Development of a presence model for driving simulators based on speed perception in a motorcycle riding simulator

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EXECUTIVE SUMMARY

Driving simulators are powerful research tools. Countless simulator studies have contributed to traffic safety over the last decades. Constant improvements in simulator technology call for a measureable scale to assess driving simulators with regard to their utility in human factors research. A promising psychological construct to do so is presence. It is commonly defined as the feeling of being located in a remote or virtual environment that seems to be real. Another aspect of presence describes the ability to act there successfully.

The main aim of this thesis is to develop a presence model dedicated to the application in driving simulators. Established models have been combined and extended in order to gain a comprehensive model of presence that allows understanding its emergence and deriving recommendations on how to design or improve driving simulators. The five studies presented in this thesis investigate specific postulated model components and their interactions. All studies deal with motorcycling or a motorcycle riding simulator as exemplary field of application.

The first study used a speed estimation task to investigate the contribution of different sensory cues to presence. While visualization plays a particularly important role, further improvements could be achieved by adding more consistent sensory stimuli to the virtual environment. Auditory, proprioceptive and vestibular cues have been subject to investigation. In the second study, the speed production method was applied. It confirmed the positive contribution of action to presence as predicted by psychocybernetic models. The third study dealt with the effect of training on presence. Hence, no positive effect was observed. The fourth study aimed at replicating previous findings on sensory fidelity and diversity in a more complex riding situation than only longitudinal vehicle control. The riders had to cross an unexpectedly appearing deep pit with the virtual motorcycle. The contribution of more consistent sensory stimulation on presence was successfully shown in this scenario, too. The final study was a real riding experiment that delivered reference values for the speed estimation capabilities of motorcycle riders. Besides higher variations in the simulator data, the general speed estimation performance was on a comparable level. Different measures, such as subjective ratings, behavioral responses, performance, and physiological reactions, have been applied as presence indicators.

These studies' findings deliver evidence for the meaningful application of the proposed presence model in driving simulator settings. The results suggest that presence can be interpreted as a quality measure for perception in virtual environments. In line with psychocybernetic models, taking action, which is seen as controlling perception, enhances this quality even further. Describing the psychological construct of presence in a theoretical framework that takes the diversity of perception and action in driving simulator settings into account closes a gap in traffic psychological research.

ZUSAMMENFASSUNG

Fahrsimulatoren sind leistungsfähige Forschungsinstrumente. Seit einigen Jahrzehnten konnte mit unzähligen Simulatorstudien zur Verkehrssicherheit beigetragen werden. Stetige Weiterentwicklungen der Simulatortechnologie machen einen Maßstab erforderlich, der es erlaubt, Fahrsimulatoren hinsichtlich ihrer Nützlichkeit für verkehrspsychologische Fragestellungen zu bewerten. Ein vielversprechendes in der Psychologie verwendetes Konstrukt ist Präsenz. Für gewöhnlich wird Präsenz als das Gefühl definiert, sich in einer entfernten bzw. virtuellen Umwelt zu befinden, die als real wahrgenommen wird. Ein weiterer Aspekt von Präsenz beschreibt die Fähigkeit in dieser Welt erfolgreich zu handeln.

Das Ziel der vorliegenden Arbeit ist es, ein Präsenzmodell für die Anwendung im Fahrsimulatorbereich zu entwickeln. Dafür werden bereits etablierte Präsenzmodelle aufgegriffen, kombiniert und um bestimmte Komponenten erweitert. Dies zielt darauf ab ein umfassendes Präsenzmodell zu etablieren, welches einerseits einen Erklärungsansatz zur Entstehung von Präsenz liefert und andererseits erlaubt, Gestaltungsempfehlungen für Fahrsimulatoren abzuleiten. Die fünf Experimente dieser Arbeit untersuchen spezifische Modellkomponenten und deren Zusammenspiel. Alle Studien befassen sich mit dem Motorradfahren bzw. einem Motorradfahrsimulator als exemplarisches Anwendungsfeld.

Die erste Studie verwendete ein Schätzverfahren für Geschwindigkeiten, um den Beitrag verschiedener Sinnesreize zu Präsenz zu untersuchen. Während der Visualisierung eine besondere Rolle zukommt, konnte die Präsenz durch die Hinzunahme weiterer sensorischer Stimuli in der virtuellen Welt noch gesteigert werden. Dabei wurden auditive, propriozeptive und vestibuläre Reize betrachtet. In der zweiten Studie wurde die Geschwindigkeitswahrnehmung mit Hilfe des Herstellungsverfahrens untersucht. Wie durch psychokybernetische Modelle vorhergesagt, hat sich die positive Auswirkung aktiven Handelns in der virtuellen Welt auf Präsenz bestätigt. Die dritte Studie befasste sich mit den Auswirkungen von Training auf Präsenz. Hier konnte jedoch kein positiver Zusammenhang festgestellt werden. Die vierte Studie zielte darauf ab, im Vorfeld gewonnene Erkenntnisse zur Vielfalt sensorischer Reize zu replizieren. Anstelle reiner Fahrzeuglängsregulation galt es, eine komplexere Fahrsituation zu bewältigen. Die Probanden mussten dabei mit ihrem virtuellen Motorrad einen unerwartet auftretenden tiefen Graben durchqueren. Der Beitrag vielfältiger sensorischer Stimulation auf Präsenz konnte auch in diesem Szenario erfolgreich gezeigt werden. Bei der letzten Studie handelte es sich um eine Realfahruntersuchung, die Referenzwerte zur Einordnung der Geschwindigkeitswahrnehmung im Motorradfahrsimulator lieferte. Außer höheren Schwankungen der Schätzwerte im Fahrsimulator bewegte sich die Güte der Schätzungen im Mittel auf einem vergleichbaren Niveau. Zur Messung von Präsenz wurden Befragungsdaten, Verhaltensmaße, Leistung und physiologische Reaktionen als Indikatoren herangezogen.

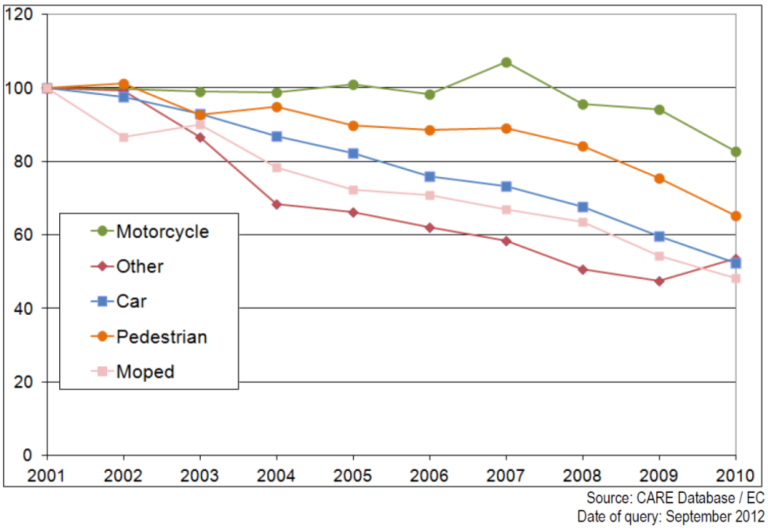
Die Ergebnisse der Studien belegen die sinnvolle Anwendbarkeit des vorgeschlagenen Präsenzmodells in der Fahrsimulation. Darüber hinaus zeigt sich, dass Präsenz als ein Gütemaß für Wahrnehmung in virtuellen Welten interpretiert werden kann. Psychokybernetischen Modellen folgend kann diese Qualität durch Handeln, welches als Kontrolle der Wahrnehmung gesehen wird, noch weiter gesteigert werden. Durch die Integration des psychologischen Präsenzkonstrukts in ein Rahmenmodell, welches der Vielfalt von Wahrnehmung und Handlung in Fahrsimulatoren Rechnung trägt, konnte eine Lücke in der verkehrspsychologischen Forschung geschlossen werden.

1 INTRODUCTION

4,228,238 and 84.74 – both numbers describe motorcycle riding in Germany somehow.

The first number indicates the number of registered motorcycles in Germany in January 2014 (DESTATIS, 2016). In the last 20 years, the stock of motorcycles in use has almost doubled. This ascending trend is not only a German but also a European and worldwide phenomenon. The so-called Powered Two Wheelers (PTW) are becoming an increasingly popular mode of transport as they are one possible answer to latest challenges such as pollution or traffic congestion and lack of parking space in metropolitan areas. Besides PTW use for commuting, there is a trend for bigger touring bikes on the market in combination with more high-mileage riding indicating PTW's popularity as leisure activity (Yannis et al., 2012).

The second figure stated above is the mean number of motorcycle casualties per day in Germany in 2014 (DESTATIS, 2015). Figure 1 compares the relative number of fatalities per mode of transport. Even if a positive development for motorcycles can be seen, the fatality rate could not be decreased comparably to other modes of transport. The risk of being involved in a fatal accident on a motorcycle is still about four times higher than in a passenger car (DESTATIS, 2015).



Source: CARE Database / EC
Date of query: September 2012

Figure 1: Fatalities per transport mode within EU-20 countries (Yannis et al., 2012, p. 6).

In order to assess this problem PTW safety became subject to different research activities. Technical improvements such as anti-lock braking systems (ABS) or traction control (Matschl, Mörbe, & Gröger, 2014) and environmental adaptations such as rider friendly road side barriers are pushed forward (Nicol et al., 2012). From a psychological point of view, measures focusing on perception and action of the rider are of special interest. One possible counter-measure to the high accident rate is rider training. For instance, improving motorcyclists' hazard perception and consequently riding skills has proved to be one promising solution (Boele-Vos & de Craen, 2015; Liu, Hosking, & Lenné, 2009). Another attempt is to assist motorcyclists in critical situations through advanced rider assistance systems (ARAS) such as a side view assist (Purschwitz, 2016). However, the interaction between motorcycle and rider needs to be assessed carefully. Visual warnings cannot be placed ideally because of the lack of space in a motorcycle cockpit and a limited field of view through helmet use. Noise damping helmets and exposure to wind and rain avoid classical auditory warnings that are well-known from passenger cars (Naujoks, 2015).

