Can We Study Autonomous Driving Comfort in Moving-Base Driving Simulators? A Validation Study

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Objective: To lay the basis of studying autonomous driving comfort using driving simulators, we assessed the behavioral validity of two moving-base simulator configurations by contrasting them with a test-track setting.

Background: With increasing level of automation, driving comfort becomes increasingly important. Simulators provide a safe environment to study perceived comfort in autonomous driving. To date, however, no studies were conducted in relation to comfort in autonomous driving to determine the extent to which results from simulator studies can be transferred to on-road driving conditions.

Method: Participants (N = 72) experienced six differently parameterized lane-change and deceleration maneuvers and subsequently rated the comfort of each scenario. One group of participants experienced the maneuvers on a test-track setting, whereas two other groups experienced them in one of two moving-base simulator configurations.

Results: We could demonstrate relative and absolute validity for one of the two simulator configurations. Subsequent analyses revealed that the validity of the simulator highly depends on the parameterization of the motion system.

Conclusion: Moving-base simulation can be a useful research tool to study driving comfort in autonomous vehicles. However, our results point at a preference for subunity scaling factors for both lateral and longitudinal motion cues, which might be explained by an underestimation of speed in virtual environments.

Application: In line with previous studies, we recommend lateral- and longitudinal-motion scaling factors of approximately 50% to 60% in order to obtain valid results for both active and passive driving tasks.

Keywords: vehicle automation, autonomous driving, multisensory integration, immersive environments, virtual environments, trust in automation, vehicle design, usability/acceptance measurement and research, driving simulation, behavioral validity, visual-vestibular integration

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INTRODUCTION

In the past decade, autonomous cars have become a rapidly evolving technology that is on current agendas of a plethora of universities, car manufacturers, and other technology and software corporations. The trend of autonomous driving does not only revolutionize the automobile industry, but it fundamentally changes the driving task itself. SAE International (2014) defines six stages of driving automation ranging from Level 0 (no automation) to Level 5 (full automation). As the automation level rises, the driving task changes considerably. Whereas the human driver is in full command at Level 0 and has to perform all tasks associated with driving, more and more aspects of the driving task are automated in the intermediate levels, changing the human's task from active driving to monitoring the automation and ultimately even removing this responsibility as well.

As automation increases, the question of how drivers prefer to be driven becomes more and more important. For instance, at first glance, traveling in the center of a lane might be a reasonable lane-keeping behavior from a technical point of view. From a psychological perspective, however, driving in the center of a lane is not necessarily the trajectory a driver would prefer, especially when driving in bends or when turning maneuvers are being considered, in which curves are usually cut on the inner side in order to keep lateral accelerations relatively low (e.g., Boer, 1996; Siegler, Reymond, Kemeny, & Berthoz, 2001). Recent surveys revealed that passengers are very hesitant in their acceptance of automated transport systems (MacSween-George, 2003; Schoettle & Sivak, 2014). Therefore, it is even more important to investigate comfort experienced in highly or fully automated driving.

The concept of comfort is complex. A common scientific definition has yet to be established. According to de Looze, Kuijt-Evers, and van Dieën (2003), all definitions of comfort to date share three aspects: (a) comfort is subjective and may vary between persons, (b) experiencing comfort is always a reaction, and (c) comfort can be influenced by internal factors, for example, sensitivity, as well as external factors, for example physical influences. One major point in the discussion on comfort as a construct is whether it should be seen as a dimension with comfort on one end and discomfort on the other (e.g., Vergara & Page, 2000) or whether discomfort is something that is evoked by biomechanical circumstances and can coexist with comfort, which is associated with well-being (Zhang, Helander, & Drury, 1996). This controversy contributes to the existing difficulties in ascertaining a widely acknowledged method of assessment.

Ellinghaus and Schlag (2001) as well as Krist (1994) specifically point at the role of drivers' expectation in experiencing comfort. According to them, expectancies of maneuvers and actually experienced maneuvers are constantly compared, eliciting a feeling of comfort if expectancies are met. Deviations between expected and actual driving behavior not only might increase symptoms of motion sickness (Reason, 1978; Sivak & Schoettle, 2015) but might considerably threaten user acceptance and user comfort. Sivak and Schoettle (2015) have further found that loss of control and the inability to foresee vehicle actions are identified as major points when rating riding comfort as a passenger. This link between expectancies and actual experience has influenced the described study, as becomes apparent in the Method section. With the intention of making a first step toward identifying preferred automated driving, this study compares different variations of an automated lane-change maneuver as well as an automated deceleration maneuver behind a slower lead vehicle regarding experienced driving comfort. These two maneuvers were chosen not only because they are among the most common maneuvers in highway settings (see Bellem, Schönenberg, Krems, & Schrauf, 2016), where higher levels of automation will be introduced first, but also because they represent a longitudinal maneuver or a lateral maneuver and both involve another traffic member.

To facilitate the study of driving comfort in automated vehicles, driving simulators not only provide a safe and cost-efficient alternative to technically demanding and cost-intensive on-road studies, but they also enable developers to test prototype systems. However, valuable insights obtained from a driving simulator are of particular use only when they can be transferred to the real world. In literature, the distinction between physical validity and behavioral validity was established in order to assess the validity of driving simulators (e.g., Blana, 1996; Mullen, Charlton, Devlin, & Bédard, 2011). *Physical validity* refers to the extent to which a driving simulator is capable of reproducing physical reality. For instance, a simulator demonstrates physical validity if physical components, such as layout, dynamic characteristics, or visual displays, correspond to on-road driving. *Behavioral validity*, on the other hand, refers to the behavioral correspondence between driving behavior in the simulator and that on real roads. Thus, it describes to what extent the behavior, performance, and experience of drivers in a simulator match those on a real road.

