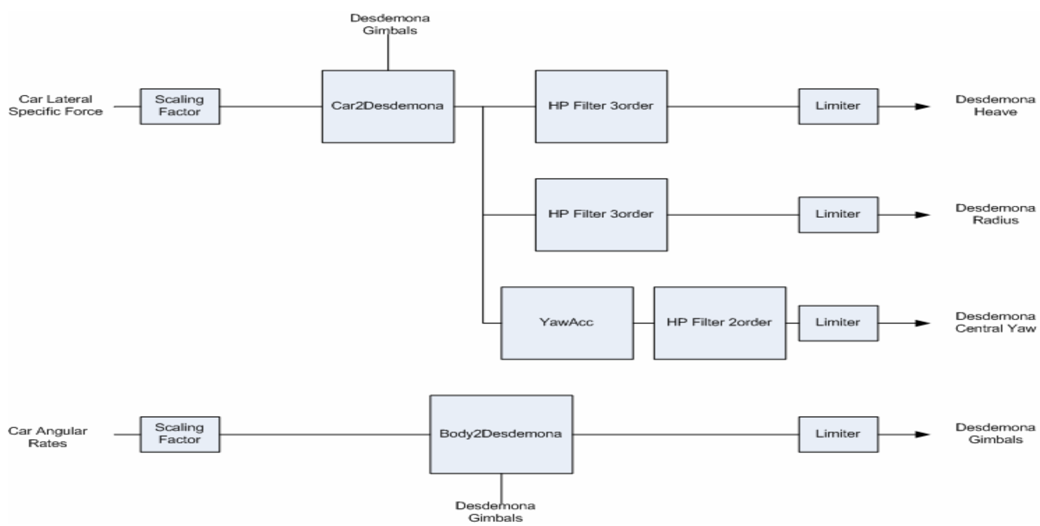

Figure 1 - Motion Cueing Algorithm.

The motion cueing algorithm is based on the principles of the Classical Washout filter [6, 7]. It uses rotation matrices (blocks Car2Desdemona and Body2Desdemona in Figure 1) to transform the car specific forces and angular rates from the car reference frame into Desdemona reference frame. This motion condition also contains the "hitting pylon" algorithm coupled to the Heave drive. The road rumble algorithm of [5] was also used in this condition. Figure 2 shows the car specific forces and angular rotations versus the ones rendered by the simulator for a given pylon section.

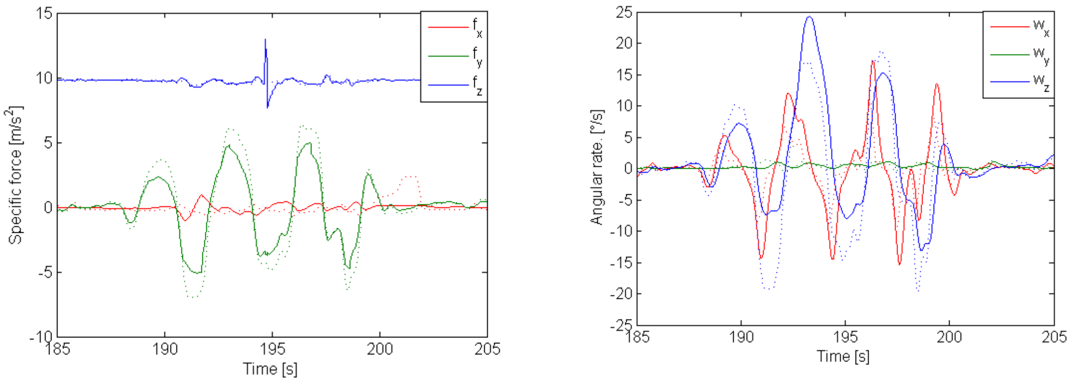

Figure 2 - Specific forces (on the left) and angular rates (on the right) of the car model (dotted lines) versus the simulator (solid lines) in one of the fastestsections of the slalom manoeuvre. The peak in fz is caused by hitting a pylon.

