Evaluation of methods for measuring speed perception in a driving simulator

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Achieving realistic sensation of longitudinal velocity and changes in velocity is a fundamental difficulty even for the most advanced driving simulators. It is also an aspect of great importance in many simulator studies. A stronger focus in recent years on driver assistance systems and CO2 issues, relating to driving style, further increase the need for realistic experience of speed and acceleration. This calls for investigation of the significance of different sensory cues to achieve realistic sensation and perception of especially longitudinal motion. A first step towards this goal was done by performing a study with the aim to explore different psychophysical methods for measuring speed perception in the context of driving simulation. The results of a conducted experiment indicate which of the evaluated methods are most suited for this task. Further, the presentation of a related literature study provides a broad overview on publications dealing with the topic of motion perception and motion cueing in driving simulation.

Keywords: *Speed perception, motion cueing, driving simulator, literature study*

Introduction

The driver's sensations and perceptions of acceleration, speed, and distance in driving simulators depend on several factors such as level of detail in the graphics, conveyance of sound and vibration, and degree of engaged peripheral vision [1]. If a motion platform is used, the strategies and control algorithms for its physical motions are of great importance in terms of experienced linear and angular accelerations [2]. The driver's abilities to appropriately accelerate, maintain speed, and decelerate all depend on the driver's sensations and perceptions. The basis for a realistic driving behaviour is realistic estimations of the driving speeds of the own and other vehicles because they directly affect performance indicators like time-headway, time-to-collision, and time-gap acceptance. However, it is a well-known problem that the driving speed is often severely underestimated in driving simulators [3], which implies that simulator studies aimed at evaluating certain driver assistance systems may be critically biased. A more realistic experience of acceleration and speed in driving simulators, that is, a perception in better correspondence with real driving, can be essential for certain types of simulator studies.

Although research has been done on how humans perceive motion (see [4-6]), more knowledge is needed on how much various sensory cues contribute to motion perception in driving simulators. In order to find ways to enable the driver to estimate the speed of the own vehicle, and other vehicles, in a similar manner as in real driving it is important to aim for quantification of the importance of different sensory cues to achieve realistic motion sensation. Based on this analysis, the following step must be the development of general methods and/or technologies to improve the motion sensation.

Method

With the aims stated above, a first step was to perform a literature study on motion perception and motion cueing aspects to obtain an overview of past research and existing knowledge. Based on this overview and several pilot tests in a driving simulator, an experiment was designed to evaluate several methods that seemed most suitable.

Literature study

For the estimation of distance, the visual impression is of highest importance (e.g. [7]). For the sensation of acceleration, the visual impression significantly adds to the sensation, but, as vision is a rather slow sense (e.g. [8, 9]) the vestibular system with its fast responses can be considered most important. However, the auditory and haptic impressions can add valuable information as well, i.e. through surrounding static or moving sound sources (e.g. [10]) or from vibrations or forces acting on the body (e.g. [11]). For the sensation of speed, all sensory cues add to the final impression, although the visual can be considered dominant. Evaluating the absolute value of the driving speed based on auditory and haptic impressions is only possible based on driving experience and is always related to a certain vehicle type. Nevertheless, these cues give a strong indication for small velocity changes. Even though there are no vestibular cues for constant speed driving, perceiving velocity changes through vestibular motion cues adds to the ability of evaluating the current driving speed. Hence, it is more difficult to determine the actual importance of each sensory channel for speed perception because each one of them may be more or less equally important for the holistically realistic perception of speed.

Subsuming, all of the main sensory inputs are important for achieving the highest level of realistic motion perception. The results of the literature study were structured into four main categories of impression in accordance with the simulator's feedback channels to the driver:

- visual
- auditory
- vestibular
- haptic (including tactile)

An overview of the literature study results is provided below in Fig. 1, which shows the identified 49 factors that influence the perception of speed and acceleration in a driving simulator.

