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Motion Cueing in BMW's Driving Simulation Center: Experiences Versus Common Knowledge

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Abstract - *The collective goal of the driving simulation community should be to share ideas to improve the motion cueing across driving simulators worldwide. Due to the active research and intensive usage of driving simulators over the last decades, knowledge in the field of motion cueing has been gained from experience gathered by the community, or practical experience by performing dedicated experiments. This paper discusses several points of 'common knowledge' in designing and evaluating motion cueing, along with their value for driving simulation. The goal of the discussion in this paper is to compare these points of common knowledge to the experiences and ideas gathered at BMW's driving simulation center in Munich, which was opened in 2021 and hosts a fleet of fourteen driving simulators. Furthermore, we aim to bring across points of interest and outlines for future research that should be of interest to the driving simulation community. With the common goal of improving motion cueing, this contribution thus aims to improve and extend the discussion between those working and researching in the driving simulator industry.*

Keywords: *motion cueing, common knowledge, motion scaling, tilt-coordination, motion perception*

1. Introduction

BMW's driving simulation center in Munich, Germany, operates a variety of driving simulators to cover a wide range of simulated driving experiments. Most experiments are known as *customer studies*, i.e., involving everyday drivers (in contrast to expert drivers) to study the impact of certain vehicle design choices. For each simulator, and in some cases even each experiment, the Motion Cueing Algorithm (MCA) and its corresponding parameter values generally need to be specifically chosen and/or redesigned. Here, the goal is often to induce high realism and as little simulator sickness as possible, while ensuring that the motion stays in the simulator workspace at all times. Most experiments require a dedicated decision on the simulator and MCA choice, as well as a tuning procedure to select the MCA parameters suitable for that experiment.

Researchers and engineers working on driving simulation benefit from the knowledge that has been gained and used in the flight- and driving simulation community for more than half a century. This knowledge has been gathered either through practical experience or through dedicated experiments, e.g., on how humans perceive motion. Examples include knowledge on how humans perceive scaled motion (Berthoz, et al., 2013), tilt-coordination (Stratulat, et al., 2011), and tilt-rate limiting (Nesti, et al., 2016). This knowledge on when and how these features can be applied can be considered as the "common knowledge" of driving simulation.

However, not all of these innovations are necessarily experimentally proven, and sometimes it is unknown under which circumstances they are valid. Many of these features are also applied at BMW's driving simulation center since its opening in 2021. Due to the experiments performed in its three years of operation, new insights on such features have been gathered. It would thus be a valuable contribution to see whether and how these experiences compare to the knowledge available in literature.

The contribution of this paper is to provide a selection of 'common knowledge' and compare these to our experiences at BMW. To this end, this paper gives an overview of the state-of-the-art in our knowledge of MCA features and analysis methods found and applied in literature. For each point, we discuss whether our experiences at the driving simulation center correspond to common knowledge, either through anecdotal or empirical evidence, and/or discuss whether specific points require further investigation. Thus, the paper aims to provide an overview of existing motion cueing features, a comparison to our experiences, and the basis for a discussion on how we should apply the collective knowledge in the future.

The paper is structured as follows. Sections 2-5 each give an overview on different points of 'common knowledge', along with the subsequent discussion. More specifically, motion scaling, tuning, motion perception, and inconsistent cueing for behavioral fidelity are examined in more detail here. A conclusion follows in Section 6.

2. Motion Scaling

2.1. Scaled Motion vs. Full Motion

Due to the limited workspace of typical motion systems, scaling down the simulated vehicle's motion is generally applied to still deliver representative and realistic simulator motion. In (Berthoz, et al., 2013), it was found that participants consider a range of scaling factors (0.4-0.75) to be most realistic. Furthermore, and perhaps somewhat surprisingly, a veridical scaling factor of 1 was found to be too strong. This would be a beneficial finding, as lower scaling factors reduce the required size of simulators' motion systems, reducing cost.

