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Effects of Simulator Motion on Driver Steering Performance with Various Visual Degradations

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***Abstract*—This paper investigates the effects of simulator motion on driver steering performance, and how this depends on the available visual information and external disturbances such as wind gusts. A human-in-the-loop driving experiment was performed in which twelve participants steered a fixed-velocity car to follow a winding road (target tracking, TT) while suppressing side-wind gusts (disturbance-rejection, DR). Driver performance with and without motion feedback is compared in six tasks: "regular" lane-keeping with optic flow, centerline tracking with optic flow, and centerline tracking without optic flow, all with both 5 and 100 m of preview. Performance is calculated in the frequency domain to separate TT and DR contributions. The results show that motion feedback always yields improved DR performance, but the actual improvement depends strongly on the available simulator visuals. TT performance is generally unaffected by motion feedback, except when preview is limited. We conclude that simulator motion is required to evoke realistic driver performance in tasks where substantial external disturbances are present, but not in disturbance-free tasks where a winding road is being followed.**

***Index Terms*—Driving simulation, manual control, physical motion, simulator visuals, vehicle steering**

I. Introduction

Self-motion perception is essential in a wide range of manual control tasks, from cycling to airplane control. Besides *visual* feedback, humans also use *physical motion* feedback for control, that is, vestibular, somatosensory, and proprioceptive sensory information [1]–[8]. The effects of physical motion feedback on aircraft pilot control behavior have been extensively investigated [9], [10], due to the wide-spread requirements for pilot training in moving-base simulators. A similar understanding of the effects of motion feedback in the steering of road vehicles would be highly valuable, as simulators are becoming increasingly important in the research and development of novel (adaptive) automation technologies. However, driving is often considered as a predominantly visual control task [11], [12] and drivers' relative use of visual and physical motion feedback have in fact never been quantified.

The effects of physical motion in addition to visual feedback have been previously investigated in driving in simulators [1]–[8]. In general, drivers steer their vehicle along the road with smaller lateral deviations and heading offsets when motion feedback is available, while displaying lower control activity [1]–[6], [8]. Nonetheless, reported quantitative performance differences vary strongly, and Damveld *et al.* [7] even measured no significant effect of motion feedback at all. Possible factors (F) that affect the driver's reliance on motion feedback include the following:

- F1: The simulator motions, including the presented degrees-of-freedom (e.g., yaw, sway, roll) and the motion cueing fidelity, as simulator hardware typically inhibits reproducing the full physical motion cues experienced in real-life driving [1], [5], [8].
- F2: The simulator visuals (e.g., availability of preview, optic flow, and the field-of-view); humans are more likely to rely on motion feedback with degraded visual, and *vice versa* [8], [13].
- F3: The presence of disturbances such as wind gusts; due to the human's lower delay for perceiving physical motion as compared to visual motion, responding to disturbances using motion feedback is faster, which often leads to better performance [7], [10].

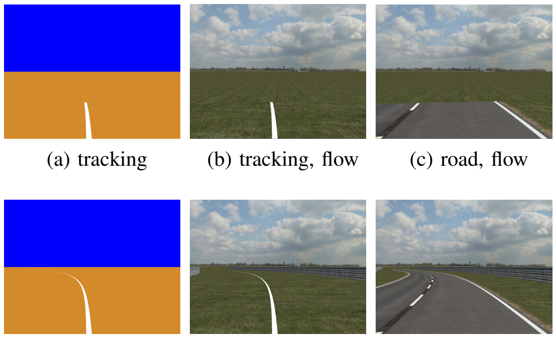
This paper aims to quantify the effects of physical motion feedback on driver steering performance, and, additionally, how these effects depend on the simulator visuals (F2) and the available disturbances (F3). To do so, a driving experiment was performed in a moving-base research simulator. Subjects followed a winding road while simultaneously suppressing side-wind disturbances, both with and without motion feedback. Six simulator visuals were tested: centerline tracking without optic flow, centerline tracking with optic flow, and lane keeping (i.e., boundary-avoidance) with optic flow, all with 5 and 100 m preview of the road's future trajectory. By analyzing experimental data in the frequency domain, lane-keeping, or *target-tracking* (TT) performance is separated from *disturbance-rejection* (DR) performance [7], [8], [14].