Blaauw (1982) subdivided behavioral validity into absolute validity and relative validity. Absolute validity is established when dependent variables, such as driving parameters, psychophysiological measures, or subjective evaluations, take on the same numerical values in a driving simulator as in a real setting. Relative validity is given when differences of the dependent variable between conditions are of the same order, direction, and magnitude (Blaauw, 1982; Godley, Triggs, & Fildes, 2002; Mullen et al., 2011; Wang et al., 2010). For most research questions, establishing relative validity is sufficient (Reed & Green, 1999; Törnros, 1998). Absolute validity, however, is required when determining absolute numerical values, such as general takeover request times, or when intervention thresholds of an advanced driver assistance system need to be identified (Gemou, 2013).

The reservation must be made, however, that behavioral validity of a driving simulator is always limited to a specifically defined research question or driving task (Allen et al., 1991; Mullen et al., 2011; Godley et al., 2002; Nilsson, 1993) and that due to the many different architectures, algorithms, and parameterizations of driving simulators employed in driving simulator research (Fischer, Eriksson, & Oeltze, 2012; Greenberg & Blommer, 2011; Nilsson, 1993), generalizations across studies and simulators concerning the effect of motion cuing can be made only with caution.

To lay the basis for studying driving comfort in autonomous vehicles using driving simulators, we determined the behavioral validity of two simulator configurations of a high-fidelity hexapod moving-base simulator on a linear rail system. The simulator configurations differed in the vehicle's being placed in the hexapod dome either in parallel to the rail system (MBS_Long) or in transverse (MBS_Lat; see Method section for details).

Even though physical and behavioral validity are often assumed or found to be positively related (e.g., Ba, Zhang, & Salvendy, 2014; Blana, 1996; Klüver, Herrigel, Heinrich, Schöner, & Hecht 2016; Lee et al., 2013; but see Grabe, Pretto, Giordano, & Bülthoff, 2010; Reed & Green, 1999), there is growing evidence that not a scaling factor of 100%, but subunity scaling factors of around 50% to 70% are preferred in slalom task driving (Berthoz et al., 2013; Pretto, Nusseck, Teufel, & Bülthoff, 2009) or in lane-change maneuvers (Greenberg, Artz, & Cathey, 2003). However, the aforementioned studies did not compare simulators results with results from an on-road study but were based on ratings of perceived realism or driving performance data. In this study, we compared two scaling parameter sets, differing regarding their scaling factors of longitudinal and lateral acceleration, to a test-track setting. In the first parameter set (MBS_Lat), lateral acceleration is simulated in the exact same manner as it was recorded in the test-track study (a scaling factor of 100%), whereas longitudinal acceleration was scaled down to 17%. In the second parameter set (MBS_Long), lateral acceleration was scaled down to 50% and longitudinal acceleration to 60%. Thus, the MBS_Lat has higher physical validity in lane-change maneuvers, whereas the MBS_Long has higher physical validity in deceleration maneuvers (for detailed description of the simulator configurations, see Method section). Ours is the first study that validated two scaling parameter sets against on-road data. Furthermore, our study is the first that validated passive driving rather than active driving.

The purpose of this study is to lay the foundation for studying driving comfort in autonomous vehicles using an advanced moving-base driving simulator. In this study, we (a) evaluate whether the moving-base driving simulator is generally capable to adequately study experienced driving comfort in autonomous vehicles by comparing results from the simulator with results from a test-track study, (b) compare two motion scaling parameter sets, and (c) compare six variations of each a lateral and a longitudinal automated maneuver regarding experienced driving comfort, allowing to draw inferences on the underlying parameters. Results concerning the validity of the driving simulator will influence the setting of future studies, whereas insights from comfort ratings will be used to further improve automated driving toward a comfortable driving experience for passive drivers.

METHOD

Participants

A total of 52 men and 20 women (age across groups, M = 41.03 years, SD = 11.38 years, range = 21–61 years; data per setting is reported in Table 1) participated in this experiment. Both employees and non-employees of Daimler AG took part in this study and were distributed evenly across groups. All participants held a valid driver's license, had normal or corrected-to-normal vision, were naive to the purpose of the experiment, and had little or no previous simulator experience. Data were collected anonymously. Informed consent was obtained after the task had been explained. Participants were free to terminate participation in the experiment at any time without any consequences. Participants received €30 for their participation. All experimental procedures were conducted in accordance with the ethical guidelines of the Declaration of Helsinki.

Design

We chose two classes of common maneuvers for this study, including a lane change to the left (producing large lateral acceleration forces)

TABLE 1: Demographic Data per Setting of Groups and ANOVA or Pearson's Chi-Square Results Comparing the Groups

		Simulator				
Variable	Test Track (n = 28)	Longitudinal (n = 22)	Lateral (n = 22)	*df*	F or χ^2	*p*
Mean age in years[a]	41.32 (10.51)	39.05 (12.82)	42.50 (11.16)	2, 69	F = 0.56	.576
Sex				2	χ^2 = 0.01	.992
Male	20	16	16			
Female	8	6	6			
Experience Level 2 automation at least weekly	4	3	3	2	F = 0.01	.997
No experience with driving automation	11	10	6	2	F = 1.61	.446

[a]Standard deviations shown in parentheses.

and a deceleration maneuver as a reaction to a slower vehicle driving ahead (producing longitudinal acceleration forces). These maneuvers were chosen because they represent two of the most common maneuvers shown in highway scenarios (see Bellem et al., 2016). Because highly and fully automated driving will first be introduced on highways, this criterion is of special relevance to the choice of maneuvers. In addition, these two maneuvers provide insight into a primarily lateral and a primarily longitudinal maneuver.