We have implemented high scaling factors up to full motion (no scaling) in several cases, such as a 1-to-1 reproduction of lateral motion in a slalom maneuver on BMW's high fidelity Diamond Space simulator (Figure 1b). Participants indeed assessed this motion as too strong, and preferred scaled motion (up to 0.8 in both longitudinal and lateral directions), in accordance to the findings of Berthoz, et al. (2013). In a recent experiment (Kolff, et al., 2024) we have also found no significant differences between scaling factors of 0.8 compared to 0.4 in terms of perceived realism and occurrence of simulator sickness, although both having a clear benefit over missing motion. One possible hypothesis is that it is caused by a lack of accurate visual information in the simulation, such as optical flow, which reduces the perception of speed and therefore of the associated motion.

2.2. Scaling Coherence

Some simulators offer the ability to increase the scaling factor in a single Degree of Freedom (DoF) only. For example, apart from the traditional hexapod, the Diamond Space (Figure 1b) has an additional single-direction linear actuator, allowing for additional translational motion. For the Diamond Space, the orientation of the vehicle mockup can be changed, such that the linear actuator can be used to either create motion in lateral or the longitudinal direction. Significantly stronger motion in one DoF is possible by increasing the scaling of the motion in that specific DoF. From our experience, however, motion that is scaled equally in all directions is often preferred over unequal scaling factors. Unequal scaling is considered as unrealistic, even if the larger allowable scaling factor in one of the DoFs would lead to an objectively smaller motion mismatch. This implies that a simulator such as the Diamond Space would not be a good choice when strong motion in *all* directions is required (e.g., in city driving), and then it is better to have a reduced motion in all directions (for example by using a smaller simulator), but at least in coherence with each. The full range of the linear actuator of the Diamond Space does provide a clear benefit if the motion of the DoF in which the linear actuator moves is also actually a lot stronger than the other DoF. Examples of this single-direction motion are slalom maneuvers on a highway scenario (motion in the y-direction) or a use-case with strong acceleration/braking (motion in the x-direction) only. We are currently not aware of any studies that have explicitly investigated this possible preference of scaling coherence. Thus, we suggest it as a crucial point for future work to investigate where the limits and opportunities for scaling coherence lie.

2.3. Group Scaling

Next to the scaling coherence in the various DoFs, another concept is important, namely *group scaling*. In some cases, it can be possible to arrive at different scaling factors in the tuning process for different DoFs. However, one returning observation we have made is that motion scaling is often preferred to be as similar as possible in certain groups of DoFs. Namely, these groups correspond to 1) lateral maneuvering: the lateral specific force, roll rate, and yaw rate, 2) longitudinal maneuvering: the longitudinal specific force and the pitch rate, and 3) on its own, the vertical specific force. It is, for example, preferable to scale the lateral specific force and yaw rate similarly, such that they are in accordance with each other for the lateral maneuvering. A lateral motion that is scaled by 50% with a yaw motion that is fully reproduced has often been perceived as a too strong yaw motion, resulting in the perception of oversteering. Only the vertical specific force component has been found to be relatively 'free' from the other DoF, perhaps because it is mainly independently active in specific driving maneuvers (bumps, hill driving). Similar to the scaling coherence, we suggest specific research on this topic, as it can reduce the tuning complexity by effectively linking the gains of the different DoFs in these groups.

3. Tuning

3.1. "Big Motion Equals Big Responsibility"

Large motion systems, such as BMW's Sapphire Space (Figure 1a) or Renault's ROADS, allow for high scaling factors. Principally, such simulators thus should allow for improved motion cueing quality compared to smaller simulators that only allow low scaling factors, as explained in the previous subsection and in Berthoz, et al. (2013).

BMW's largest motion simulators, the Sapphire Space (9 DoF, see Figure 1a) and the Diamond Space (7 DoF, see Figure 1b), indeed allow for a high fidelity motion cueing for driving scenarios. However, the redundant axes in these overdetermined motion systems increase the complexity in MCAs and their parametrization, requiring additional effort in the tuning for each experiment.