In the following, first, the driver steering task is analyzed, to identify possible interactive effects of visual and motion feedback on TT and DR performance. Based on this, we formulate a set of hypotheses, which are then tested in a driving experiment. This paper ends with a discussion of our experimental results and our main conclusions.

II. Visual and Motion Feedback in Driving

A. Control Task

Drivers rely on a variety of sensory feedbacks from the environment when steering their vehicle. In a typical view



(a) tracking (b) tracking, flow (c) road, flow

(d) tracking (C3, C4) (e) tracking, flow (f) road, flow

Fig. 1. Presented visuals in the experiment, available preview was restricted to either 5 m (a-c) or 100 m (d-f).

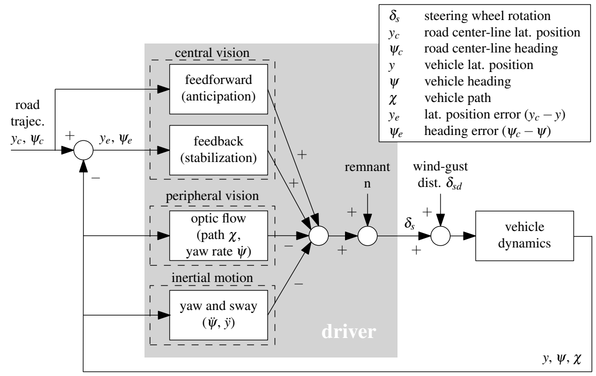


Fig. 2. Schematic overview of the key driver response channels involved in visual-vestibular steering.

from the driver's perspective, Fig. 1f, *preview* of the road's lane edges ahead indicates where to drive in the near future, facilitating anticipatory feedforward control [15]. Moreover, the road close ahead provides a reference for the vehicle's current lateral position in the lane and the heading deviation, facilitating stabilizing feedback control [15]. The movement of texture elements within the driver's field-of-view generate a specific *optic flow* pattern that provides information of the vehicle's direction of motion (path angle) and heading rate [16]. Finally, *physical motion*, perceived as vestibular, somatosensory, or proprioceptive feedback, provides information about the vehicle's lateral acceleration and angular velocity [7], [8].

When responding to all available sensory feedbacks, drivers are inherently organized as multiloop controllers, see Fig. 2. Feedforward control has been shown to be most important for TT, that is, for drivers to guide their vehicle along a certain desired trajectory y_c over the road [8], [17]–[19]. The main role of the feedback channels is to minimize residual errors and to suppress the effects of external perturbations δ_{sd} (DR), such as wind gust [7], [8], [10], [19]. Limited preview (see Fig. 1c) inhibits drivers from anticipating the road's trajectory, such that the feedforward path in Fig. 2 weakens, or disappears completely. In this case, drivers may rely stronger on the remaining available sensory feedbacks. Therefore, it is no surprise that larger performance benefits of physical motion feedback have been reported in tasks with limited preview [8]. Similarly, limited optic flow due to a lack of texture in the visual scene (e.g., driving in snow) may also cause drivers to rely stronger on motion feedback.

B. Frequency-Domain Analysis

In this paper, the variances of the vehicle's lateral deviation $\sigma^2_{y_e}$ and the heading deviation $\sigma^2_{\psi_e}$ from the road's centerline are used as measures for performance. Driver control activity is quantified by the variance of the applied steering wheel rotations $\sigma^2_{\delta_s}$. Frequency domain analysis enables identification of different contributions in these signals. Thus contributions due to due to TT (following y_c) and DR (suppressing δ_{sd}) can be distinguished, when the external input signals y_c and δ_{sd} are multisines [8], [18], [20]. For example, a multisine target signal is given by: $y_c(t) = \sum_{j=1}^{N} A_j \sin(\omega_j t + \phi_j)$, with t the time, N the number of sinusoids, and A_j, ω_j, and ϕ_j the amplitude, frequency, and phase of the j-th sinusoid. The variances of the performance measures are equal to the integrated power-spectral density functions S [8], [18], [20], for example: $\sigma^2_{y_e} = \frac{1}{\pi}\int_0^\infty S_{y_e y_e}(\omega)\,\mathrm{d}\omega$, with ω the radial frequency. By designing y_c and δ_{sd} as multisines with mutually exclusive frequencies, and integrating the power-spectra of y_e, ψ_e, and δ_s only over each respective set of input frequencies, the TT and DR contributions to the performance measures are obtained. Integrating over the remaining, non-excited frequencies yields an estimate of the contribution of the remnant n, that is, the lumped combination of nonlinear and time-varying driver steering behavior, and driver perception and motor noise.