A well-established research method to train driver skills and to assess human-machine interfaces is the use of driving simulators. The advantages of this technology are obvious and manifold. The virtual environment can easily be adjusted to the study's needs. Rare hazardous situations occur meticulous and without endangering the driver respectively rider. Drivers' and riders' interaction with newly arising assistance systems can be optimized in early stages of the development process. As it is the case for car driving simulators, motorcycle riding simulators bear huge potential to contribute solutions to the safety challenges of these vulnerable road users. However, the above mentioned advantages can only be of consequence as long as motorcyclists accept the riding simulator adequately and behave as usual. One approach to ensure this is to replicate physical parameters of motorcycle riding as much as possible (e.g., vehicle acceleration, steering torque…). Admittedly, in close future, a motorcycle riding simulator will always be limited in terms of its ability to simulate motorcycling physically correct. Limited motion space of motion platforms and missing centrifugal force, to name just two examples, provoke different vestibular and proprioceptive sensations than real riding. Thus, another scale to optimize simulators is needed. One possibility is to adjust a simulator regarding its ability to create a virtual environment that facilitates to feel and act like being part of this artificial world. In human factors research, this psychological construct is called 'presence'. According to Slater and Wilbur (1997) presence is even a very important prerequisite to enable transfer from a virtual to a real scenario, for instance in training. The crucial underlying concept is that presence facilitates behavior in virtual environments that is similar to that in everyday life (Usoh, Alberto, & Slater, 2013). Originally, the concept of presence was used to describe the effect of telecommunication where one person could talk to another person in a remote environment. Later, the concept was taken up in fields such as game industry or psychotherapy to describe the experience of people in a virtually created environment. Due to this emergence, no presence model could simply be applied to driving simulators covering multisensory perception and complex action or performance likewise.

Therefore, the aim of this thesis is to develop a presence model for driving simulators. The postulated components and interactions of the model are subject to investigations in four studies. All studies focus on speed perception in a motorcycle riding simulator. A fifth study deals with the comparison of behavior observed in the riding simulator and during real riding in order to deliver a reference frame for the motorcyclists' behavior and performance on the simulator.

2 THEORY

The following chapter gives insights into the theoretical background of the fields of research that are related to this thesis' work. It starts with a brief introduction of driving simulators in the field of traffic sciences, followed by a summary of motorcycle riding simulators for research and development. Afterwards, psychocybernetic models are presented that provide an important psychological framework for this thesis' work to describe perception and action of human beings. Subsequently, an overview of existing theories on presence is given that lead to the development of a presence theory dedicated to be used for the assessment of driving simulators. The chapter closes with a short summary of findings on speed perception while driving.

2.1 Driving simulation in the field of traffic sciences

Simulation plays an increasingly important role in various fields of application. For instance, medics train complex surgery technics by using virtual environments (Kusumoto et al., 2006; Lin et al., 2014) and modern psychotherapy enables patients with phobic disorders to get in contact with their feared stimuli, such as spiders, in a controlled and safe environment (Eichenberg, 2007; Krijn, Emmelkamp, Olafsson, & Biemond, 2004; Mühlberger & Pauli, 2011).

Comparable remarkable advances of simulator use have been observed in the field of traffic sciences during the last three decades. It began with flying simulators. Then, driving simulators followed and became increasingly popular tools to investigate action and perception of operators steering airplanes or cars in a fully controlled environment. Up until now, a great variety of simulators is known in the field of traffic sciences and the expression 'driving simulator' covers quite heterogeneous setups. It starts from very generic versions using a combination of game steering wheel and computer monitor and ends with extremely expensive solutions including a completely equipped vehicle as mockup mounted on a motion base. Depending on their configurations, driving simulators are usually referred to as low-level, mid-level or high-level simulators (Kaptein, Theeuwes, & van der Horst, 1996; Slob, 2008). According to Carsten and Jamson (2011) the following components characterize a driving simulator:

- one or more monitors, projectors or a head-mounted display (HMD) for visualization,
- an input device to steer the vehicle ranging from a joystick or keypad to more or less realistic steering wheels, pedals or handlebars,
- a sound system to deliver acoustic feedback of vehicle and environment,

- a dashboard or cockpit, respectively their visual model, projected in the field of view of the mockup.

The increasing popularity of driving simulator studies in traffic psychology was driven by a variety of apparent advantages. All investigations can be conducted in a safe and controlled environment that facilitates reproducible conditions across participants and conditions. It is also easily possible to investigate situations that appear rather seldom in real life, such as avoiding a crash with a red light runner. Furthermore, the laboratory setting enables precise measurement of all relevant vehicle data (e.g., position on lane, velocity) as well as rider data (e.g., physiological parameters, eye-tracking). In the field of research and development another upside is added to the list: Advanced driver and rider assistance systems can be simulated and investigated early in the development process. This test procedure safes money and time.

On the other hand, driving simulators are complex and high-maintenance machines that claim for rather high investment. Even high-level simulators face limits in terms of realistic replication of vestibular or visual cues. For example, motion bases are limited in their freedom of movement and screens or head-mounted displays may not cover all directions with human eye-like resolution. The simulator driver has to cope with these shortcomings of missing or faulty sensory cues due to latencies between sensory stimulation which calls for more or less elaborate participant trainings. Finally, it has to be assured that external validity allows generalizing simulator findings to the appropriate real-world applications.

Depending on the specific research question, these advantages and disadvantages need to be weighted up against each other. Usually, a driving simulator study can be a useful addition to real driving investigations that focus on different aspects of the same research topic. These general remarks hold also true for the field of powered two wheelers.

2.2 Motorcycle riding simulators

The rise of motorcycle riding simulators for research and development can more or less be interpreted as a consequence of the above mentioned factors: a concurrence of increasing popularity of PTWs combined with an overrepresentation in accident statistics and the positive experience with simulator technology in the automotive sector. Furthermore, this development got pushed by recent advancements in the motorcycle sector. Upcoming comfort, infotainment and safety systems, such as ride mode adjustment, board computers or side view assist, call for redesigning motorcycles' display and control concepts. All these new functionalities need buttons, switches and levers to be adjusted and displays to communicate the system state to the rider (Guth et al., 2016; Will, Hammer, Pleß, & Guth, 2016). All this has to be done under the challenging conditions of limited space and field of view caused by helmet use in combination with exposure to environmental impact such as precipitation and glare, to name just a few. Therefore, this process opens a wide field of human factors research dealing with rider distraction or workload measurement that traditionally refers to simulator research (Buld, Will, Kaussner, & Krüger, 2014; Di Stasi et al., 2009; Will & Schmidt, 2015).

Generally, there is a certain bandwidth of motorcycle simulators ranging from entertainment and gaming over training to research and development. Two prominent examples of motorcycle simulators in the entertainment sector are the ifz-simulator (Institut für Zweiradsicherheit e.V.) and the Motorbike Simulator (VR-Project). They are, for instance, used as eye catchers on trade fairs and lack software interfaces, data recording and validated vehicle dynamics models. A second category of motorcycle simulators is designed for training purpose (see Figure 2). Prominent examples for this class are the models EF Scoot and EF Bike from ECA Faros or the Honda Riding Trainer respectively Honda Riding Simulator. These motorcycle simulators use realistic rider input concepts such as a fully functional handlebar. However, they have insufficient riding dynamics models, only a fix number of prescripted scenarios, deficient data recording and a lack of interfaces to modify rider feedback adequately. Therefore, these categories of motorcycle simulators are not suitable for research regarding presence.

Figure 2: Motorcycle riding simulators for training. Left: EF-Bike (ECA Group, 2016, p. 1). Right: Honda Riding Trainer (Honda Motor Europe (North) GmbH, 2005, p. 4).

The third category contains motorcycle simulators applied in the field of research and development. Table 1 contains a summary of the most important simulators with regard to the provided sensory stimulation. Most of the known motorcycle simulators belong to universities or research institutes. One exception to the rule is the MORIS simulator from Piaggio (Ferrazzin, Barbagli, Avizzano, Di Pietro, & Bergamasco, 2003). The simulator was used as a rapid prototyping tool (Nehaoua, Arioui, & Mammar, 2011). A scooter is mounted on a hydraulic 6 degrees of freedom (6 dof) Stewart platform. A servo-motor at the handlebar and a DC motor for engine vibrations deliver haptic feedback. Visualization is ensured via a retro projected screen and a not further defined acoustic subsystem is responsible for the sound.

Another motorcycle manufacturer that uses a simulator for human factors related research is BMW Motorrad (see Figure 3 left). A BMW K1600 GT is used as mockup with fully functional instrument cluster and control units. A front projection with a size of 3 x 4 m visualizes the virtual environment. Furthermore, two 46 inch TFT-monitors, located behind the rider, provide visual information for the rear mirrors. Auditory cues in form of real engine sound samples and environmental noise are provided by a 4.1 sound system. Structure-born noise actuators simulate engine vibrations in the chassis. Small ventilators on the left and right hand side of the handlebar account for air flow imitation. Further haptic feedback comes from a steering-torque motor actuating the handlebar. Proprioceptive stimulation is provided by a G-Vest which produces pressure on the rider's torso and imitates longitudinal accelerations. Finally, a 6 dof motion base delivers vestibular feedback to the rider.

Honda was the first OEM to develop a motorcycle riding simulator for research purposes in the late 1980s. After launching different complex prototypes, the major effort went into the development of the above mentioned Honda Riding Trainer that was successfully sold to driving schools back then. No further activity with riding simulators for research and development is known today. Yamaha is also said to operate a motorcycle riding simulator at their facilities in Japan, but once again no further information is available.

In order to investigate aspects of rider human factors and motorcycle ergonomics, a motorcycle simulator was designed at the University of Nottingham (see Figure 3 right). A sports motorcycle type Triumph Daytona 675 is used as mockup and mounted between pneumatic actuators that allow the motorcycle to roll while cornering (Stedmon, Brickell, Hancox, Noble, & Rice, 2012; Stedmon et al., 2009). All motorcycle controls are mechanically linked to automotive game controllers that deliver input to the STISIM-Drive software. Visualization is provided via a single front projection illuminating a surface of about 2.5 m^2. Surround sound is used to simulate engine noise as well as environmental sounds. No further haptic or proprioceptive cues are used.

