An optimisation of Classical motion cueing in the University of Leeds Driving Simulator

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Abstract *– This investigation examined the perception of self-motion in a research driving simulator, focussing on the dynamic cues produced by a motion platform. The study was undertaken in three stages, evaluating both subjective ratings of realism and objective measures of driver performance against two specific driving tasks involving braking and cornering. Using a Just Noticeable Difference methodology, Stage 1 determined that scale factors over 90% could not be perceptibly differentiated from unscaled motion. Stage 2 suggested that participants were also unable to perceive a change in the point in space at which platform translations and rotations were centred, however a position closer to the human vestibular system did result in marginally smoother braking. Stage 3 explored the perceptual trade-off between the specific force error and tilt rate. For both driving tasks, whilst slow tilt that remained sub-threshold was perceived as the most realistic, driving task performance was superior when a more rapid tilt was experienced. Several interactions were also observed, most notably between platform tilt rate and the availability of extra translational capability afforded by a XY-table.*

These interactions provide system design guidance research driving simulator motion cueing. Assuming accurate driving performance is a design goal, for simulators without significant extra translational capability, priority should be given to the minimisation of specific force error through motion cues, even if this means that cues at a presented at a perceptibly high tilt rate. However, large amplitude motion should be complimented by a slower tilt. Such a design supports accurate driving task performance whilst also accomplishing maximum perceived realism.

Key words: *motion cueing, classical algorithm, driving simulator.*

Introduction

Typically, driving is a much more challenging environment for motion cueing compared to commercial flight simulation. Significant longitudinal acceleration is not limited to a specific portion of the journey, i.e. take-off and landing. Laterally, turns are more frequent and uncoordinated, occupants sensing the side-slipping of a cornering vehicle as a specific lateral force, unlike the normally imperceptible heading changes of a commercial airliner. Rotationally, suspension characteristics need to be mimicked over a broad range of frequencies not experienced in controlled flight.

For specific individual driving manoeuvres, the perception of acceleration cues presented via the classical filter can be superseded by alternative algorithms (e.g. adaptive cueing [Par1], Model Predictive Control strategy [Dag1], Lane Position Algorithm [Nor1], Fast Tilt-Coordination [Fis1]). However, the flexibility, simplicity and elegance of the classical filter make it highly appropriate to cope with the expansive and varied nature of driving. Nevertheless, it suffers from the difficulties associated with tilt-coordination and the typical trade-off between specific force and tilt rate errors. Managing this trade-off is essential in the formation of an effective research driving simulator. Optimal parameter selection, or tuning, therefore now becomes the unenviable task of the simulator engineer.

Classical algorithm in driving simulation

In the example of driving simulation, the classical filter is applied to the six orthogonal accelerations generated from the vehicle dynamics model. These are the three linear accelerations of longitudinal acceleration (braking/accelerating), lateral acceleration (cornering) and the vertical acceleration (road roughness and bumps). These are supplemented by the three angular accelerations of pitch (suspension effects of braking/accelerating), roll (suspension effects of handling) and yaw (actual yawing of the vehicle in a turn). The output of the classical filter describes the desired attitude that the motion platform should adopt [Con1; Rei2].

Consideration in the frequency domain of classical filter response to a control input allows the simulation engineer to assess the accuracy of the motion system's response in both gain (magnitude of the expected motion) and phase (timeliness of the motion). However, except in the case of very low accelerations or very small filter scale-factors, the transfer function of even a well-tuned classical algorithm is not flat. Transfer function fidelity criteria have been postulated in flight simulation (e.g. the "critical" Sinacori/Schroeder 1 rad/s motion fidelity criterion [Sch1]), but these do not yet exist in driving simulation.

The complementary nature of the classical filter allows independent control of high-frequency translational and low-frequency tilt-coordination channels. Flattening the transfer function by quickening the response of the tilt-coordination channel requires the development of tilt at a rate above perceptual threshold. Hence, an optimal solution, must be found solution between a platform response which is perceived as timely but with too much tilt (maximising specific force error at the expense of tilt rate error), or a response which feels lagged but without detectable tilt (maximising tilt rate error at the expense of specific force error).

Specific force error and tilt rate error trade-off

This trade-off between specific force errors and angular velocity errors is not new, having vexed researchers for some time in flight simulation (e.g. [Hos1]), but is governed predominantly by the flying task at hand. In their helicopter bob up/down simulator motion study with pilots undergoing a vertical tracking task of hovering to various target heights, [Sch2] suggested that flattening the transfer function by lowering high-pass onset filter cut-off frequency resulted in a greater degradation of tracking performance than by reducing the onset scale-factor. Additionally, in an evaluation of the perceived horizontal acceleration of a simulated a take-off run, [Gro1] observed a high correlation between the perceived discontinuity and the perceived magnitude of surge motion, indicating that pilots tolerate variations in filter natural frequency less than they do variations in filter scale-factor. Hence, in the design of commercial flight simulators, downscaling the specific force is commonly preferred over rapid tilt.

Influence of Motion Reference Point

Another design choice faced by the simulator engineer is the location of the motion reference point (MRP). The MRP denotes the point in space at which the platform translations and rotations are centred. Analogous to the design eye-point at which optimal viewing of a display system is achieved, in effect it is the point at which the perceived acceleration is ideally felt.

Since the vestibular system is located in the inner-ear, the ideal location for the MRP should be centred on the head of the observer [Rei1]. However, due to the geometric constraints of the hexapod, moving the MRP vertically upwards to this point requires significantly greater actuator strokes to achieve the same degree of tilt. Locating the MRP at the upper joint rotation points of a conventional hexapod will maximise the angular displacement capability and therefore the largest achievable specific force though tilt-coordination, but risks cue conflicts [see Fis1]. These false cues are at a maximum for at the lowest possible MRP.

[Fis1]'s study using the DLR driving simulator showed a subjective preference for a higher MRP (fewer false cues). However the geometry of the simulator's motion platform was an inverted hexapod, where the cab hangs below the main platform. Contrary to a traditional six degree of freedom motion platform, the inverted hexapod allows the MRP to be located above the driver's head without any loss of platform angular displacement. Hence, yet another compromise is faced by the simulation engineer who must decide, for a standard hexapod, whether the false cue or the loss of angular displacement capability is the lesser of two evils.

Influence of scale factor

Given an appropriately sized motion envelope, using a unity scale-factor where the onset acceleration of the motion platform directly matches that of the input may seem an intuitive choice. However, there is evidence that the selection of high scale-factors can lead to the perception of unrealistically strong motion cues. Based on their pilots' subjective response, [Gro1] observed the range of realistic motion parameters was centred around a scale-factor as low as 0.2 for the onset filter. Unity scale-factors were unanimously rejected as too powerful.

To achieve an acceptable perception of motion within the constraints of a typical motion platform, the onset filter scale-factor is typically set at a value around 0.7 [Rei2]. [Gra2] even observed accurate lane keeping and acceptable subjective ratings to a range of slalom steering manoeuvres undertaken by drivers of Ford's VIRTTEX simulator with a classical MDA onset filter scale-factor of 0.5. The manoeuvre used in this experiment was a double lane change demarcated by a set of cones. However, decreasing the scale-factor still further to 0.3 resulted in a significant deterioration of driver performance and an accompanying worsening of subjective motion assessment. [Sch2] achieved improved vertical tracking task performance and better accepted motion perception with an onset scale-factor of 0.5 than with unity, a result they attributed to the reduction in the filter's scale-factor reducing its phase error.

Aims and objectives

The fundamental aim of the overall study was investigate how best to manage these trade-offs of specific force/tilt rate error, MRP location and scale-factor in order to achieve the best possible classical motion cueing in the University of Leeds Driving Simulator (UoLDS). It was undertaken in a three-staged approach.

Through a Just Noticeable Difference procedure, Stage 1 examined the maximum perceptible scale-factors of both pure translational and rotational motion platform movement. With knowledge of the maximum perceptible scale-factor, Stage 2 made use of maximally-scaled motion without needless platform excursion, examining the effects of relocating Motion Reference Point (MRP) and specific force/tilt rate trade-off. With the maximum perceptible scale-factor and most suitable MRP location established, it was possible in Stage 3 to make a more thorough evaluation of the perceptual trade-off of specific force and tilt rate errors.