Additionally, such multisine target and disturbance signals allow for estimating the frequency-response functions of two of the driver responses in Fig. 2 [14], [18], [19], [21], [22]. As discussed, drivers likely initiate more than two responses. Therefore, in this paper, we only estimate frequency-response functions of the (lumped) target and disturbance *open-loop* dynamics (see Fig. 2 and [14], [18]):

$$H_{ol}^{y_c}(j\omega_{y_c}) = \frac{y(j\omega_{y_c})}{y_e(j\omega_{y_c})}, \quad (1)$$

$$H_{ol}^{\delta_{sd}}(j\omega_{\delta_{sd}}) = -\frac{\delta_s(j\omega_{\delta_{sd}})}{\delta_s(j\omega_{\delta_{sd}}) + \delta_{sd}(j\omega_{\delta_{sd}})}. \quad (2)$$

Open-loop dynamics whose magnitude is larger than one indicate adequate TT and DR performance; drivers typically achieve such high-magnitude open-loop dynamics at low frequencies, but not at high frequencies [14]. The crossover frequency ω_c, where the open-loop magnitude drops below unity, is thus a measure for the tracking bandwidth; the corresponding phase margin ϕ_m is a measure for stability.

C. Hypotheses

Due to the driver's multiloop control organization, Fig. 2, the target (y_c) and disturbance (δ_{sd}) signals propagate differently through the closed-loop system before affecting the performance measures y_e, ψ_e, and δ_s. The loops closed by the driver, or lack thereof due to the absence of certain cues, thus determine the observed performance to a large extent. We therefore formulate the following hypotheses (H) regarding the effects of motion feedback on driver steering:

H.I Availability of physical motion feedback leads to improved DR performance in all tasks, due to the additional feedback-loop closure (Fig. 2), for which the response delay is lower than the visual channel delay [2], [10].

H.II Physical motion feedback yields a larger improvement in DR performance in tasks with degraded visuals (limited preview and a lack of optic flow), where drivers can mechanize fewer other control loops to attain adequate performance (Fig. 2).

H.III Availability of physical motion feedback has no effect on TT performance, except when the available preview is severely limited, inhibiting adequate anticipatory feedforward control [8].

These hypotheses are next tested using data from a human-in-the-loop simulator driving experiment.

III. Driving Experiment

A. Experiment Design

1) Apparatus: The experiment was performed in the SIMONA Research Simulator (SRS) at the TU Delft, Fig. 3, which has a six degree-of-freedom hydraulic hexapod motion system capable of a maximum yaw rotation of $\pm 41.6°$ and a maximum sway movement of ± 1.031 m. The SRS has a collimated visual screen that provides subjects with a $180° \times 40°$ field of view. Although the SRS is primarily intended for flight simulation, it was successfully configured for car driving simulations for the current experiment, identical to the setup of [8]. Subjects gave inputs with the yoke, as a true steering wheel was not available at the time of the experiment.

2) Independent Variables: The full factorial of three independent variables was tested. First, physical motion feedback was switched off or on. Second, the presented visuals were the road's centerline without optic flow (tracking task), the centerline with optic flow (tracking, flow), or a road with 3 m wide lanes with optic flow (lane keeping, flow). Third, the available preview was either 5 or 100 m. Fig. 1 shows all tested experimental visuals.