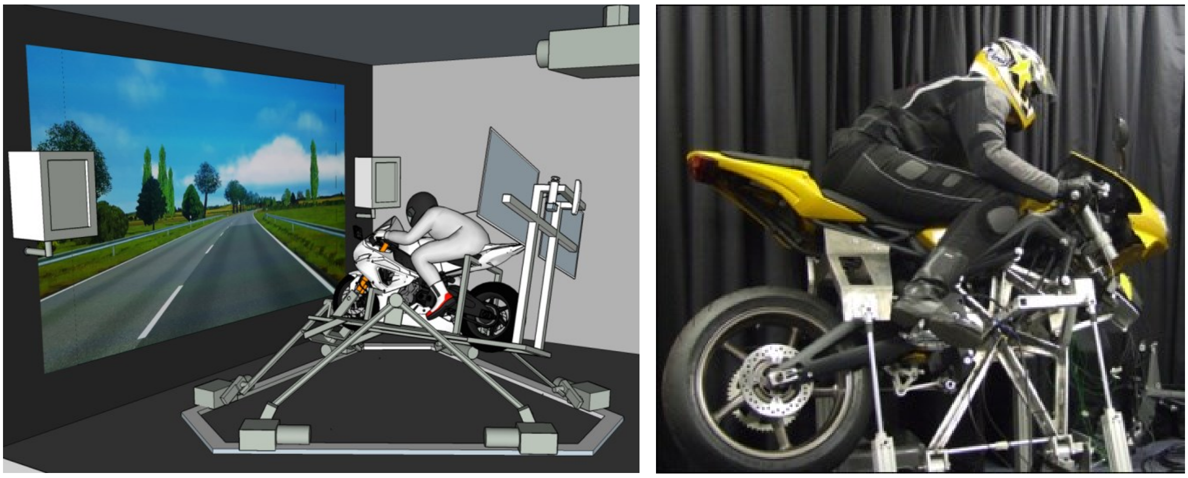


Figure 3: Motorcycle riding simulators for research and development (I). Left: BMW Motorrad Riding Simulator, Germany (Guth et al., 2016, p. 4). Right: MotorcycleSim at the University of Nottingham, UK (Stedmon et al., 2009, p. 1015).

The motorcycle simulator at IFSTTAR (former INRETS) uses a more generic mockup with body parts from Yamaha and fully functional control units (see Figure 4 left). In different configuration levels either three projectors or three 42 inch TFT-screens visualize the virtual environment. The cockpit is displayed in the front projection. All sound signals were rendered using a 5.1 surround sound system. As it is successfully applied in other simulators, an electro motor is used to produce a steering torque at the handlebar. Unique to this installation is another haptic cue: A repositioning bar adjusts the distance between rider seat and handlebar. This produces the impression of pulling the grips while accelerating and pushing against the handlebar while braking. Furthermore, a 3 dof mechanical platform delivers vestibular stimulation while riding (UNIMORE, 2012).

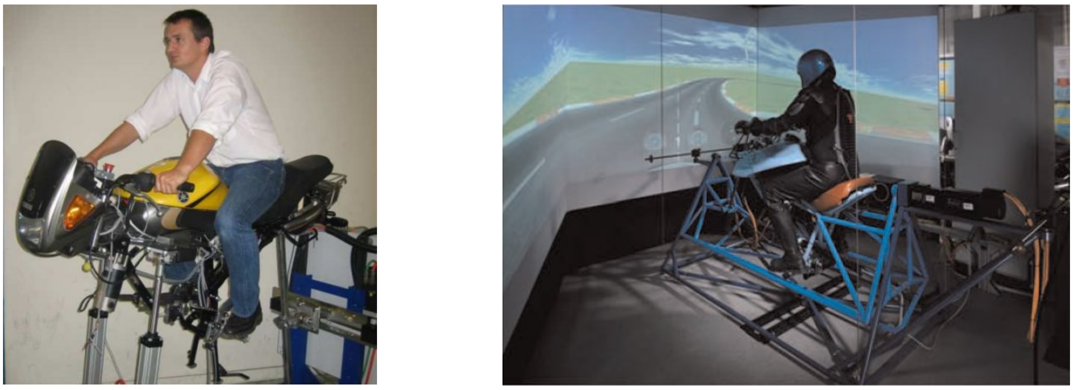


Figure 4: Motorcycle riding simulators for research and development (II). Left: IFSTTAR, France (Nehaoua, Hima, Arioui, Séguy, & Éspié, 2007, p. 180). Right: University of Padova, Italy (Cossalter, Lot, Massaro, & Sartori, 2011, p. 709).

In Greece, another version of this simulator with corresponding technology is in use at the Centre for Research and Technology Hellas – Hellenic Institute of Transport (CERTH-HIT; Symeonidis, 2016).

Figure 4 (right) shows the motorcycle riding simulator from the University of Padova. It was developed in the Department of Industrial Engineering. The aim is to investigate man-machine interaction but with higher focus on the impact of safety systems and motorcycle performance (e.g., ABS systems, traction control). All relevant body parts and fully functioning controls that motorcyclists use on a real motorcycle are mounted on a space frame. Three 1.5 m x 2 m wide projection screens are used to visualize the virtual environment with a 180° horizontal field of view. Auditory feedback is given by a 5.1 surround system. Four degrees of freedom actuated by electric servomotors account for vestibular feedback while the fifth dof delivers haptic feedback by applying a steering torque to the handlebar (Cossalter et al., 2011).

Figure 5: Motorcycle riding simulators for research and development (III). WIVW Static I (left, private picture) and Static II (Will, in press), Germany.

In 2010, the first motorcycle riding simulator at WIVW was constructed within the scope of a project with the German Federal Highway Research Institute (BASt). The project dealt with workload assessment for motorcycle riders (Buld et al., 2014). A BMW R 100S was fixed rotatable along its longitudinal axis in a steel frame (see Figure 5 left). The rider-induced lean angle in combination with steering torque, throttle position and brake pressures controlled the motorcycle's motion. When actively leaning into a curve, the rider felt a vestibular stimulation. Hence, there was no active motion of the mockup, so that the usual steer-roll-coupling was missing. In reality, a steering input leads to a roll movement of the motorcycle and vice versa. This connection did not exist for the simulator. Haptic feedback was only delivered in a passive manner. The roll mechanism as well as the steering was centered through elastic bands. Producing a steering or leaning angle meant to stretch these rubber bands. The bigger the angle the higher was the force to bring the motorcycle or respectively handlebar back to its upright or straight default position. One front projector with a 2.0 m x 1.7 m wide screen delivered visual cues. Sound simulation was done by a 2.0 stereo system. This simulator was substituted by a further developed second one called "Static II" in 2014 (see Figure 5 right). A full-size BMW R 1200RT is used as mockup. The simulator can deal with intermountable mockups. The rider can interact with all relevant motorcycle controls like on a real motorcycle. Three 55 inch flat screens offer a 180° horizontal field of view to the rider. An additional 10 inch touchscreen works as cockpit while two 7 inch TFT-displays are installed as mirrors. Auditory feedback is provided by a 2.0 sound system. Haptic feedback comes from a body shaker imitating engine vibrations in the chassis and from an electrical actuator producing a steering torque to the handlebar (Will, in press).

Table 1: Motorcycle riding simulators (alphabetical order) for research and development with regard to the sensory cues provided. Specifications are given where available.

Simulator	**Sensory cues**			
	visual	**auditory**	**proprioceptive**	**vestibular**
BMW Motorrad	3 x 4 m frontal projection; real mirrors with two 46 inch TFT-monitors	4.1 sound system; three structure-born noise actuators at the chassis	G-Vest imitating longitudinal forces; 75 Nm steering-torque motor; two ventilators	6 dof motion base
IFSTTAR / CERTH-HIT	Three 42 inch TFT-screens or three projectors (depending on configuration)	5.1 sound system	Steering-torque motor; repositioning bar between seat and handlebar	3 dof motion base
MOTORIST	Head-mounted display	Headphones integrated in the helmet	Steering-torque motor	6 dof motion base

Table 1 Continued

Simulator	Sensory cues			
	visual	auditory	proprioceptive	vestibular
Piaggio (MORIS)	Retro projected screen	Sound available; structure-born noise actuator	Steering-torque motor	6 dof motion base
University of Nottingham (MotorcycleSim)	2.5 m^2 single front projection	Surround sound	---	1 dof motion base (roll motion available)
University of Padova	Three 1.5 x 2 m wide projection screens (180° field of view)	5.1 sound system	Steering-torque motor	4 dof motion base
WIVW (Static I)	1.7 x 2 m frontal projection	2.0 stereo sound system	Passive steering force feedback through elastic bands	Rotatable along longitudinal axis (no active motion)
WIVW (Static II)	Three 55 inch TFT-screens (180° field of view); two 7 inch TFT-displays as mirrors	2.0 stereo sound system; structure-born noise actuator	Steering-torque motor	---
WIVW (DESMORI dynamic simulator)	Cylindrical screen with 4.5 m diameter and 2.8 m height (220° field of view); two 7 inch TFT-displays as mirrors	Head phones integrated in the helmet; structure-born noise actuator	80 Nm steering-torque motor; Rope towing mechanism imitating longitudinal forces	6 dof motion base

The simulator development process has been moving forward continuously. Besides steady improvements of already existing simulators, new ones arise such as the MOTORIST simulator by TU Delft and Siemens (Celiberti, Grottoli, Di Gesu, Gubitosa, & Donders, 2016; Grottoli, Toso, Gubitosa, Holweg, & Happee, 2015; Kovacsova et al., 2015). They are about to mount a scooter mockup on a hexapod and use a head-mounted display for visualization. Auditory cues are delivered by headphones integrated in the helmet. A steering-torque motor delivers haptic feedback. The primary use case shall be training. Also in Wuerzburg, a significant part of the above mentioned project DESMORI was the development and construction of a dynamic motorcycle riding simulator that pushes the limits of already existing riding simulators. The simulator development process followed the "control loop paradigm", in which the rider is seen as a controller that receives input from the simulator and regulates this input by adjustments of his action (output) in relation to a reference value. The concept of seeing a human being as controller is discussed in the following chapter from a psychological point of view.

2.3 The human being as controller

The following chapter summarizes the fundamental ideas of a class of theories often called "psychocybernetic models". These theories are highlighted because they emphasize the connection between perception and action in accordance with the control loop paradigm. The term "cybernetics" (Greek "kybernetes" meaning "helmsman") in its psychological meaning was coined by Wiener (1948). He adopted it as an analogy of the engineering sciences that describes the automatic control of a machine. A prominent example is the control of temperature by means of an automatic thermostat. It measures the actual temperature and compares it to the set reference value. As soon as a difference is noticed, it corrects the thermostat up or down in order to reach the reference temperature again. More general: "The term referred to the return of a feedback signal of the effects of a machine's output to its input to correct its operation." (Smith & Smith, 1987, p. 255).

In order to understand the origin of the human being as controller, a theory from the beginning of the 19th century is outlined in the first instance. The ideomotor principle or effect-based action control, postulates a bidirectional working link between an "idea" – in other words the subjective imagination of an action's aim or effect – with the action itself (Herbart, 1825; James, 1890). In the context of driving simulation an aim of action could be, e.g., driving at 100 kph (idea in Herbart's nomenclature). This aim is represented in form of sensory feedback such as a certain visual flow or engine noise. This set of sensory feedback (effects) is linked to a specific action that usually produces this sensory feedback. In the given example this might be a certain proprioceptive-tactile feedback while pressing the accelerator pedal down 20 % (goal-directed behavior). According to the ideomotor hypothesis, this link works in both directions. The action triggers the anticipation of the typically produced effects (so called feedforward). The other way round, the imagination of a specific effect triggers the according action to produce it. Consequently, the underlying principle of this approach is the process of learning. The coupling of a specific perception with an action has to be acquired first and gets strengthened by consistent repetitions. This idea has had another upswing more than 150 years later, when cognitive psychology specified it to describe perception and action more in detail (Hoffmann, 1993; Hommel, 1998, 2009; Kunde, 2001). Some theories go even beyond the idea of describing the link between perception and action. The theory of event coding (TEC) postulates that perception and action are inseparable with regard to their cognitive representation. This is the case, because, according to TEC, actions are represented in terms of their perceptual consequences (Hommel, 2009).