Slalom Manoeuvre

The slalom designed for this study is an extension to the one used in the MOVES (MOtion cueing for VEhicle Simulators) Eureka project [4]. The manoeuvre was created based on a car sinusoidal path like the one in Figure 3, where *a* is the sinusoidal path amplitude and *d* is the distance between pylons.

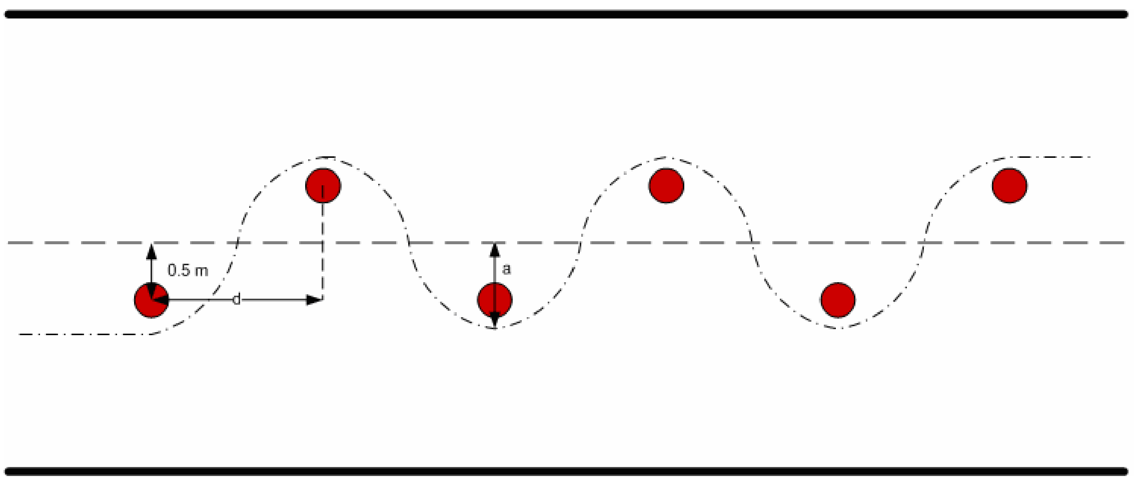

Figure 3 - Theoretical driving path.

The amplitude of the lateral force is given by equation
(1), where a is the sinusoidal path amplitude, d is the distance between pylons and v is the car velocity.

$$a_y = a\left(\frac{\pi}{d}v\right)^2 \tag{1}$$

Nine different pylon sections were created using equation
(1), each of them containing six pylons. The constant parameters of equation
(1) were the sinusoidal path amplitude, a (1.25 meters) and the car velocity v (70 Km/h). Distance between the pylons was the variable parameter. Table 1 shows the characteristics of the pylon sections.

Section	Theoretical lateral force (m/s^2)	Distance between pylons (m)
1	1	68.30
2	1.5	55.76
3	2	48.29
4	2.5	43.19
5	3	39.43
6	3.5	36.51
7	4	34.15
8	4.5	32.20
9	5	30.54

Table 1 – Slalom characteristics.

The nine sections are 200 meters apart from each other to cancel dynamic driving effects between sections. The pylons are at 0.5 meters from the centreline of the road as is shown in Figure 3.

Procedure

The experiment started with a practice run. In this run, the easiest slalom section was driven multiple times, since the objective was to familiarize subjects with the driving task. Subjects were instructed to drive through the slalom as fast as possible; however, the velocity was saturated at a maximum speed of 70km/hour. They were told only to lower 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 losing the control over the car.

After the practice run, subjects had to drive through the slalom (all the nine pylon sections) in the two different conditions. Drivers had to drive each condition twice to test if their driving is influenced by any training effect. This means that subjects had to drive the slalom four times in total. To decrease order effects subjects were divided into two randomized groups, shown in Table 2, where NM refers to the no motion condition and M refers to the condition with motion feedback.