3) Controlled Variables: The simulated vehicle dynamics are of a neutrally steering passenger car, identical to those used in [7], [23]. The velocity of the vehicle was fixed at 50km/h throughout the experiment. The road's trajectory y_c and wind-gust disturbance δ_{sd} were multisines, with identical amplitudes, frequencies, and phases as published in [7]. However, here, the disturbance signal's standard deviation was increased by a factor of 3.3 to more accurately detect how motion feedback affects DR performance.

4) Motion Cueing Algorithm: In the motion conditions, the simulator was configured to provide subjects with yaw and sway cues. Due to the SRS's limited motion space, it is impossible to reproduce the full physical motion that is

Fig. 3. The SIMONA Research Simulator

experienced in real-life driving tasks, in particular the cues due to sustained, low-frequency movements. Therefore, the following high-pass filter was applied to the vehicle's yaw and lateral axes:

$$H_{mf}(s) = K_{mf} \frac{s^2}{s^2 + 2\zeta_{n_{mf}}\omega_{n_{mf}} s + \omega_{n_{mf}}^2} \frac{s}{s + \omega_{b_{mf}}}, \quad (3)$$

with the respective filter parameters given in Table I. These parameters were selected to make optimal use of the available simulator motion space, using an iterative algorithm, as the yaw and sway motions are coupled. No tilt-coordination was implemented to further optimize the use of available motion space, as initial tests yielded nauseating false motion cues.

	K_{mf}, -	$\zeta_{n_{mf}}$, -	$\omega_{n_{mf}}$, rad/s	$\omega_{b_{mf}}$, rad/s
yaw	0.55	0.7	0.3	0
lateral	0.12	0.7	0.7	0.7

TABLE I
Motion filter parameters.

B. Participants and Procedure

1) Participants: Fifteen subjects participated in the experiment, of which three withdrew before fully completing the experiment due to signs of motion sickness. The remaining twelve participants experienced very little to no motion sickness. On average, participants were 24.6 years old (σ=1.8 years), were in possession of a driver's license for 6.3 years (σ=1.9 years), and drove 8,033 km/year (σ=12,116 km/year).

2) Procedure: Prior to the measurements, subjects could familiarize themselves with the vehicle dynamics, the controls, the visuals, and the motion cueing. First, a trial was performed with simulator motion turned off and no external disturbance δ_{sd}. The simulator motion and the disturbance were subsequently turned on in individual trials such that subjects could experience their contribution. Then, subjects repeatedly performed the lane-keeping task with optic flow, motion and 100 m preview (see Fig. 1f), until they were comfortable with the control task and acquired steady performance.

Next, the measurement part of the experiment commenced. Each subject performed all 12 experimental conditions in a randomized order (balanced Latin-square design). Each condition was performed until steady performance was attained in at least three consecutive runs, which were then used as measurement data; a minimum of five runs was performed per condition. A single run was 1,806 m and was completed in approximately 140 seconds. After each run, subjects were informed of their performance score to motivate them, and were asked to report on signs of motion sickness using a ten-point scale. The experiment was performed in three sessions of four conditions, with breaks between sessions of around 20 minutes, and was completed in approximately four hours.

3) Dependent Measures and Statistical Analysis: Calculated dependent measures correspond to Section II-B: $\sigma^2_{y_e}$, $\sigma^2_{\psi_e}$, and ω_c are used to quantify driver performance, $\sigma^2_{\delta_s}$ is used as measure for driver control activity, and ϕ_m is used as measure for stability. Contributions due to TT and DR are computed for all dependent measures. A repeated-measures analysis of variance (ANOVA) is performed to test for statistically significant differences between all conditions, but only the interaction and main effects are presented; simple main effects are not considered to avoid excessive detail. The three-run driver average for each condition is used for the analysis. In case Mauchly's test of sphericity was violated (p<0.05), a Greenhouse-Geisser correction was applied.

IV. Results

Fig. 4 shows the results for ω_c and ϕ_m, Fig. 5 shows $\sigma^2_{y_e}$, $\sigma^2_{\psi_e}$, and $\sigma^2_{\delta_s}$, and Table II shows a summary of all ANOVA results. The experimental results will be discussed in the order of the columns of Table II, from left to right.