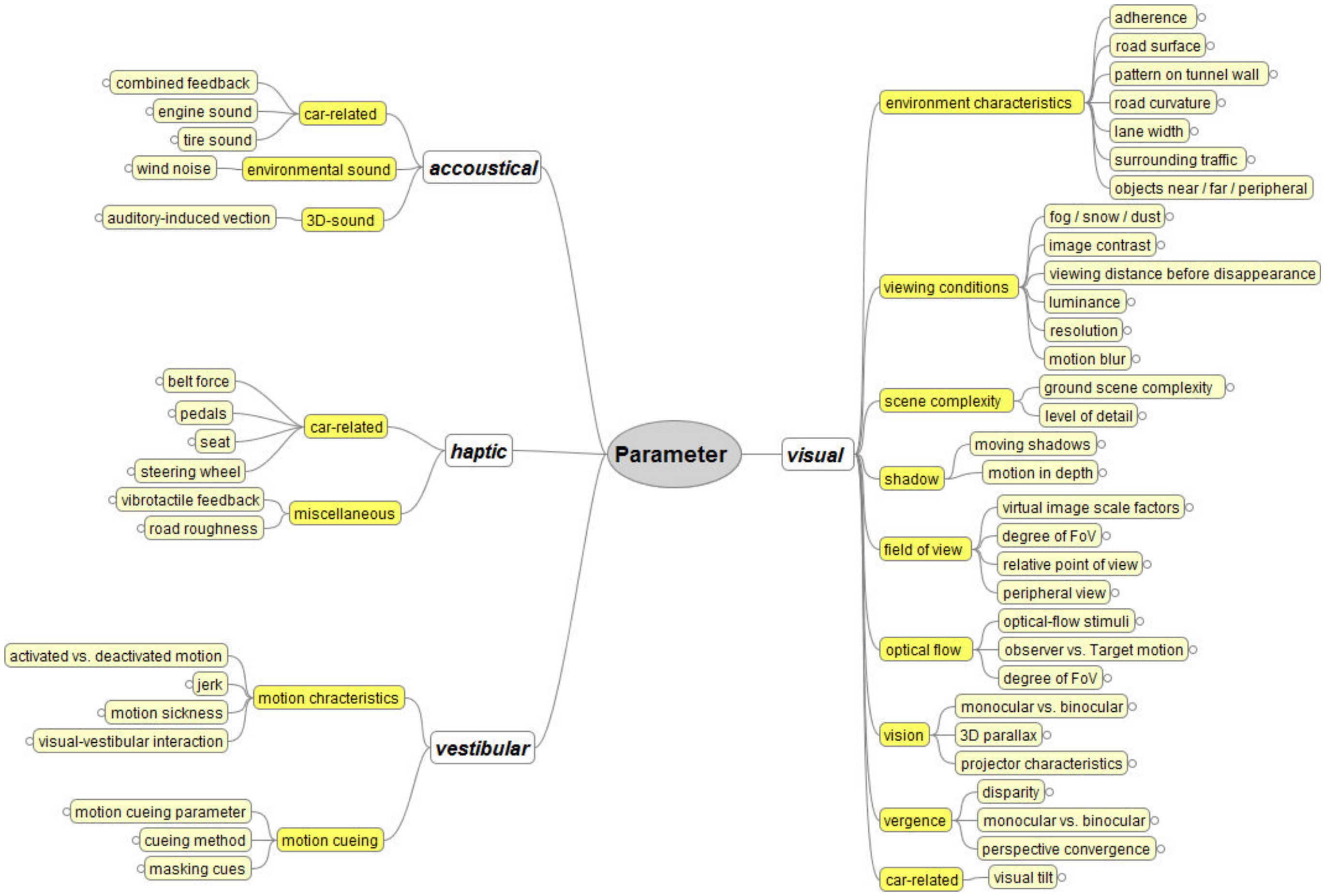

Fig. 1. Overview of parameters influencing the motion perception in driving simulators classified by motion cue type

The aim for the literature study was mainly to get a broad overview on publications about motion perception and motion cueing. Thus, the resulting listings (Tab. 1 - Tab. 4), which contains the most relevant articles examined during the study, is by no means to be treated as complete. For each referenced article, the main findings are shortly summarised. As the context of the gained results (facility, test subjects, applied method, etc.) is of high importance, the lecture of the original text is necessary for detailed interpretation of the results. However, the overview shall provide the reader a good base for understanding the different aspects of the topic and can serve as a base for deeper studies

Tab. 1: Visual cueing

ENVIRONMENT CHARACTERISTICS		
Adherence	drivers were able to discriminate different conditions of Loss of adherence (LOA) without vestibular feedback cues (fixed-base simulator); effect of intensity on duration, danger and intensity perception, fear and feeling of control significantly higher for longer LOA	[12]
Road surface	reaction time shorter with road markings; shorter intervals of road marking lead to longer response time; visual anticipation depends on visual cues included in road environment; environmental cues important for visual anticipation of collision & self-motion sensation	[13]
	realistic road roughness visualisation (coupled to corresponding acoustic and haptic feedback) improves perceived realism	[14]
	dot density of road texture has an significant influence on perceived speed; perceived speed with 10% dot density matches actual velocity best; perceived velocity more affected by image than sound information; perceived velocity improved by diversifying location of environmental objects	[15]
	higher chosen speed with abstract texture and no vertical markers present; no difference in simulator sickness and distance judgement; speed overestimation when driving without speedometer	[16]
Pattern on tunnel wall	no effect of pattern; more accurate estimation of TTC with higher approaching velocity	[17]
	pattern has no effect on lateral position or speed choice; no subjective favour for any pattern; access to speedometer had no effect	[18]
Road curvature	significant effect of curve radius on min. speed during curve negotiation; TLC as regulating mechanism for controlling speed (i. e. less experienced drivers compensate larger steering errors by choosing lower speed, so that constant TLC is maintained)	[19]
	lower speed with raised curve sharpness; correct subjective estimation of curve sharpness; left curves rated sharper than right curves; driving speed lower in left curves; no effect of age on ratings or speed selection	[20]
Lane width	visual feedback is used to control steering actions; variations in lane width and speed are compensated by steering choice in order to maintain certain safety margins	[21]
Surrounding traffic	general underestimation of distance; better position adjustments at higher speed; no effect on positioning error relative to distance between cars; performance better when targets did not move; performance improved with increase in speed and decrease in distance between vehicles; driving experience most important in differentiation of subjects' performances	[22]
	significant effects for vehicle type (motorcycle, compact car, full-size car, van) and viewing distance on time-to-arrival estimations before a left-turn; overall underestimation of time-to-arrival	[23]
	increased speed in surrounding traffic makes subjects drive faster during free driving on a highway	[24]
Objects near / far / peripheral	approaching peripheral stimulus appears slower than identical central stimuls; no effect of duration	[25]
VIEWING CONDITIONS		
Fog / snow / dust	no effect of fog on speed perception; overestimation of headway; headway perception improved by appropriate rear fog-light	[26]
	increase in the perceived distance of vehicles in fog as compared with normal visibility conditions; overall distance overestimation, effects reduced when using more than one light	[27]
	lower speed in foggy condition	[28]
	higher speeds in foggy condition	[29]
Image contrast	visual contrast between lead vehicle and road surface has larger impact on car following behaviour than field of view, motion or sound	[30]
	vehicle speed harder to discriminate and appears slower with reduced image contrast	[31]
Viewing distance	significant effects for vehicle type (motorcycle, compact car, full-size car, van) and viewing distance on time-to-arrival estimations before a left-turn; overall underestimation of time-to-arrival	[23]
Luminance	change of luminance has minor effect on the perception of motion-in-depth	[32]
	higher circular vection (CV) velocity and shorter latency with high luminance in the central vision field; CV velocity and CV latency depend on spatial frequency	[33]
Resolution	motion feedback and reduced blurred image leads to lowest simulator sickness; image quality is an important factor for reducing simulator sickness	[34]
	better sign readability with higher resolution; higher subjective ratings for environment clarity and realism	[35]
	increasing the spatial resolution leads to a significant increase in visibility; the level of spatial and temporal resolution has to be almost equivalent	[36]
	no significant effect of image resolution on validity of speed choice and lane position	[37]
	speed choice more closely matches the real world driving with a narrow FoV and high resolution; contrariwise lane position is closer to real world driving with wide FoV and low resolution	[38]
Motion blur	significant effect of motion blur on perceived speed; underestimation of speed decreases with motion blur	[39]
SCENE COMPLEXITY		
Ground scene complexity	increase of scene complexity leads to better performance in altitude control; estimates of altitude highly dependent on distance from impact point (more accurate estimating at closer distances and lower altitudes)	[40]
Level of detail	improved altitude judgements through level-of-detail constancy	[41]
SHADOWS		
Moving shadows	detection of an “approaching” target defined by moving cast shadows is faster than the detection of a “receding” target	[42]