Group	First run	Second run	Third run	Fourth run

1	NM	M	NM	M
2	M	NM	M	NM

Table 2 - Motion condition order.

Experimental Design

Twenty-two participants (15 males and 7 females) participated in the experiment, with an average age of 38 years. Two had to be discarded due to motion sickness issues. Of the twenty remaining subjects, ten started with the no motion condition (Group 1 of Table 2) while the other ten participants started with the motion feedback condition (Group 2 of Table 2).
Starting in the second run, a paired comparison technique was used to test if the condition with motion feedback is preferred to the no motion condition. Subjects had to compare the current run with the previous run in terms of overall impression of realism by forcing them to say which condition they preferred.

After each run, subjects had to fill in a questionnaire that dealt with the following topics: immersion in the simulator task, controllability of the car, slalom performance, simulation realism, motion realism and training value.

In the questionnaire we used a list of statements on which subjects had to agree or disagree using a 7 point Likert scale. See Figure 4. Figure 5 shows in which order the experiment was conducted.

Strongly Disagree	1	2	3	4	5	6	7	Strongly Agree

Figure 4 - Seven point Likert scale.

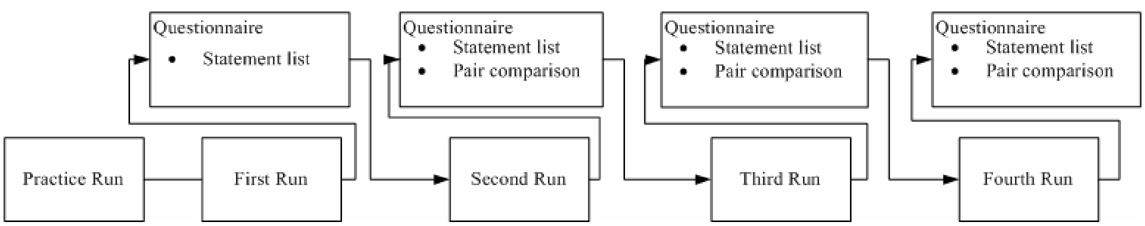

Figure 5 - Experimental order.

Objective measures

The objective measures used in this study were the car average speed and the lateral specific forces generated by the car model. From these measures it is possible to draw conclusions about the subjects' driving behaviour. In our study, we assume that differences in driving behaviour show up as differences in measurable car variables such as car speed, car specific forces and driving trajectory. In addition, we observed that the number of accidents occurring was different for both motion conditions, so these results were also reported. Note that in all conditions, the only difference was the motion feedback while all other simulator characteristics such as steering wheel dynamics and visual scene were kept equal.

Results

Paired comparison

Subjects indicated the overall impression between two motion conditions three times during the experiment. They compared the first run with the second, the second run with the third and the third run with the last one. Figure 6 shows the total scores for each of the comparisons. Like stated in Grant et al. [8], the score is the number of times that a condition was preferred over the other. A chi-square test was used to check the significance of the paired comparison analysis. In the first comparison (1 vs 2 in Figure 6) there was not a significant effect of the motion condition in the subject's overall impression, $\chi^2(1)=3.2$, $p=0.074$. For the second and third comparisons it was found a significant effect of the motion condition at the 5% level, respectively $\chi^2(1)=5$, $p=0.025$ and $\chi^2(1)=9.8$, $p=0.02$. When the scores of the paired comparison 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, $\chi^2(1)=17.067$, $p<0.001$.