Apparatus

University of Leeds Driving Simulator

The University of Leeds Driving Simulator (UoLDS) is the U.K's most advanced such research facility. Operational since early 2007, UoLDS is the second generation of driving simulators developed at the University. Its hardware is tuneable and its software, developed in-house, is fully flexible such that driving scenarios can be tailored to the needs of an individual research project.

UoLDS's vehicle cab is based around a 2005 Jaguar S-type, with all of its driver controls fully operational. The Jaguar is housed within a 4m diameter, spherical projection dome. A real-time, fully textured graphical scene of the virtual world is presented over eight visual channels. The five forward channels are front-projected providing a horizontal field of view of 250°. The three rear channels can be seen through the vehicle's central view and side mirrors.

The vehicle cab and dome are mounted on an eight degree-of-freedom (DoF) motion system, designed, manufactured and installed by Dutch company Rexroth Hydraudyne B.V. Systems & Engineering. The electrically-driven, synergistic EMotion-2500-8DOF-500-MK1-XY consists of a typical six DoF hexapod built upon a two DoF XY-table and can achieve a peak linear acceleration of 0.5g. The maximum excursion is 5m both longitudinally and laterally. The system's bandwidth is over 5.3Hz in all DoFs.

Implementation of the Classical Motion Drive Algorithm

The full block diagram of the implementation of the classical MDA in the UoLDS can be found in Figure 1, controlling the movement of the hexapod in translation and rotation along with the XY-table in translation.

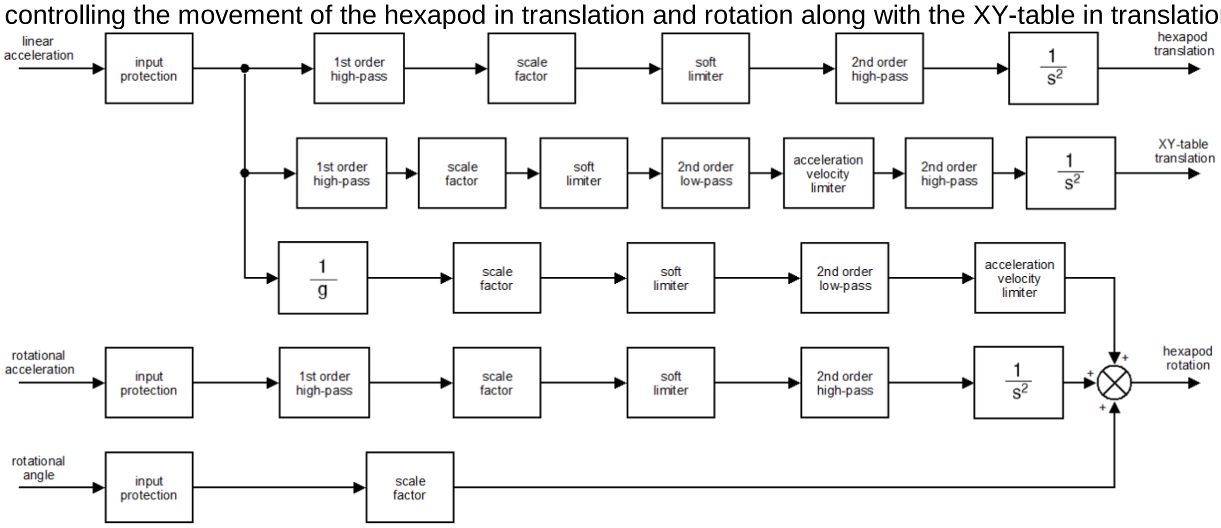


Figure 1: classic MDA used in the study

Experimental Stage 1: Just Noticeable Difference – maximum perceptible scale-factors in motion platform translation and tilt

The performance of the classical MDA to an acceleration input in each of the three linear and rotational vehicle degrees-of-freedom is characterised most easily in the frequency domain. The resultant transfer function is commonly illustrated by a Bode plot, the magnitude describing the system gain and the phase depicting the timing of the output with respect to the input. In terms of driving simulation, the system gain effectively describes the magnitude of the perceived acceleration: the extent to which the simulator achieves the required acceleration demand. The controllability of the simulator, on the other hand, is a direct result of the phase error between demanded and perceived accelerations. For a particular frequency of input, the mismatch can be expressed in units of time. Phase error affects the overall transport delay or latency of a driving simulator motion. Such latencies lead to handling difficulties [Rei2] and can contribute towards simulator sickness (see [Sta1] for a review).

In assessing only the maximum perceptible scale-factor, Stage 1 simply considered motion system gain. Participant drivers were not required to actively handle the simulator through the vehicle controls, simply to ride as observers to a pre-scripted series of control inputs. Dynamically, the performance of the simulator, including the update of the visual scene, was as though drivers had actually made those control inputs. The phase lag associated with motion filtering and the consequent issues of simulator controllability of the simulator was considered later in Stages 2 and 3.

Stage 1 was split into two phases; the first investigated maximum perceptible scale-factor error for motion platform translation (or more accurately the maximum perceptible scale-factor closest to unity). A second, complimentary phase deciphered the equivalent for platform tilt. Stage 1, therefore, required four driving scenarios, designed to assess the maximum perceptible scale-factor for platform translation and tilt for both longitudinal and lateral vehicle manoeuvres. Each trial consisted of a scenario pair, one for which motion was scaled and one for which it was unscaled (unity scale-factor), the order of which being presented randomly. Participants were required to indicate for which of the scenario pair they felt motion had been unscaled.

A Levitt 1 up / 3 down [Lev1] procedure was used to estimate the maximum perceptible scale-factor using a Just Noticeable Difference technique. The stimulus, therefore, was the error between the scaled and unscaled, “ideal” motion cue. Thus the perceptual threshold measured was the minimum error that could be sensed at the 79% probability level (c.f. [Gra2]).

Method

Scaling of motion platform displacement in translation

For platform translation, the simulation of linear acceleration was realised through raw, unfiltered cueing, using surge and sway generated only by the XY-table. Naturally, the greater the scale-factor, the larger the XY-table displacement required. Two scenarios were designed at a driver control input frequency of 1.35rad/s (0.215Hz) in order to remain comfortably inside the bandwidth of both XY-table surge and sway. The value of 1.35rad/s was selected to be close to the 1rad/s “critical” frequency suggested by the Sinacori / Schroeder motion fidelity criterion [Sch1] whilst also allowing the scenario to be achieved unfiltered and unscaled within the excursion limits of UoLDS’s XY-table.

Longitudinal translation driving scenario

The longitudinal translation scenario involved braking and accelerating during car following. The participant was seated in the vehicle cab viewing the visual scene as normal, but the display showed full white. Over a 1s period, the scene was faded-in to present a typical rural road with the participant “driving” at the speed limit of 60mph (96kph). Another vehicle, also travelling at 60mph was situated in front at a distance headway of 25m. After 10s the lead vehicle first slowed then sped up, its linear acceleration following one cycle of a continuous sine function. The peak of the sine wave was ±1.5m/s^2 at the selected frequency of 1.35rad/s (0.215Hz) implying a period of 4.65s to complete the “manoeuvre”. Simultaneously, pre-scripted vehicle control inputs were made on behalf of the driver.

Participants were instructed that their vehicle would behave in the same way as the lead vehicle. The main aim of the lead vehicle was to allow participants to form a concept of how the pre-scripted driving controls were handling their vehicle. To them, the scenario appeared as though they had gently applied the brakes in an attempt to keep a constant gap to the lead vehicle, before accelerating to close the gap and maintain a constant following distance to the lead vehicle. The speedometer in the simulator cab displayed the gentle speed reduction of approximately 5mph followed by its return to 60mph.

Lateral translation driving scenario
The achievement of unfiltered and unscaled motion within the excursion limits of UoLDS's XY-table, close to the Sinacori / Schroeder motion fidelity criterion, was equally desirable to assess the scale-factor for lateral translational platform excursion in sway. Hence, its scenario was also designed at the same driver control input frequency (steering) of 1.35rad/s (0.215Hz). Again, this demand fell well within the bandwidth of XY sway with no appreciable signal attenuation or phase error at this frequency. Participants were instructed that pre-scripted vehicle control inputs would be made on their behalf that allowed the vehicle to follow the short, S-shaped chicane, designed to achieve a peak linear lateral acceleration of ±1.5m/s^2 from the vehicle model.