	information provided by the motion of an object`s shadow overrides other strong sources of information and perceptual biases; natural constraint of shadow darkness plays a role in the interpretation of moving image patch as a shadow	[43]
Motion-in-depth	The visual system is more sensitive to expanding convex circles (impression of approaching objects) ; anisotrophy for the perception of motion in depth caused by shading cue	[32]
FIELD OF VIEW		
Virtual image scale factors	significant effect of visual scale factor; perceived speed increases with higher visual scale factors; modification of the geometric FoV (GFoV) remained unnoticed; perception of distances may be affected	[44]
	visual speed is underestimated for GFoV/FoV ratios of 1 or below; larger GFoV/FoV ratio leads to reduced errors in perceived speed	[45]
	both, minification and magnification of the image scale factor leads to greater sickness symptoms than in neutral condition; no effect of changes in time delay	[46]
Degree of FoV	FoV has less impact on car following behaviour than visual contrast between lead vehicle and road surface	[30]
	no effect of FoV on performance	[47]
	wide FoV (230 degrees) improves speed keeping and lane selection performance when compared to actual on road driving	[37]
	speed choice more closely matches the real world driving with a narrow FoV and high resolution; contrariwise lane position is closer to real world driving with wide FoV and low resolution	[38]
	strong underestimation of distances in observing proximal objects with reduced FoV; no effect of monocular/binocular vision on distance estimation	[48]
Relative point of view	with high eye height (relative to the road) subjects tend to drive faster with more variability and less consistent lane position keeping; no effect of eye height on following distance	[49]
	low vertical angle of the driver's view-point lead to a higher perceived velocity; minimized difference between actual and perceived velocity with a vertical angle of about -3 deg	[15]
Peripheral view	peripheral stimulus approaching subject appears slower than identical central stimulus; no effect of duration	[25]
OPTICAL FLOW		
Optical-flow stimuli	motion-in-depth information can bias perceived stereoscopic-based depth; with simulated motion towards the observer objects appear closer to observer than the depth signalled by disparity information; simulated motion away from the observer made it seem further away	[50]
	observers are more sensitive to contracting than to expanding patterns with large-field stimuli	[51]
	linear relationship of perceived and real distance, but consistent undershoot of absolute magnitude; motion simulation has no effect on distance judgement	[52]
	using a vertically oscillating display leads to more severe simulator sickness and stronger vection ratings	[53]
	drivers slow down with increased optic flow and speed up with slower optical flow	[28]
	perceived self-speed increases with stimulus area; perceived self-speed in central and peripheral conditions increase with circular border size; retinal image velocity strongly contributes to perceived self-speed	[54]
Observer vs. Target motion	dominant nature of the visual condition for the discrimination of forward linear translation	[55]
	perceived TTC shorter during observer motion; overestimation of actual TTC; significant interaction between motion type and closing speed; overestimation of TTC decreases as the proportion of observer motion increases	[56]
	objects perceived to have higher closing speed when self-motion and object-motion are in same direction; effect saturated with increase in ratio between the speeds of self- and object-motion; perceived direction of object-motion-in-depth (MID) shifted towards focus of expansion of the flow pattern	[57]
	overestimation of TTC, significant difference in the estimated TTC for observer vs. target motion only for high closing velocities	[58]
	saturated vection more robust for translations than for rotations; subjects didn't perceive any visual scene deceleration; subjects did perceive sudden changes in self- and visual scene velocity	[59]
Degree of FoV	visual flow perturbed spatial orientation, but effect varied as a function of the visual information provided; wide-angle display caused high levels of postural sway in the conditions of forward motion; omitted central field of 30° with added horizon-line effects at relatively high levels for y-translation and x-rotation; greater separation of peripheral screens from the central screen generated decreased display effectiveness	[60]
	strong underestimation of distances in observing proximal objects with a reduced FoV for both, real and virtual scenes; the more FoV is reduced the more underestimation can be observed	[48]
VISION		
Monocular vs. Binocular	no effect of monocular/binocular vision on distance estimation	[48]
	binocular information about MID helps to reduce biases in perceived speed and direction	[57]
	positioning errors smaller with monocular than binocular viewing; driver performance shows distance underestimation with monocular as well as with binocular vision; target cars were perceived farther in depth and more accurately using monocular vision in sections where significant performance differences occurred; alignment with static cars turned out to be easier than tasks with cars in motion	[61]
Projector characteristics	better driving performance using a projection system compared to usage of an head-mounted-display	[47]
	different technologies of projectors as they are relevant for the use in driving simulation are mentioned including their basic properties various testing procedures and gained experiences; the influence of spatial and temporal resolution is explained	[36]

	turning cabin and/or projectors while cornering; indication that not only the bodily sensation but the image quality is important factor in order to reduce simulator sickness	[34]
VERGENCE		
Disparity	conflict between disparity and perspective contributes to depth contrast	[62]
	vergence induced by disparity change is an effective cue for motion in depth; looming gives stronger cues when looming and disparity are in conflict	[63]
Perspective Convergence	the visual system uses perspective convergence to perceive slant and the effective use of convergence requires the presence of spectral components aligned with the tilt direction; in case of nearly frontal surfaces perspective convergence becomes the primary factor when available and has greater influence on perceived slant than the combined contributions of size, density, or other gradient texture cues	[64]
CAR-RELATED		
Visual tilt	adding visual tilt leads to better control and higher stopping accuracy of braking	[65]

Tab. 2: Acoustical cueing

CAR RELATED		
Combined feedback	sound has less impact on car following behaviour than visual contrast and vehicle dynamic cues	[30]
	only with combined high quality haptical, acoustical and visual feedback, extra strain on the driver is minimised and simulator experiments will produce reliable outcomes	[66]
	vehicle feedback is strongly associated with driver's situational awareness (SA) ; the addition of non-visual vehicle feedback increases SA above vision alone; drivers seem not to be self-aware of changes in the presence/absence of different feedback signals; significant effect of auditory feedback compared to visual only condition; effect of auditory feedback combined with tactile feedback (under-seat resonators) and steering wheel feedback on sensitivity and SA compared to visual feedback alone	[67]
Engine sound	perceived velocity is accurate when sound is applied; with mismatch of visual and sound information the perceived velocity is more affected by image information	[15]
	adding auditory feedback (engine and aerodynamics noise) leads to earlier onset braking, less, but longer braking and increasing number of inversions of deceleration profile	[65]
	addition of engine sound significantly affected participants sensation of illusory self-motion	[68]
Tire sound	subjective rating of tire/road noise variations for different road surfaces; all roads received high mean ratings according to realism	[14]
	no significant effect of screeching tires on braking and cornering driving behaviour; adaptation of maximum deceleration over runs when screeching sound was added; subjectively rated as useful for adaption of cornering speeds	[11]
ENVIRONMENTAL		
Wind noise	Adding auditory feedback (engine and aerodynamics noise) leads to earlier onset braking, less, but longer braking and increasing number of inversions of deceleration profile	[65]
3D-SOUND		
auditory-induced vection	An auditory aftereffect occurs from adaptation to visual motion-in-depth; adaptation to combined auditory and visual stimuli changing in compatible directions increases magnitude of aftereffect; sound intensity changes do not cause a visual aftereffect	[69]
	sound source characteristics (type) is a determinant of auditory-induced vection; type plays minor role when multiple sound sources are present, indication for an increase of vection by realistically rendered environment sounds; high probability that interaction between type of sound source and environment is of importance	[70]
	moving sound stimuli add to visual induced vection; no effect of non-moving/ambient sound sources; mono sound increased convincingness of self-motion illusion	[71]
	significant auditory after-effects following adaptation to unisensory auditory and visual motion in depth; auditory effects can fill-in sparsely sampled visual motion	[72]