Furthermore, an important insight has been that large scaling factors also amplify any imperfections in the motion. These imperfections can come from limitations in the motion cueing, or even from imperfections in the simulated vehicle model. Therefore, experiments in which large scaling factors were applied we also required more extensive and precise tuning and vehicle models, as without these it is likely that the large motion potential enhances or amplifies bad motion. In contrast, for the motion cueing on smaller simulators it has been easier and faster to achieve an acceptable tuning (relative to the possible fidelity on

(a) The 9-DoF Sapphire Space simulator.

(b) The 7-DoF Diamond Space simulator.

Figure 1: Simulators at BMW's driving simulation center. Image credit: BMW Group.

that simulator). Thus, compared to a small system, a larger motion system also amplifies the need and responsibility of a properly tuned motion cueing, as well having a more detail-rich vehicle model. Using a bigger simulator thus does not automatically result in a better experience and results in a higher “responsibility” in getting the tuning of the motion cueing right.

4. Motion Perception

4.1. Vestibular System Models

Considering that the perception of inertial motion mainly occurs through the vestibular system, it is not surprising that models of the vestibular system are often applied in motion cueing research (for an overview, we refer to Ellensohn, 2020; Reymond and Kemeny, 2000).

Especially in Model-Predictive Control (MPC) motion cueing, a vestibular model can be used directly to compare the simulator to the reference motion in the cost function, e.g., (Ellensohn, et al., 2019). Including these models can potentially make the cueing better (Rengifo, et al., 2021), by focusing motion cueing optimization on errors that are actually perceivable. There are several problems with including models of the vestibular system, however. First, many of these models are overly simplified. They do often not include other motion channels, such as the proprioceptive system, which has also shown to matter for the perception of motion (Hlavačka, Mergner, and Schweigart, 1992). Vestibular models are also often based on uni-directional research under simplified conditions, e.g., by excluding the role of visual information. Finally, vestibular models are often structured as (linear) filters which implies that certain frequencies are not considered. This means that information on those frequencies does not matter to the cost function of MPC.

From our experience, vestibular models induce additional complexity without always offering a clear advantage. MPC MCAs use both a model for the simulator dynamics and a vestibular model (Kolff, et al., 2023). While the dimension of the simulator model depends on the number of simulator DoFs, the vestibular models have a fixed dimension. The most commonly used models of the vestibular system (Telban, Wu, and Cardullo, 2000) introduce 15 additional states, which, compared to the 14 states used to model BMW's 9-DoF simulator, significantly enlarge the total models. This increase in problem dimension leads to higher computational complexity, which further challenges the real-time capability of MPC MCAs.

This appears to contradict the need for more accurate and therefore more complex models of human motion perception, which integrate visual and vestibular motion perception. Nevertheless, integrating such more complex models might justify their added complexity in MPC algorithms. Especially in driving simulators, where the visual sense of motion is relatively strong, it's not about only matching vestibular cues, but about ensuring the combination of visual and vestibular feels realistic. At this moment, we do see a clear shortcoming in perception models that account for this integration of visual and vestibular (Kotian, et al., 2024). Together with the complexity of the resulting models, this stands in the way of including these models in MCAs in a meaningful and effective way.

4.2. Tilt-coordination Preference

Tilt coordination is an often applied method in driving simulation, where sustained specific forces are generated through platform tilt (Stratulat, et al., 2011). Through the roll angle φ and pitch angle θ, a specific force component induced with a tilt with respect to gravity can be perceived by humans as a translational acceleration, as long as the rotational motion tilting the simulator remains below the human perceptual threshold (Nesti, et al., 2016). In flight simulation, hexapod motion simulators also combine translational and rotational motion to reproduce the slow motion of the aircraft. For driving, however, vehicle motions are naturally highly dynamic and asymmetric, for example in urban driving (Ellensohn, 2020). This makes effective application of tilt coordination, without exceeding rotation motion perception thresholds, more difficult.