Scaling of motion platform displacement in tilt

For the assessment of the maximum perceptible scale-factor in platform rotation, the simulation of linear acceleration was realised entirely through tilt-coordination, the input signal merely being low-pass filtered to command a corresponding platform angular position. Unsurprisingly, the greater the scale-factor in question, the larger the tilt displacement required.

In order for this tilt-coordination to remain below perceptual thresholds, the longitudinal and lateral driving scenarios were designed at a much lower control input frequency than for the previous assessment of translational scale-factor. The lower input frequency ensured that, even with a unity scaling, the specific force built up sufficiently slowly to demand only an imperceptibly low tilt rate and acceleration. This was managed by the selection of the cut-off frequency (1.5Hz) and damping ratio (1.0) of the low-pass filter. For the selected control input frequency, the filter demonstrated no appreciable modification of the input in terms of the magnitude or phase of its output. Hence, motion was effectively unfiltered, to all intents and purposes specific force demand directly affecting tilt angle.

Longitudinal tilt driving scenario
Similarly to motion platform translation, the longitudinal tilt scenario involved braking and accelerating during car following. Once more the linear acceleration of lead vehicle followed one cycle of a continuous sine wave with a peak of ±1.5m/s^2. However, this time it did so at the lower frequency of 0.333rad/s (0.0531Hz): a time period of 18.85s to complete the manoeuvre.

Lateral tilt driving scenario
A similar, slowly-developing motion platform rotation, but this time in roll, was also required to assess the scale-factor for lateral platform tilt. Hence, its scenario was also designed at the same driver control input frequency (steering) of 0.333rad/s. Like its lateral translation equivalent, the lateral tilt scenario involved a steering through a section of virtual test-track marked out by cones. However, the lower control input frequency called for a much longer, sweeping S-shaped curve as opposed to the short chicane.

Again, participants were instructed that pre-scripted vehicle control inputs would be made on their behalf that allowed the vehicle to follow the long, S-shaped curve. The amplitude of the sine steer at the wheel was 6.35° to achieve the designed peak linear lateral acceleration of ±1.5m/s^2.

Participants

Twenty drivers were recruited for Stage 1 with experience provisos that each had to have held a valid U.K. driving licence for at least five years and were currently driving at least 5000 miles (8000km) per annum. Seven of the sample were female. The demographics of the participants is shown in 1. Payments of £20 were made for participation in Stage 1.

Table 1: participant demographics

	age (♂/♀)	years licensed (♂/♀)	annual mileage (♂/♀)
mean	37.1 / 36.6	17.7 / 17.4	8846 / 9286
standard deviation	10.2 / 7.4	11.0 / 7.3	2968 / 1496

Procedure

The appearance of scaled and unscaled motion within a scenario pair was ordered randomly. The initial scale-factor was 0.5. In order to speed up convergence, a slightly modified version of the Levitt procedure was used such that each time the scaled motion was correctly identified, scale-factor was increased by a step size of 0.1. Once the first error was made, the step size was halved and the scale-factor reduced by 0.05. This was the point of the first reversal, where the direction of scale-factor modification changed sense. At this moment, standard Levitt 1 up / 3 down was used such that three consecutively correct responses had to be achieved before any further increases in scale-factor were made. Any error led to a decrease in scale-factor by the 0.05 step size. The session was terminated after six reversals or thirty scenario pairs, whichever occurred first. The participant's threshold in motion scaling was estimated by taking the mean value of the third and subsequent reversals. [Gra1] used a similar Levitt Just Noticeable Difference technique to motion-visual phase error detection in a flight simulator.

Results

A repeated-measures ANOVA was undertaken, for two independent variables, each of two levels: Motion System Movement (translation / tilt) and Movement Modality (longitudinal / lateral). The assumptions of ANOVA were not violated in any way, with the resulting maximum perceptible scale-factor threshold (79% detection likelihood) shown in Figure 2. The error bars show the 95% confidence intervals of the means displayed.

Maximum perceptible scale factors were significantly higher in translation that in tilt, $F_{(1,19)}=4.56$, $p=.046$, $\eta^2=.20$ However, there was no significant effect of driving scenario modality ($F_{(1,19)}=0.098$) nor was there any significant interaction of motion system movement and scenario ($F_{(1,19)}=0.198$). Hence, for the consideration of maximally-scaled motion conditions in the upcoming experimental investigations of Stage 2 and Stage 3, the same scale-factors were used for both longitudinal and lateral motion, the mean of their respective values to two significant figures: 0.90 for motion platform translation movements and 0.87 for platform tilt.

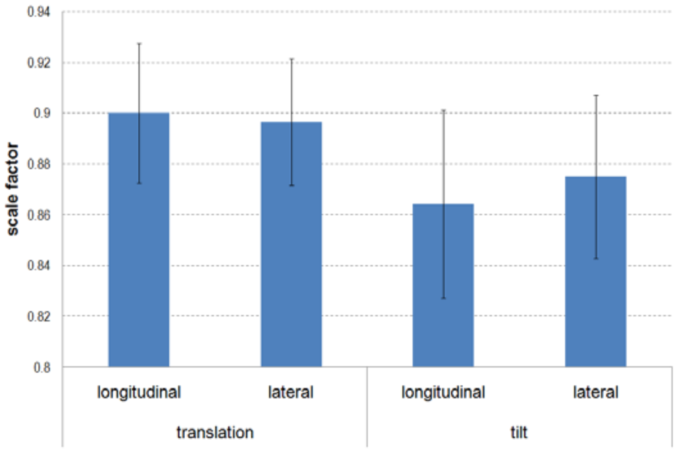


Figure 2: maximum perceptible scale-factors for motion system movements in translation & tilt for longitudinal & lateral driving scenarios (error bars 95% C.I.)

Experimental Stage 2: Paired Comparison – the effects of motion reference point and tilt rate on drivers' task perception and performance

By taking into account only the maximum perceptible scale-factor, Stage 1 simply considered the perception of motion through Bode gain: the relationship between the magnitude of the demanded acceleration and the achieved specific force. Stage 2 considered the second vital element in motion cueing, controllability of the simulator resulting from the implementation of its MDA and the consequential filtering of the input acceleration signal. This filtering leads to a phase difference between the demanded and achieved specific forces. Large phase errors result in a significant time delay between the expected and perceived specific forces, rendering the closed-loop driver control process difficult to manage [Rei1]. Hence rather than riding as observers to a pre-scripted series of control inputs, Stage 2 closed the driver control feedback loop as participants now took on the role of interactive simulator drivers .

Motion cueing in Stage 2 was achieved using the classical algorithm. To begin the process of its optimisation in driving simulation, the overall scale-factors used were based on the maximum perceptible gleaned from Stage 1. This ensured that precious actuator stroke was not unnecessarily utilised in order to produce needlessly high specific forces through overly-scaled motion.

Two independent experimental factors were manipulated in Stage 2: MRP location and the maximum tilt rate achieved during tilt-coordination. The two independent experimental factors each had two levels:

- ***MRP-Location***
  - low (MRP level with hexapod upper rotation datum) - MRP_{hi}
  - high (MRP level with driver's eye-point in the simulator, 1.1m above datum) - MRP_{lo}
- ***Maximum-Tilt-Rate***
  - low (0.05rad/s, 2.86°/s) - $Tilt_{hi}$
  - high (0.15rad/s, 8.59°/s) - $Tilt_{lo}$

The four resulting motion cueing conditions were assessed both subjectively through a paired comparison (c.f. [Gra2]) and objectively by an analysis of driver performance measures. Hence, two specifically designed driving scenarios had to be developed, requiring both longitudinal and lateral control of the vehicle, that were sufficiently manageable to allow predictable and repeatable demands on motion cueing whilst allowing a continuous determination of task accomplishment against well-understood vehicle handling criteria. Furthermore, the scenarios had to appear natural and familiar to the participant driver. For these reasons, scenarios analogous to a tracking task were designed that mimicked common driving situations.