Tab. 3: Haptic cueing

CAR-RELATED		
Belt force	effect of seatbelt tensioning system on braking behaviour: maximum decelerations are lower, earlier braking, better stopping position consistency, lower braking onset jerk; subjective rating showed that seatbelt force-feedback improved realism	[11]
Pedals	a stiffer brake pedal leads to better stopping consistency, lower maximum decelerations and lower onset jerk; rated as more realistic than soft pedal	[11]
Seat	effect of vibration seat on speed choice in curve driving; no effect of pressure seat	[11]
	vehicle feedback is strongly associated with driver's situational awareness (SA) ; the addition of non-visual vehicle feedback increases SA above vision alone; drivers seem not to be self-aware of changes in the presence/absence of different feedback signals; effect of auditory feedback combined with tactile feedback (under-seat resonators) and steering wheel feedback on sensitivity and SA compared to visual feedback alone	[67]
Steering wheel	small effect of vibrating steering wheel; vibrations lead to lower onset jerk	[11]
	effect of different steering feedback modalities on driver behaviour; only with combined high quality haptical, acoustical and visual feedback extra strain on the driver is minimised and simulator experiments will produce reliable outcomes	[66]
	vehicle feedback is strongly associated with driver's situational awareness (SA) ; the addition of non-visual vehicle feedback increases SA above vision alone; drivers seem not to be self-aware of changes in the presence/absence of different feedback signals; no effect of steering wheel feedback on increasing	[67]

	SA on its own; effect of auditory feedback combined with tactile feedback (under-seat resonators) and steering wheel feedback on sensitivity and SA compared to visual feedback alone	
	driver are able to adapt their behaviour to a range of different steering feedback configurations; control of vehicles in curves possible with both linear and non-linear torque feedback; driving almost impossible with zero torque or inverted torque feedback	[73]
MISCELLANEOUS		
Road roughness	Realisation of road roughness related vibrations; subjective rating of simulated vibrations caused by different road surfaces lead to high mean ratings according to realism	[14]
Vibrotactile feedback	clear improvement of response time due to the use of vibrotactile feedback; vibrotactile cues are slightly more efficient than sound	[74]

Tab. 4: Vestibular cueing

MOTION CHARACTERISTICS		
Activated vs. deactivated	motion feedback leads to improved altitude judgements; no effect on control of climb rate or descent rate	[41]
	with motion the braking duration is shorter and the onset of braking later; small additional longitudinal motion cues lead to higher stopping accuracy; significant interaction between speed and motion	[65]
	with motion feedback the drivers are closer to the optimal speed as compared to the no-motion condition; effect of a motion platform on speed choice strategy: greater safety margin, higher level of lateral acceleration; underestimation of driving 'danger' in the no-motion condition due to a poorer anticipation of lateral acceleration based on visual cues only	[75]
	motion feedback leads to more realistic deceleration levels; braking strategy remains stable in presence of motion cues; lateral cues influences the drivers choice of driving trajectory; longitudinal cues influences linear velocity in turns	[76]
	yaw motion cues have large impact on pilot performance; translational motion cues improves performance and increase fidelity; if translational motion was present, addition of yaw motion provided only little additional benefit to performance, workload, compensation or fidelity	[77]
	motion has less impact on car following behaviour than visual contrast and vehicle dynamic cues	[30]
	simulator translational motion had a larger impact on perceived motion fidelity and motion perception than yaw motion; simulator sway reduced control activity and therefore pilot workload	[78]
Visual-vestibular interaction	dominant nature of the visual condition for the discrimination of forward linear translation (heading) due to less uncertainty	[55]
	sensation of linear self-motion becomes more realistic when applying whole body tilt; tilt rate shall remain below 3 deg/s	[6]
	both visual and vestibular cues are used to estimate the self-motion	[79]
Jerk	both jerk and acceleration contribute significantly to the perceived strength of motion; rating of motion larger for some conditions with lower level of acceleration when presented jerk was larger	[80]
	strong effect of jerk on linear motion detection thresholds	[81]
Motion sickness	habituation greater for longer exposure and more severe motions; pitch and roll motion failed to increase motion sickness incidence	[82]
MOTION CUEING		
Motion cueing parameter	with large motion (high scaling, optimized filters) pilot-induced oscillation and handling qualities ratings matched flight data more closely; large motion feedback increased pilot confidence, reduced safety pilot interventions and lowered touchdown velocities	[83]
	roll and lateral motion gain variations have significant effect both on pilots perception of motion fidelity and on handling quality ratings; subjective and objective measures decreased for lower gains	[84]
	scaling around 0.45 is optimal according to controllability of the vehicle and perceptual rating of combined visual and motion feedback	[85]
	the preference for a certain motion cueing feedback is more depending on the parameter choice than on the applied motion cueing algorithm (comparing classical washout and lane dependant approaches); best performance and ratings are reached with a 0.5 scaling and a lane dependant approach	[86]
	different expert driver prefer different parameter settings	[87]
	tilt coordination is to be avoided if possible; if used, tilt with rather unrestrictive rate in order to avoid time lags in signal presentation; use the drivers head as tilting point; chose filter parameter such that the need to washout signals is reduced; preferably apply weak washout;	[88]
Cueing method	vector substitution vs. leaning vehicle method; with leaning vehicle method the motion were rated as more natural subjects judged curves more correctly	[89]
	With offline motion cueing it is possible to produce the best possible representation of a specific driving manoeuvre for a given motion system	[90]
	In order to get a well performing motion feedback, the difference between algorithms (classical, optimal, adaptive) is to a great extend the effort in getting a good parameterisation; the classical algorithm seems to be a good starting point; gradually introduction of adaptive elements should be advantageous	[91]
	When designing a motion cueing algorithm, consider to avoid tilt coordination, compensate for washout false cues and use the road position for lateral cueing	[88]
Masking cues	no significant effect of heave masking cue on pitch rate perception threshold frequency description	[92]
	motion detection performance may be expressed as a function of the signal-to-noise ratio; random motion can mask a sinusoidal signal; the masking is most effective when containing frequency components near the signal frequency	[93]
	mentally "loading" subjects with additional tasks considerably increases motion perception thresholds	[94]

