Roll rate thresholds and perceived realism in driving simulation

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Abstract: Due to limited operational space, in dynamic driving simulators it is common practice to implement motion cueing algorithms that tilt the simulator cabin to reproduce sustained accelerations. In order to avoid conflicting inertial cues, the tilt rate is kept below drivers' perceptual thresholds, which are typically derived from the results of classical vestibular research where additional sensory cues to self-motion are removed.

Here we conduct two experiments in order to assess whether higher tilt limits can be employed to expand the user's perceptual workspace of dynamic driving simulators. In the first experiment we measure detection thresholds for roll in conditions that closely resemble typical driving. In the second experiment we measure drivers' perceived realism in slalom driving for sub-, near- and supra-threshold roll rates.

Results show that detection threshold for roll in an active driving task is remarkably higher than the limits currently used in motion cueing algorithms to drive simulators. Supra-threshold roll rates in the slalom task are also rated as more realistic. Overall, our findings suggest that higher tilt limits can be successfully implemented in motion cueing algorithms to better optimize simulator operational space.

Key words: motion cueing, tilt coordination, perceptual threshold, driving simulation, motion perception

Introduction

Motion based driving simulators have a limited physical workspace. One method to perceptually expand this workspace is to simulate sustained linear acceleration by a combination of translation and tilt (tilt coordination). Indeed, when the tilt occurs below perceptual threshold our vestibular system cannot distinguish between the effects of linear acceleration and gravity [Mac8]. This leads to practical motion cueing solutions in which the results of vestibular research on perceptual thresholds are used to limit simulators tilt [Zai19]. However, these limits might be too conservative for an ecological driving simulation, as several works have shown that increasing the complexity of the stimulation affects the perception of motion. Indeed, vestibular thresholds increase for motion with multiple degrees of freedom (e.g. pitch threshold increases with heave motion intensity [Zai19]). Tilt perceptual threshold varies as well when visual cues are also provided (see [Gro4], [Val18] for reviews). Finally, there is evidence that the mental load induced by complex tasks such as flying increase threshold values [Hos5].

Active driving simulation provides a variety of complex visual and vestibular cues as well as demands on attention which vary with task difficulty. It is thus important to measure motion perceptual thresholds in conditions that closely resemble typical driving to determine how the variability of these thresholds can contribute to the sensation of realistic driving. This will allow for tilt coordination in which the tilt/translation ratio is based on perceptual threshold variability, leading to more optimized simulated driving.

We conducted an experiment to measure roll rate detection threshold in a curve driving simulation, where drivers experience multisensory stimuli such as vestibular and visual information and cognitive load. The detection threshold indicates the lowest level at which a stimulus can be detected, i.e. the lowest roll rate at which the tilt is noticed by the driver. The measured thresholds are then compared with the tilt rate detection threshold found in literature [Gro3] to assess the effect of an active driving task. A second experiment was also conducted which relates these thresholds to slalom driving preferences using a paired comparison design in order to determine which roll rate values are most appropriate for driving simulators so as to present the most realistic driving experience. In addition, whether sub- or supra-threshold tilt coordination interferes with preferred motion during driving simulation was assessed.

We hypothesised that: *i.* roll rate thresholds increase during active driving; *ii.* subjective preferences in the slalom task are similar as long as tilt-coordination roll rates remain sub-threshold; *iii.* realism drops for supra-threshold tilt-coordination.

Method

Apparatus and Visual Stimuli

Two experiments were performed using the MPI CyberMotion simulator (Figure 1a): a six degrees-of-freedom anthropomorphic motion simulator derived from an industrial heavy load robot manipulator [Teu16], [Kuk6], [Bar1], [Ber2]. This simulator allows for accelerations up to 4 m/s^2 and rotatory ranges of ± 58 deg pitch and infinite roll and yaw. A driving cockpit was mounted at the end effector, providing drivers with an immersive virtual environment for visual feedback. The simulated vehicle was controlled by the driver through a Sensodrive force-feedback steering wheel and pedals. The visualization was done on a cylindrical projection screen mounted in front of the seat with a horizontal FoV of 90 deg and a vertical FoV of 45 deg. A video projector displayed an image of 1152x450 pixels with refresh rate of 60 Hz at a distance of approximately 70 cm from the driver's eyes. The visual environment resembled a typical slalom course and presented a 4m-wide sinusoidal path (2m amplitude and 125m period), outlined by pylons on both sides (Figure 1b). In the first experiment only one curve of the path was presented; whilst in the second experiment nine curves were provided, for a total length of 501.3 m.