From our experience, tilt coordination is indeed preferred more by customers/non-expert drivers (Kolff, et al., 2022b). In contrast, however, it is not preferred by expert drivers. This may be due to a variety of reasons. First, tilt coordination is relatively slow, which is less suitable for the direct and dynamic driving style of expert drivers. Second, the perceptual threshold of the rates of expert drivers might also be lower, such that they notice rotational motion earlier, which is to be avoided in tilt-coordination. Third, the additional added rotations must be accounted for if the driver is not located in the point where the motion is applied (Kolff, et al., 2023). If the rotational motion is fast (even if it occurs below the rotational threshold), this can lead to erroneous motion that can be perceived by the driver. Correcting for this is a complex operation, which is currently not done in available MCAs. Thus, tilt-coordination should always be used carefully, and only for sustained accelerations. Note, however, that tilt-coordination sometimes appears naturally, and cannot simply be turned off. For example, MCAs using a cost function minimization of the specific force (such as in MPC) result in tilt-coordination even without the explicit instruction to the MCA to do so (i.e., see Dagdelen, et al., 2009.

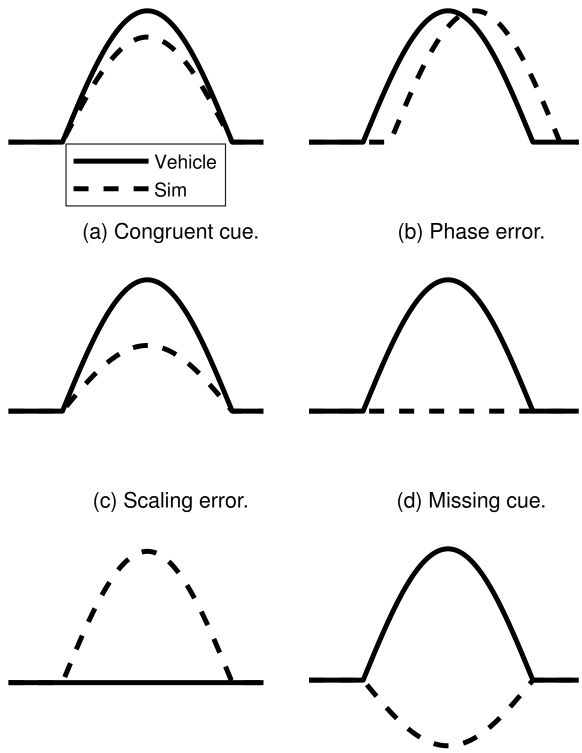
4.3. Tilt-rate Limiting

Tilt-rate limiters are used to ensure that the realisation of inherently unrealistic motion cueing features such as tilt coordination always occurs below the rotational perceptional threshold of a human driver, by limiting how fast the cabin can rotate. In recent years, several works (such as Kraft, He, and Rinderknecht (2021)) have used tilt-rate limiting formulations for tilt coordination in motion cueing. It is often argued that the addition of a limitation on the associated rotational rate increases the test subject's reported fidelity of the motion cueing, as below a certain threshold on the tilt-rate, the human and its vestibular system cannot perceive the rotational motion (Reymond and Kemeny, 2000).

From our experience, however, tilt-rate limiting does not always lead to an increase in the reported quality of the motion. This argument is two-fold: First of all, the application of tilt-coordination can be considered a trade-off. The sensation of rotational motion is sometimes considered acceptable by drivers, if in return they obtain a large increase in acceleration through the tilt-coordination. If tilt motion is strongly limited, this will also limit the success with which a sustained specific force is replicated. Second, tilt-rate limiting can also result in an increase of false cues in the rotational motion. If a maneuver is (partially) cued using tilt-coordination, the rotational motion can be kept under the perceptual threshold using the tilt-rate limiting. After finishing the maneuver, however, the constrained rotational motion cannot immediately bring the simulator back to its original attitude, such that an acceleration cue is still present where it should be absent.