The analysis of the literature study revealed two aspects with a strong need of more exploration:

1) Most of the examined studies mainly (or exclusively) used the chosen driving speed as criterion for the evaluation of perceived speed or perceived overall motion. This seems to be problematic as the final driving speed is not only depending on the perceived speed, but also on the gas and brake pedal characteristics of the simulator and the sensitivity of the vehicle model to driver inputs. In order to avoid this closed loop between driver action and motion perception, a method that presents a certain motion to the driver and focuses the driver's task on perception and estimation seems to be favourable. The chosen experimental approach, which aims for assessing different speed-perception evaluation methods, is explained in the following section.
2) Among the different types of cues, the field of visual perception has been most thoroughly investigated so far. The majority of the examined articles focus on the investigation of one or two single factors. Only a few discuss the visio-vestibular interaction (see Tab. 4). None is considering and comparing all four types of motion cues in the context of motion perception (Walker et al. [67] compare all cues, though with a strong focus on situation awareness). Thus, there is still a great need for understanding the overall relation between certain cues on speed perception. This problem shall be explored in a later study.

Simulator experiment design

An experiment was performed with the aim to evaluate primarily two methods for measuring driver's estimation of speed in a fixed-base driving simulator. Among several methods tested in simulator pilot-tests, prior to the experiment, the passive driving approaches "forced choice paired comparison" and "staircase paired comparison" were considered most suitable. The experimental sequence that was used in both methods, shown in Fig. 2, is adapted from a study on motion blur by Breithecker et al. [39]. The sequence uses masks to separate the presentation of two driving scenes with different speeds (i.e. different optical flow).

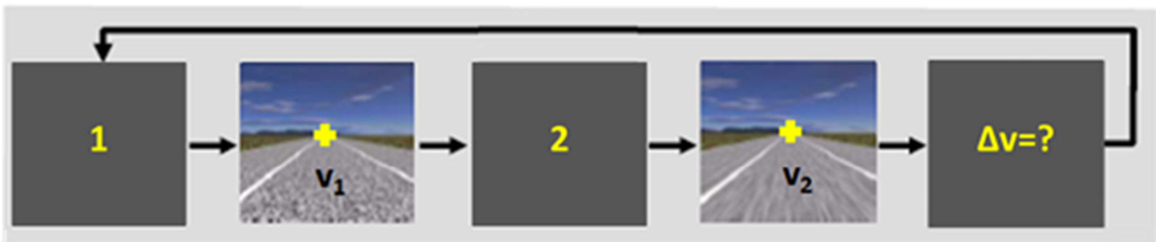

Fig. 2. Passive driving sequence (adapted from [39])

The used road was a normal straight road with no bricks or patches and without curves or intersections. The surroundings had no "regularities" at all (i.e. no dashed centre line, no delineators, no guide posts, no alley) in order to avoid cues that enable speed estimation based on counting seconds between certain objects or similar strategies. Only randomly distributed trees were placed in the surroundings to support the participant in the speed estimation tasks.

Besides the different speeds used, the main independent variable was the field-of-view of the visual presentation, which had two levels consisting of 45 and 180 degrees horizontally. Field-of-view has been shown to have an influence on speed choice and lane-keeping performance (e.g. [37, 38, 95]). We therefore hypothesised that the field-of-view could be used to reveal which speed estimation method is most sensitive. That is, if one of the methods shows levels of speed estimates dependent on the field-of-view the method would be judged more sensitive.

In the experimental scheme, shown in Fig. 3, the order of both the passive driving methods (PD) and the field-of-view settings (FoV) were balanced between participants.

	1.PD							2.PD				
Introduktion Training	Baseline before 1. FoV	1.Run 1.FoV	Break	Baseline before 2. FoV	2.Run 2.FoV	Break	Training	3.Run 1.FoV	Baseline after 1. FoV	Break	4.Run 2.FoV	Baseline after 2. FoV

Fig. 3: Experimental scheme

Based on the experiences of the pilot tests we further hypothesised that the resulting speed perception threshold will vary with the direction of speed change, that is whether the second speed is higher (corresponding to an acceleration) or lower (corresponding to a deceleration). More specifically, we expected higher thresholds for decreasing speeds. Only visual cues were presented (no sound, no physical motion, no haptic feedback).

A within-group design was used. The participants were 13 men and 3 women with a mean age of 42 years and a mean driving experience of 20 years. The speedometer was turned off during the whole experiment.

Forced choice paired comparison

In the forced choice paired comparison, successfully used by e.g. Haycock and Grant [80], either the first or the second scene is one of four base speeds (30, 50, 70 or 90 km/h). The other one shows an additional speed of +1, +5 or +10 km/h. For example, for the base speed of 30 km/h six different pairs of speeds are obtained including both increasing and decreasing speed: 30-31, 30-35, 30-40, 31-30, 35-30 and 40-30. The participant's task was to make a judgement of how the second speed of each pair differed from the first by responding with one of the six forced choice alternatives: -10, -5, -1, +1, +5, or +10 km/h. The total number of pairs of speeds was 24 (four base speeds with six pairs each) for each of the two levels of visual field, and each participant evaluated all 48 pairs. The presentation order of the pairs was varied over participants to avoid order effects.

Staircase paired comparison

In the staircase paired comparison, described by Ehrenstein and Ehrenstein [96], the participant also judges the speed difference between two different scenes. As opposed to the forced choice paired comparison, the staircase method requires the participant only to judge whether the presented velocities were different or not. If the response is "yes" (a difference), the speed difference is lowered for the next presentation of pair of speeds, and if the response is "no" (no difference) the speed difference is raised for the next pair. The aim of such a staircase method is to reach the threshold for perceiving a change of a given stimulus, which in this case is the speed difference to a certain base speed (Fig. 4, left). Ehrenstein and Ehrenstein propose to use two interleaved staircases were one initial stimulus is chosen to be below the expected threshold value and the other one above (Fig. 4, right). This reduces the risk that the participant notices the logic behind the staircase variation and thus increases the probability for establishing an unbiased threshold value.