A 3 × 6 factorial design was chosen for each of the two maneuvers. The first factor, environment, is a between-subjects factor describing the setting, with the levels test track, MBS_Lat, and MBS_Long. The second factor, scenario, is a within-subjects factor encompassing six differently parameterized variations of a deceleration maneuver and six variations of a lane-change maneuver (see Figure 1).

Of the 72 participants in total, 28 participants experienced the on-road setting, 22 participants experienced the MBS_Lat setting, and another 22 participants experienced the MBS_Long configuration of the moving-base simulator. For each of the two maneuvers, the six scenarios comprised different combinations of three parameters that were found in earlier studies to be classified by participants as comfortable driving (Bellem et al., 2016). Mean values and their standard deviations from the study by Bellem et al. (2016) are the basis for the parameters of the study reported here.

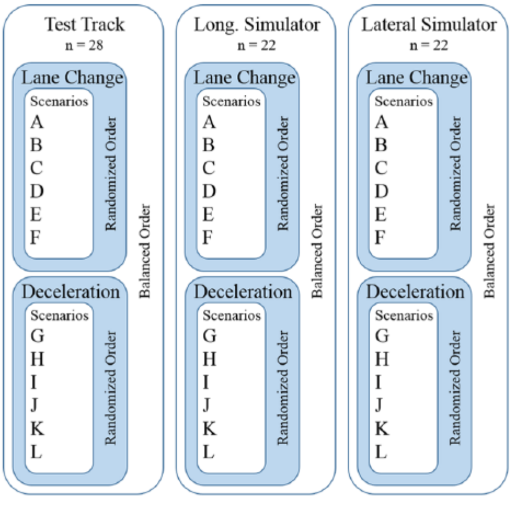

Figure 1. Illustration of the study design. The between-subjects factor, environment, encompasses two within-subjects maneuvers with six within-subjects scenarios each per environment.

The parameters are described in more detail in Apparatus and Stimuli and are further illustrated in Figure 3. Due to physical and technical constraints, a fully factorial design of the parameters could not be established. Combinations were thus chosen such that they were feasible and comparable, for example, not requiring a significantly longer track, but also in such a way that they could still be expected to be rated differently based on just noticeable differences (see Müller, Hajek,

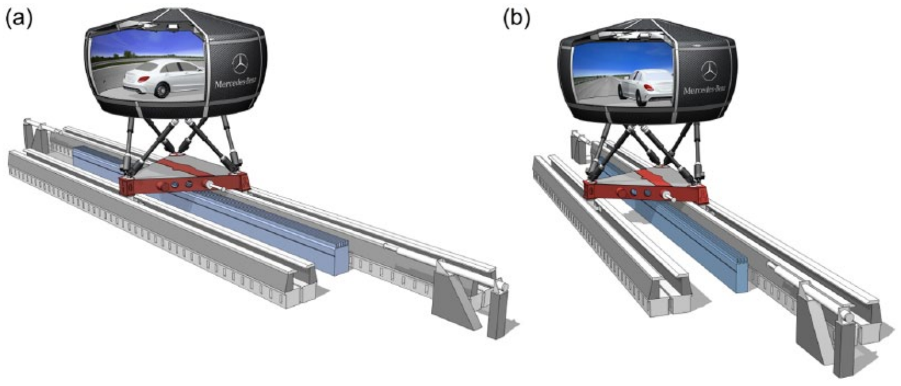

Figure 2. Illustration of the advanced moving-base simulator at Daimler AG. As can be seen in (a), the full-scale mock-up is positioned transversely to the linear axis so that the linear axis can be fully used to simulate lateral motion cues (MBS_Lat). In (b), the mock-up is positioned parallel to the linear axis (MBS_Long) in order to use the linear axis for the simulation of longitudinal motion cues.

Radic-Weissenfeld, & Bengler, 2013) and still be representative of the original data they were based on. Hence, the variations were designed to be experienced as comfortable but not equally comfortable.

The experiment was divided into two blocks, in which either lane-change maneuvers or deceleration maneuvers were driven. To prevent order effects, the order of the two blocks was counterbalanced, and the order of scenarios within the blocks was randomized across participants (see Figure 1).

Apparatus

Test-track study environment. The test-track study took place on a 280-m-long test track with two lanes closed off to public traffic. The ego vehicle, a Mercedes Benz CLS (C218), drove autonomously and was equipped with a software-and-hardware system enabling the vehicle to drive according to the predefined scenarios without any intervention of the participant. In order to synchronize the behavior of the ego and target vehicles in the deceleration scenario, the target vehicle was controlled through a high-precision GPS tracking system and several software and hardware components.

Driving simulator environment (MBS_Lat and MBS_Long). The high-fidelity moving-base simulator is based on a 12.5-m-long linear rail system. A hexapod, which moves along this linear rail via air bearings, comprises six linear actuators and carries a spherical dome with a height of 4.5 m and an inner diameter of 7.5 m. In this dome, a full-scale vehicle mock-up can be positioned either parallel or transversely to the linear rail. Hence, depending on the orientation of the mock-up, the motion space of the linear rail can be used to simulate either lateral (MBS_Lat) or longitudinal motion (MBS_Long). Orthogonally to the linear rail, the moving-base simulator has a motion space of ±1 m. The motion-cuing system of the MBS_Lat was parameterized with a lateral scaling factor of 100% and a longitudinal scaling factor of around 17%. In the MBS_Long setting, 60% of the longitudinal accelerations and 50% of the lateral accelerations were simulated by the motion system. In order to reproduce the scenarios from the test-track study, the measured accelerations in the test-track study were directly transmitted to the motion system. Consequently, no vehicle dynamics model was interposed to simulate the scenarios. However, due to the limited workspace, a classical washout algorithm was used, which attenuates low-frequency accelerations.