A. Main Effects

1) Motion: Subjects consistently attained lower error variances when motion feedback was available, compared to visual-only tasks (Fig. 5a, b). Although no significant effects of motion feedback occur in TT (see the first column of Table II), in DR the error variance and control activity decrease significantly, while the phase margin increases significantly.

2) Preview: With 100 m preview, subjects consistently attained lower error variances than in tasks with 5 m preview (Fig. 5a, b). This is most clear in TT (black portion of the bars), which is a well-known effect of restricted preview [17], [18]. DR performance (gray portion of the bars in Fig. 5) also improves significantly, but not consistently in all visual conditions. Moreover, the TT control output variance (Fig. 5c) is significantly lower with 100 m preview, while the phase margin is significantly higher (Fig. 4c).

3) Visuals: Variations in visual presentation produced highly significant effects on almost all dependent measures (Table II). In TT, tracking with optic flow yields lower error variances (Fig. 5a, b), a higher crossover frequency and a lower phase margin (Fig. 4a, c), compared to tracking without optic flow. On the contrary, in DR, the introduction of optic flow leads to a lower crossover frequency and a higher phase margin (Fig. 4b, d). Lane keeping, as compared to tracking, yields significantly higher error variances, lower crossover frequencies, and higher phase margins, both in TT and DR, which has been referred to as *satisficing* control behavior [24].

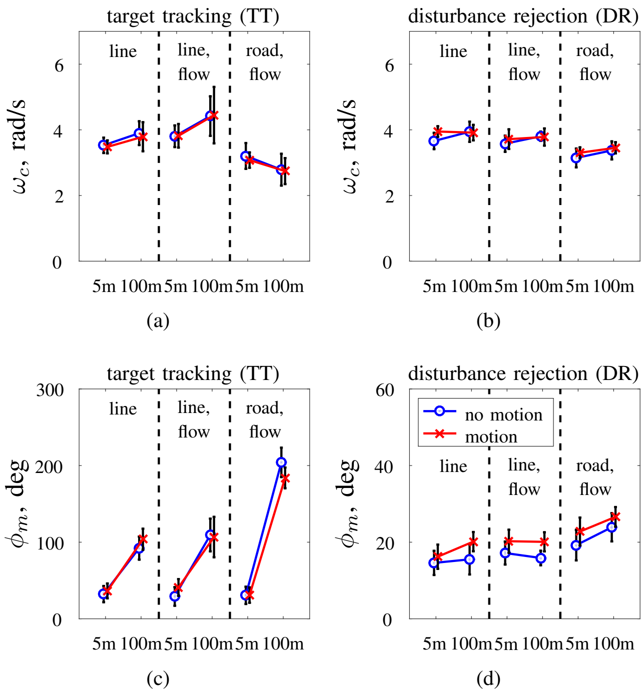


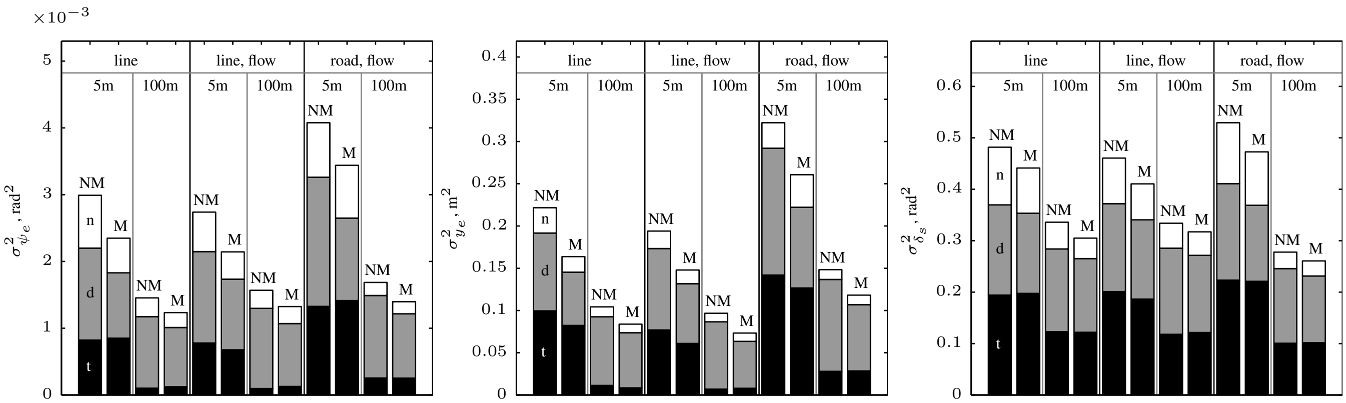
Fig. 4. Average crossover frequencies ω_c and phase margins ϕ_m of the estimated target and disturbance open-loop dynamics; errorbars indicate the 95% confidence interval, corrected for between-subject variability.