Because this method is quite time consuming, the experiment design considered only two base speeds for the exploration of speed perception thresholds, which were 50 and 90 km/h. Each base speed included a fixed staircase sequence of 24 trials that was performed for both levels of visual field. A variable step size between the trials were used in order to be able to use a start value which is reasonable far away from the expected threshold range, to approach the threshold region with only a few trials, and then to have the major parts of the trials within the threshold range. Thus the step size was first set to 5 km/h and after the first changes of answer (i.e. previous answer was "yes" but actual answer is "no" or the other way round) it was reduced to 3 km/h, then 2 km/h and finally to 1 km/h. In the single staircase example given in Fig. 4, between trial 1 and 4 the step size would be -5 km/h, after trial 4 it would be +3 km/h, after trial 5 -2 km/h and in the following + or – 1 km/h. Furthermore, both starting stimuli were chosen to be above the expected threshold value, but with the lower speed presented first in one sequence (speed increase from scene 1 to scene 2) and the higher speed presented first in the other sequence (speed decrease). As mentioned above, differences in threshold values related to this condition (speed increase or decrease) were hypothesised based on the experience gained from the pilot-tests.

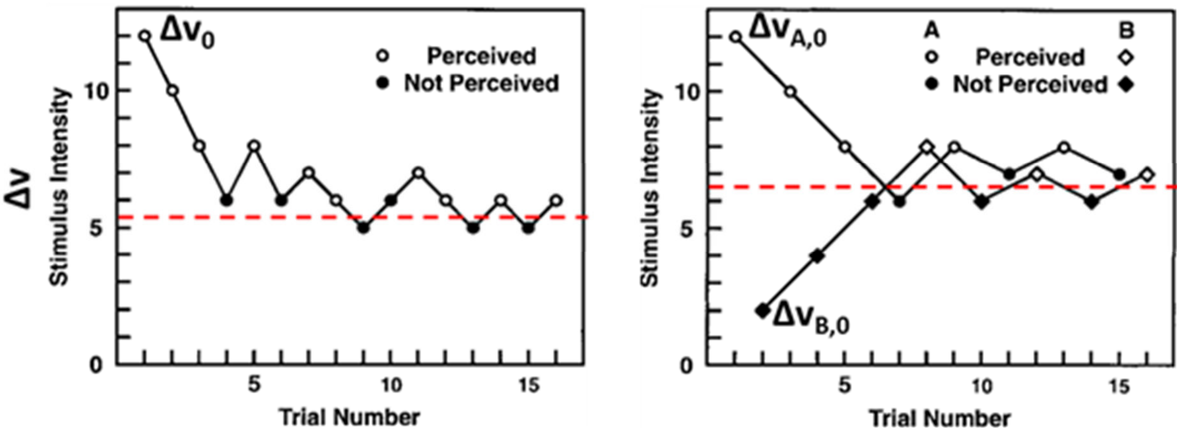

Fig. 4. Staircase method sequence in order to obtain a threshold for perceiving change of a certain stimulus (here: speed difference), Left: single staircase, Right: Two interleaved staircases. Adapted from Ehrenstein and Ehrenstein [96]

Baseline driving

A baseline task was performed to obtain indications of driver ability to estimate absolute speeds. The participant was passively accelerated and the task was to judge when a certain target speed was reached. The target speeds were 30, 50, 70 and 90 km/h. Each speed was estimated twice, once starting with an initial speed of 0 km/h (estimation during acceleration) and once with an initial speed of 120 km/h (estimation during deceleration), for each level of visual field. The participant indicated reached target speed by pressing a button on the steering wheel.

Questionnaires

Before and after the experiment, each participant answered a questionnaire about physical and mental states based on the simulator-sickness questionnaire (SSQ), described in Kennedy et al. [12], that includes a four-point rating scale for each of 16 stated symptoms. After the experiment, some additional questions were answered on 7-point rating scales:

- *How was the speed perception with the narrower/broader presentation field?*

Not at all realistic			Neither … nor			Very realistic
☐	☐	☐	☐	☐	☐	☐

- *How good judgments/responses did you make with the narrower/broader presentation field?*
- *How good judgments/responses did you make when only responding by indicating whether there was a difference or not?* [Staircase paired comparison]
- *How good judgments/responses did you make when responding by indicating how large the difference was?* [Forced choice paired comparison]
- *How good judgments/responses did you make when responding by indicating when a specific speed was reached?* [Baseline driving]

Very bad			Neither … nor			Very good
☐	☐	☐	☐	☐	☐	☐

Results

The following paragraphs show the results of the statistical analyses of the logged data from the simulator experiment as well as of the responses in the questionnaires filled in by the participants.

Forced choice paired comparison

An analysis of variance (ANOVA) for repeated measures was conducted with the design of field of view (2) × base speed (4) × speed sequence (6).

The ANOVA showed significant main effects of base speed, $F(3, 45) = 3.66$, $p < .025$, and speed sequence, $F(5, 75) = 52.28$, $p < .0001$, and a significant interaction effect of base speed by speed sequence, $F(15, 225) = 2.50$, $p < .01$, with no other significant effects. The interaction effect is shown to the left in Fig. 5.

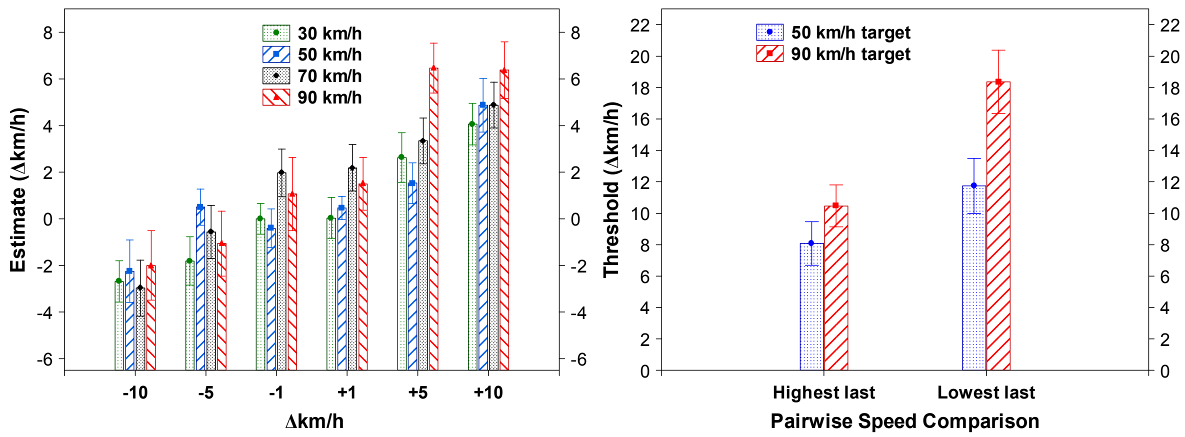

Fig. 5. To the left, the significant interaction effect of base speed by speed sequence with the forced choice paired comparison; to the right, the significant interaction effect of base speed by speed sequence with the staircase paired comparison

Staircase paired comparison

An ANOVA for repeated measures was conducted using the design of field of view (2) × base speed (target) (2) × speed sequence (2).