Driving scenarios

Given that the highest of the two levels of MRP-Location was 1.1m above the motion platform datum, the maximum possible roll and pitch angles achievable by UoLDS's motion system were subsequently limited to just under ±12° (0.209rad). Hence, any driving manoeuvre requiring a corresponding maximum sustained specific force through tilt-coordination could not exceed approximately 0.2g. To allow for extra hexapod actuator excursion in the handling of rotational accelerations by the motion system during the manoeuvre, the driving scenario was further limited to a linear acceleration of 0.15g. Longitudinally, a scenario was developed that required this value in braking by a near step-input of brake activation and resulting deceleration of the simulator vehicle. Laterally, the scenario required a similar acceleration in cornering through a near step-input of steering angle.

Longitudinal driving task

The common longitudinal driving situation chosen was braking at a set of traffic-lights. Car following on the approach to the traffic-lights was exploited in order to sufficiently control the degree of braking required.

The participant was seated in the vehicle cab viewing the visual scene as normal, but with the display showing full white. Once both the participant were ready (denoted by depressing the accelerator pedal), the visual scene was faded-in to present a typical two-lane urban scene with the participant "driving" at the speed limit of 40mph (64kph). A speed controller maintained this forward speed regardless of the driver's accelerator input. Another vehicle, also travelling at 40mph was located in front at a distance headway of 17.8m (time headway of 1s). Both vehicles were heading towards a signalised intersection, the state of the traffic-lights always being visible to the simulator driver beyond the low-profile lead vehicle. After 7s at constant speed, the traffic-lights changed from green to amber; 3s later they turned to red. As this moment, the lead vehicle underwent a step deceleration of $1.5m/s^2$ in response to the red light and its brakelights illuminated.

During their pre-study briefing, participants were informed that the lead vehicle would decelerate the moment the traffic-light changed to red and at this point to "brake as smoothly as possible, maintaining a constant distance to the car in front". Whilst the driving task was to keep the distance gap stable, in effect it also became matching the step change in deceleration of the lead vehicle, guaranteeing (as much as possible in an interactive simulation) that the specific force demand of the motion system was equivalent between scenarios. Both subjective preference and objective performance in the tracking task of maintaining distance headway were assessed.

Lateral driving task

Laterally, the controllable driving situation selected was the negotiation of a circular curve requiring a near step-input of steering angle, undeniably a natural and familiar driving task. The curve radius (737.4m) and entry speed (74.4mph) were such that a $1.5m/s^2$ linear lateral acceleration would be developed during the handling task. Its tracking element was the stipulation for accurate maintenance of the centre of the driving lane.

Once motion system parameters had been selected and the participant had indicated their readiness by depressing the accelerator pedal, the visual scene was faded-in to present a typical three-lane motorway with the participant located in the centre of the left-most lane. In order to manage forward speed throughout the 12.7s straight approach to the upcoming left-hand curve and to guarantee that the required lateral acceleration would be achieved during its negotiation, a speed controller maintained the forward speed regardless of the driver's accelerator input. Participants had been briefed to steer the curve "as smoothly as possible, keeping as close as you can to the middle of the lane that you are in".

Motion system tuning

In order to achieve the two levels of Maximum-Tilt Rate ($Tilt_{hi}$ and $Tilt_{lo}$), two different parameter sets of the classical algorithm were drawn up. They were obtained by trial and error as a result of objective, off-line tuning through an analysis of the MATLAB/Simulink model of the classical algorithm. Tuning was an iterative process involving two fundamental stages in both the frequency and time domains. Parameter sets were selected to obtain the flattest possible transfer function given the tilt-limiting constraints. No additional parameter sets were required for the two levels of MRP height (MRP_{hi} and MRP_{lo}) since the demands of the MDA were identical in both situations.

The two levels of Maximum-Tilt-Rate were achieved through varying the cut-off frequency of the second-order low-pass tilt-coordination filter rather than by any non-linear rate-limiting of the filter's output. This ensured a smooth tilt acceleration, free of any jerks caused by rate-limiting. Although only tilt rate was specifically manipulated in the experimental design, tilt acceleration also has perceptible threshold limits and was also considered in the development of sub-threshold tilt-coordination, especially important in the $Tilt_{lo}$ condition.

Participants

In an effort to maintain consistency in the ratings offered by the randomly-selected sample, it was the intention that those who took part in Stage 1 would also participate in Stage 2. However, only eighteen of the twenty drivers did so. Both withdrawals (P15, ♂, 44.7yrs and P20, ♀, 41.1yrs) were due to issues of participant availability and the limited data collection epoch available prevented any replacements. Payments of £10 were made for participation.

Procedure

Each driving situation was presented twice, forming a scenario pair, each trial with a different permutation of MRP-Location and Maximum-Tilt-Rate in order to allow the paired comparison to be made. Participants had been briefed that during each pair the motion system would behave differently. At this point of the trial they were asked "compared to real driving, was the simulation of motion more accurate in the first or second presentation of the scenario pair?" The question had been introduced during their pre-experiment briefing, when they were also told that the visual scene would reinforce the illusion, but that it was important to answer based on their perceived realism, rather than their success in the tracking task.

Stage 2 was scheduled for a single, one-hour visit to the simulator. Each visit was split into two sessions, limited to the experience of either longitudinal or lateral driving tasks. One half of the participant sample undertook braking (longitudinal task) first with the other half's initial session involving steering (lateral task).

After a practice session, scenario pairs were presented so that participants could make their paired comparisons of motion cueing based on the question "was the simulation of motion more accurate in the first or second presentation of the scenario pair?". With four cases, six pairs were necessary. The order of the motion condition was balanced for order and carry-over effects across participants in a balanced design [Rus1].

Results

Results are presented separately for the longitudinal and lateral driving tasks. For each, both the subjective ratings of motion cueing condition realism and particular driving task performance were assessed.

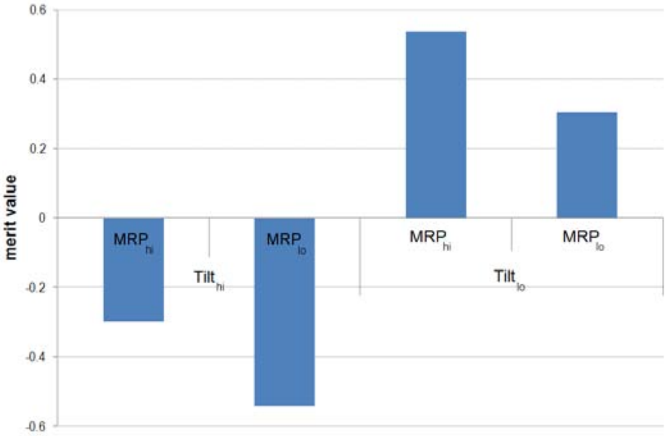
The subjective data were analysed through a Least Significance Difference of the overall rating scores for each motion cueing condition in order to assess the significance of the variation in those scores [Ken1]. In addition, the maximum likelihood estimation of the preference probabilities (Bradley & Terry model [Bra1]) was also undertaken, resulting in the Noether "merit" value [Noe1]. These models provides the ability to express the relationship between conditions on a linear scale between -1 (lowest possible preference probability) and +1 (highest possible preference probability).

The objective data, on the other hand, were analysed through a repeated-measures ANOVA for the driver metrics in question. During the paired comparison, each motion cueing condition was experienced on three separate occasions. The mean of these three was taken as the participant's overall performance for the metric under evaluation.

Longitudinal driving task

Subjective measures

For Maximum-Tilt-Rate the subjective data (merit value, Figure 3, left) indicated that a slow tilt was considered more realistic than a more rapid one. However, the LSD analysis (Figure 3, right) suggested that participants had no significant preference for, or maybe any awareness of, a shifting in MRP-Location.



	$Tilt_{hi}$ MRP_{hi}	$Tilt_{hi}$ MRP_{lo}	$Tilt_{lo}$ MRP_{hi}	$Tilt_{lo}$ MRP_{lo}
$Tilt_{hi}$ MRP_{hi}		n.s.	sig.	n.s.
$Tilt_{hi}$ MRP_{lo}			sig.	sig.
$Tilt_{lo}$ MRP_{hi}				n.s.
$Tilt_{lo}$ MRP_{lo}				

Figure 3: merit value (right) and Least Significant Difference test of scores (significant or non-significant at p<0.05)

Objective measures
A repeated-measures ANOVA was carried out for task performance using standard deviation of longitudinal acceleration *sd_long_acc* (Figure 4) as the related dependent variable. A lower *sd_long_acc* was associated with better task performance. The error bars show the 95% confidence intervals of the means displayed. Both were normally distributed according to Kolmogorov-Smirnov tests.