An eight-channel projection system inside the dome created a 360° horizontal field of view with a resolution of 2,048 × 1,536 pixels for each projector. Additionally, two LCD displays with a resolution of 800 × 600 pixels were mounted on the side mirrors in order to simulate mirror images. An illustration of the MBS_Lat and MBS_Long is given in Figure 2. A more detailed description of the moving-base simulator can be found in Zeeb (2010).

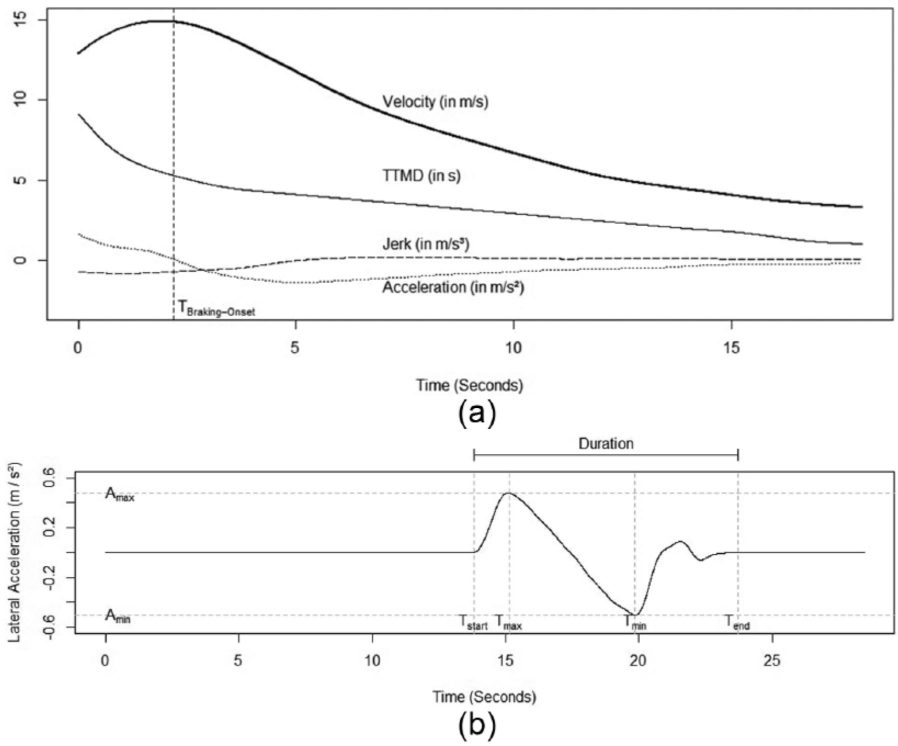

Figure 3. Illustration of the parameters for both the lane-change maneuver and the deceleration maneuver for comfortable driving. In (a), the deceleration maneuver, D, is illustrated. In (b), the lane-change maneuver, L, is shown. Additionally, the assignment of parameter combinations to the scenarios is given.

The simulation environment was a replica of the test-track environment. The scenarios were presented as completely automated and needed no input from the driver. Both steering wheel and pedals were monitored, however, in order to record driver input if it occurred.

Stimuli

Deceleration scenario. The deceleration maneuvers started with the ego vehicle accelerating to 50 km/h and the target vehicle synchronously accelerating to 10 km/h. While approaching the target vehicle, the ego vehicle initiated a deceleration maneuver with the given parameterization.

The deceleration scenarios were generated by combining values of jerk upon application of brakes (jerk), gradient of time to minimum distance ($TTMD_{grad}$) and TTMD at the onset of the maneuver ($TTMD_{init}$). The onset of the maneuver was defined as the moment when the acceleration pedal was released. Jerk is defined as the derivate of acceleration (or second derivate of velocity) upon application of brakes. TTMD is defined similarly to time to collision. However, instead of taking collision as a reference, TTMD refers to the point of minimum headway distance in seconds, which is constant throughout all variations. $TTMD_{grad}$ is defined as the change rate of TTMD throughout the deceleration. A higher $TTMD_{grad}$ may be experienced as a faster adaptation to the head vehicle's speed. $TTMD_{init}$ is defined as the TTMD at maneuver onset. A smaller $TTMD_{init}$ may be experienced as a deceleration that begins closer to the obstacle than with a larger $TTMD_{init}$. These three parameters had been shown to be relevant for perceived driving comfort in an on-road study (see Bellem et al., 2016). The absolute values of the different metrics either are the mean of metrics classified as comfortable in Bellem et al. (2016) or correspond to the standard deviation around these mean values. Parameters are illustrated in Figure 3.

(a) Deceleration Maneuver

Parameter	Description	Scenario A	B	C	D	E	F
Jerk	Jerk at $T_{BrakingOnset}$ in m/s^3	–1.67	–1.10	–0.53	–0.53	–1.67	–0.53
$TTMD_{grad}$	Gradient or slope of the time to minimum distance after $T_{BrakingOnset}$	–0.71	–0.48	–0.26	–0.26	–0.26	–0.71
$TTMD_{init}$	Time to minimum distance at $T_{BrakingOnset}$ in seconds	5.47	3.66	1.86	5.47	1.86	1.86

(b) Lane Change Maneuver

Parameter	Description	Scenario G	H	I	J	K	L
A_{max}	Maximum of acceleration in m/s^2	2.68	1.76	0.43	2.50	1.70	0.48
Gamma	Ratio between acceleration minimum and maximum ($\|A_{min}\| / A_{max}$)	1.21	1.09	1.01	0.93	1.13	1.05
Alpha	Relative time point of A_{max} in seconds (T_{max} / Duration of Maneuver)	0.44	0.32	0.32	0.20	0.44	0.20

Lane-change scenario. At the beginning of each lane-change maneuver, the ego vehicle accelerated to 50 km/h in the right lane. After approximately 2.5 s of maintaining the desired velocity, an automated lane change to the left according to the given parameters was performed in order to avoid a stationary vehicle, which was positioned in the right lane. During the lane-change maneuver, the steering wheel moved in accordance with the vehicle's lateral movement.