The ANOVA showed significant main effects of base speed, $F(1, 15) = 54.71$, $p < .0001$, and speed sequence, $F(1, 15) = 19.89$, $p < .001$, and a significant interaction effect of base speed by speed sequence, $F(1, 15) = 6.24$, $p < .025$, with no other significant effects. The interaction effect is shown to the right in Fig. 5.

Baseline driving

An ANOVA for repeated measures was conducted using the design of time (2) × field of view (2) × speed sequence (2) × speed (4). The time variable included the two conditions of baseline driving "before" and "after" using the respective paired comparison methods, the field of views were 45 and 180 degrees, speed sequence included the conditions of acceleration and deceleration phases, and the category speed referred to the target speeds of 30, 50, 70, and 90 km/h.

The ANOVA showed a significant main effect of speed, $F(3, 45) = 348.67$, $p < .0001$, and a significant interaction effect of speed sequence × speed, $F(3, 45) = 15.67$, $p < .0001$, with no other significant effects. The significant interaction effect is shown to the left in Fig. 7. However, there was also a tendency of a three-way interaction effect of field of view, speed sequence, and speed, $F(3, 45) = 3.31$, $p = .06$, which is shown to the right in Fig. 7.

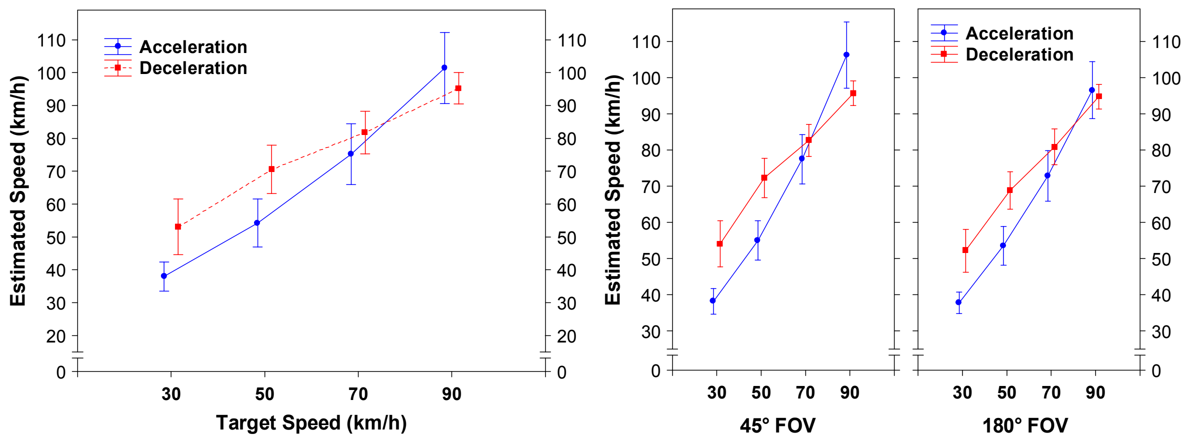

Fig. 6. To the left, the significant interaction effect of speed sequence by speed with the baseline driving. To the right, the tendency of a three-way interaction effect of field of view by speed sequence by speed with the baseline driving.

Questionnaires

The questionnaire data were analysed with several non-parametric Wilcoxon matched pairs test.

There was a significant difference in speed perception quality between the 45° and the 180° fields of view ($p < .01$). The broader 180° was considered to give a significantly more realistic experience of speed (to the left in Fig. 8). There was also a significant difference in positive speed perception quality between the 45° and the 180° fields of view ($p < .025$), showing that the 180° was considered to give a significantly more positive experience of speed (to the right in Fig. 8).

There was a significant difference in self-estimated response quality between the 45° and the 180° fields of view ($p < .05$) in which the 180° was considered to lead to significantly better speed perception estimations (to the left in Fig. 9). The difference in response quality between the forced choice paired and the staircase paired comparison methods was also significant ($p < .05$), with the staircase paired comparison method considered to enable significantly better speed perception estimations (to the right in Fig. 9).

Further, the significant difference in response quality between the forced choice paired comparison and the baseline driving methods ($p < .025$) shows that the baseline driving method was rated to enable significantly better speed perception responses (to the left in Fig. 9). (There was no significant difference in response quality between the staircase paired comparison and the baseline driving methods ($p = .083$).) Finally, there was no significant difference in total SSQ scores between before and after the experiment ($p = .06$). However, it indicates a tendency of a slight effect of simulator exposure on simulator sickness symptoms (to the right in Fig. 9).

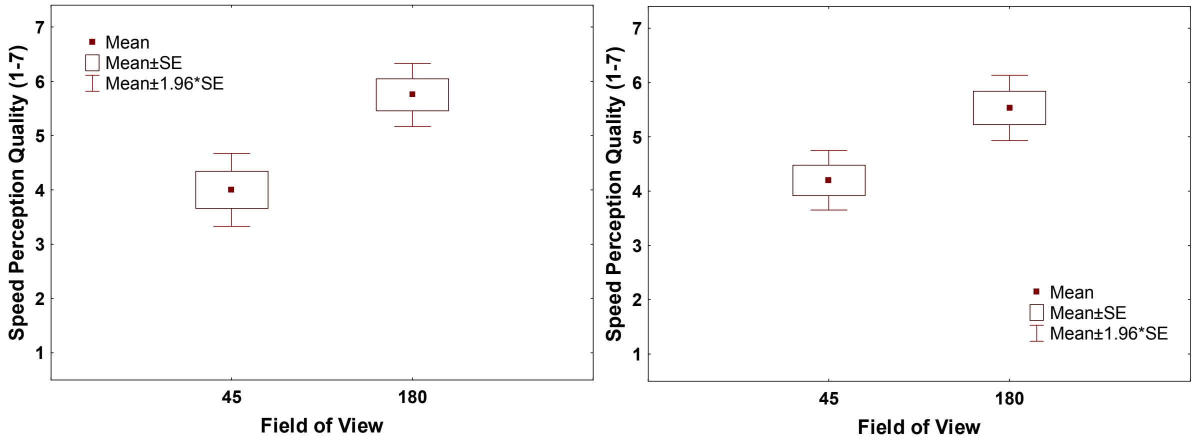

Fig. 7. To the left, the significant difference in realistic speed perception between the two visual fields. To the right, the significant difference in positive speed perception between the two visual fields.