B. Interaction Effects

1) Motion and Preview: In TT, the availability of motion feedback leads to a lower lateral deviation variance (Fig. 5b) in tasks with 5 m preview, but not when 100 m preview is available. In DR, motion feedback yields lower error variances both with and without preview, but the performance improvement is significantly larger in tasks with 5 m preview. Whereas the improved DR performance results from a higher crossover frequency in tasks with 5 m preview, in 100 m preview tasks this is due to a higher phase margin (Fig. 4b, d).

2) Motion and Visuals: In TT, motion feedback and the visual presentation have no significant interaction effects, except in the phase margin, due to the extremely stable behavior in the lane-keeping task with 100 m preview (see Fig. 4c). In DR, motion yields a larger decrease in error variance in lane-keeping tasks, compared to centerline tracking, where tracking errors are much smaller in general (Fig. 5a, b).

3) Preview and Visuals: The performance benefit of additional preview depends strongly on the visual presentation. Increasing the available preview from 5 to 100 m in lane-keeping tasks yields a larger TT performance benefit and a stronger reduction in control activity than in tracking tasks (Fig. 5). Additionally, increasing the available preview from 5 to 100 m yields a higher TT bandwidth (higher ω_c, Fig. 4a) in tracking tasks, while a decreased bandwidth is in fact measured in lane-keeping tasks, indicating more corner cutting at higher frequencies. ϕ_m for TT increases significantly with preview for both tracking and lane-keeping tasks, with the strongest increase for lane keeping tasks (Fig. 4c).



(a) heading error

(b) lateral deviation

(c) control output

Fig. 5. Variances of the measured heading error, lateral position error, and control output, decomposed into contributions at the target (t, black portion of the bars), disturbance (d, gray), and remnant (n, white) frequencies. NM and M indicate no motion and motion conditions, respectively.

		motion (M)		preview (P)		visuals (V)		M×P		M×V		P×V		M×P×V	
		df = (1,11)		df = (1,11)		df = (2,22)		df = (1,11)		df = (2,22)		df = (2,22)		df = (2,22)	
		F	sig.	F	sig.	F	sig.	F	sig.	F	sig.	F	sig.	F	sig.
target tracking (TT)	$\sigma^2_{\psi_e}$	0.2	-	88.9	**	38.9	**	0.0	-	0.3	-	13.2	**	1.3	-
	$\sigma^2_{y_e}$	4.1	-	72.0	**	20.6	**	5.9	*	0.3	-	4.8	*	0.0	-
	$\sigma^2_{\delta_s}$	0.4	-	761.2	**	1.4	-	1.9	-	0.7	-	68.4	**	2.2	-
	ω_c	0.2	-	1.1	-	15.1	**	0.0	-	0.4	-	5.0	*	0.1	-
	ϕ_m	0.1	-	155.0	**	40.7	**	2.5	-	4.5	*	53.0	**	1.9	-
disturbance rejection (DR)	$\sigma^2_{\psi_e}$	51.0	**	63.8	**	13.0	**	22.6	**	11.4	**	13.0	**	5.7	*
	$\sigma^2_{y_e}$	28.9	**	6.5	*	24.2	**	8.7	*	8.4	**	4.0	*	1.1	-
	$\sigma^2_{\delta_s}$	32.9	**	17.0	**	5.4	*	4.0	-	1.8	-	11.9	**	4.1	*
	ω_c	1.6	-	2.1	-	17.7	**	8.2	*	0.4	-	0.1	-	0.4	-
	ϕ_m	7.6	*	2.5	-	15.8	**	0.9	-	0.1	-	3.2	-	0.7	-

TABLE II
REPEATED-MEASURES ANOVA RESULTS, ** IS HIGHLY SIGNIFICANT ($p<.01$), * IS SIGNIFICANT ($p<.05$), AND - IS NOT SIGNIFICANT ($p\geq.05$).