In both experiments, each trial was started by pressing the gas pedal until the vehicle reached 70 km/h. Then, the driver's speed control was disabled to keep the speed constant throughout the remainder of the trial.

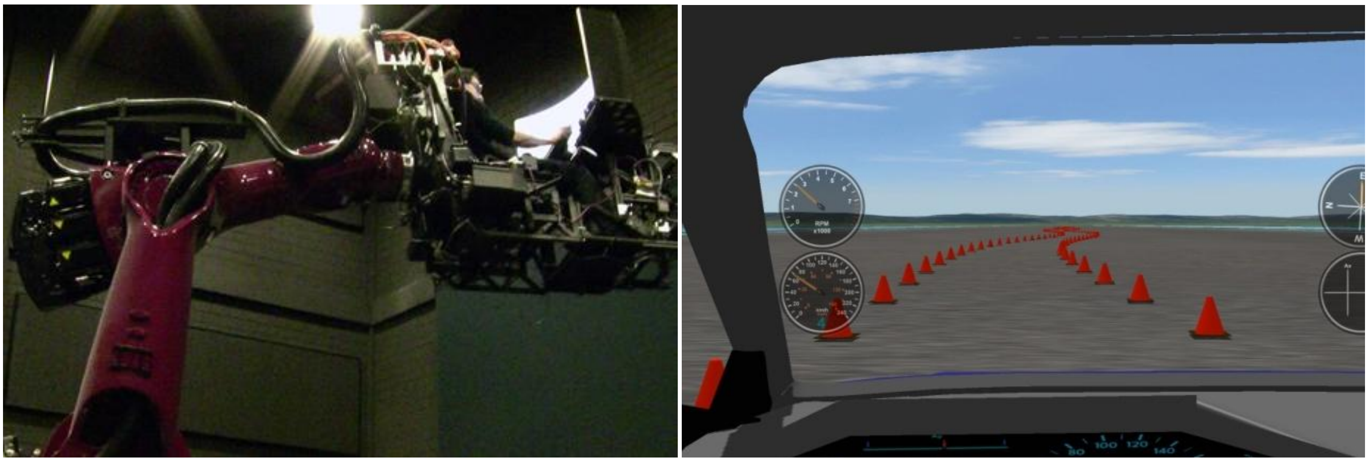

Fig. 1. MPI CyberMotion Simulator (a) and visual environment as seen from the driver (b).

Motion rendering and experimental manipulations

Vehicle motion, generated by CarSim mid-sized hatchback car model, was transformed into simulator motion using an extension of the well-known classical washout filter [Rei11], [Rei12], [Rei13] designed in cylindrical coordinates [Rob14]. In the classical motion algorithm accelerations are high-pass filtered, so that the high-frequency components are reproduced by actual translation of the simulator in the direction of the vehicle motion (onset cue). The low-frequency components are achieved by properly orienting the gravity vector in the driver's frame, so to reproduce the illusion of persistent acceleration in a given direction (tilt-coordination). In our experiments, tilt-coordination was operated on roll motion.

Roll rate was manipulated in order to determine how fast the driver can be rolled in simulated sustained lateral acceleration without noticing the roll component of the tilt-coordination technique. In the first experiment, roll rate was systematically saturated according to whether or not the rotation was perceived by the drivers. In the second experiment, roll rate was saturated according to the individual detection thresholds measured in the previous experiment (see the experiment procedures for further details).

In a typical simulation the driver experiences a combination of roll provided by the suspensions model of the vehicle and roll output by the tilt coordination algorithm [Nah9]. In these experiments the former was set to zero in order to fully control the total amount of roll presented to the driver.

Participants

Seven male participants with normal or corrected-to-normal vision and no history of vestibular dysfunctions, aged from 25 to 53 years (mean 30), took part in both experiments. All had a valid driving license and gave their informed consent to the study.

Experiment 1 procedure

Drivers were asked to complete one curve section of the path without leaving the borderlines, as if they were driving on a real track.