4.4. Error type classifications

With the limited motion space of driving simulators, angular velocities and specific forces acting on a test subject will inevitably differ from those perceived in a real vehicle. These resulting mismatches can differ in both magnitude and direction. A typical method to distinguish between errors is to classify these in different *types* of errors. Here, different definitions exist, for example as defined by Grant and Reid (1997) for flight simulators. These authors defined three different types of errors: false cues, missing/scaling error cues, and phase-error cues.



(a) Congruent cue. (b) Phase error.

(c) Scaling error. (d) Missing cue.

(e) False cue. (f) False direction cue.

Figure 2: Various typical error type definitions.

A typical definition for false cue motion is a motion cue that is in the opposite direction of the vehicle motion (Grant and Reid, 1997; Kolff, et al., 2022a), indicated in Figure 2f, or a motion cue where no motion is expected from the vehicle (Grant and Reid, 1997) (Figure 2e). On missing cues (Figure 2d) and scaled cues (Figure 2c), Grant and Reid (1997) notes that "*Experience has shown that scaled or missing cues do not lead to the same reduction in perceived fidelity as false cues, which is also indicated by Baarspul (1986), although no experimental proof is presented.*" Phase errors were also defined by Grant and Reid (1997), in which the simulator motion is shifted in time (i.e., leading or lagging) with respect to the vehicle reference motion, see Figure 2b. Variations of these definitions exist, such as defined in Cleij (2020), Kolff, et al. (2022a).

Our experience is that error type classifications are helpful as a heuristic method of describing the quality of the motion. However, they are not so useful when objectively describing the quality. This might be because they are useful in describing and categorizing motion by a test driver ("*This drive contained more false cue motion than the previous drive*"), whereas objectively they are more difficult to quantify ("*Drive 1 is . . . % better than drive 2*").

A further point of discussion is presented in Figure 2, where the surface area between the vehicle and simulator motion represents the total amount of error between the two signals. For false direction motion, which is the typical source of false cue motion in driving simulation due to washout, the objective error is simply larger than the other error types, such as for scaling errors. Thus, the question arises whether false cues are also *disproportionately* worse than the other types, even if they would have the same objective mismatch. We would thus recommend to further investigate the roles of scaling, missing, and false cues in the case of equal mismatch magnitudes, as this could reveal whether it is truly the *type* of error that disproportionately impairs the quality of driving simulator motion.

Our experience is that for driving simulation, both the subjective ratings, as well as the occurrence of simulator sickness indeed increase proportionally with the size of the mismatch. This is shown in Figure 3, which shows the preliminary results of a study on subjective evaluations and simulator sickness as a function of motion cueing mismatches (Kolff, et al., 2024). Here, Figure 3a shows the Motion Incongruence Rating (MIR), i.e., a subjective rating of motion cueing quality provided by the participants. Furthermore, this is extended by similar results on simulator sickness by measuring the Misery Scale (MISC) (Bos, MacKinnon, and Patterson, 2005) in Figure 3b. The baseline had a scaling of 0.8, whereas the scaling condition was scaled with 0.4. Missing and false direction had scaling factors of 0 and -0.8, respectively. The ordering of the data in both figures is fully consistent with the objective motion mismatches for the different cueing error types in Figure 2.

Future research should investigate explicitly how these error types compare when their objective mismatch sizes are forced to be equal (e.g., comparing a large scaling mismatch with a small false direction cue error). In preliminary tests, we have seen, perhaps somewhat surprisingly considering the popular usage of error types in literature, no direct proof that this is indeed the case. Even if there would be no fundamental difference in these error types, however, they can still be used as a heuristic for error evaluations. But then perhaps they are not so suitable in improving motion cueing. A missing link to connect both worlds might be to investigate how such heuristic evaluations relate to subjective ratings of the motion. Although Cleij (2020) has incorporated error types based on signal differences, similar to Figure 2, future work could investigate how subjective error type experiences affect the subjective ratings of the motion.

A final point is that we have noted that although false direction cues occur during washout, which is common in driving simulation, their occurrence becomes less frequent with larger motion systems and more optimized MCAs. Large excitation reduces the need of washout, which directly implies less false direction cue errors.