4) Motion, Preview and Visuals: Interactive effects between all three independent variables only occur in DR. The introduction of motion yields a significantly larger reduction in heading error variance (Fig. 5a) and control output variance (Fig. 5c) in lane-keeping tasks with 5 m of preview, as compared to any other combination of the visual presentation and preview.

V. Discussion

Experimental data were presented to investigate the effects of physical motion feedback on driver steering performance, and how these effects depend on the visual presentation and the TT or DR part of the task. Experiment results from 12 subjects were obtained; the cybernetic analysis showed consistent results, indicating the number of subjects was sufficient.

Our first hypothesis (H.I) was confirmed; relative to visual-only tasks, drivers suppressed external disturbances better with motion feedback for all tested visual combinations: tracking and lane-keeping, with and without optic flow, and with 5 and 100 m of preview. The key mechanism underlying this improved performance is that drivers close an additional feedback loop using the available physical motion, see Fig. 2. The response delay in this loop is shorter than the driver's visual delay, yielding improved DR stability (higher phase margin) [2], [7], [8]. Our second hypothesis (H.II), that physical motion feedback yields larger DR performance improvements in tasks with degraded visuals, was only partially confirmed. Whereas motion feedback indeed led to a larger DR performance improvement when the available preview was severely limited, no clear effect was measured of the availability or absence of optic flow. Moreover, opposite to our expectations, performance improved more by providing motion feedback in lane-keeping tasks than in tracking tasks, suggesting that simulator motion is in fact most critical when performing realistic driving tasks. Finally, our third hypothesis (H.III) was confirmed: the availability of physical motion feedback generally has no effect on TT performance, except when the available preview is severely limited, which corresponds to [8].

This research was motivated by the varying effects of simulator motion on driver steering performance in previous experiments (e.g., [1], [2], [4]), or even a complete absence of significant effects [7]. Our results suggest that the primary explanation for these differences is the presence and strength of an external disturbance, such as side-wind gusts. Physical motion predominantly affects DR performance, such that larger effects of providing simulator motion are evident in driving tasks with stronger disturbances. Indeed, the disturbance signal in the experiment of [7] had a 3.3 times lower standard deviation than our disturbance; consequently, their motion cues were possibly (partly) below the human's physical motion perception thresholds such that no effects of simulator motion could be measured. Additional experiments are required to investigate how the quality of the simulator motion (e.g., degrees-of-freedom, cueing fidelity) affects driver steering performance, which was not investigated here.

We recommend future work to also use uncorrelated multisine perturbation signals, were possible. Besides the TT and DR *performance* measures presented here, such multisines can be further exploited by explicitly estimating the *control dynamics* of multiple of the driver response blocks in Fig. 2 using system identification techniques [17]–[19], [21], [22]. Ultimately, modeling the identified driver dynamics can lead to an even better quantitative understanding of driver steering and cue utilization [12], [17], [19], similar as obtained for piloting tasks with motion feedback [10]. In fact, control-theoretic modeling of the driver's behavior is perhaps the only approach that we currently have available for actually quantifying the relative contributions of visual and physical motion feedback on the driver's steering behavior.

VI. Conclusion

This paper quantified how the effects of physical motion feedback on driver steering performance in a simulator depend on the visual presentation and the target-tracking or disturbance-rejection nature of the driving task. Relative to visual-only tasks, drivers always suppress external disturbances better with motion feedback, regardless of the visual degradation or realism. The absolute performance improvement depends strongly on the available visual feedback. In particular, motion feedback is more important when the available preview is limited and when a "regular" road is being following, opposed to centerline tracking. We conclude that providing motion feedback in simulators is essential to evoke realistic driver performance in tasks where substantial external (wind-gust) disturbances are present, but would be less important in disturbance-free lane-keeping tasks.

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