There was a very strong main effect of Maximum-Tilt-Rate with significantly poorer task performance demonstrated when tilt rate was slow (*sd_long_acc* = 0.897m/s^2) rather than more rapid (*sd_long_acc* = 0.792m/s^2); $F_{(1,17)}$=17.0, p<.001, η^2=.50. There was also a reasonable main effect of MRP-Location with better performance exhibited when the MRP was in the higher (*sd_long_acc* = 0.802 m/s^2) rather than the lower position (*sd_long_acc* = 0.847 m/s^2); $F_{(1,17)}$=4.89, p=.041, η^2=.22. No interaction was evident; $F_{(1,17)}$=2.11.

In contrast to the subjective data, for Maximum-Tilt-Rate this performance measure (*sd_long_acc*) revealed convincingly that more accurate task performance was achieved in conditions of rapid tilt rather than one that developed more slowly. However, drivers also demonstrated no significantly smoother braking, in accordance with the task demands, when the MRP-Location was situated closer to their vestibular organs, rather than when it was positioned at the motion platform datum.

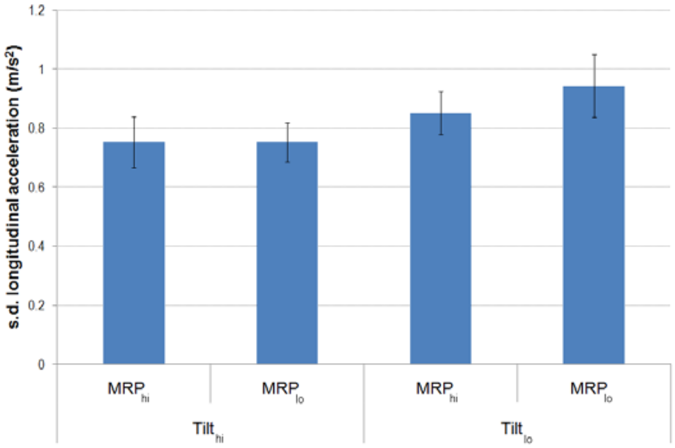


Figure 4: standard deviation of longitudinal linear acceleration (error bars 95% C.I.)

Lateral driving task

Subjective measures
Contrary to the longitudinal braking task, when participants were faced with curve negotiation, neither Maximum-Tilt-Rate nor MRP-Location appeared to have any influence over perceived motion cueing realism. The Least Significant Difference test of scores showed no significant difference between the motion-cueing conditions.

Objective measures
A repeated-measures ANOVA was carried out for the task performance the related dependent variables of standard deviation of lateral acceleration *sd_lat_acc* (Figure 5).In contrast to the longitudinal braking task, lateral task performance was hardly affected by either Maximum-Tilt-Rate or MRP-Location. With regard to standard deviation of lateral acceleration, there was a marginal (borderline but non-significant at 95%) effect of Maximum-Tilt-Rate with task performance degraded very slightly when tilt rate was slow (*sd_lat_acc* = 0.448m/s^2) rather than more rapid (*sd_lat_acc* = 0.430m/s^2); $F_{(1,17)}$=3.94, p=.064, η^2=.19. There was no effect of MRP-Location ($F_{(1,17)}$=0.480) and most definitely no interaction ($F_{(1,17)}$=0.002).

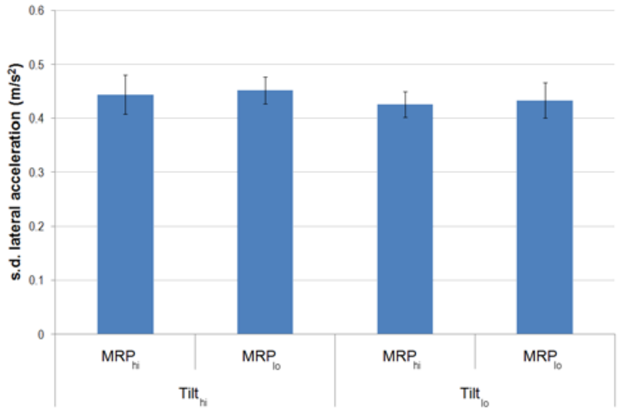


Figure 5: standard deviation of lateral linear acceleration (error bars 95% C.I.)

A fuller discussion of the significance of Stage 2 results with regard to the rest of the experimental design is made in the Discussion. But, based predominantly on the longitudinal performance data, a decision was made to fix MRP at the higher location of 1.1m above the platform datum level. The scene was now set for the most comprehensive evaluation of the three-staged experimental plan, Stage 3's three-factor optimisation of the perceptual trade-off of specific force and tilt rate errors.

Experimental Stage 3: Paired Comparison – the effects of overall scale factor, tilt rate and extended motion platform displacement on drivers' task perception and performance

With the maximum perceptible scale-factor and most suitable MRP location established, it was now possible to make a more thorough evaluation of the perceptual trade-off of specific force and tilt rate errors. Arguably, motion platform tilt rate, manipulated through the classical MDA's filtering of low frequency specific force input, has the greatest impact on this trade-off due to its significant effect on the speed with which tilt-coordination is developed. However, overall scale-factor also plays a significant role, since its scaling of the desired output reduces specific force error; effectively, less demand is easier to achieve.

In addition to scale-factor and tilt-coordination, the accuracy and longevity of the onset cue, handled by the classical algorithm high-frequency channel, also significantly affects specific force / tilt rate error. By sustaining the onset cue for a longer period, less specific force sag is perceptible. This can only be achieved by increasing the available displacement of the motion system in translation. Hence, the final piece in the classical MDA jigsaw is best found from an optimisation of all three of these factors. In combination they characterise the behaviour of the motion system and the inherent role that the classical algorithm plays in driving simulation. This motivation drove the fundamental aim of Stage 3: the appropriate combination of scale-factor, tilt rate and platform translational capacity. In all cases, the onset cue was always realised to some extent through hexapod translation; however, for platform translational capacity, the extra surge and sway provided by UoLDS's XY-table was either exploited or not. The resulting three independent experimental factors under manipulation each had two levels:

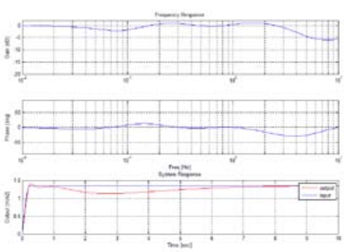
- ***XY***
  - on (XY-table in use)
  - off (XY-table not in use)
- ***Maximum-Tilt-Rate***
  - low (0.05rad/s, 2.86°/s)
  - high (0.15rad/s, 8.59°/s)
- ***Scale-Factor***
  - low (0.50)
  - high (0.87 / 0.90)

As in Stage 2, the motion cueing conditions were assessed subjectively through a paired comparison and objectively by an analysis of driver performance measures. The same longitudinal and lateral driving tasks were also employed. The MRP was located 1.1m above the platform datum level in line with the findings of Stage 2.

Motion system tuning

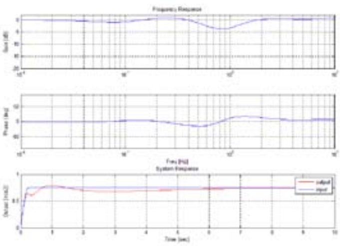
To achieve the required motion cueing conditions, eight different parameter sets of the classical algorithm were defined. These were tuned using the MATLAB/Simulink classical MDA model and the same idealised driver model as in Stage 2. Hence, each parameter set was optimised for best performance given the constraints of the independent variable manipulations. The symmetrical nature of the UoLDS motion system allowed identical parameters sets to be utilised for both longitudinal and lateral motion platform movement. The motion characteristics of the eight conditions are shown below:

Parameter set for $XY_{on}Tilt_{hi}SF_{hi}$



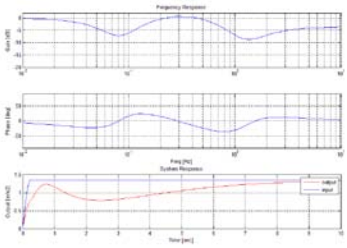
The Parameter set for $XY_{on}Tilt_{hi}SF_{hi}$ was typified by a low specific force error achieved through compromising tilt rate error. As a result, the Bode plot (opposite) shows a relatively flat transfer function as the output specific force is achieved quickly through a combination of rapid tilt and strong onset cueing, requiring a XY-table displacement of almost 3m in the process.