4.5. Quality of the Vehicle Model

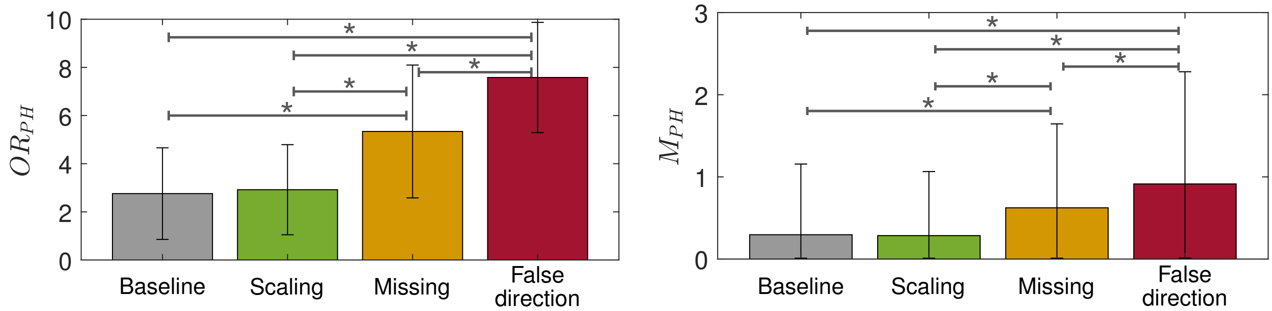
A prime goal in motion cueing development is to make the Motion Cueing Algorithm (MCA) produce simulator motion that feels as natural as possible. In general, this means decreasing the mismatches between the vehicle reference motion and the motion of the simulator. This also implies that the evaluation of the motion cueing compares the simulator's motion to the vehicle reference to see whether objective differences exist. The vehicle reference, however, often comes from a vehicle *model*, which is an approximation of the real-world vehicle. This is an important distinction, because if we obtain subjective evaluations of the motion through test drivers, they will compare their simulator experience to what they would expect from real-life driving (Kolff, et al., 2022b), and not what they expect from the vehicle model.

Our experience is that the role of the quality of the vehicle model is often overlooked. Especially if we aim to quantify the quality of the motion cueing, a comparison to the vehicle model data should be performed with great care. For example, a significant increase in the quality of the presented motion may be obtained by improving the fidelity of the simulated vehicle motion, and not the motion cueing itself. This point is further amplified in the case of large, high-fidelity motion systems, as explained in Subsection 3.1. Future experimental MCA comparisons could thus benefit greatly from also reporting the quality of the vehicle model, or by objectively comparing the simulator motion to both the vehicle model and the real vehicle, if this information is available. For example, a specific real-life measurement could be compared to the vehicle model response, as well as to how the MCA would cue this motion.

5. Inconsistent Cueing for Behavioural Fidelity

In driving simulation, the goal is often to make the simulation as realistic as possible, without actively requiring the behaviour of the driver to be the same as in the real vehicle. In that case, also an MCA is preferred that increases the realism as much as possible, known as *perceptual fidelity*. In flight simulation, most simulators are used to train pilots. This typically requires a direct focus on 'behavioural' fidelity (Pool, 2012). Different than in driving simulation, flight simulation has not seen a strong surge towards MPC algorithms. Considering its focus on behavioural fidelity, this might be only logical, also with an important lesson for driving simulation if behavioural fidelity *is* desired.

Future research should focus on a better understanding of how certain MCAs perform regarding these fidelity types. For example, MPC algorithms are known to be able to provide a better quality of motion (Cleij, et al., 2019), and hence a more realistic simulation. However, they come with the intrinsic problem that due to their optimization nature, the algorithms always optimize the motion with the available workspace in mind. Consider a vehicle that drives through a corner with 40 km/h and after that drives through a second corner with 80 km/h. A Classical Washout Algorithm (CWA) would be tuned considering the two maneuvers, such that it fits within the workspace of the simulator for the most stringent maneuver (i.e., the 80 km/h corner). As a result, the 40 km/h results in a lateral motion ($\sim \frac{v^2}{r}$) with a quarter of the intensity, which might not correspond to the full 40 km/h motion *even if the full motion would be possible*. An MPC MCA solves this problem differently, as it optimizes every part of the motion with the workspace available at that moment. Thus, it can create a situation where a 40 km/h corner and a 80 km/h corner are cued with the same intensity. The resulting inconsistency in what a driver would expect from the



(a) Subjective ratings as function of the error type.