Effects of one's action manifest themselves in changing sensory stimulation. Some of these sensory cues might be noticed very fast, such as changed proprioceptive feedback from the brake pedal, and some might be noticed rather late, such as the reduced optical flow when the car finally decelerates. One theory that aims at explaining human or more precisely any living systems' behavior, including these different levels of control loops, is the Perceptual Control Theory (PCT). The general idea is that human behavior is not the triggered response to certain stimuli but that behavior is a means to produce a specific pursued perception (Powers, 2005). Behavior is nothing more or less than the control of perception. Behavior and perception are part of a control loop (Stallings, 1974). Human beings compare what they perceive with a certain reference value. If discrepancies arise, action is undertaken to change the perception to get closer to the reference value. A figurative example of this control theory is the cruise control in a car. An ideal velocity is set as reference value. A sensor measures the actual speed (perception) and adjusts the throttle (action) in order to have minimal discrepancies between actual and reference speed. In literature, this closed loop control unit is also often referred to as negative feedback loop as it aims at avoiding negative feedback in terms of high discrepancies between actual and ideal system state.

Powers (1998) suggests that these control loops are organized in hierarchical levels. The behavior resulting from a higher level works as reference frame for the next lower level. Perceptions from lower levels are fed upwards to higher levels. Applied to driving simulation, one level's aim could be to drive at 160 kph. Then, the next level's aim could be to engage the fifth gear and adjust the throttle position to 80 %. This action would influence the more specific action on the next level. Following this example, it could be visual feedback from the instrument cluster indicating that the fifth gear is engaged and proprioceptive feedback from the accelerator pedal and so on. Different models suggest a different number of levels while no strict limitations on the absolute number of levels exist.

Independent of which specific control loop model is applied, the actor is in need to judge the success of his action. Therefore, typically three types of comparisons between model components are included (Schütz-Bosbach & Kuehn, 2014). A comparison between expected and generated action effects delivers the information whether the primarily set goal has been reached or whether further action is needed. This could be interpreted as the success of the action. The smaller the discrepancy, the higher the action's success (Adams, 1971; Schmidt, 1975). Most models include a feedforward component in order to optimize the perception-action control loop. This optimization can be done by adjusting the action even before it has begun on the basis of the aim of action and anticipated effect comparison. The third comparison takes place between anticipated action effect and the actual effect. This delivers information on whether one is responsible for the registered effects or not.

As the name already states, a driving simulator aims at simulating a well-known situation from reality, namely driving. Regarding external validity of simulator studies, the transfer of in real driving acquired action – effect relations to the simulator setting is important. According to Hommel (2009), this is possible, if real driving and simulator driving share features of their cognitive representations. This successful transfer process from real to simulated environment is described as presence in several models. The following chapter summarizes a state of research on presence with respect to the field of driving simulation.

2.4 State of research on presence and its application to driving simulators

The idea of getting immersed in virtual environments was already born in the late sixties of the last century. At that time, for instance, Ivan Sutherland (1968) conducted first experiments with a simple head-mounted display. The origin of presence research is usually dated about 20 years later. Minsky (as cited by Slater, 2009, p.3551) was one of the pioneers investigating the feeling of being located in a distant place, in order to describe perception and action of people working with a remote controlled robot. At this time, presence was often referred to as "telepresence". The prefix "tele" (Greek for "far" or "distant") highlights the construct's meaning of feeling present in a distant location. The rapid technological progress and the related rise of virtual environments in the early 90s led to a considerable upturn in presence research. This involved a reinterpretation of the construct. As from that time, presence did not only describe the feeling of being present in a distant physically existing environment, but also the entering of artificial virtual environments (Sheridan, 1992a; Steuer, 1992).

Besides (tele-) presence, a bunch of other expressions describe the same construct or closely related phenomena. Most wide spread is the mix of "immersion" and presence. Other authors refer to terms such as "feeling of realism" or "place illusion". This is the case because presence is not clearly defined and different authors highlight different aspects of the same global idea. Within this thesis, the following definitions based on Slater, Lotto, Arnold, and Sanchez-Vives (2009) and Mestre (2005) are applied:

Definition Immersion is an objectively measurable quality of a technical setup. It can be regarded as an originally psychological construct that is determined by technical characteristics. It describes the variety, fidelity and coherence of display technologies that address a person's senses. For instance, the immersion of a driving simulator may be described in terms of display resolution, brightness or screen size for visual cues and degrees of freedom, motion range or payload for motion systems that account for vestibular stimulation. An immersive system is able to provoke presence in a human being. Thus, presence is a person's state that arises from the interaction with an immersive system such as a driving simulator but maybe also a simple computer. Presence is commonly defined as the feeling of being located in a remote or virtual environment that seems to be real to the user. Another aspect of presence describes the ability to act there successfully. It has to be emphasized that the same technical setup with one specific measurable level of immersion may produce different levels of presence in different persons. For instance, a highly immersive driving simulator may provoke a high level of presence in a person who is e.g., generally prone to experience presence already in a simple computer game such as packman. On the other hand, the same simulator may produce almost no presence at all in a person that gets sick by the movements of the simulator right away. Presence is accessible through different measures. These measures deal with subjective ratings besides physiological responses and more general behavior and performance. A detailed description can be found in chapter 3.

Generally speaking, two classes of presence theories can be identified (Draper, Kaber, & Usher, 1998). Namely, technological and psychological approaches whose most popular representatives will be described in the following section. The class of technological theories defines presence as a unique construct that deals with the phenomenon of being part of a virtual environment. These theories mainly describe the phenotype of presence and focus on its determinants. On the contrary, psychological theories do not agree on the definition that presence is a new and unique psychological construct. According to them, presence is just another expression for the phenomenon of accepting an artificial world as real. These theories explain the occurrence of this phenomenon with already existing psychological constructs such as attention allocation between virtual and physically existing environment.

These two classes define the structure of this chapter complemented by measurement techniques and followed by a common evaluation with respect to the models' application to driving simulation. If no driving related literature was found, general findings with respect to the specific presence models were discussed.

2.4.1 Technological approaches

As stated above, the technological approaches regard presence as a new and unique phenomenon. Generally, these theories describe how the feeling of being part of a remote environment can be supported (determinants of presence) and how the success can be measured (phenotype of presence). Most approaches include comparable factors and differ only in their precision of the concept definitions. The description of different technological approaches is followed by a summary of empirical evidence on the contribution of different sensory cues to presence, as this aspect is considered essential in all technological theories.

Two researchers whose names are closely connected to the construct of presence are Bob G. Witmer and Michael J. Singer. They were active in this field of research for decades and developed their own model as well as measurement techniques to assess presence. In the mid-nineties they conducted an extensive literature research in order to identify the main determinants of presence (Witmer & Singer, 1994). Four major factors were identified:

1) Control factors describe how closely connected and how intuitive a person's action is transferred into changes in the remote environment.

2) Sensory factors focus on the diversity and multimodal consistency of sensory information and describe how intuitive this information is displayed to the actor.
3) Distraction factors describe the ability of a technical system to attract the operator's attention (their definition of immersion).
4) Realism factors describe how well the virtual environment matches the real one and how meaningful the virtual world respectively task is to the user.

Akin, Minsky, Thiel, and Kurtzman (1983) support the importance of scope and fidelity of sensory feedback. Besides these determinants, the authors see manipulator dexterity, i.e. the quality of interaction with the virtual world, as important.

Almost the same determinants have been identified in Sheridan's (Sheridan, 1992b) as well as in Steuer's model of presence (Steuer, 1992). According to Sheridan, fidelity and richness of sensory information is the most relevant requirement. This is followed by the dexterity of sensor control in the virtual environment and the ability to receive sensory feedback from the remote environment. These last two prerequisites deal with the interaction quality in the virtual world. Steuer names the two major determinants vividness of sensory feedback and interactivity with the electronically mediated remote environment.

Zeltzer (1992) took up these ideas in his so called AIP model. The main aim of this approach is to provide taxonomy for the description of remote environments. This model includes presence as one element besides others. According to this author, three components are necessary:

1) Autonomy describes how well the virtual world can simulate interactions that are possible in the physical world.
2) Interaction specifies how well a remote environment can respond to operator inputs in real-time.
3) Presence is characterized by number and fidelity of displays and controls.

Schloerb (1995) was one of the first to include performance in his presence model. His theory separated different qualities of presence.

1) Subjective telepresence is the extent to which a person feels present in the virtual environment. This definition is close to the understanding of a lot of other authors.
2) The new aspect is the definition of objective telepresence, describing the extent to which a person can successfully complete a specific task in a virtual environment. This could objectively be measured in terms of performance in a given task.

As the class of technological approaches concentrates especially on the contribution of different sensory cues to presence, this aspect will be described more in detail in the following section. According to Slater (2009) it makes sense to investigate the influence of different sensory cues within one system, in this case a driving simulator, as the comparison between different systems is biased by too many uncontrollable influences. No research has been conducted on the influence of taste and smell on driving respectively riding. It can be assumed that these sensory cues are not of high importance for the driving task and are therefore not further considered. The following section is organized according to the different sensory cues that were subject to investigation.

Visual cues Visualization has high face validity when it comes to the enhancement of presence. For instance, positive effects of the level of displayed details (pictorial realism) and reduced visual delay on presence have been reported by Welch, Blackmon, Liu, Mellers, and Stark (1996). They had $N = 20$ participants experiencing different driving simulator scenarios. The participants rated the level of presence in pairwise comparisons while pictorial realism, delay of visual feedback and interactivity were systematically varied. As result, the proper height of the eyes over the road surface as well as the position in relation to the vehicle have an influence on driving behavior and presence (Kemeny & Panerai, 2003; Smith, 1971 as cited by Smith & Smith, 1987). Freeman, Avons, Meddis, Pearson, and IJsselsteijn (2000) had $N = 24$ students watch video sequences of a racing rally car through a head-tracked stereoscopic display. The perspective of the visual stimulation was varied between driver perspective and observer perspective from the road side. A significant higher portion of presence was measured in the first condition.