In each trial, as soon as the vehicle passed the end of the curve, the screen turned black and the question "did you feel tilted? (yes/no)" appeared. The participant provided the answer by button press. The simulator was then repositioned to the starting position and after a pause of 10 seconds the participant start the next trial by pressing the gas pedal. Written instructions explicitly asked participants to answer the question relying on the sensation they felt while negotiating the curve, i.e. when the lateral motion occurred, and not before or after the curve.

A psychophysical two-alternative forced-choice procedure (2-AFC) with two adaptive staircases (one ascending and one descending, using the “2-down, 1-up” rule) was used to set the saturation value for roll rate at every trial, according to the driver’s previous answers [Lev7]. The saturation in the first trial was set to 0 and 12 deg/s for the ascending and descending staircases respectively. Every two consecutive “yes” answers (felt tilted) the saturation was decreased by a predetermined step size.

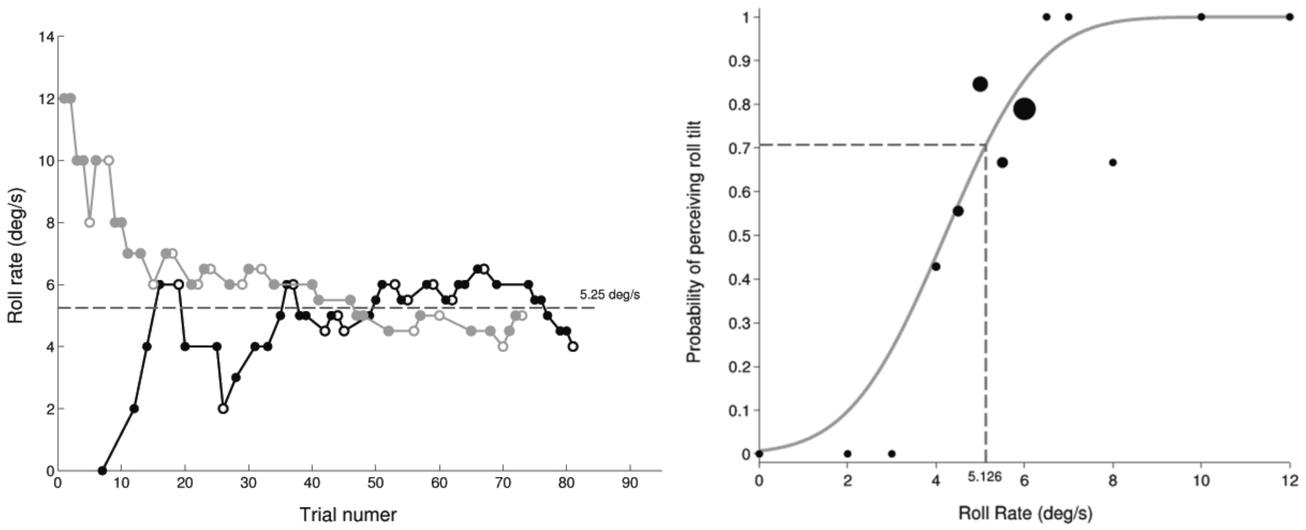

Fig. 2. Adaptive staircases (a) and corresponding psychometric function (b) for one participant. The horizontal line in (a) indicates the detection threshold calculated from the average of the last 5 reversals in both staircases (white dots). This average value, resulting from a “2-down, 1-up” tracking rule, corresponds well with the theoretical 70.7% probability of perceiving roll tilt when fit with a psychometric function (b).

Similarly, every “no” answer (did not feel tilted) the saturation was increased by the same step size. The step size was initially set to 2 deg/s and halved every seven trials to a minimum of 0.5 deg/s, in order to allow for fine estimation when detecting near-threshold values. The experiment was finished when both staircases reversed in direction 12 times (see Figure 2a, white dots). The detection threshold was then calculated by averaging values over the last five reversal points in both staircases. In this procedure the stimulus (roll rate) oscillates around an asymptotic value representing where the participant’s detection is equal to chance. At that point, the probability *P* of providing a wrong answer (1-up) equals the probability *P* of providing two correct consecutive answers (2-down), so that *P* = 0.5. Therefore, the “2-down, 1-up” staircase targets a roll rate value that is perceived with a probability of 0.707 (square root of 0.5). For each participant we also calculated the corresponding psychometric function (Figure 2b), which describes the probability of perceiving the tilt on a continuous scale. We assumed the psychometric function to be a cumulative Gaussian distribution and we fit this model to our data by minimizing the sum of squared errors (SSE).