The scenarios were generated by combining the acceleration maximum (A_{max}), the ratio between acceleration minimum (A_{min}) and A_{max} (Gamma), and the relative point in the maneuver at which the A_{max} occurs (Alpha). Whereas acceleration is a widely used metric (see Winner, Hakuli, and Wolf, 2012), Alpha and Gamma are rather novel. They are an approach to capturing the course of the lane change. Alpha describes how symmetrical the buildup of acceleration is with respect to maneuver duration. A small Alpha represents a lane change that is performed with an early maximum of lateral acceleration and may thus be experienced as a lane change with earlier distinctly perceivable onset. Gamma, on the other hand, expresses how symmetrical the maneuver is with regard to the magnitude of lateral acceleration. A Gamma of 1 represents a lane change during which lateral A_{max} both to the left and to the right have identical strength. The smaller the Gamma, the stronger the acceleration to the left (A_{max} in Figure 3) compared with the acceleration to the right (A_{min} in Figure 3). This value may be experienced as jerkier to the left than to the right because a larger A_{max} has to be built up in less time when compared with a Gamma of 1 with the same Alpha. As in the deceleration maneuver, the absolute values of the parameters are based on mean and standard deviation values classified as comfortable in a previous study (see Bellem et al., 2016). Lane-change onset was held constant to allow results to be based on the varied characteristics of the lane change and not on mere rating of risk.

Procedure

At the beginning of the experiment, participants filled in a questionnaire to obtain both standard demographic information and subjective ratings of their experience with driving simulation, automated driving, and various driver assistance systems. Subsequently, participants were made familiar with the experimental procedure. They were instructed to provide a comfort rating for each scenario, indicating the extent to which the experienced scenario corresponded to their preference for comfortable automated driving. The rating was given on a scale from 1 to 7, with 1 meaning *not at all* and 7 meaning *exactly this way*. Participants also had the opportunity to comment on the maneuvers with regard to comfortable automated driving.

In general, the experimenter made the participants aware that they should base their judgments on the lane-change or deceleration maneuver alone and not, for example, on the basis of the acceleration at the beginning of each scenario. Thus, the rating was intended to capture the comfort of the subject rather than evaluate the presence or quality of the simulation in case of the simulator studies. The intertrial interval lasted approximately 60 s for the lane-change maneuvers and 150 s for the deceleration maneuvers.

Each of the two blocks began with a training scenario to familiarize participants with the procedure (Scenarios B and H as middle variation). After each scenario, the participant took over the ego vehicle in order to drive it back to its initial starting position in the test-track study, whereas in the simulator studies, the simulation was reloaded with a new scenario.

RESULTS

For each of the two maneuvers, we performed two separate repeated-measures ANOVAs using the afex-package in R (Singmann & Bolker, 2014; R Core Team, 2013) to contrast each simulator with the test-track study. Environment (levels: test track vs. MBS_Lat or test track vs. MBS_Long) was treated as a between-subjects factor and scenario as a within-subjects factor. Comfort ratings were squared to correct for their negatively skewed distribution. A visual inspection of the skewness-corrected ratings revealed no obvious deviations from normality, and subsequent Box's *M* tests indicated no violation of homoscedasticity for each model. Since the assumption of sphericity was violated, we used the Greenhouse-Geisser correction for the degrees of freedom. Results are given in Table 2. In order to further illustrate the results, we plotted the means in Figure 4.

Matching of the verbal comments showed that in scenarios with higher comfort ratings, it was mentioned more often that the scenario had been experienced as smooth and/or anticipatory. Further analysis of the comments will be omitted here but can be obtained from the authors.

In statistical terms, absolute validity is supported by the absence of significant main and interaction effects. Relative validity is given when no interaction between environment and scenario can be found. Hence, the nonsignificant interaction and main effects of the MBS_Long reported in Table 2 support that relative validity and absolute validity can be concluded for the MBS_Long. The MBS_Lat, however, was not found to have relative validity. Whereas in the lane-change maneuver the interaction effect is particularly large and relative validity has to be clearly rejected, in the deceleration maneuver it is a matter of argument whether an effect size of 0.05 and a statistical significance of 0.05 are of practical relevance, especially when considering Bonferroni-corrected significance levels of 0.0125.

To further examine which maneuver parameters might be at the basis of these differences, we performed a multilevel regression analysis using the lme4-package in R (Bates, Maechler, Bolker, & Walker, 2014) with repeated measures on the first level and participants on the second level. As the dependent variable, the comfort rating was used. For each of the six parameters describing the deceleration and lane-change maneuvers, we built a separate model and added the maneuver parameter and its square to the model as first-level predictors to allow for a curvilinear relationship. At the second level, we added environment as a dummy-coded variable to the model, with the test-track environment being set as the reference level. Additionally, a cross-level interaction between environment and the maneuver parameters was entered. Again, comfort ratings were squared to meet the assumption of normally distributed residuals. Subsequently, comfort ratings and maneuver parameters were subjected to a *z*-transformation before model fitting to prevent biased parameter estimation due to multicollinearity produced by the high correlation between the linear and curvilinear term of the maneuver parameter. For

TABLE 2: Results From the Repeated-Measures ANOVAs Concerning Comfort Rating

	MBS_Long				MBS_Lat			
Maneuver	df_1, df_2	F	p	η^2	df_1, df_2	F	p	η^2
Deceleration								
Environment	1, 48	0.66	.42	.01	1, 48	4.07	.05*	.08
Scenario	3.73, 179.21	54.84	<.0001***	.53	4.21, 202.08	47.62	<.0001***	.50
Environment × Scenario	3.73, 179.21	1.39	.24	.03	4.21, 202.08	2.36	.05*	.05
Lane Change								
Environment	1,48	1.93	.17	.04	1, 48	8.52	.005**	.15
Scenario	3.33, 159,91	43.22	<.0001***	.47	3.54, 169.76	64.22	<.0001***	.57
Environment × Scenario	3.33, 159.91	1.73	.16	.03	3.54, 169.76	9.70	<.0001***	.17

Note. MBS_Long = simulator setting with vehicle positioned parallel to the linear rail system; MBS_Lat = simulator setting with vehicle positioned traversely to the linear rail system.
*$p \leq .05$. **$p \leq .01$. ***$p \leq .001$.