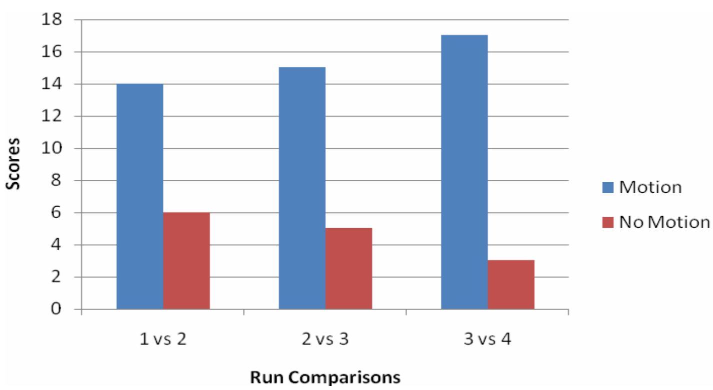

Figure 6 - Paired comparison total scores for each run.

Questionnaires

From this section on, we will define Trial 1 as run one and two and Trial 2 as run three and four. This is done to show the difference between the first time a motion condition was driven and its repetition. The questionnaire used in this experiment contained 26 statements, where subjects had to indicate whether they agreed or not with the statement. Because of time issues only four statements were analysed. The statements are:

- *"The motions and forces helped me conducting the task"*.
- *"The simulator motion and forces felt realistic"*.
- *"I sometimes had the feeling of losing control over the car"*.
- *"I was really focused"*.

The choice of these statements is related with the experiment hypothesis since they show how motion feedback can influence driving behaviour in terms of task performance, realism, control and concentration. Note that the original statements were in Dutch, which means that part of the meaning can be lost in translation.

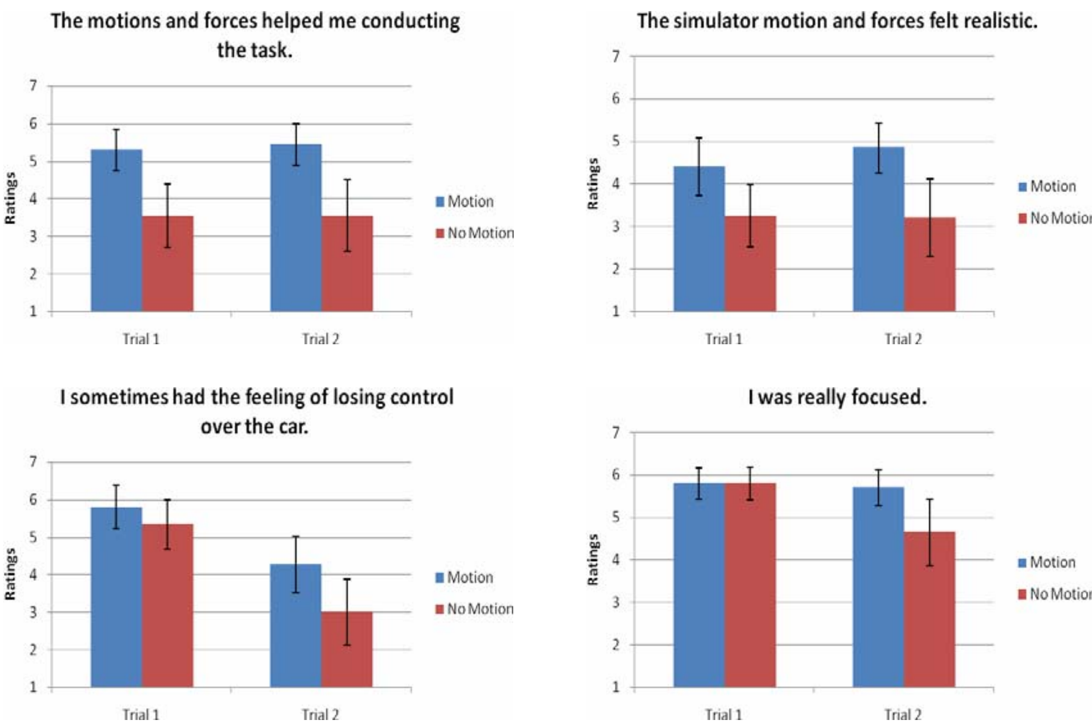

Figure 7 - Question average ratings and 95% confidence intervals.