(b) Simulator sickness as function of the error type.

Figure 3: Impact of motion cueing error type on subjective evaluations and simulator sickness, adapted from (Kolff, et al., 2024).

motion potentially affects the simulation's behavioural fidelity (or perhaps even perceptual fidelity). A crucial next step for MPC MCAs is thus to investigate how inconsistent cueing could affect the fidelity of the simulation.

6. Conclusion

In the development and application of motion cueing, knowledge about human perception is crucial, as this can be used to improve the motion cueing of driving simulator experiments. By operating BMW's driving simulation center, we have tested several points of 'common knowledge' and compared these to the experiences acquired from many experiments and driving simulation use-cases. By sometimes reconfirming, and sometimes reconsidering existing knowledge, the contributions in this paper can in turn contribute to the common knowledge of the driving simulation community, improving the motion cueing of our collective effort. From this comparison, it can be concluded that many heuristics currently applied in the tuning of motion cueing in driving simulation are not based on sufficient proof and would need reevaluation or specific experimental proof to be truly reliable for motion optimization and interpretation of driving simulator experiment outcomes. Moreover, we would suggest an active discussion on such technical features, focusing on if and how these are applied in the driving simulation community. This way, our collective knowledge of motion cueing in the driving simulation can be consolidated, unified, and improved.

References

Baarspul, M, 1986. *Flight Simulation Techniques with Emphasis onthe Generation of High Fidelity 6 dof Motion Cues*. Tech. rep. M-533. Delft University of Technology.

Berthoz, A., Bles, W., Bülthoff, H. H., Correia Grácio, B. J., Feenstra, P., Filliard, N., Hühne, R., Kemeny, A., Mayrhofer, M., Mulder, M., Nusseck, H.-G., Pretto, P., Reymond, G., Schlüsselberger, R., Schwandter, J., Teufel, H. J., Vailleau, B., Paassen, M. M. van, Vidal, M., and Wentink, M., 2013. Motion Scaling for High-Performance Driving Simulators. *IEEE Trans. on Human-Machine Systems*, 43(3). doi: 10.1109/TSMC.2013.2242885, pp. 265–276.

Bos, J. E., MacKinnon, S. N., and Patterson, A., Dec. 2005. Motion Sickness Symptoms in a Ship Motion Simulator: Effects of Inside, Outside, and No View. *Aviation, Space, and Environmental Medicine*, 76(12), pp. 1111–1118.

Cleij, D., Venrooij, J., Pretto, P., Katliar, M., Buelthoff, H. H., Steffen, D., Hoffmeyer, F., and Schoener, H.-P., 2019. Comparison between filter- and optimization-based motion cueing algorithms for driving simulation. *Transportation Research Part F: Traffic Psychology and Behaviour*, 61. doi: 10.1016/j.trf.2017.04.005, pp. 53 –68.

Cleij, D., 2020. Measuring, modelling and minimizing perceived motion incongruence. doi: 10.4233/uuid:45fd3f70-2ba6-43fa-a2c4-018967bfdc88. PhD Dissertation. Delft University of Technology.

Dagdelen, M., Reymond, G., Kemeny, A., Bordier, M., and Maïzi, N., Apr. 2009. Model-based predictive motion cueing strategy for vehicle driving simulators. *Control Engineering Practice*, 17(2009). doi: 10.1016/j.conengprac.2009.03.002, pp. 995–1003.

Ellensohn, F., Hristakiev, D., Schwienbacher, M., Venrooij, J., and Rixen, D., 2019. Evaluation of an Optimization Based Motion Cueing Algorithm Suitable for Online Application. In: *Proceedings of the Driving Simulation Conf. 2019 Europe*. Strasbourg, France, pp. 93–100.