Auditory cues Besides obviously relevant visual cues, several researchers advocate the meaning of auditory stimulation (Gilkey & Weisenberger, 1995; Murray, Arnold, & Thornton, 2000; Sanchez-Vives & Slater, 2005; Short, Williams, & Christie, 1976). Gilkey and Weisenberger drew their conclusions from studies with deafened humans due to a trauma. These individuals feel like being decoupled from their surroundings. Transferred to virtual environments the authors postulate that "…background auditory stimulation may be useful or even critical for achieving full sense of presence." (Gilkey & Weisenberger, 1995, p. 357). This was subject to investigation in a study conducted by Riecke, Väljamäe, and Schulte-Pelkum (2009). All participants watched a rotating panorama scene of a market place on a cylindrical screen. The visualization was accompanied by different sound configurations (no sound vs. mono vs. spatial). While the first two conditions had no effect, spatial sound presentation increased presence as well as vection. In this study, presence was measured with the Igroup Presence Questionnaires (IPQ, Schubert, Friedmann, & Regenbrecht, 2001). The positive effect is mainly attributed to increased spatial presence. A comparable approach was already reported by Hendrix and Barfield (1996) who had $N = 16$ participants navigate freely through a virtual environment. In two studies they varied the general availability of sound and if the sound was spatialized or not. The results showed a significant increase of reported presence with active spatialized sound.

Haptic and proprioceptive cues In order to create a richer virtual environment, haptic or proprioceptive cues are more and more implemented in driving simulators (Ambrož, Prebil, Kamnik, & Munih, 2012; Lobjois, Dagonneau, & Isableu, 2016). This seems to be a promising approach when focusing on motorcycles as Chen, Chen, Liu, Chen, and Pan (2009) investigated whole-body vibrations on riders of different motorcycles, scooters and sedan vehicles that were equipped with measurement technique. They pointed out that riders of powered two wheelers experience strong tri-axial accelerations and vibrations. This partly proprioceptive, partly vestibular feedback depends on speed, road type and vehicle. This effect is not only valid for motorcycling: Proprioceptive feedback plays an important role in our daily life (Cole & Paillard, 1995). Every behavior relies on proprioceptive feedback in order to determine muscular tension and body position. Missing proprioception has to be compensated by other senses such as visual control. For instance, a motorcyclist that is riding in cold and heavy rain has numb fingers. The usual proprioceptive feedback that delivers the important information whether the hand has reached the brake lever is missing. Visual control is necessary to check the hand's position and to fulfill the set aim of deceleration. This example shows that missing sensory feedback affects behavior. Here, the gazes are directed unnaturally in order to compensate the proprioceptive feedback. This might also be the case on a more general level. Missing or inconsistent sensory cues that people typically rely on may affect the behavior and lead to usually not occurring compensation mechanisms. This should be kept in mind when discussing sensory feedback that is not immediately related with the driving task.

Still, there is research delivering evidence that proprioceptive cues are part of the control strategies while driving (Reymond, Kemeny, Droulez, & Berthoz, 2001). In a study conducted by Mourant and Sadhu (2002), eight participants drove a static driving simulator with either a generic spring-loaded steering wheel or a force-feedback system delivering appropriate proprioceptive steering torque. The first system simply used the force of a spring that got stretched while steering in order to deliver any feedback. Hence, participants rated the complete simulation as more realistic when driving with the latter system. This could be due to the fact that the more realistic steering torque delivers important information on the tire-road contact. Thereby, the drivers' anticipations of the typical feeling were met. This interpretation is in line with the findings of Mohellebi, Kheddar, and Espié (2009) that did a comparable driving simulator study with focus on the algorithm to model the steering mechanism. The famous pit-room experiment provides more proof of the contribution of proprioceptive cues to presence. Participants, wearing a head-mounted display, faced a deep pit when they were about to enter another virtual room (Meehan, Insko, Whitton, & Brooks Jr., 2002). As a consequence, a raised heart rate and increased subjective ratings as measures of presence were observed. This could even be increased by delivering haptic feedback through a small wooden ledge that lay on the laboratory floor simulating the pit edge.

Vestibular cues The specific contribution of vestibular cues to presence has not been subject to investigation so far. Though, several studies could prove the positive effect of vestibular cues on the driving task. For instance, Alm (1995) had $N = 17$ participants drive an instrumented car in real traffic and a driving simulator, once with and once without vestibular feedback. An active hexapod led to more comparable lane keeping behavior with the naturalistic driving. Furthermore, more recent studies report less heading error (Greenberg, Artz, & Cathey, 2003) and less lateral swerving (Engström, Johansson, & Östlund, 2005) with active vestibular stimulation in driving simulators. The supporting effect of vestibular cues on lateral vehicle control could be on the one hand confirmed and on the other hand even be extended to longitudinal driving behavior (Malaterre & Fréchaux, 2001; McLane & Wierwille, 1975; Reymond et al., 2001). Carsten and Jamson (2011) go even beyond this in their argumentation: Missing vestibular feedback could lead to higher cognitive workload in static driving simulators as the drivers have to compensate these missing cues. This could bias study results that investigate, for instance, the effects of advanced driver assistance systems (ADAS) on driver workload.

Conclusion In summary, the technological approaches to presence highlight the importance of diversity and consistency of different sensory cues as determinants of presence. The previously reported studies investigated the contribution of specific sensory cues to presence or the driving task respectively. Therefore, visual, auditory, proprioceptive as well as vestibular cues should be taken into account when investigating the influence of sensory feedback in a driving simulator setup on presence.

2.4.2 Psychological approaches

In this chapter's introduction, the idea of psychological approaches to presence has already been mentioned. These theories share the conviction that presence is no new state of human beings that has not been there before virtual environments were invented. Simulated environments do not provoke unique human experiences, but states that can be traced back to already known psychological constructs.

Situation awareness A well-known psychological construct that has been brought in relation with presence is situation awareness. It describes the perception of environmental elements in a given situation, their comprehension and the anticipation of their status in the near future (Endsley, 1988). These processes are necessary to enable successful goal-directed behavior. Draper et al. (1998) suggest that presence can be defined as the maximization of situation awareness in the virtual environment and reduction of focus to the physically existing environment such as the laboratory. By definition, a driving simulator is a kind of mixed reality setting. In order to act appropriately, information from the virtual world is necessary (e.g., visual information on the road network) as well as from the local environment (e.g., the steering wheel in the mockup). A pure maximization of one or the other could therefore not be the aim in this use case.

Attention A comparable approach is the idea of attentional resource allocation. Common models are based on the assumption that attentional resources are limited and follow a certain structure (Navon & Gopher, 1979; Wickens, 1980). In 1996, Draper and Blair published their attentional model for synthetic environments. The main idea is that the level of presence is high if more attentional resources are allocated to stimuli of the computer-mediated environment than to the physically existing local environment. In sum, this approach considers presence to be calculated as the relation between attention allocation to the virtual compared to the physical environment. As for situation awareness, a pure maximization of attention allocation to the virtual environment cannot reasonably be pursued in a mixed reality setup such as a driving simulator.

Flow Another psychological approach defines presence as an experience of flow in virtual environments. According to Csikszentmihalyi (1999) flow describes a state of action where personal skills and task demands meet perfectly. People that are acting in flow forget about their environment and solely focus on the task performance (Csikszentmihalyi, 2000;

Csikszentmihalyi & Jackson, 2000). This definition is regarded as the most characteristic element of the presence construct, too: The complete involvement in an activity with exclusion of distracting stimuli (Draper et al., 1998). Transferring this to simulator driving means, that a participant, who perfectly fulfills a given driving task, would forget about the laboratory setting and feel like acting in the virtual environment. By outlining the task-skill match, this approach is not able to include situations without action into the presence construct.

Externalization Loomis (1992) introduced the phenomenon of externalization or distal attribution respectively to describe presence. The main idea is that even if human beings use their sense organs to perceive, most parts of the perceptual experience are attributed to distal elements in the environment instead of the sense organs themselves. In other words, people tend to include parts of their environment into their self. For instance, a person that tightens a nut with a wrench feels the contact between nut and wrench as haptic feedback instead of the hand holding the wrench. The wrench as tool was included into the self. This phenomenon may also appear in virtual environments. A driver in a simulator may feel the tire – road contact from the simulated environment instead of the contact between hands and the mockup's steering wheel. Consequently, presence can be seen as the degree to which a person makes these distal attributions to the virtual environment. These distal attributions are especially made, when a person's action is lawfully related to the effects he or she provokes. This leads to another concept of presence, namely the behavioral cybernetics.

Psychocybernetic models The psychocybernetic models of presence have their origin in the general psychocybernetic models of action and perception that have already been discussed in chapter 2.3. In principle, they assume that human beings manipulate their environment in order to control the sensory feedback. The provoked changes in terms of sensory feedback are anticipated prior to the execution of goal-directed behavior (feed-forward). This is a continuous process (Smith & Smith, 1987). The level of presence is high, if this process is free of or low on perturbations. In other words, the relationship between feed-forward and feedback has to be clear. Any disturbance between one's action and the following feedback (perception), for instance due to a temporal delay coming from the technical setup, reduces the level of presence. Presence is more or less seen as the disturbance-free and successful operation in virtual environments. By the way, this definition includes performance as a correlate of presence. According to the authors it has to be emphasized that presence is not necessarily connected with a physical replication of the real environment, but with the provision of feedback that meets the people's expectations (Draper et al., 1998). These ideas are in line with the model of Stanney and Hash (1998) that postulate a higher level of presence as result of higher user-initiated control.

Another approach that can be attributed to the tradition of psychocybernetics is the one of Slater (2009). He distinguishes between place illusion and plausibility illusion. The first includes the impression of being located in the virtually created environment. This part of presence can be enhanced by improved sensorimotor contingencies that enable so called „valid actions". More precisely, motor activities (action) shall provoke perceivable changes in the environment (perception of any modality) that people are used to. Imagine a motorcycle riding simulator with video projection and without head tracking. An invalid action in this simulation, according to Slater, would be to move one's head sideways in order to look behind an obstacle. In reality, this is possible due to the new viewing angle. Therefore, improved place illusion can be achieved by the allowance of common actions. In the before mentioned simulator example, this could be the inclusion of head tracking that modulates the viewing angle according to the rider's head position. Another means to optimize place illusion is to ensure that people can see their own body in the virtual environment. There is also specific research on the importance of design, perspective or resemblance of an avatar that is controlled by the user on presence (Alshaer, Regenbrecht, & O'Hare, 2017). Driving simulators usually provide close-to-reality or real control units to the driver. These inputs do directly affect the virtual environment so that no third person or avatar is needed. Indeed, it would even make it worse because it adds another level of artificiality. It is not only that the participant needs to feel that he is responsible for changes in the environment but additionally one has to deal with challenges of embodiment. Plausibility illusion focuses more on the ability of a system to create the impression that a situation really occurs in a credible way. This may be enhanced by strengthening the correlation between action and changes in the environment. For instance, plausibility illusion in a driving simulator may be high if surrounding vehicles react to the driver's behavior by e.g., stopping if the own vehicle blocks their way. It has to be emphasized that the participants may well know on a higher cognitive level that they are in a laboratory setting all the time. Close to the idea of valid actions is the so called Potential Action Coding Theory of Presence (Schubert, 2003; Schubert et al., 2001). Therein, the level of presence depends on the construction of mental representations of bodily actions that can be performed in the virtual environment. Besides forming these representations, participants have to learn to suppress irrelevant stimuli from the local environment. The more complete and sophisticated these representations are the higher is the level of presence.