Parameter set for $XY_{on}Tilt_{hi}SF_{lo}$



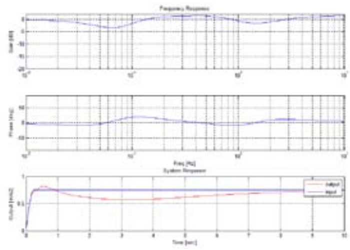
$XY_{on}Tilt_{hi}SF_{lo}$ showed a more rapid conversion to the required steady-state conditions than when a higher scale factor was used. As a result of this reduced specific force error, its Bode plot is flatter.

Parameter set for $XY_{on}Tilt_{lo}SF_{hi}$



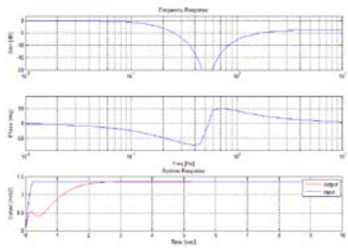
The response of $XY_{on}Tilt_{lo}SF_{hi}$ demonstrated the typical sag associated with slowly developing tilt-coordination. Its Bode plot shows significant gain and phase errors around the 0.07Hz and 1Hz input frequencies and the underlying specific force takes quite some time to build up for the specific driving task at hand. These delays were mitigated as much as possible by the use of the maximum 5m available XY-table excursion.

Parameter set for $XY_{on}Tilt_{lo}SF_{lo}$



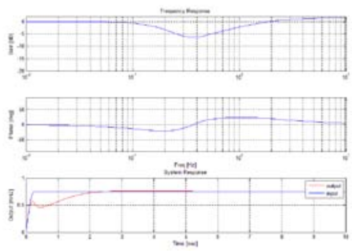
In comparison to its highly scaled equivalent, $XY_{on}Tilt_{lo}SF_{lo}$ boasts a better frequency response due to the reduced specific force demanded. Apart from less phase lag, its response does not differ all that much from the corresponding high tilt rate condition $XY_{on}Tilt_{hi}SF_{lo}$ due to the impact of the XY-table.

Parameter set for $XY_{off}Tilt_{hi}SF_{hi}$



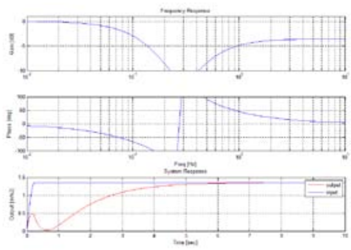
The impact of no additional translational capacity afforded by the XY table is immediately apparent for $XY_{off}Tilt_{hi}SF_{hi}$. Even though hexapod translation has been maximised, the Bode plot shows a considerable attenuation and phase lag around the 0.5Hz region. This is characterised in the time history by a specific force that takes around 2s to reach the desired level, despite the high tilt rate, for the specific driving task.

Parameter set for $XY_{off}Tilt_{hi}SF_{lo}$



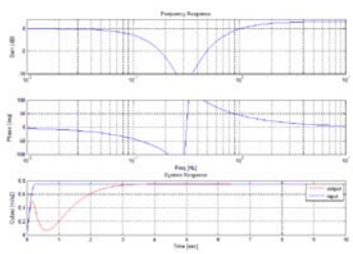
For $XY_{off}Tilt_{hi}SF_{lo}$, lowering the scale factor does mitigate somewhat the poor frequency response associated with no XY-table movement, personified by a much flatter Bode plot. However, in terms of onset cueing, it does not differ at all from its highly scaled cousin $XY_{off}Tilt_{hi}SF_{hi}$.

Parameter set for $XY_{off}Tilt_{lo}SF_{hi}$



$XY_{off}Tilt_{lo}SF_{hi}$ is epitomised by one of the least flat transfer function of all eight of the motion cueing conditions, suggesting attenuated and delayed motion cueing at best. Limited translation and slow tilt combine to result in a theoretically laboured development of specific force.

Parameter set for $XY_{off}Tilt_{lo}SF_{lo}$



In terms of its off-line assessment, the unfortunate frequency response of $XY_{off}Tilt_{lo}SF_{hi}$ is marginally enhanced by a reduced scale-factor. That said, there is still a significant sag in the perceived specific force, although the reduced demand does allow the output to reach the input somewhat more promptly.

Stage 3 Hypothesis

According to the offline tuning, the flattest transfer functions, i.e. those involving low scale factors, rapid tilt and extended XY motion capabilities would affect the most appropriate cueing and hence the best available conditions for accurate task performance. However, the super-threshold nature of the associated tilt coordination would prove unpopular in terms of perceived accuracy of this cueing.

Participants

The same eighteen drivers who took part in Stage 2 also formed the population sample for Stage 3. Due to the increased duration of the study (see next section), payments of £20 were made for participation.

Procedure

After a practice session, the experimental paired scenarios began in one of four pre-defined sequences outlining the order of presentation of the 28 pairs of motion cueing conditions. A central, single sequence was exactly balanced for order and carry-over effects according to Russell's balanced paired comparison design [Rus1]. This was reversed for a second ordering. Finally, a third and fourth sequence were found by alternating the order of presentation of a condition within a specific scenario pair. For each participant, two of these four sequences were presented for each modality of the two driving tasks. The result was the quasi-counterbalancing of the motion cueing conditions witnessed during Stage 3. The large number of scenario pairs resulted in a one-hour experimental session. Hence, to alleviate participant fatigue and boredom, a short break was allowed at the half-way stage, after the presentation of scenario pair 14.

Results

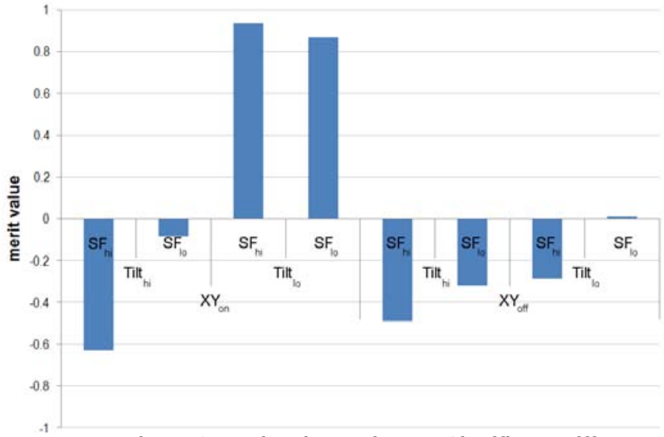
Results are presented separately for the longitudinal and lateral driving tasks. As in Stage 2, the subjective data were analysed through a Least Significance Difference of the overall ratings and the objective data by repeated-measures ANOVA. The mean of all seven experiences of each motion cueing condition was taken as the participant's metric of task performance for each dependent variable under evaluation.

Longitudinal driving task

Subjective measures

Fitting a Bradley-Terry linear model to the subjective ratings revealed that the null hypothesis indicating an equality of objects could be rejected with a high degree of confidence (p=1.39x10^{-11}). An application of Maximum Likelihood Ratio theory demonstrated a satisfactory test of fit the model using (p=.37). The resulting assessment of the Noether merit value for each of the eight motion cueing conditions, on a linear scale between -1 and +1, is illustrated in Figure 6.

Overall, the subjective data indicated a strong preference, in terms of more realistic motion cues, for the low Maximum-Tilt-Rate than a more rapid development of tilt angle. However, this was the case only when the slow tilt was supplemented by extended motion platform translation, made available by the XY-table. In the other six motion conditions, there was a general inclination towards the lower of the two Scale-Factors, but this effect never reached statistical significance at the 95% confidence level.