A typical experimental session for one participant is shown in Figure 2. Each session lasted approximately 40 minutes and required between 78 and 98 trials to complete. Participants had breaks every 15 minutes. A training session of six consecutive curves, with roll rate saturation values similar to the staircases first trial, allowed drivers to familiarize with the simulated motion range and the commands before the experiment.

Experiment 2 procedure

Drivers completed a slalom course driving within the pylons, as if they were driving on a real track. Different roll rate saturation values were selected in the motion filters according to the individual results of the previous experiment. For each participant, we defined sub-, near- and supra-threshold roll rate saturation values to be employed in the slalom driving task (see Table 1, experiment 2). A training session of six consecutive slalom courses allowed drivers to familiarize with the simulator commands and learn how to drive smoothly as required by the instructions. To avoid possible influences on the experiment, drivers experienced in this phase all the three roll rate conditions, in random order.

The paired comparison method was used as a subjective measure to produce a scaling of preferred roll rates. This method allows the construction of a standardized interval-type scale [Tor17] from which a preferred roll rate can be obtained. In this study, the

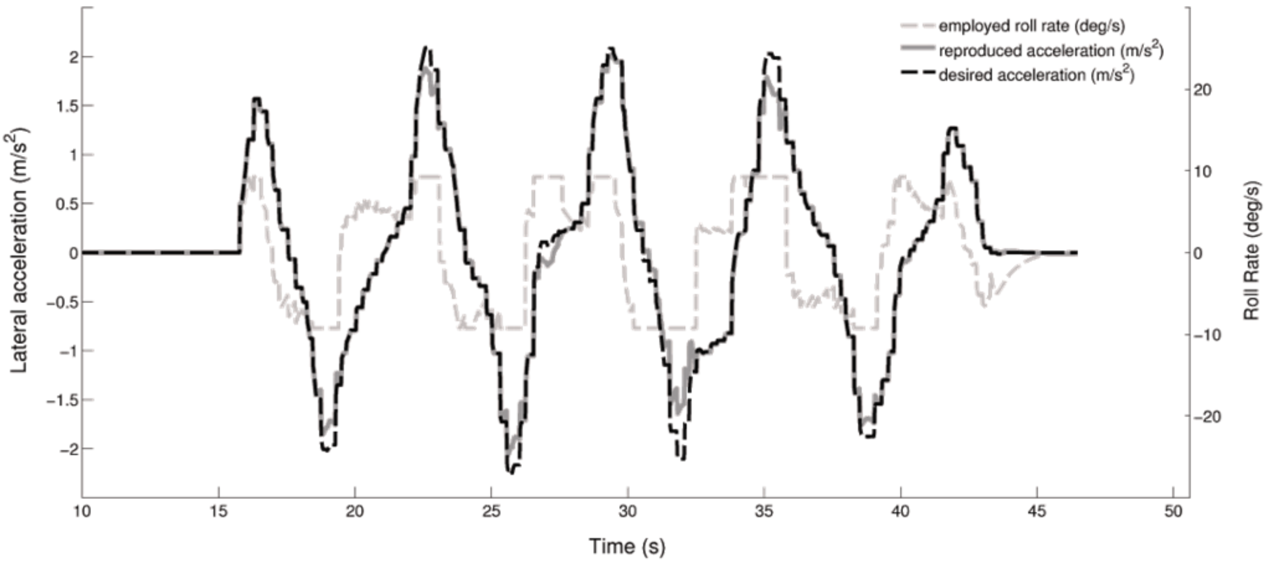

Fig. 3. Example of lateral accelerations (left y-axis) and roll rate output by the tilt coordination (right y-axis) during slalom driving. The lateral acceleration output by the vehicle model (desired acceleration) is provided to the driver as a combination of linear acceleration and roll tilt relative to gravity (reproduced acceleration). In the example, the roll rate was limited to 10 deg/s, causing the reproduced acceleration to occasionally be lower than desired.

preferred value corresponds to the roll rate that provides the most realistic lateral motion. In each trial, two slalom courses with different roll rate saturations were presented consecutively, and then the question “Which slalom felt more realistic? (First/Second)” was displayed on the screen. The participant provided the answer by button press. The simulator was then repositioned to the starting position and the next trial began. Written instructions invited drivers to compare the two previously completed slaloms to the sensation of lateral motion that they would feel in a real car on a similar path. All possible combinations were tested twice for a total of 6 pairs of slaloms for each driver.