These ideas of valid and successful actions, suppression of irrelevant stimuli and Slater's (1995) distinction between immersion as quantifiable parameters of display technologies and presence as a state of psychological consciousness are summarized in the IPP framework model of Bystrom, Barfield, and Hendrix (1999). IPP stands for Immersion, Presence and Performance that are all components of the model. This model can already be seen as a summary of technological and psychological aspects. The authors name spatial, auditory and haptic information as relevant to actors in virtual environments. These sensory cues should match real-world experiences as much as possible. If this precondition is met and an actor allocates enough attentional resources to aspects of the virtual world, a so called "suspension of disbelief" shall occur. This means that the participants view the remote environment as a real place. This in turn is necessary to experience presence, defined as "The sense of being there in the Virtual Environment" (Bystrom et al., 1999, p. 243). The allocation of attentional resources is further influenced by task requirements. Challenging tasks or those that meet the actor's ability will make it easier to focus on the virtual environment and support presence. Performance depends on these task requirements in connection with attention to the task. Presence is seen as a necessary condition for performance to occur. More detailed definitions on how much attention is needed to be allocated to the virtual world or what the underlying processes of the suspension of disbelief are, are not given. Nevertheless, the IPP model delivers a conceptual framework that includes components that has previously been separated most of the time.

There is also a controversial discussion on whether the ability or proneness to be immersed in a virtual environment is an individual trait (Johns et al., 2000; Slater et al., 2009; Witmer & Singer, 1998). Witmer and Singer (1998) designed an Immersive Tendencies Questionnaire (ITQ) that shall measure this trait. The underlying assumption is that people who show the tendency to be easily involved in other activities, such as reading books or watching movies, are also more prone to be immersed in virtual environments.

Conclusion In summary, the main idea behind so called psychological approaches to presence was to explain presence by already existing psychological constructs such as situation awareness or attention. A class of very comprehensive models of presence traces back presence to basic patterns of perception and action in virtual environments. These so called psychocybernetic models will therefore be taken into account when modelling presence in driving simulator setups.

2.4.3 Measurement of presence

“Presence is a construct, a variable with various levels and dimensions.” (Biocca & Delaney, 1995, p. 62). This quote from Biocca and Delaney describes the nature of and consequences for the measurement of presence quite well. As could be seen in the sections above, there were many different approaches to presence, each of them suggesting other measures. The following subchapters summarize empirical evidence for the meaningful application of different dependent variables for presence measurement.

2.4.3.1 Performance & Behavior

This section deals with exemplary results delivering evidence for the meaningful inclusion of performance and broadly formulated behavioral measures. There have always been models that see presence and performance closely connected. For some authors presence can help to improve performance (e.g., Akin et al., 1983; Sheridan, 1992b; Steuer, 1992). For others, such as Schloerb (1995), performance is one objectively measurable part of presence. This objective assessment can directly be seen as one of the advantages. Behavioral measures are applied as additional indicators for presence (Freeman et al., 2000; Slater et al., 2009). These are natural responses to typical real-life scenarios that also occur in the simulated environment. This could, for instance, be a person that ducks his head when passing through a low, but only virtual, door. An advantage of this dependent variable is that actors are usually not aware of it and thereby deliver less biased outcomes (Freeman et al., 2000).

Deligiannidis and Jacob (2006) had twelve participants riding on a virtual reality scooter. Two conditions were compared. One enriched virtual reality with vibrotactile tactors and active fans to give more realistic speed and motion impressions and one without. As expected, the results indicated higher feelings of realism in the enriched condition. Furthermore, the subjects showed better performance measured by faster completion of the parkour.

Bailenson et al. (2004) investigated social situations in virtual environments. They found out that the interpersonal distance to a familiar avatar is closer than the one to a stranger. This spontaneous behavior that is well-known from social sciences was transferred to the virtual environment and delivered valuable information in addition to the self-reported measures of presence. An example for the successful application of behavioral measures in a driving related setup comes from Freeman et al. (2000). They investigated the relationship between the perspective of a video and different measures of presence. The subjects that watched the videos of a racing rally car from the driver's perspective showed lateral body movements according to the rally car. If the car took a right, the participants leaned spontaneously to the right, too. Freeman and colleagues call these actions, which are the consequence of subconscious reactions to the virtual environment, "postural responses". Watching the same rally car from an observer perspective next to the track did not evoke postural responses. Subjectively rated presence, vection and involvement in addition to postural responses could even be increased by stereoscopic instead of monoscopic presentation. On a group level, participants' behavior and subjective ratings pointed to the same direction. However, on an individual level these dependent variables were not highly correlated. Therefore, the authors suggest including postural responses as useful additional parameter instead of substituting questionnaires or other typically applied measures. Furthermore, what kind of behavior can be regarded as presence indicator depends highly on the simulated environment.

2.4.3.2 Physiology

The application of physiological parameters as measurable surrogates for presence has been suggested by several researchers (IJsselsteijn, de Ridder, Freeman, & Avons, 2000; Insko, 2003; Meehan et al., 2002). It goes back to the so called "ground truth" paradigm (Freeman et al., 2000; Slater et al., 2009). This paradigm claims that it is a sign of presence if a person's reaction in the virtual environment resembles the person's response to the same situation in reality. In principle, the same paradigm has been applied for behavioral measures before. One has to state that the use of physiological measures depends on the research setting and question. Prior research on physiological derivates of presence has often been conducted in social or clinical psychological research settings dealing for instance with emotions, phobia or stress (e.g., Dillon, Keogh, & Freeman, 2002; Meehan et al., 2002). In this field, responses to e.g., sadness are quite well-known and it is easier to apply the ground truth paradigm as one knows what to expect. Switching to more mundane situations such as driving on a highway without any specific events, it is not that obvious what to expect from physiological measures. On the other hand, physiology can show its strength in surprising or extreme situations where sufficient physiological responses in real scenarios can be expected. As one huge advantage of simulator studies is to investigate critical situations in a safe and controlled environment, it is reasonable to include physiological responses in the measurement model.

For instance, Johnson et al. (2011) showed that several physiological measures are valid parameters to detect and describe presence. This holds also true for the context of driving simulation. Their study compared the sensitivity of different physiological responses to critical events, such as a car that suddenly crosses the own trajectory while leaving a parking lot. This was done in a driving simulator as well as on the road. The subjects' reactions to the surprising situations were comparable between conditions. For instance, all participants showed an increased heartrate within 15 seconds after the event onset. Another vivid example for the application of the heart rate as presence indicator is the pit-room experiment (Meehan et al., 2002). The ability of a technical setup including a HMD to create presence was measured by an increased heart rate as response to a stressful situation. In this case, it was the unforeseen confrontation with a deep pit when the participants were about to enter another virtual room. Besides heartrate, the use of galvanic skin response has also been proofed useful in order to assess participants' presence in virtual environments such as a driving simulator (Jang et al., 2002).

Skin conductance is primarily associated with emotional arousal. Fingers and palmar regions are typically used to measure skin conductance in experimental settings. This is not possible for motorcycle simulator studies as both hands are essential for the riding task. Besides steering, the left hand pulls the clutch and the right hand pulls the lever for the front brake. In a study with $N = 17$ subjects van Dooren, de Vries, and Janssen (2012) compared 16 different locations to measure skin conductance while the participants had to watch emotional film fragments. In terms of responsiveness and similarity, the feet and shoulder areas came closest to the SCL response at the fingers. As both feet are also involved in riding a motorcycle (shifting gears, rear brake), the SCL could be measured at the shoulder area in simulator studies. Tagliabue and Sarlo (2015) used the skin conductance level as a measure of risk identification. Presence can be assumed to be high if virtual scenarios elicit high SCL similar to real scenarios. In a study with $N = 36$ college students, watching a video of risky traffic situations got compared with actively riding the Honda Riding Trainer through these risky situations. As hypothesized the skin conductance response was higher and thereby closer to reality in the riding simulator condition.

Rashid et al. (2015) investigated different EMG measurement locations while real riding. Anecdotal references report a high muscular tension of the trapezius muscles in periods of high concentration or stress. No relevant effects of laterality were observed. Unfortunately, the researchers faced huge problems concerning the loss of connection to the wireless EMG sensors resulting in fragmented data. Just as reported in this study, lots of measurement artefacts can occur by simple problems such as friction of cloths on electrodes or variations due to naturally circadian physiological activity or just a coffee. Once again, it is therefore recommended to use physiological measures always just in addition to other measures (Dillon, Keogh, Freeman, & Davidoff, 2001; IJsselsteijn et al., 2000).

2.4.3.3 Subjective rating

Research from the last three decades brought up different possibilities of measuring presence by means of subjective ratings. One can distinguish between continuous and post-test ratings. For continuous presence assessment, participants rate their sense of presence e.g., by changing the position of a control lever between low and high experienced presence (Freeman, Avons, Pearson, & IJsselsteijn, 1999; IJsselsteijn et al., 1997). This delivers valuable information on variations in presence over time. On the other hand it requires attention allocation to the laboratory that might interfere with presence and it limits the actors' degree of freedom in terms of interaction with the remote environment.