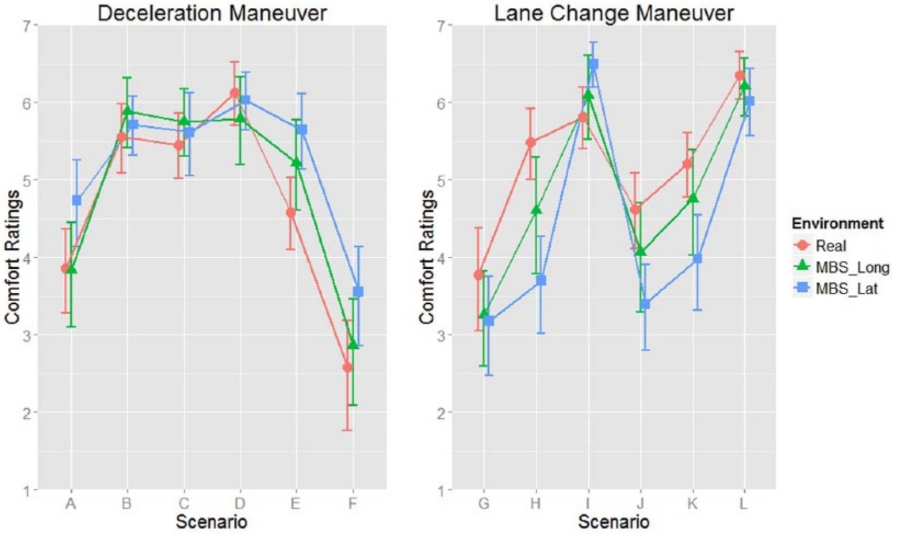

Figure 4. Illustration of the comfort ratings. Squared comfort ratings were averaged across environments and scenarios and subsequently transformed back to their original scaling. Error bars indicate 95% confidence intervals.

each model, a visual inspection of the residual plots revealed no obvious deviations from normality or homoscedasticity. To determine the variance explained by the parameters, we calculated R^2 for each model according to the algorithm suggested by Xu (2003). To illustrate the results, we simulated expected values based on the multilevel regression models as proposed by King, Tomz, and Wittenberg (2000). Results and illustrations of the multilevel analyses are given in Figure 5.

No significant effects of both linear and curvilinear components of the six parameters in the MBS_Long can be found. Therefore, the effects of the parameters on driving comfort are identical between the test-track study and the MBS_