			XY_{on}				XY_{off}			
			$Tilt_{hi}$		$Tilt_{lo}$		$Tilt_{hi}$		$Tilt_{lo}$	
			SF_{hi}	SF_{lo}	SF_{hi}	SF_{lo}	SF_{hi}	SF_{lo}	SF_{hi}	SF_{lo}
XY_{on}	$Tilt_{hi}$	SF_{hi}		n.s.	sig.	sig.	n.s.	n.s.	n.s.	sig.
		SF_{lo}			sig.	sig.	n.s.	n.s.	n.s.	n.s.
	$Tilt_{lo}$	SF_{hi}				n.s.	sig.	sig.	sig.	sig.
		SF_{lo}					sig.	sig.	sig.	sig.
XY_{off}	$Tilt_{hi}$	SF_{hi}						n.s.	n.s.	n.s.
		SF_{lo}							n.s.	n.s.
	$Tilt_{lo}$	SF_{hi}								n.s.
		SF_{lo}								

Figure 6: merit value and Least Significant Difference test of scores (significant or non-significant at p<0.05)

Objective measures

A repeated-measures ANOVA was carried out for the task performance related dependent variable of standard deviation of longitudinal acceleration (Figure 7). The error bars show the 95% confidence intervals of the means displayed. Both were normally distributed according to Kolmogorov-Smirnov tests of normality.

Regarding driving task success as inversely proportional to the variability of longitudinal acceleration (*sd_long_acc*), there were very strong main effects for all three experimental factors. First, performance was superior when extended translational movement was available during the onset cue ($0.758 m/s^2$), compared to when the XY-table was not active ($0.876 m/s^2$); $F_{(1,17)}=25.6$, $p<.001$, $\eta^2=.60$. There was also less variation in braking when tilt rate was rapid ($0.756 m/s^2$) rather than more slow ($0.879 m/s^2$); $F_{(1,17)}=47.2$, $p<.001$, $\eta^2=.74$. Finally, there was also a considerable benefit of reducing the specific force demand, smoother braking being demonstrated when the motion was unscaled ($0.791 m/s^2$) compared to scaled ($0.843 m/s^2$); $F_{(1,17)}=18.2$, $p<.001$, $\eta^2=.52$.

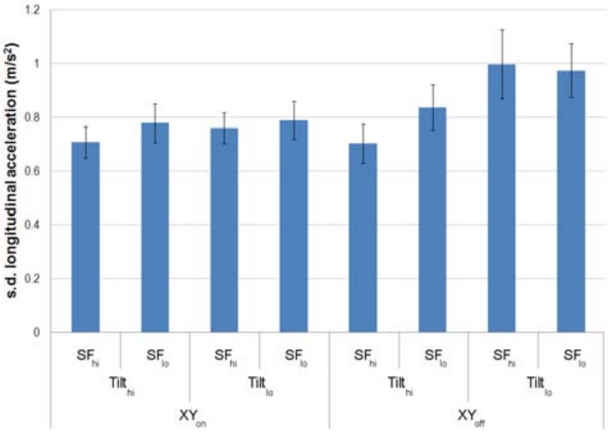


Figure 7: standard deviation of longitudinal linear acceleration (error bars 95% C.I.)

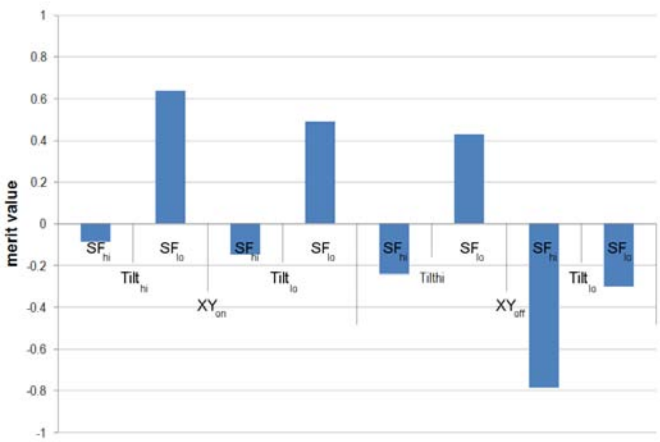
In addition to the main effects, there was also a significant interaction of Maximum-Tilt-Rate and Scale-Factor. When tilt-coordination was slow, task performance was similar with unscaled ($0.878 m/s^2$) and scaled motion ($0.881 m/s^2$). However, as tilt rate increased, braking performance was more inconsistent with a scale-factor of 0.5 ($0.806 m/s^2$) rather than in conditions of no effective scaling ($0.704 m/s^2$); $F_{(1,17)}=5.86$, $p=.030$, $\eta^2=.25$.

Lateral driving task

Subjective measures

A Bradley-Terry model of the subjective data revealed that the variations made to the parameters sets of the eight motion cueing conditions did impact significantly perceived realism; $p=1.93 \times 10^{-8}$. The model fitted the observed data reliably ($p=.85$) and allowed an assessment of the Noether merit value of the four motion cueing conditions illustrated in Figure 8.

On the whole, for the lane keeping task, the consistent subjective data indicated a strong preference in terms of perceived realism for motion cues scaled by 50%, especially when supplemented by the extended motion platform translation capabilities afforded by the XY-table. However, for the handling manoeuvres required, Maximum-Tilt-Rate had no impact on participant ratings.



			XYon				XYoff			
			Tilthi		Tiltlo		Tilthi		Tiltlo	
			SFhi	SFlo	SFhi	SFlo	SFhi	SFlo	SFhi	SFlo
XYon	Tilthi	SFhi		sig.	n.s.	sig.	n.s.	sig.	sig.	n.s.
		SFlo			sig.	n.s.	sig.	n.s.	sig.	sig.
	Tiltlo	SFhi				sig.	n.s.	sig.	sig.	n.s.
		SFlo					sig.	n.s.	sig.	sig.
XYoff	Tilthi	SFhi						sig.	sig.	n.s.
		SFlo							sig.	sig.
	Tiltlo	SFhi								n.s.
		SFlo								

Figure 8: merit value and Least Significant Difference test of scores (significant or non-significant at p<0.05)

Objective measures

A repeated-measures ANOVA was carried out for the dependent variables related to lateral task performance: standard deviation of lane position (*sd_lp*), normally distributed according to Kolmogorov-Smirnov tests. Figure 9 illustrates the strong main effect of XY observed on sd_lp.

Steering performance was significantly more accurate, demonstrated by a reduced variation in lane position when the XY-table was active (0.162m) compared to when it was inactive (0.183m); $F_{(1,17)}=17.3$, $p<.001$, $\eta^2=.51$. No main effects of either Maximum-Tilt-Rate ($F_{(1,17)}=1.90$) or Scale-Factor ($F_{(1,17)}=3.79$) were apparent.

One of the major findings of Stage 3 was the notable significant interaction of XY and Maximum-Tilt-Rate; $F_{(1,17)}= 5.23$, $p=.036$, $\eta^2=.21$. With the XY-table in operation, task performance differed little as tilt rate was reduced from high to low (from 0.164m to 0.160m). However, without any additional sway motion, a reduction in tilt rate resulted in a marked performance degradation (from 0.173m to 0.193m).

A similar interaction was also observed between XY and Scale-Factor. When XY-table sway was available, a reduction in scale-factor had little impact on participant's ability to execute the task (from 0.162m to 0.163m). Conversely, without such platform movement, lane tracking became more varied with unscaled motion as opposed to that scaled by 50% (from 0.190m to 0.176m).

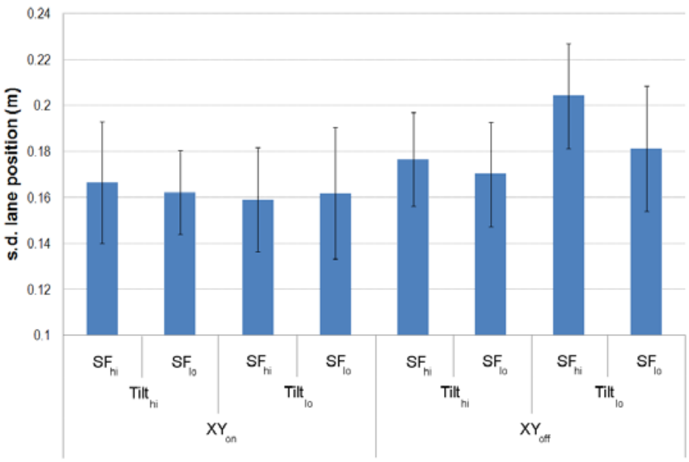


Figure 9: standard deviation of lane position (error bars 95% C.I.)