Definitely more wide spread is the use of post-test rating scales. One possibility is the application of visual analogue rating scales. Participants have to mark their present feeling on a vertical line with displayed verbal anchors such as "I feel not at all there" and "I feel completely there" (Freeman et al., 2000; Mestre, 2005). Depending on where exactly the marking has been made, a score is calculated afterwards. However, it is regularly doubted whether millimeter differences can be meaningfully interpreted. Another possibility is the construction of questionnaires that are commonly based on a specific presence theory. Witmer and Singer (1998) developed a presence questionnaire grounded on their four identified major determinants of presence: control factors, sensory factors, distraction factors and realism factors. Later in time, they evaluated their presence questionnaire with data from $N = 325$ participants that were exposed to virtual environments and completed a questionnaire afterwards (Witmer, Jerome, & Singer, 2005). A four factor model for the subscales fitted the data best. The contributing factors to presence were involvement, adaptation / immersion, sensory fidelity, and interface quality. Another questionnaire, the Immersive Tendencies Questionnaire ITQ, from the same authors tries to identify whether a person tends to become immersed in virtual environments. Slater and Steed (2000) hypothesized that people oscillate between the virtual and the real world due to technical shortcomings such as delays or inappropriate sensory cues in the virtual environment. Their subjective rating tool just asked for "breaks in presence". These were counted and delivered information on the experienced presence in the given virtual environment. Other established questionnaires are the Igroup Presence Questionnaires (IPQ) by Schubert et al. (2001) and the University College London (UCL) questionnaire. The first is based on the Potential Action Coding Theory of Presence (see chapter 2.4.2). It was the result of a survey study with $N = 246$ players of 3D games that was later replicated with another $N = 296$ subjects. The resulting three-components structure contains spatial presence, involvement and realness (Schubert, 2003). The UCL was, for example, used by Slater and colleagues who investigated an interactive technique to move through virtual worlds (Slater, Usoh, & Steed, 1995). They were interested in whether walking on the spot (detected by a tracking device) is superior to the usual hand-pointing method in terms of presence. The results of the UCL confirmed this hypothesis. The authors explain the effect by a better match of proprioceptive feedback from the body movements and sensory feedback from the virtual environment. Scheuchenpflug, Ruspa, and Quattrocolo (2003) aimed at developing a presence questionnaire that can specifically be applied in driving simulator setups. Therefore, they took items from already published presence questionnaires besides adding new items. Then, an item analysis was conducted with $N = 165$ virtual environment-experienced persons in an online survey. A following principal components analysis revealed three contributing factors: spatial presence, quality of the interface and emotional involvement. Additionally, twelve items for the assessment of immersive tendencies as individual trait remained. In the end, a verification study with different driving simulator setups was conducted.

Another frequently subjectively rated important factor deals with simulator sickness as a form of unintended artefact of action and perception in a virtual world (Kennedy, Lane, Berbaum,

& Lilienthal, 1993; Neukum & Grattenthaler, 2006). Discrepancies in terms of latency between different sensory inputs due to e.g., a low refresh rate of the projection are typical problems of virtual environments that increase sickness symptoms and reduce presence (Stanney & Hash, 1998). The authors attribute this effect to the mismatch of action and anticipated reafferences. This explanation matches the previously discussed psychocybernetic models very well. The provoked symptoms of sweating or nausea may reduce the normal behavior and thereby rip people out of the virtual world and back into the laboratory setting. This negative effect of so called "cybersickness" on presence has already been discussed by Stanney, Kingdon, Graeber, and Kennedy (2002) in terms of performance decrease. In line with psychocybernetic models, Stanney and Hash (1998) point out that a higher level of user-initiated control shall reduce simulator sickness that can be seen as improvement of presence. They had N = 24 participants moving through a virtual maze. In a within-subject design the level of control was varied. In the passive condition, the participants were moved through the maze automatically. The active-passive group could control their movement in one dimension and the active group had free control over their linear and rotational movement. Sickness symptoms were measured with the Simulator Sickness Questionnaire (Kennedy et al., 1993). The highest level of sickness symptoms was experienced in the passive condition while the least amount was reported in the active-passive condition. It is assumed that motion control reduces sickness as the reafferences are easier to anticipate. The problem in the action condition is explained by the challenge to integrate the high number of degrees of freedom in the anticipation model. This negative correlation between simulator sickness and experienced presence has also been reported by other authors such as Slater et al. (2009) summarizing their findings from a series of four experiments. This shows the close interaction between presence, simulator sickness and performance and delivers a reason to surveille the level of simulator sickness when assessing presence.

Conclusion In summary, previous research suggests that there is no single presence indicator. Presence is a multi-level construct that is measurable by different means depending on the underlying model of presence. Models that define presence as a feeling of being located in the virtual environment typically include subjective ratings to assess presence. Other models that define presence more with regard to the successful action in virtual environments regard rider behavior and physiological responses that resemble those of real-life as useful presence indicators. A comprehensive evaluation of presence should take all these facets into account.

2.4.4 Evaluation with respect to driving simulation

Existing models cannot be seen as satisfactory concerning their application to driving simulation. One reason is that some models have been developed to describe processes of telecommunication. In this use case, the people's actions are limited to talk to each other or see each other on displays while being in different locations. Therefore, these models do not satisfy the importance and diversity of actions in driving simulation (e.g., shifting gears, steering, braking…). Another reason is the strict separation of people's experiences in virtual environments and their performance in some of the presence models. A presence model for driving simulators shall include both aspects. On the one hand, an adequate level of realistic experience is necessary so that the drivers take the driving task and scenarios seriously and show compliant behavior. Not until this is fulfilled can simulator studies generalize their findings completely (Cossalter et al., 2011; Kaptein et al., 1996). On the other hand, the performance of drivers is of utmost importance. For instance, a study aims at investigating the potential distraction of a new human-machine interface (HMI) solution. A criterion with high face validity is that a driver interacting with the new HMI shall not end up on the opposite lane or off road. However, this dependent variable only makes sense if a non-distracted, attentive driver is able to keep his vehicle in lane. Therefore, the presence model for driving simulators should also consider performance.

Another shortcoming of some models is the following: It is neither possible to classify nor to derive recommendations for improvements of driving simulators with some of the presence models. For instance, a simulator tuning according to flow experience hardly delivers starting points as flow is dependent to aspects such as task characteristics and individual skills that cannot be adjusted that easily on the simulator side. A further reason in favor of the development of a new model is the separation of technological and psychological approaches in several models in the past. Hence, each of the approaches has its justification. A small TFT-screen positioned on a desk may not immerse people as much as a passenger car mockup surrounded by a huge cylindrical screen does. On the other hand, it cannot be justified to neglect the impact of successful behavior or attention towards cues of the virtual environment. Finally, several models such as those going back to attentional resource allocation strictly separate information from the virtual and the local environment. In a driving simulator setup that is commonly a mixed environment with task-relevant cues coming from the local (e.g., mockup) as well as the virtual (e.g., visualized road network) environment, this distinct separation is inappropriate.

These considerations led to the development of a presence model for driving simulators that will be described in chapter 3. In order to proof parts of that proposed model a specific simulator driving task was necessary. Generally, different tasks that include crucial driver skills or constant demands would have been possible: either focusing on lateral or longitudinal vehicle control. For this thesis speed perception was chosen, as it is a well reproducible task that investigates a driver or rider skill, while the performance can be measured quite easily. An overview of literature on speed perception with respect to the driving task is given in the following chapter.

2.5 Speed perception while driving

Speed can surely be measured objectively. Hence, how a person perceives a certain velocity differs between individuals. Speed perception is said to be a subjective sensation that is, of course, related to the real speed, but also far from a one-to-one mapping (Denton, 1966).

Early investigations on speed perception commonly applied either the production method or the estimation method (Schleinitz, Petzoldt, Krems, Kühn, & Gehlert, 2015). The first involves active production of an instructed velocity without feedback from the speedometer.

The second uses estimations of passively experienced speed. These methods have been applied in real driving scenarios as well as in driving simulators focusing on different influences on speed perception. The majority of studies deal with different aspects of visual cues.

Driving simulators deliver most of the relevant optical cues from real driving. In first line, optical flow through moving textures. However, some naturalistic cues such as motion parallax resulting from the driver's head movement are regularly missing (Kemeny & Panerai, 2003). The peripheral vision, in other words a large field of view, plays an important role in ego speed perception. Kemeny and Panerai (2003) mention a threshold of at least 120 ° horizontal field of view. Levine and Mourant (1996) showed in a simulator study that the own velocity is judged lower when the delineator poles are located farther away from the road side. In general, studies with different methods revealed that speed estimation seems to be difficult – especially at low speeds. Recarte and Nunes (1996) conducted two experiments investigating speed perception. $N = 60$ drivers estimated the speed they were passively experiencing in a real car. In a second experiment $N = 30$ drivers additionally actively produced different speeds. On average, the real speed was underestimated. The participants rated the perceived speed lower or respectively over adjusted their velocity by driving faster than they should. A stable influence of target speed could be seen in both studies. The estimation error decreased as the target speed increased. At rather low speeds of 60 kph a mean error of about 30 % was observed. At higher speeds of 120 kph the mean error decreased to 3 %. A review of Schleinitz et al. (2015) showed that this underestimation effect occurred independently of day- or nighttime driving and on straight roads as well as on curved roads.

Evans (1970) investigated the importance of sight and hearing for speed estimation in a passenger car. Therefore, $N = 18$ participants were located on the front passenger seat and experienced different velocities under four conditions. These were being a normal passenger, wearing a blindfold, wearing ear muffs and wearing blindfold and ear muffs. On average the speed was underestimated. This held especially true for low speeds under 25 mph. Diminished hearing had the most obvious negative results on performance and stability of estimates. The author concluded that auditory cues are of special relevance for speed perception. Ohta and Komatsu (1991) compared speed perception in a simulator with that in a real passenger car by means of magnitude estimation technique. $N = 64$ participants passively experienced different velocities. In pair-wise comparisons they had to judge whether the second velocity was higher or lower than the first reference speed. In between the trials random acceleration and deceleration occurred in order to avoid carry-over effects. The reference speed has always been 40 kph. The second velocity varied between 20 and 60 kph in steps of 10 kph. The focus lay on deprivation of different sensory cues (visual vs. auditory vs. combined). In addition, two different passenger cars were used in order to control the degree of tactile feedback through vibrations (Suzuki Alto with 550 cc vs. Toyota Crown with 3000 cc). All participants were seated on the passenger seat in the real cars. The simulator setup consisted of a screen, sound system and body shaker, but was not specified in detail. In the simulator the participants were seated on the driver seat. The psychophysical relation between physical speed and perceived speed in the real car showed that the perceived speed increases disproportionately with increasing physical speed. No kind of sensory deprivation changed the participants' ratings significantly. A slight tendency to more instable ratings was observed under combined visual and auditory deprivation in the smaller passenger car. The psychophysical function in the simulator was almost comparable. Only the exponential increase with rising speed was not as high. Hence, sensory deprivation led to more inconsistent and inaccurate ratings in the driving simulator. The estimation performance in the condition without auditory feedback decreased. Visual or combined auditory and visual deprivation delivered the most inaccurate ratings. In the first instance, these experiments showed that comparable speed perception in the simulator and the real car is possible, even without proprioceptive and vestibular feedback. In the second instance, it became obvious that sensory deprivation had different effects in reality and simulation. In real driving, a compensation of particular sensory cues through other sensory feedback seems to be possible. The role of visual cues is much more dominant in the simulator.