Figure 7 shows the subject's ratings for the four chosen statements. A repeated measure ANOVA with contrasts focusing on the differences between the two independent variables (motion condition and Trial number) was performed. For the statement, "*The motions and forces helped me conducting the task*" there was a significant main effect of the motion condition on questionnaire ratings, $F(1,19) = 13.589$, $p = 0.002$. Contrasts revealed that the effect of the motion condition in the subject ratings was significant for Trial 1, $F(1,19) = 9.404$, $p = 0.006$ and for Trial 2, $F(1,19) = 14.625$, $p = 0.001$. The statement, "*The simulator motion and forces felt realistic*" also showed a significant main effect of the motion condition on questionnaire ratings, $F(1,19) =11.406$, $p = 0.003$. Contrasts showed significant effects of the motion condition in the subjects ratings for Trial 1, $F(1,19) = 5.550$, $p = 0.029$ and for Trial 2, $F(1,19) = 10.715$, $p = 0.004$. For the statement, "*I sometimes had the feeling of losing control over the car*" there was a significant main effect of the motion condition on questionnaire ratings, $F(1,19) = 7.452$, $p = 0.013$. There was also a significant main effect of the trial number on the questionnaire ratings, $F(1,19) = 30.523$, $p < 0.001$. Contrasts showed a significant effect of the motion condition on the subjects ratings for Trial 2, $F(1,19) = 4.952$, $p = 0.038$, but not for Trial 1. In the statement "*I was really focused*" there was a significant main effect of the motion condition on questionnaire ratings, $F(1,19) = 7.356$, $p = 0.014$. There was also a significant effect of the trial number on the questionnaire ratings, $F(1,19) = 12.435$, $p = 0.002$. There was a significant interaction between the motion condition and the run number, $F(1,19) = 6.450$, $p = 0.020$. Contrasts revealed a significant effects of the motion condition in the subjects rating for Trial 1, $F(1,19) = 7.912$, $p = 0.011$, but not for Trial 1.

Objective Measurements

Number of sections finished

In the experiment the slalom got increasingly more difficult with each section (see Table 1).The runs were again divided in two groups (Trial 1 and Trial 2), to show the difference between the first time a motion condition was driven and its repetition. For Trial 1, thirteen subjects out of twenty were able to drive through the nine slalom sections without crashing the car in the Motion condition. For the No Motion condition only nine subjects out of twenty were able to drive the slalom without crashing. For Trial 2, sixteen out of twenty subjects finished the full slalom for the Motion condition while for the No Motion condition fifteen out of twenty subjects were able to finish the slalom. Table 3 shows in which pylon section accidents occurred.

Pylon section	Trial 1		Trial 2	
	Motion	No Motion	Motion	No Motion
1	0	0	0	0
2	0	0	0	0
3	0	0	0	0
4	0	0	0	1
5	0	0	0	0
6	1	2	1	0
7	2	5	1	1
8	4	1	1	3
9	0	3	1	0

Table 3 - Number of accidents in each section.

Average speed

The average speeds were analysed to check differences in driving strategy between the two motion conditions. Figure 8 shows the mean car speed and the 95% confidence intervals for the nine pylon sections. From Figure 8 one can observe that the average speed decreases with the pylon sections, since they got increasingly difficult. The Motion condition average speeds are slightly smaller than the No Motion condition average speeds.