Ellensohn, F., 2020. Urban Motion Cueing Algorithms - Trajectory Optimization for Driving Simulators. PhD Dissertation. Technische Universität München.

Grant, P. R. and Reid, L. D., 1997. Motion Washout Filter Tuning: Rules and Requirements. *Journal of Aircraft*, 34(2), pp. 145–151. `https://doi.org/10.2514/2.2158`.

Hlavačka, F., Mergner, T., and Schweigart, G., 1992. Interaction of vestibular and proprioceptive inputs for human self-motion perception. *Neuroscience Letters*, 138, pp. 161–164. `https://doi.org/10.1016/0304-3940(92)90496-t`.

Kolff, M., Himmels, C., Venrooij, J., Parduzi, A., Riener, A., Pool, D. M., and Mulder, M., 2024. Effect of Motion Mismatches on Ratings of Simulator Sickness and Motion Incongruence in Urban Driving Simulations. *To be submitted*.

Kolff, M., Venrooij, J., Schwienbacher, M., Pool, D. M., and Mulder, M., 2022a. Motion Cueing Quality Comparison of Driving Simulators using Oracle Motion Cueing. In: *Proceedings of the Driving Simulation Conference 2022 Europe*. Strasbourg, France, pp. 111–118.

— 2023. The Importance of Kinematic Configurations for Motion Control of Driving Simulators. In: *2023 IEEE 26th International Conference on Intelligent Transportation Systems (ITSC)*, pp. 1000–1006.

Kolff, M., Venrooij, J., Schwienbacher, M., Pool, D. M., and Mulder, M., 2022b. Reliability and Models of Subjective Motion Incongruence Ratings in Urban Driving Simulations. *IEEE Trans. on Human-Machine Systems*. Submitted.

Kotian, V., Irmak, T., Pool, D., and Happee, R., 2024. The role of vision in sensory integration models for predicting motion perception and sickness. English. *Experimental Brain Research*, 242(3), pp. 685–725. `https://doi.org/10.1007/s00221-023-06747-x`.

Kraft, E., He, P., and Rinderknecht, S., 2021. Development and Evaluation of a Threshold-Based Motion Cueing Algorithm. *Vehicles*, 3(4), pp. 636–645.

Nesti, A., Nooij, S., Losert, M., Buelthoff, H. H., and Pretto, P., 2016. Roll rate perceptual thresholds in active and passive curve driving simulation. *SIMULATION*, 92(5). doi: 10.1177/0037549716637135, pp. 417–426.

Pool, D. M., Sept. 2012. Objective Evaluation of Flight Simulator Motion Cueing Fidelity Through a Cybernetic Approach. PhD Dissertation. Delft University of Technology, Faculty of Aerospace Engineering.

Rengifo, C., Chardonnet, J.-R., Mohellebi, H., and Kemeny, A., 2021. Impact of Human-Centered Vestibular System Model for Motion Control in a Driving Simulator. *IEEE Trans. on Human-Machine Systems*, 51(5). doi: 10.1109/THMS.2021.3102506, pp. 411–420.

Reymond, G. and Kemeny, A., 2000. Motion Cueing in the Renault Driving Simulator. *Vehicle System Dynamics*, 34(4). doi: 10.1076/vesd.34.4.249.2059, pp. 249–259.

Stratulat, A., Roussarie, V., Vercher, J., and Bourdin, C., 2011. Does tilt/translation ratio affect perception of deceleration in driving simulators? *Journal of vestibular research: equilibrium & Orientation*, 21(3). doi: 10.3233/VES-2011-0399, pp. 127–139.

Telban, R. J., Wu, W., and Cardullo, F. M., Mar. 2000. *Motion Cueing Algorithm Development: Initial Investigation and Redesign of the Algorithms*. Contractor Report NASA-CR-2000-209863. NASA Langley Research Center, Hampton (VA).