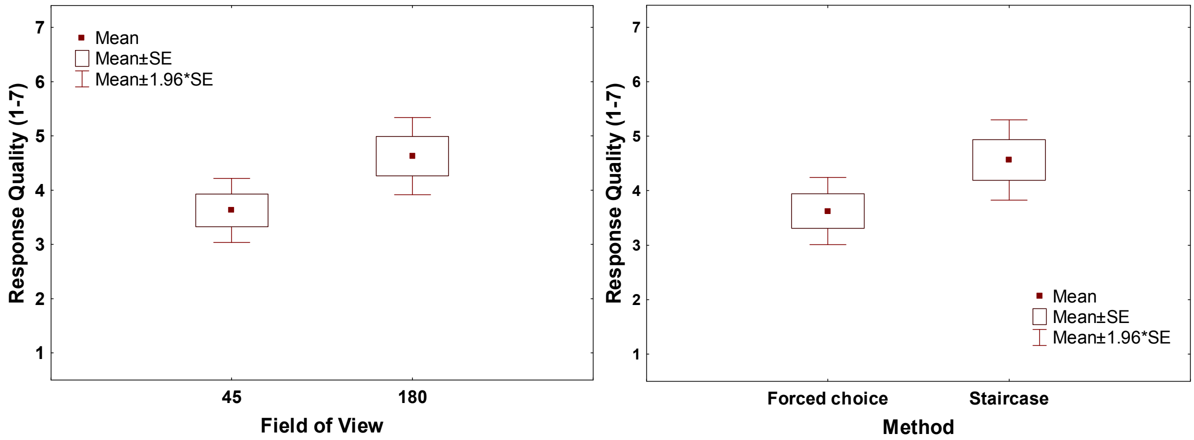

Fig. 8. To the left, the significant difference in judgment/response quality between the two visual fields. To the right, the significant difference in judgment/response quality between the forced choice paired comparison and the staircase paired methods.

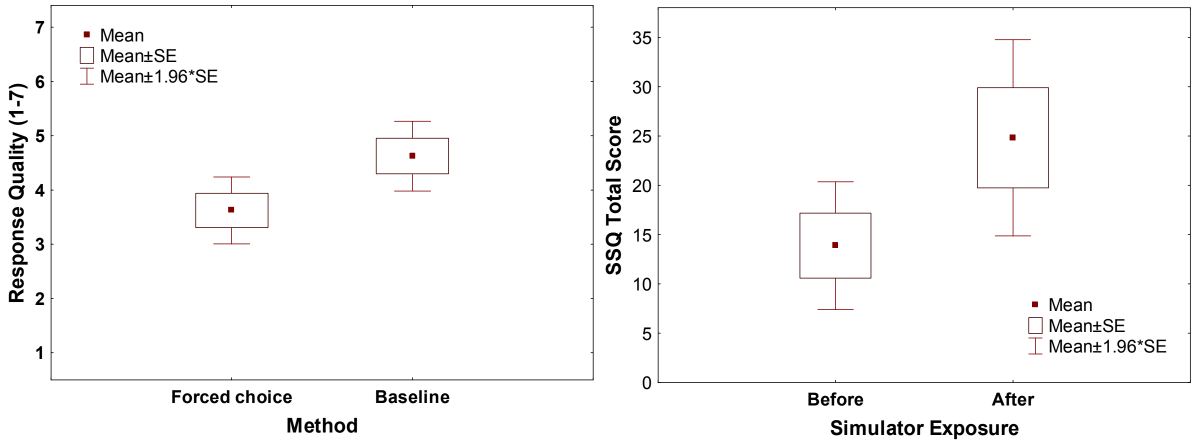

Fig. 9. To the left, the significant difference in judgment/response quality between the forced choice paired comparison and the baseline driving methods. To the right, the non-significant difference in SSQ total score between before and after simulator exposure.

Summary and conclusions

Presenting the lowest speed last in a paired speed comparison makes it more difficult to judge the difference correctly, as indicated by the results from both the forced choice paired comparison and the staircase paired comparison method. Hence, the threshold for perceived speed differences is substantially higher for decreasing speeds. In addition, the forced choice paired comparisons indicate that speed differences with the base speeds of 70 and 90 km/h are more correctly judged when the highest speed is presented last.

The staircase paired comparisons show that the threshold values for both base speeds, 50 and 90 km/h, are in the same range when the highest speed is presented last, whereas the threshold is significantly higher for 90 km/h when the lowest speed is presented last. However, the threshold values increase for both based speeds when applying a speed decrease compared to speed increase.

The results of the baseline driving show that the lower speeds of 30 and 50 km/h are more correctly judged when accelerating. At the higher speeds of 70 and 90 km/h there is no difference in speed judgement between accelerating and decelerating. The baseline driving results also indicate a tendency of an interaction effect including field of view, which may imply that at 90 km/h with the smaller field of view the speed may be more overestimated during acceleration than during deceleration.

The questionnaire results reveal that the larger field of view is preferred in terms of more realism, more positive experience, and better judgment/response quality of the speed perception. Both the methods of staircase paired comparison and baseline driving were rated to entail better judgment/response quality than the method of forced choice paired comparison. Finally, the SSQ total scores indicate a tendency of a slight effect (i.e. non-significant) of simulator exposure on simulator sickness symptoms.

Our conclusion is that the hypothesis of higher thresholds for speed differences with decreasing speeds was supported, whereas the influence of the size of the field of view was not supported. At least there was a tendency of an effect of field of view with the baseline driving, and the participants in fact considered the larger field of view better in terms of realism, positive experience, and judgment/response quality. The most probable explanation for the performance result is that the scene was too simplified (e.g. no mid-line, no guide posts) so that the larger field of view did not add significantly to the speed estimation ability.

There was no clear advantage of either method of pairwise comparison for judging speed differences. However, the staircase paired comparison method was preferred by the participants, and it also has the advantage of flexible levels of speed difference (i.e. no predefined speed differences) that can make the method more valid for measuring speed perception. Furthermore, considering the identified threshold levels by using the staircase method, places the results of the forced choice method into the region of chance, as the used pre-defined speed variations are mainly below these threshold levels. Of course, these two methods are fundamentally different, with the staircase method specifically designed for finding just noticeable differences (i.e. JNDs). As such, and in agreement with the overall results, the staircase method seems to be preferable and will be used within the following experiments.

The baseline driving method for establishing absolute judgements of speed perception seems to be a good complement to methods for measuring the perception thresholds of relative speed differences.

A coming experiment shall try to quantify the importance of different sensory cues. Different combinations of sensory cues of motion will be explored in order to evaluate their effect on driving behaviour and speed perception. Both a passive estimation task (staircase paired comparison) and an active driving task will be included.

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