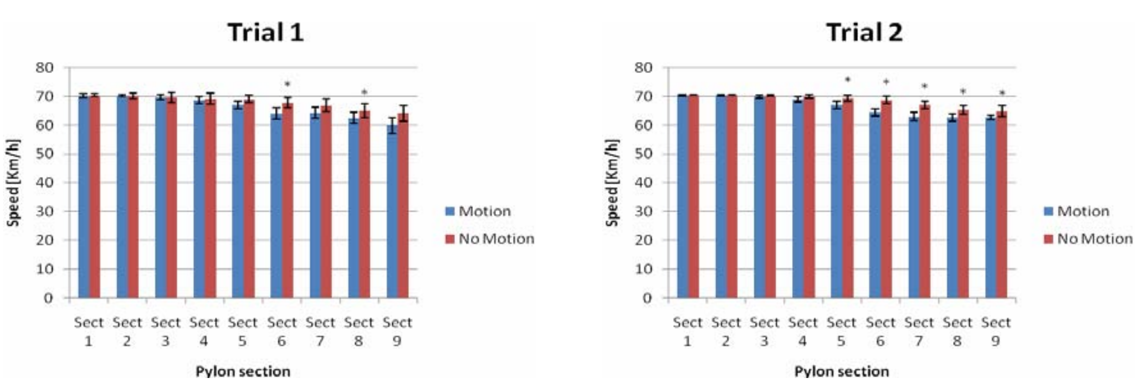

Figure 8 - Average car speed and 95% confidence interval for all pylon sections in Trial 1 and 2.

Significant differences between motion conditions for the average car speed were found from section 5 to section 9. The available data decreases with the section number because of the occurred accidents. Since we are only interested in the differences between Motion and No Motion for Trial 1 and 2, a dependent t-test will be used in the analysis instead of a repeated measure ANOVA. Note that the results for Trial 2 will have more statistical power than the ones of Trial 1 since there were fewer accidents in the last runs. Table 4 shows the results of the dependent t-test. Significant effects (at the 5% level) of the motion condition in the car average speed were found for the highlighted rows in Table 4, and indicated by asterisks (*) in Figure 8.

Section		M Δ	SE	t	p
5	Trial1	-2.017	0.981	t(19)= -2.056	0.054
	Trial 2	-2.101	0.712	t(18)= -2.949	0.009
6	Trial1	-3.522	1.579	t(17)= -2.230	0.039
	Trial 2	-4.179	0.952	t(18)= -4.391	0.000
7	Trial1	-2.513	1.983	t(14)= -1.267	0.226
	Trial 2	-3.808	0.757	t(17)= -5.030	0.000
8	Trial1	-4.947	2.148	t(10)= -2.303	0.044
	Trial 2	-2.851	1.170	t(14)= -2.437	0.029
9	Trial1	-5.713	3.409	t(6) = -1.676	0.145
	Trial 2	-2.577	1.114	t(11)= -2.313	0.041

Table 4 - Mean difference, standard error, t-test score and significance of the car speed for the last 5 pylon sections.

Car model specific forces

Figure 9 shows the average specific force generated by the car model. The average was calculated using all the participants in all the four runs

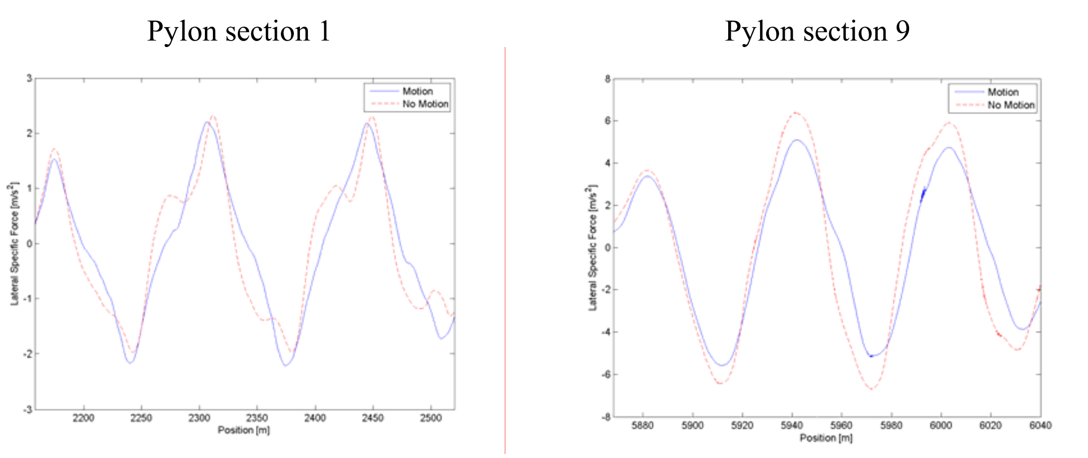

Figure 9 - Car model average specific forces for pylon section 1 (on the left) and pylon section 9 (on the right). The averages are calculated using all the participants in all runs.