A typical experimental session lasted approximately 15 minutes. The lateral accelerations produced during a slalom run and the effects of roll rate saturation on the reproduced motion are shown in Figure 3 for one participant.

Results

Experiment 1

Roll rate perceptual thresholds were calculated using the adaptive procedure described in the method (Table 1, experiment 1). The average perceptual threshold among all participants was 6.3 deg/s (s.d., 2.8 deg/s; Figure 4).

A one-sample t-test executed on the measured detection thresholds compared to the tilt rate saturation value commonly used in many simulators (3 deg/s) showed a significant difference (t(6) = 3.17 p < .01). This result constitutes a main finding of the study and shows that there is a strong influence of motion and task complexity on perceptual thresholds. No signs of motion sickness were aroused during this experiment and no session had to be interrupted.

Table 1. Experiment 1: Roll rate detection thresholds in deg/s. Experiment 2: roll rate (in deg/s) values used in the slalom.

Experiment 1				Experiment 2		
Participant	Roll rate threshold	Standard error		Roll rate 0.5*threshold	Roll rate threshold	Roll rate 2*threshold
1	2.05	0.2409		1	2	4
2	9.75	0.6292		5	10	20
3	8.5	0.8913		4.5	8.5	15
4	5.85	0.4537		3	6	10
5	5.25	0.2911		2.5	5.5	10
6	8.8	0.4163		4.5	9	20
7	4.2	0.4422		2	4	8.5

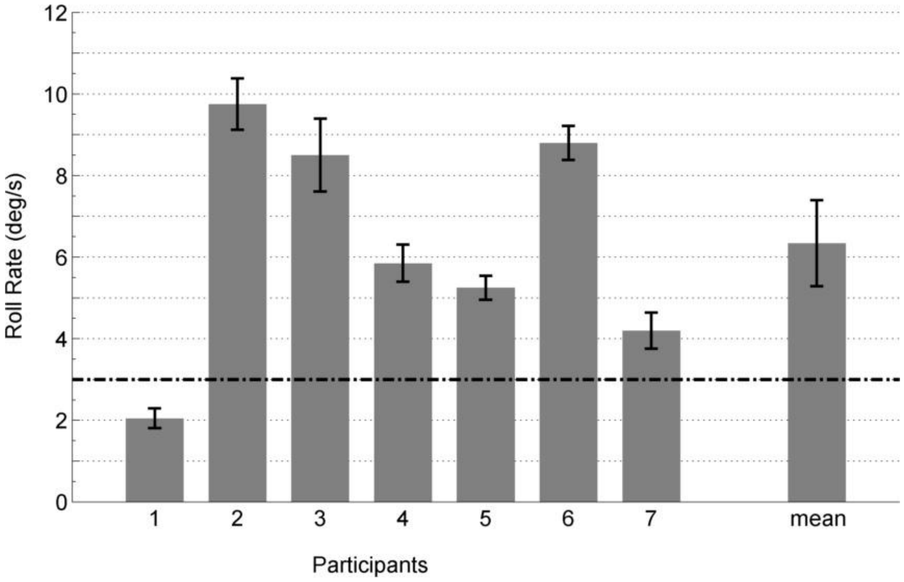

Fig. 4. Individual detection thresholds for roll rate. The dashed line indicates the roll rate saturation value suggested by Groen and Bless (2004) and commonly used in many motion cueing algorithms [Gro4], [Str15]. Error bars indicate the standard error of the mean.

Experiment 2

All participants were able to complete the experiment, but three of them required a break due to dizziness symptoms. The observed preferences counts (Table 2) were converted into proportions and then transformed into standardized scores. (Fig. 5).

Table 2. Preference count for different roll rates in the slalom task. The value on each cell indicates the number of times that the corresponding condition in row has been preferred over the condition in column. The last column reports the preference count for each roll rate condition.