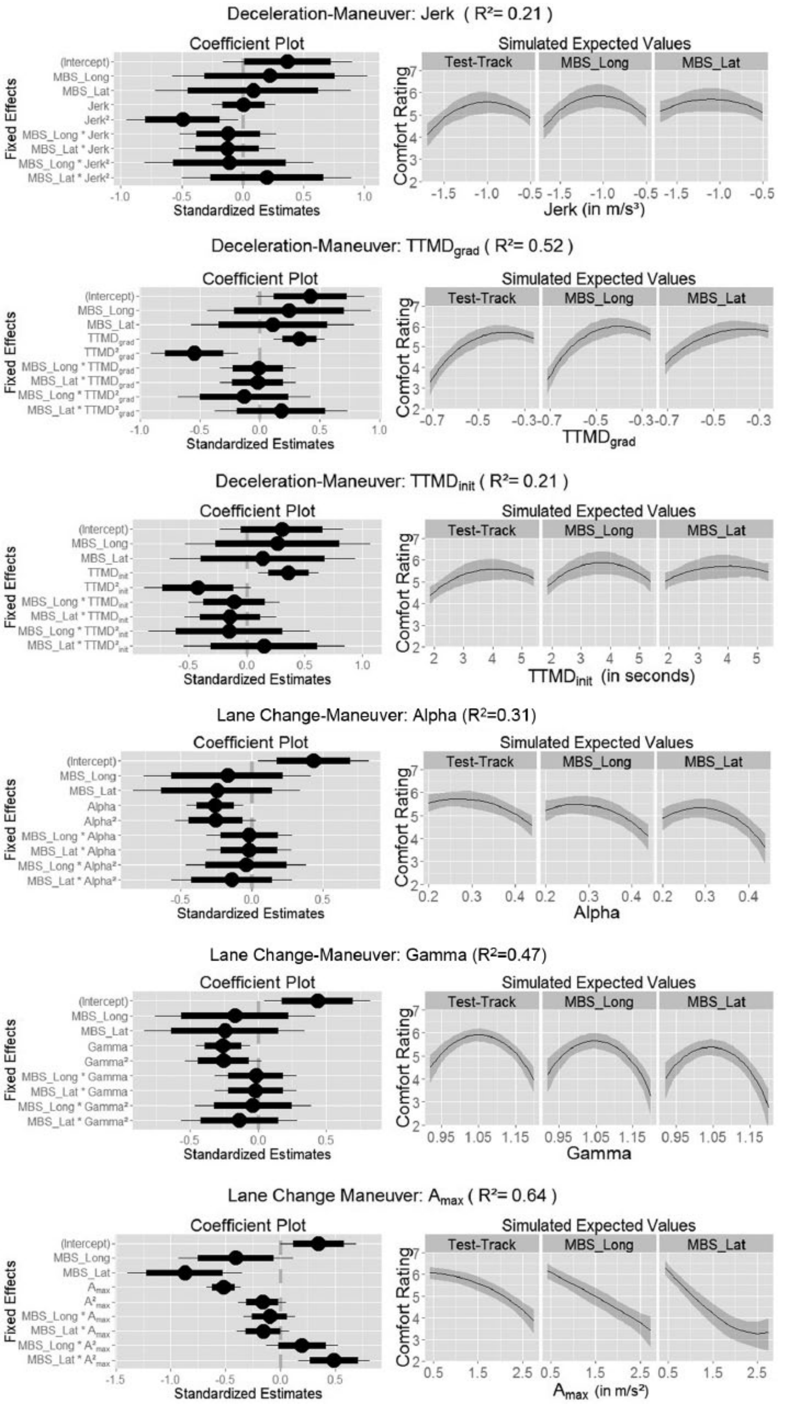

Figure 5. Results of the multilevel analyses. In the left column, standardized regression coefficients are illustrated in a coefficient plot. The thick error bars indicate the 95% confidence interval, and the thin error bars indicate the 99.9% confidence interval. A fixed effect is significant on the alpha level of 0.05 (0.001) when zero is outside of its thicker (thinner) confidence interval. In the right column, simulated expected values are plotted for each environment. Note that comfort ratings were transformed back to their original scaling. Error bands indicate the 95% confidence interval. R^2 was calculated using the algorithm proposed by Xu (2003).

Long. In the MBS_Lat, however, the effect of the linear and curvilinear component of the predictor A_{max} was significantly different from those of the test-track study. In addition, the results show, A_{max} and $TTMD_{grad}$ are able to explain most variance in the lane-change or deceleration maneuver, respectively.

DISCUSSION

For both lane-change and deceleration maneuvers, results support relative and absolute validity for the MBS_Long. In the MBS_Lat configuration, however, relative validity for the lane-change maneuver cannot be supported. Also, data only hint at a weak relative validity for the deceleration maneuver. Consequently, only the moving-base simulator configured with lateral and longitudinal scaling factors of 50% and 60% (MBS_Long) seems to be a valid research tool to examine driving comfort in automated lane-change and deceleration maneuvers. In contrast, the lateral configuration (MBS_Lat) seems inadequate for studying driving comfort, especially for lane-change maneuvers. Furthermore, we found not only that the relative comfort ratings among the lane-change conditions did not correspond to those of the test-track environment but that driving comfort was generally rated lower in the MBS_Lat, compared with the test-track environment.

Because the MBS_Long configuration optimally exploits the available motion space to simulate longitudinal motion cues, it is not surprising that this configuration is superior, compared with the MBS_Lat configuration in the deceleration maneuver. However, it is surprising that in this study the MBS_Long seems to be superior to the MBS_Lat configuration, which is optimized for simulating these lateral cues, in the lane-change maneuver, even though a lane change requires an adequate simulation of lateral motion. In the following paragraphs, several explanations for these counterintuitive findings are discussed.

As can be seen from the multilevel analyses, the effect in the MBS_Lat of the linear and curvilinear component of the maximal acceleration A_{max} on driving comfort was significantly different from those in the test-track study, whereas in all other parameters the MBS_Lat produced identical results. At the same time, A_{max} was found to be the best predictor of driving comfort, as it explained most of the variance. This finding indicates that the source of the poor validity of the MBS_Lat may be traced back to an erroneous simulation of maximal lateral acceleration cues. From the simulated expected values illustrated in Figure 5, we see that already a little increase in lateral acceleration in the MBS_Lat led to a severe decrease in comfort ratings, compared with a rather mild decrease in the test-track study. Thus, A_{max} seemed to be also responsible for driving comfort being rated significantly lower in the MBS_Lat, compared with the test-track environment. When considering the scaling factors for lateral accelerations in the two simulator configurations, it is evident that simulating only 50% (MBS_Long) of the lateral acceleration produced more valid comfort ratings than a physically valid 100% scaling factor (MBS_Lat).

This counterintuitive result was also found in previous studies. Pretto et al. (2009) varied four scaling factors (0.5, 0.75, 1.0, 1.25) for lateral acceleration in a slalom driving task and concluded a scaling factor of 60% as being the perceived optimal motion gain. Greenberg et al. (2003) varied three scaling factors (0, 0.25, 0.5, 0.7) in a lane-change task and concluded that lateral motion scale factors of around 50% are sufficient to produce naturalistic driving performance. Probably one of the most comprehensive motion-cuing studies was carried out by Berthoz et al. (2013). Across three advanced moving-base driving simulators, they examined the effect of lateral motion scaling on the perceived realism and driving performance in a slalom driving task. They concluded a factor between 0.4 and 0.75 as being the optimal motion gain for lateral acceleration. As potential explanations, they noted that the preference for subunity motion scaling might be attributable to constraints of the vehicle dynamics models. However, our findings contradict this notion, because no vehicle model was interposed in this study. Rather, measured accelerations from the test-track study were directly transmitted to the motion system.

A plausible and promising explanation was proposed by Berthoz et al. (2013). They suggested that motion cuing has to be scaled down in order to match an underestimated speed in virtual environments. Thus, the basis of this effect might be found rather in the physical validity of the display system than in the motion system (Correia Grácio, Bos, van Paassen, & Mulder, 2014). Indeed, many studies showed that speed and distance were underestimated in virtual environments (e.g., Banton, Stefanucci, Durgin, Fass, & Proffitt, 2005; Fischer et al., 2012; Harris, Jenkin, & Zikovitz, 2000; Knapp & Loomis, 2004).