Discussion

Stage 1

Whilst influenced by [Gro1]'s and [Gra1]'s studies, the fundamental aim of Stage 1 was to ensure that, during the optimisations of the classical MDA in Stages 2 and 3, those motion cueing conditions incorporating a high scale-factor did not unnecessarily utilise precious actuator stroke through overly-scaled motion. The results were determined using a robust and well-established Just Noticeable Difference methodology.

The observed maximum perceptible scale-factors did not differ particularly in terms of the modality of the driving manoeuvres, longitudinal or lateral. However, there were slight, but statistically significant, differences detected between motion cues characterised by translation (0.9) and tilt (0.87). Nevertheless, the variation in maximum perceptible scale-factor of just 0.03 between the two degrees-of-freedom of platform movement is practically negligible. To all extent and purposes, the results indicated that any scale-factor of linear acceleration in any direction need never exceed 0.9.

Of the two studies, Stage 1 probably more closely resembled a study of [Ber1] than that of [Gro1]. Accordingly, the results were more closely aligned to the former's insinuation that unity scale-factors are most appropriate in providing a convincing perception of the magnitude of motion cues. However, Stage 1 differed from both in that participants were not required to rate the believability or realism of the motion cues, simply to discriminate between those that were scaled and those that were not. Hence, rather than emulating the previous studies, which concluded implementation strategies for MDA based merely on the perceived magnitude of motion cues, Stage 1 was able to inform Stages 2 and 3 to reach such conclusions based also on the inherent MDA phase lag and its subsequent impact on simulator controllability.

Stage 2

The significance of these results varied considerably depending on the modality of the driving task in question. In braking, whilst participants expressed no particular preference for a MRP location close to the head, such placement of the MRP did result in marginally better longitudinal task performance (lower sd_long_acc). During the same manoeuvres, they also consistently and strongly favoured the development of slow tilt rate over one that arose more rapidly. However, the fondness for a slow tilt rate was not borne out by the performance metrics, which indicated, conversely, that the driving task was achieved more accurately in rapid-tilt motion cueing conditions.

The lateral task did not show any such substantial and sizeable differences. Participants demonstrated no partiality towards any of the motion cueing conditions and only for a single performance metric, minimum time-to-line-crossing, was anything approaching a robust effect revealed. That result confirmed high Maximum-Tilt-Rate as the most likely to produce more accurate steering performance, although its impact was far from substantial in terms of the amount of that improvement.

By and large, the findings of Stage 2 opposed those of [Fis1] and [Fis2] whose drivers favoured rapid tilt rates, also demonstrating a weak predilection towards a high MRP location. Whilst the dramatic nature of the emergency stop task required [Fis1] may have influenced participants' desire for a fast acting motion cue, the preferences expressed during the more mundane roundabout negotiation [Fis2] are harder to explain away.

Stage 3

A consistent theme in the results observed in both of Stage 3's driving tasks was the lack of consistency between the subjective perception of realism and the objective measures of task performance. Such an issue did not crop up during [Gra2]'s lane-change study, which reported that perceived realism correlated well with lateral task performance. The nature of this steering task was generally dictated by relatively high frequency steering inputs, demanding a similarly high frequency response of the motion cueing. The present study, on the other hand, utilised a lane keeping rather than a lane changing task, characterised by a dominant low frequency domain. Its results undeniably demonstrate that more significant differences exist between the perception and performance with motion cues under longitudinal tasks compared to lateral tasks. That Grant et al. (2009) did not employ a longitudinal task and the fact that the lateral task existed in an altogether different frequency range could easily explain the observed perception/performance correlation differences between the two studies.

Conclusions

Summary of main findings

The lack of perception/performance consistency reported here leads to a dilemma as how best to handle the specific force / tilt rate error trade-off when making use of the classical MDA in research driving simulation applications. When large motion platform translations are made possible by a XY-table, the motion cues most realistic to drivers stem from the reduction of tilt rate errors at the expense of specific force errors. The same is true, admittedly not as clear cut statistically, even when onset cues are handled less effectively without such additional translation capabilities of the motion system. However, the motion cues that are most beneficial in terms of the successful accomplishment of longitudinal and lateral driving tasks doubtlessly originate from the reduction of specific force errors at the expense of tilt rate errors.

With its three-stage experimental plan, this study has attempted to provide a robust, defendable and original investigation into a topic area that is sparsely populated in the driving simulation literature. Given the caveat that its conclusions can only be drawn for the specific longitudinal and lateral driving tasks examined, the following can be drawn from the various stages of the present investigation:

- Scale-factors over 0.9 for motion platform translation or tilt are unnecessary. Above this point, motion cues cannot be perceptibly differentiated from unscaled motion.
- Drivers are not able to perceive a relocation of Motion Reference Point to a position close to the head. Such placement does, however, result in marginally smoother braking, in line with the longitudinal task requirements employed in this study.
- Especially when complemented by extended motion platform translation, braking cues that result from sub-threshold tilt-coordination are rated as more realistic than those emanating from a rapid development of tilt angle.
- Conversely, in line with the longitudinal task requirements of this study, braking is performed more smoothly in conditions of rapid, above-threshold tilt-coordination.
- Braking is smoother with the improved onset cueing made possible by extended motion platform surge.
- Braking is smoother when longitudinal motion cues are effectively unscaled.
- Especially when complemented by extended motion platform sway, the perceived realism of steering cues is enhanced when motion cues are scaled by 50%. Realism is not influenced by the rate limiting of tilt-coordination.
- Cornering is smoother in conditions of rapid, above threshold tilt-coordination.
- Lane position is less varied during cornering with the improved onset cueing made possible by extended motion platform sway.

Implications for simulator design

Motion platforms exist in various guises. Specifications stretch from relatively cheap, small systems limited in their available displacement to those more costly, but affording the simulation engineer a much more expansive representation of the dynamic range of typical driving. By comparing subjective assessments of realism and objective measures of performance, the main objective of this work was to investigate the most appropriate motion cueing to achieve both a strong perceived correlation between real and virtual conditions (perceptual validity) and behavioural correspondence (behavioural validity). Generally, drivers consider scaled motion cues developed at a low tilt rate most realistic. Conversely, unscaled cues presented at rapid tilt rates appear to foster more accurate driving task performance.

These results do suggest an apparent conflict. However, armed with the data summarised in the bulleted list above, design implications for research driving simulators can be drawn. In terms of fidelity and motion cueing, the most appropriate tuning depends on the specific focus of the driving simulator. The fundamental characteristics of the simulator should maximise its internal validity, a concept introduced at the start of this chapter. Internal validity is lost if driver behaviour is specifically affected by the limitations of the simulator (Kaptein, Theeuwes & van der Horst, 1996). Consequently, should driver behavioural research be the simulator's focus, it is logical to place the importance of behaviour and performance over that of perceived realism. Therefore, the first main theoretical contribution of this work is that optimal motion cueing (resolution of the specific force / tilt rate error trade-off) in a research driving simulator is achieved by minimising specific force error at the expense of tilt rate error.

However, before we jump to too hasty a main conclusion, it should be remembered that the interaction of motion platform translation capability and tilt-rate was significant. This interaction occurred repeatedly, observed in both the performance metrics used in the longitudinal task and two of the three lateral task measures. When the XY-table was operational, driving task performance varied little between sub-threshold and more rapid tilt-coordination. However, while the XY-table was inactive, both driving tasks were better achieved with a high platform tilt rate.

This interaction supports the following theoretical contribution. In a small motion system, without the benefit of the XY-table, the constraints of internal validity force the hand of the simulation engineer to minimise specific force error at the expense of tilt rate error. However, a more expansive motion platform, characterised by greater translational capacity, affords the luxury of achieving motion cues that not only bring about accurate driving task performance, but also attain maximum perceived realism. In such a system, the apparently conflicting goals of perceptual and behavioural validity can be aligned much more closely. Whether the benefits of such a system can actually outweigh is another debate.

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