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Time-varying perceived motion mismatch due to motion scaling in curve driving simulation

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Introduction

Motion simulators aim to present subjects with a sensation of motion similar to the sensation one would perceive when operating a real vehicle. This is done by combining visual, vestibular, auditory and somatosensory cues. Due to simulators' finite motion envelopes, a conversion from the desired vehicle motion to simulator motion is needed. One of the most straightforward methods for limiting simulator displacement is motion (down)scaling.

Various studies have investigated humans' ability to distinguish motion with different scaling factors [CG10, CG13] and the effect of motion scaling on a simulation's realism [Ber13, Gra03]. These studies conclude that downscaling inertial simulator motion does not necessarily reduce a simulation's fidelity and may even improve it [CG10, CG13, Ber13]. The effects of motion scaling on the control behavior of subjects in a roll and pitch tracking task have also been studied [Ber70, Vro09], showing that gains closer to unity improve pilots' control performance.

These studies investigated the effect of motion scaling on the total simulation and did not investigate the time-varying influence of motion scaling. Such an influence is expected since the magnitude of the induced signal distortion over a simulation segment inherently varies over time for typical motion cueing algorithms (such as washout filters [Rei86]). For example, a high-pass filter applied to curve-driving motion has little influence on the curve onset, but filters out the sustained cue in the curve's steady-state part and will induce a false cue at the curve exit [Gra97].

First evidence of a time-varying effect of specific force scaling in longitudinal motion was found by Groen, Valenti Clari and Hosman [Gro01], who concluded that onset cues can be scaled down further than sustained cues in aircraft take-off maneuvers. Up till now, however, no study has formally verified this finding using continuous subjective evaluations of simulator motion to explicitly measure the effects of motion scaling on perceived simulation fidelity over time.

This paper describes a simulator experiment carried out to investigate the time-varying effects of lateral specific force scaling in curve driving simulation.

Research goal

The main goal of this research is to investigate whether the effects of lateral specific force scaling on the perceived fidelity of a curve-driving simulation are time-varying. We hypothesized that the effect of lateral specific force scaling on the perceived motion mismatch would not be equal during the curve onset, the sustained part of the curve and the curve exit.

Methods

To investigate the time-varying effects of motion scaling during motion simulation, a within-subjects simulator experiment was performed. In this experiment 16 subjects were a passenger in a car driving through a series of left and right curves. Subjects were instructed to focus on continuously rating their perceived motion mismatch (PMM, the difference between the simulator's inertial and visual motion) using the rating method first used by Cleij *et al.* [Cle15]. The experiment was carried out in the CyberMotion Simulator at the Max Planck Institute for Biological Cybernetics [Teu07], shown in Fig. 1.

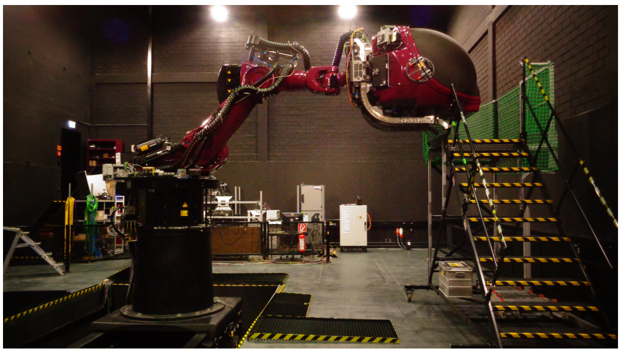

Figure 1: The CyberMotion Simulator (CMS) at the Max Planck Institute for Biological Cybernetics.

During the experiment runs, a simulated car accelerated from 0 to 50 km/h, then went through left and right 90-degree turns (r = 120 m) with 150 m straight sections in between, and finally decelerated back to standstill.

Out of the twenty-two curves in a single run, two featured a one-to-one replication of the lateral specific force (i.e., $k_y = 1$). Six others featured scaled versions of the lateral specific force ($k_y = 0.4, k_y = 0.5, k_y = 0.6, k_y = 0.8, k_y = 1.2$ and $k_y = 1.275$).

Results & Conclusion

For all participants, the ratings given over the four experiment runs were averaged, see Fig. 2. The time-varying effect of motion scaling was studied by analyzing these average ratings separately for the curve onset, the sustained part of the curve and the curve exit of each condition.

These ratings showed that the lateral specific force could be scaled up by 30% without subjects indicating a significant increase in PMM in any of the three curve segments. Scaling down the lateral specific force did increase the ratings: during the curve onset only a scaling factor of $k_y = 0.4$ led to a significant increase in ratings, during the curve's sustained part and exit a scaling factor of $k_y = 0.6$ or lower led to a significant increase in ratings.

It is thus concluded that the lateral specific force can be scaled down further during the onset of a curve than during the remainder of the curve. The results of this study can be used to improve simulator performance in the future, by scaling down motion where possible. Any part of the simulator motion envelope that is saved using this approach can then be used to simulate the inertial motion more realistically.

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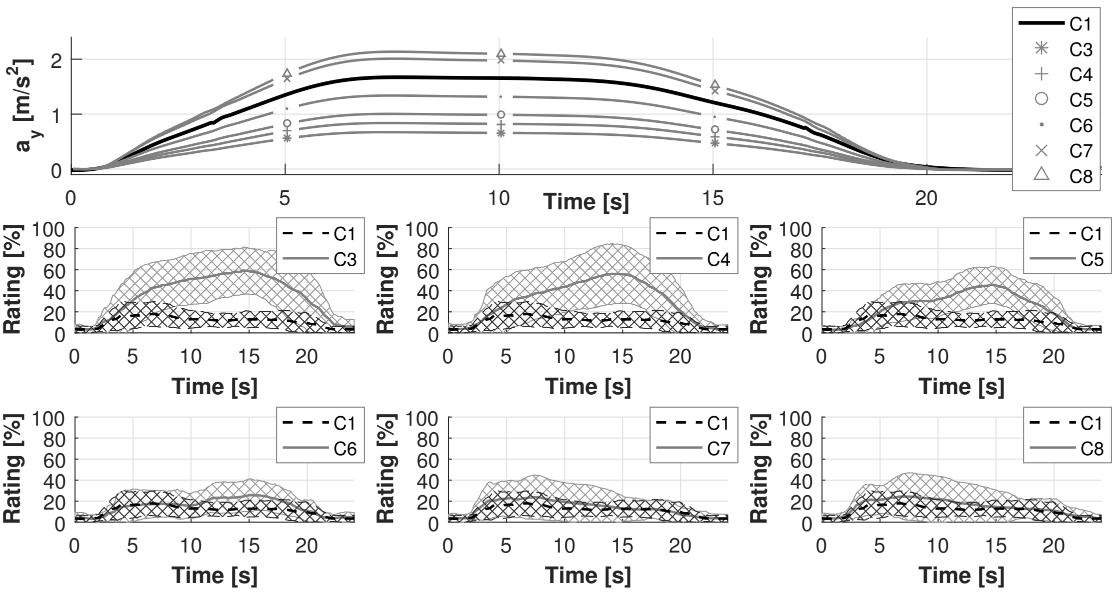

Figure 2: Lateral specific force presented in each condition (top), and average ratings given for all conditions. Shaded areas indicate the mean rating plus/minus one standard deviation. Condition C1 corresponds to $k_y = 1.0$, C3 to $k_y = 0.4$, C4 to $k_y = 0.5$, C5 to $k_y = 0.6$, C6 to $k_y = 0.8$, C7 to $k_y = 1.2$ and C8 to $k_y = 1.275$.