Discussion

Motion feedback has been used in flight simulation for many years. It has been shown that this feedback has beneficial effects on pilot performance [9]. In driving simulation, visual feedback is assumed to be the primary source of information [10], nevertheless several studies that assess the effect of motion in a driving task have already been performed [11,12]. In this study, we also want to investigate the effect of motion feedback, but this time in advanced driving manoeuvres.

The condition with motion was much more preferred by the subjects than the condition with no motion. From the 14 subjects that rated the Motion condition the best when the first run was compared with the second run, only one subject changed its opinion in the other comparisons (rated No Motion better when comparing the second run with the third run). It can also be seen that with progression of the experiment, the No Motion condition was rated best fewer times (Figure 6). At the end of the experiment, the difference between the two motion conditions was highly significant as one can see from the paired comparison results. This means that for advanced manoeuvres like this slalom, subjects prefer to have a simulation with motion feedback, rather than a fixed based simulator. Some of the participants commented that it was much easier to “catch up with the cadence” (the sinusoid) of the slalom when motion was present.

Motion seems also necessary to help subjects conducting the driving task better as can be seen from the questionnaire results. The participants agreed that motion helped them in the driving since the average rating for the statement “The motions and forces helped me conducting the task” in the Motion condition was 5.30 for Trial 1 and 5.45 for Trial 2. Regarding how realistic the motion was, it can be seen that subjects in the Motion condition were undecided whether what they were feeling was realistic or not (the ratings for this statement were 4.4 for Trial 1 and 4.85 for Trial 2). This had to do mainly with control differences of their car and the used car model (some subjects did not have power steering in their car for example) and also because the used manoeuvre was not comparable with the type of manoeuvres they normally do in their car. For the No Motion condition, subjects rated it unrealistic (3.25 in Trial 1 and 3.20 in Trial 2) even though that some of them believed that simulator movements were present in this condition. This phenomenon of reporting the presence of motion in a no-motion condition was already reported by Wentink et al. [5]

Motion feedback changes driving behaviour as one can see from the average speed differences between the two motion conditions. Subjects had a lower average speed in the Motion condition compared to the No Motion condition. This means that with motion feedback, in the harder pylons sections (which is where this difference is noticeable) subjects are more aware of how the car is reacting and drive it more carefully to prevent a crash. Figure 9 shows that in the earlier pylon sections (section 1 in this case) the car model specific forces are very similar, which indicates that the driving behaviour of subjects in both motion conditions is the same. This is no longer true in the fastest sections (section 9 in Figure 9) where the car model specific forces have different amplitudes. The Motion condition has smaller force amplitudes than the No Motion condition since subjects have feedback about the magnitude of the specific forces and try to drive with smaller lateral forces. Nevertheless this data has to be analysed in more detail to draw more conclusions about how subjects drove the slalom manoeuvre.

Motion feedback has an effect on driver performance and driving behaviour, especially on the fastest sections of the slalom. This means that drivers adopt different strategies when they are feed with extra sensorial information (motion cues in this case). In flight simulation, it was already shown that motion feedback has a beneficial influence on pilot control performance [9]. A similar effect seems to be present in extreme driving simulation. This has consequences in training, since advanced driving training is still mainly performed with fixed based simulators [3]. Research using driver-on-the-loop would also be affected if a fixed based simulator is used whenever extreme manoeuvres are present. This could happen in road safety research or research that explores driving disturbances, since advanced driving manoeuvres are normally required to overcome difficult driving situations. Therefore, if motion is not present, drivers are losing important information that ultimately would make them react to the situation in a totally different way.