Even though an underestimation of speed is evident in decades in driving simulator research, the theoretical basis still remains unknown. Considering that the aforementioned studies relied on visual systems with monoscopic cues, there is growing empirical evidence that providing stereoscopic cues enhances the visual-vestibular integration (Butler, Campos, Bülthoff, & Smith, 2011) and might reduce the visual-vestibular mismatch, which is often assumed to evoke simulator sickness (Reason, 1978). Furthermore, it was found that stereoscopic cues considerably improved heading judgments (Van den Berg & Brenner, 1994), increased perceptions of ego speed and self-displacement (Palmisano, 2002), and decreased vection onsets and increased vection duration (Palmisano, 1996; but see Ijsselsteijn, Ridder, Freeman, Avons, & Bouwhuis, 2001). As a consequence, introducing stereoscopic cues to fixed-base simulators might enhance their physical validity at first sight, but they would most likely decrease the behavioral validity due to a higher visual-vestibular mismatch. This possibility might explain why a stereoscopic display in an otherwise identical fixed-base driving simulator was barely found to improve driving performance, compared with a monoscopic display (Forster, Paradies, & Bee, 2015).

Nevertheless, this hypothesis remains speculative and it will be the task of researchers to determine whether the preference for subunity scaling factors might dissolve when providing stereoscopic visual cues.

Leaving the theoretical basis aside, our data support that the preference for subunity scaling factors seems to apply not only to active driving tasks but also to passive driving tasks. Furthermore, we could demonstrate for the first time that a moving-base simulator can be utilized to study perceived comfort in autonomous vehicles, given the motion-cuing algorithm is adequately parameterized. However, we want to point out that it is difficult to generalize findings across several research questions and different architectures of driving simulators. Considering that a growing body of traffic psychology research relies on driving simulators, it is crucial that driving simulators are subject to constant validation. Furthermore, as Godley et al. (2002) noted, the accumulated evidence that different driving simulators were found to be useful research tools for a variety of driving tasks adds weight to the validity of driving simulator research.

In addition to the findings on simulator validity, it was possible to identify in which way the characteristics of the maneuvers influence comfort ratings. Results point in the direction of acceleration being the strongest influence on comfort. As expected, less acceleration is perceived as favorable. Participants' verbal comments regarding the smoothness of scenarios and anticipatory qualities in combination with the found importance of $TTMD_{grad}$ also suggests the course of the maneuver plays an important role in experiencing comfort.

Potential Limitations

We have performed many statistical tests, which increased the risk of Type I errors. However, we believe that corrections for the alpha level (e.g., Bonferroni correction) would have been too conservative, especially when considering that the simulators were not tested against being valid but tested against not being valid. In addition, we point out that using a within-subjects design would have provided the method of choice but was not feasible due to the large logistical challenge and reasonableness toward participants. It can further be discussed whether a multidimensional measure of comfort may have been a stronger measure. However, participants in pretests have shown difficulty rating comfort on a multidimensional scale. This finding is also reflected in the comments participants gave after each variation, which mainly reduced comfort to smoothness and anticipation.

A further possible limitation addresses the method used to assess driving comfort. Also due to the fact that no common understanding exists on the precise definition of comfort, finding a valid tool for assessment has proven to be difficult. In retrospect, we suspect that the unidimensional 7-point scale used may not have been the optimal choice. There have been different approaches to objectively measure driving comfort, such as via physiological measures (e.g., Engeln & Vratil, 2008), or indirectly by measuring discomfort (e.g., Hartwich, Beggiato, Dettmann, & Krems, 2015). However, a residual variance remains even when using objective measures (Engeln & Vratil, 2008). We are also aware that other aspects, such as feeling safe, may have influenced the ratings as they are closely linked or, in some theories, a part of comfort (see Summala, 2007). However, we also believe that comfort is not obtainable if a person is not feeling safe. A valid and widely supported questionnaire or assessment method has yet to be established.

Especially in simulators, motion sickness can be an important influence on data. Because participants in this study reported mainly no or only seldom little discomfort regarding motion sickness, we did not control our results for symptoms of simulator and motion sickness. Also because trials were randomized, we believe that a systematic bias of motion or simulator sickness is unlikely. At last, our analysis and discussion might be characterized as having a post hoc character. However, we want to point at the explorative nature of this study, which is due to the novelty of studying perceived comfort of autonomous vehicles in driving simulators.

CONCLUSION

We found that participants preferred downscaled motion cues to physically correct motion cues, which can be plausibly attributed to an underestimation of speed in virtual environments. It would be interesting for further research to test whether providing stereoscopic cues would enhance speed perception and thus resolve the preference for subunity scaling factors. In summary, we were able to demonstrate relative and absolute behavioral validity for the MBS_Long for both lane-change and deceleration maneuvers within the range of parameterization that is relevant for driving comfort in autonomous cars. For the MBS_Lat in the given configuration (100% scaling factor for lateral motion cues, 17% scaling factor for longitudinal motion cues), however, we could conclude only weak relative validity for the deceleration maneuver and no relative validity for the lane-change maneuver. A scaling factor of 50% to 60% appears to be the key factor for behavioral validity of the driving maneuvers under consideration in this study, which can be provided by the MBS_Long configuration consistently for both lateral and longitudinal motion cues.

Regarding experiencing comfort, maximum acceleration and how parameters change over the course of a maneuver seem to be key influences.

KEY POINTS

- Perceived driving comfort of differently parameterized lane-change and deceleration maneuvers of an automated vehicle was studied on a test track and in two moving-base simulator configurations.
- Acceleration shows to have the strongest influence on experienced comfort in the used maneuvers.
- Basically, moving-base simulators are capable of reproducing results from a test-track study.
- In line with previous findings, we recommend linear motion scaling factors in the range of approximately 50% to 60% in order to obtain valid results.

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