Roll rate condition	sub-threshold	near threshold	Supra-threshold	Total
sub-threshold		7	5	12
near threshold	7		5	12
Supra-threshold	9	9		18

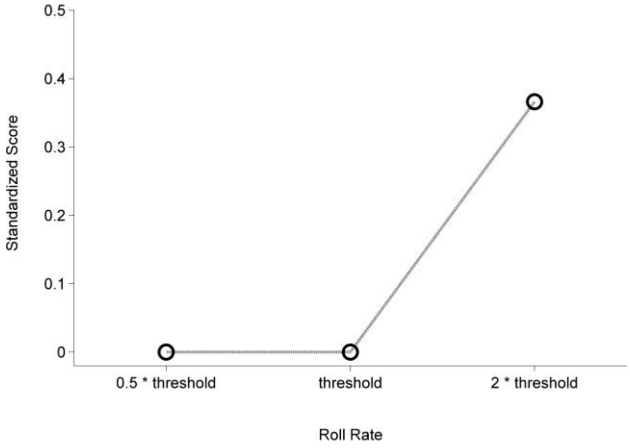

Fig. 5. Standardized scores of the preferred roll rate. The method of paired comparison transforms preference counts into standardized scores, providing a representation of the perceived difference between the roll rate conditions.

As expected, no difference resulted between sub- and near-threshold values, as confirmed by a chi-square test of the preference count ($\chi^2(1) = 0.57$; $p = 0.45$). Data showed higher preference for driving simulation with supra-threshold roll rate, although the difference to sub- and near-threshold values were not statistically significant ($\chi^2(1) = 1.43$; $p = 0.23$).

Discussion and conclusions

We have shown that the detection threshold for roll in an active driving task (6.3 deg/s) is remarkably higher than the threshold reported in literature (3 deg/s) and commonly used in motion cueing algorithms to drive simulators [Gro4], [Str15]. As reported by [Gro3], the presentation of visual stimuli during vestibular measurements on pitch detection increased the perceptual threshold from 0.5 deg/s to about 3 deg/s. In line with this, our results show that in an active driving task the cognitive workload and the complex motion stimuli lead to even higher perceptual threshold [Hos5], [Zai19]. Indeed, despite large individual differences, only one participant revealed a detection threshold lower than 3 deg/s. Our findings suggest then that roll rates similar to the thresholds we have measured can be employed in motion cueing algorithms to better optimize simulator operational space. This would lead to a subjective expansion of the perceptual workspace of dynamic simulators by allowing more intense motion to be reproduced in the same physical workspace.

In addition to being able to increase the amount of roll during tilt coordination, our results show that supra-threshold roll rates are judged as more realistic. This is surprising considering that tilt coordination is expected to fail for roll rates above perceptual threshold, as it evokes the sensation of tilt in addition to a linear acceleration smaller than expected. It is possible, however, that our participants attributed this tilt component to the effect of vehicle suspension, which would provide a more natural feeling of vehicle roll movement when driving around a curve. Supporting evidence for this can be found from previous work by [Pre10], who found that a lateral motion gain smaller than one was preferred in a similar slalom driving simulation. Another explanation could be that the fraction of lateral acceleration lost for low roll rate saturation values is too big, and significantly compromises the realism of the simulation.

Our results show that roll rate saturation values close to detection threshold in an active driving task can be employed for driving simulations without losing motion fidelity. For applied purposes it is unpractical to use filter parameters individually tuned for each driver taking part in a simulation. Therefore, we suggest to implement in tilt-coordination a roll rate saturation of about 6 deg/s, i.e. a value close to the mean of the detection thresholds measured in experiment 1. Even if this choice might lead in some cases to inefficient tilt-coordination, results from experiment 2 show that perceived realism will not be impaired.

During the experiments some participants reported that they could not disentangle physical from visual roll, i.e. whether they were physically tilting or whether the image on the screen was tilting. Unlike physical roll, visual roll was always consistent with the output of the vehicle model. This caused sometimes a tilt of the visual environment even though there was no physical tilt, and more generally a mismatch between visual and physical roll. This might have induced the illusion of being tilted even when the physical roll was not perceivable. Without such an illusion, the individual detection thresholds we measured in the experiment could have been even higher.

Overall, our work shows that higher tilt limits are tolerated by simulators users and can be effectively employed in tilt coordination techniques without impairing the realism of the simulation. The development of more optimized motion cueing algorithm will need to take this into account.

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