Conclusions

This experiment showed that it is important to have motion feedback in the simulation of advanced driving manoeuvres. From the results we see that subjects much prefer the condition with motion feedback and that motion supports them in conducting the task better. In the fixed base condition, the participants had difficulties to keep the control over the car and therefore the number of crashes was higher. Motion feedback also influences driving behaviour as can be concluded from the differences in the car average velocity for both motion conditions. With motion feedback, subjects drove more carefully and had better control of the car; therefore they could anticipate on the car dynamic behaviour better and were not that surprised when the car did crash.

Motion feedback is desirable in this type of manoeuvres since it helps drivers in their driving task. With motion it was easier for subjects to catch up the correct sinusoidal path of the slalom as well as to predict when control actions were needed. It also helped to reduce the accident rate since participants had a better control approach due to the extra feedback that motion produces. With motion, subjects also identified situations of under- and oversteer better and some of them were able to recover without crashing the car. Without motion, subjects failed to identify these events, making accidents an unexpected occurrence.

Further analysis of other objective measurements like the steering wheel angle and the specific forces has to be done in order to draw more conclusions about the driving control behaviour differences. Future experiments should focus on investigating the most important cues for driver control in advanced driving manoeuvres, since from this experiment one can conclude that motion feedback is very important in these types of manoeuvres.

Acknowledgements

This work was conducted in the framework of the MOVES (Motion cueing for Vehicle Simulators) Eureka #3601 European research project, which aims at increasing the scientific knowledge on the human multi-sensory 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

[1] Grant, P. R. & Reid, L. D., "Motion Washout Filter Tuning: Rules and Requirements", *Journal of Aircraft,* **1997***, 34*, 145-151

[2] Milliken, W. & Milliken, D., "Race Car Vehicle Dynamics", *SAE International, Warrendale, PA.,* **1995**

[3] Kappé, B. & van Emmerik, M. Mogelijkheden van rijsimulatoren in de rijopleiding en het rijexamen TNO Defence, Security and Safety, **2005**

[4] Feenstra, P.; Wentink, M.; Correia Grácio, B. J. & Bles, W. “Effect of Simulator Motion Space on Realism in the Desdemona Simulator” DSC 2009 Europe, **2009** (presented in this conference)

[5] Wentink, M.; Valente Pais, A. R.; Mayrhofer, M.; Feenstra, P. & Bles, W., "First Curve Driving Experiments in the Desdemona Simulator", *DSC 2008 Europe,* **2008**, 135-146

[6] Conrad, B.; Schmidt, S. F. & Douvillier, J. G. “Washout circuit design for multi-degrees-of-freedom moving base simulators.” *Visual and Motion Simulation Conference, AIAA***, 1973**

[7] Reid, L. D. & Nahon, M. A. “Flight simulation motion-base drive algorithms: part 1 - developing and testing the equations”, Institute for Aerospace Studies, University of Toronto, **1985**

[8] Grant, P. R.; Blommer, M.; Cathey, L.; Artz, B. & Greenberg, J. “Analyzing Classes of Motion Drive Algorithms Based on Paired Comparison Techniques”, DSC North America 2003 Proceedings, **2003**

[9] Hosman, R.J.A.W. “Pilot's perception and control of aircraft motions”, Ph.D. Thesis, Faculty of Aerospace Engineering, Delft University of Technology, **1996**

[10] Kemeny, A. & Panerai, F. “Evaluating perception in driving simulation experiments” TRENDS in Cognitive Sciences, **2003**, 7, 37-37

[11] Fortmüller, T.; Tomaske, W. & Meywerk, M. “The Influence of Sway Accelerations on the Perception of Yaw Movements” DSC 2008 Europe, **2008**

[12] Brünger-Koch, M.; Briest, S. & Vollrath, M. “Do you feel the difference? - A motion assessment study” Driving Simulation Conference - Asia/Pacific, **2006**