Conclusion Chapter 2 summarized the theoretical background for this thesis' work focusing on the development of a presence model for driving simulators. Starting with an introduction on the potential of driving simulators in general, an overview of existing motorcycle simulators was given. Furthermore, the project DESMORI was introduced within which most of the studies were conducted. The development process of the new motorcycle riding simulator within DESMORI followed the control loop paradigm. The rider is seen as a controller who receives input from the simulator and regulates his / her perceptions by his / her action. Therefore, psychological theories that explain this paradigm of the human being as controller were discussed in the following chapter. Subsequently, different presence theories including so called technological and psychological approaches were presented followed by possible presence measures. These theories were evaluated with respect to their applicability in driving simulator setups, which deliver the basis for the development of a new presence models for driving simulators. The new model as core content of this thesis is presented in the following chapter 3. In order to proof components of the newly developed presence model studies on speed estimation were conducted. Therefore, chapter 2 closed with an overview of research on human speed perception.

3 DEVELOPMENT OF A PRESENCE MODEL FOR DRIVING SIMULATORS

The following chapter describes the proposed presence model for driving simulators introduced by the summarized aim of this thesis. As depicted in Figure 6, the model consists more or less of two parts that will be described separately: First, a general model of action and perception in virtual environments; Second, a proposed measurement model of presence. This combination takes up the ideas of Bystrom et al. (1999) expressed in the IPP model (see chapter 2.4.2). Preceding these sections is a paragraph on how to read the model.

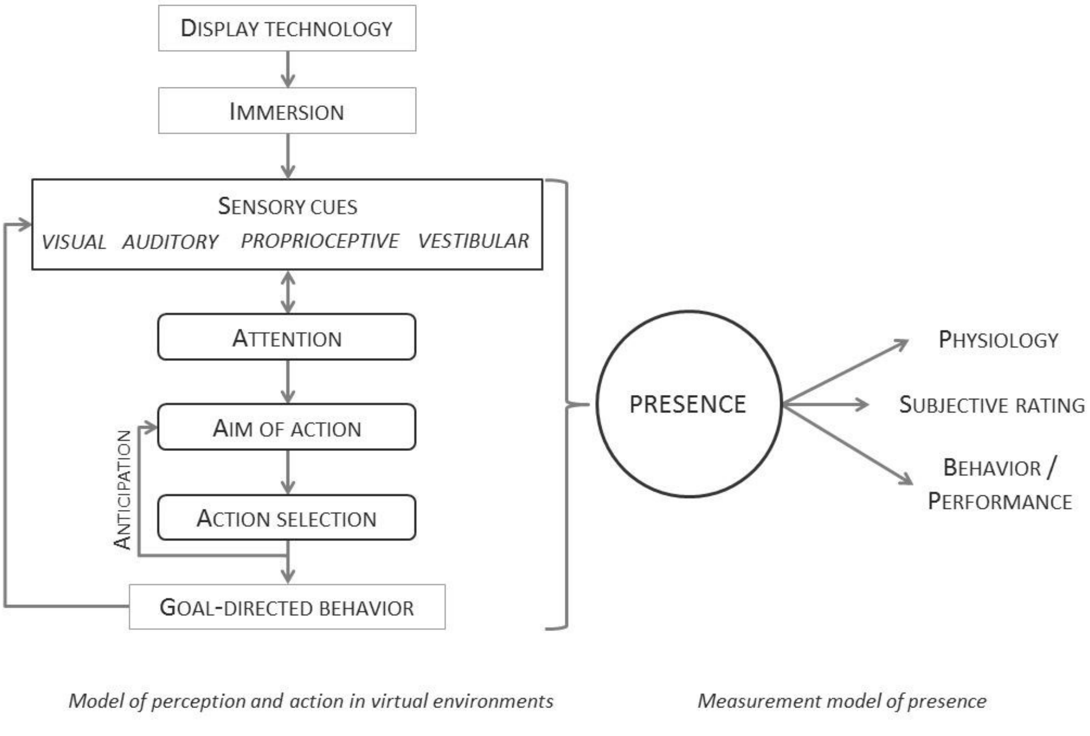


Figure 6: Presence model for driving simulators.

The following two types of components are included in the presence model:

- The rectangular boxes contain manifest variables, which are subject to direct observation and measurement. An example in this case is the simulator technology for auditory cues. One can describe the amount, type and arrangement of sound sources (e.g., 4.1 dynamic speaker system) or physically measure the applied sound level (e.g., 94 dB).

- The boxes with rounded corners comprise latent variables that can only be observed indirectly. For instance, there is no unique tool to measure one's attention. Nevertheless, it is possible to conclude about a person's attention by means of different tests. An example is the dual task paradigm that is based on a resource model of attention. The more attention is attributed to the primary task, the less attention is attributed to the secondary task (Kahneman, 1973; Wickens & Gosney, 2003). This can for example be measured by a performance decrease in the secondary task. For the simulator setup, one could use a peripheral detection task as done by Lee, Lee, and Cameron (2003) in a car diving simulator, and Buld et al. (2014) in a motorcycle riding simulator. A person has to respond as quickly as possible to a peripherally provided visual stimulus. The reaction time between stimulus onset and action of the person delivers one possible indication of whether one is more or less attentive (Martens & van Winsum, 2000).

3.1 Aim of thesis

Driving simulators are powerful tools regarding research and development as more concrete, and road safety as well as fundamental understanding of human behavior as more abstract aims. In order to optimize these tools a scale is needed to evaluate people's experience in existing driving simulators, and to facilitate the design of upcoming simulators according to the drivers' action and perception. A promising scale that could be used for the assessment of driving simulators is the concept of presence. However, existing models can only insufficiently describe the action and perception of human beings in a complex driving simulator setup. Therefore, the aim of this thesis is to develop a presence model for driving simulators based on already established presence models. Furthermore, specific postulated model components and links shall be subject to investigation.

3.2 Model of perception and action in virtual environments

The interaction between rider and motorcycle is a complex system of tight integration and mutual adaptation. While steering, motorcyclists do not only feel the handlebar in their hands but also the tire-road contact, as if the motorcycle acts as an extension tool for human perception (Spiegel, 2012). This interaction pattern is not unique to motorcycle riding simulators. Other types of simulators had to be taken into account adequately, when modeling action and perception in a driving simulator setting. Therefore, elements of the above described psychological theories dealing with human perception and action in general were included in the model. There is no adequate reason to assume that the perception of certain sensory input such as auditory feedback from an engine is fundamentally different in a simulator setting than in a real vehicle. It has to be emphasized that there might be differences between the sensory cues themselves. For instance the quality, sound level, and interfering noise etc. from auditory cues may vary between simulator and real vehicle, but the process of perceiving and processing sensory information should be comparable.

The upper part of the model is based on technological approaches to presence research.

Display technology The display technology was prominently taken into account as own component, because driving simulators use multi-sensory feedback in order to create the virtual environment. In this context, 'display' does not only refer to devices used for visualization but to devices addressing any sensory organ. As mentioned in chapter 2.1, there are huge differences between simulators in terms of the amount of addressed senses, as well as how these sensory stimulations are produced. These differences between e.g., steering a vehicle with gaming controllers in front of a single TFT-screen, and a fully functional car positioned on a Steward platform cannot be ignored. The display technology is a physical description of the simulator setup.

Immersion Following Slater and Wilbur (1997) this display technology defines a certain level of immersion. This is still a physical description that deals with the performance of the display technologies that defines the quality of interaction with the driver's senses. It can be regarded as an originally psychological construct that is determined by technical characteristics. It is an objectively measurable characterization of the simulator setup; for example in terms of display resolution or spatial arrangement of sound sources. Therefore, immersion is defined as manifest variable in this presence model (see chapter 2.4).

Sensory cues The physically present simulator setup interacts with the driver by presenting sensory stimuli. In line with the above mentioned argumentation, the relevant ones for driving simulators are visual, auditory, proprioceptive and vestibular stimuli.

This leads to the lower part of the model that summarizes elements of different psychological approaches to presence. It consists of an outer feedback loop and an inner feedforward loop.

Feedback loop The 'aim of action' can be seen as a reference value, which is represented as a set of sensory feedback (perception). Meanwhile, this component defines the model of action and perception as a motivational model. It represents what the driver wants to achieve with his / her behavior. This aim might be set either voluntarily and internally motivated or subliminally respectively externally motivated. The 'action selection' describes the process of motor control, and thereby the planning and initiation of movement. For instance, this could be to pull the brake lever until a certain tactile feedback from the lever is reached. The observable action itself is called 'goal-directed behavior', which is responsible for changes in the virtual environment, and these are in turn recognized by the actor through changed sensory feedback. This feedback is then compared with the formerly set aim of action. If there is no discrepancy, then the aim has been successfully reached, and no further action is needed. The phenomenon of "sensory attenuation" describes that the expected effects of one's action are attenuated. However, if any discrepancy is noticed, this becomes more easily salient and further action is needed to achieve the aim.

The comparison of sensory input with the reference aim is mediated by attention. Control of the visual effects of the goal-directed behavior may direct the attention towards visual input and lead to a reduced focus on auditory feedback for the moment. In contrast, certain sensory information can automatically attract one's attention. For instance, the driver sets the gear position to neutral by accident; the unexpectedly roaring engine automatically directs the driver's attention towards auditory information, even if this might not have been part of the control loop.

Feedforward loop The presence model in this thesis also includes an inner loop, namely the comparison of anticipated sensory effects of the selected action, with the aim of action that is both coded in terms of sensory information. This comparison allows correcting for discrepancies even before the selected action becomes manifest in an observable behavior. For instance, the aim of action was stored in terms of a specific optical flow in combination with certain proprioceptive feedback from the right hand controlling the throttle position. This aim is translated in movement planning of the right arm. When this step is taken, the anticipated effect of the arm movement gets compared with the intended effect. A divergence would lead to renewed movement planning before actually turning the throttle twist grip. These feedforward models typically encompass a third comparison. Comparing the anticipated effect of a selected action (prior to taking the action) with the actually resulting effects of the action (after the action) delivers information on whether the own behavior was responsible for the changed sensory feedback. For instance, if there is congestion on an urban road in either direction, as the preceding car slowly starts to move, one aims at following with a certain speed represented in terms of a specific optical flow. At the same time, the cars on the lane left, driving in the opposite direction, start to move, too. The result is a higher optical flow than one has expected to produce with the own behavior. The changed set of sensory information is therefore not solely a consequence of the own behavior and other action might be necessary to reach the primarily set aim.

3.3 Measurement model of presence

Different approaches to presence measurement were discussed in chapter 2.4.3. This review led to the inclusion of a measurement model that regards presence as a multi-level construct. Previous studies have shown that e.g., pure subjective ratings can be biased and should be supported by other measures (Freeman et al., 1999). This gives the chance to overcome the shortcomings of one measure by the advantages of another (IJsselsteijn et al., 2000). The proposed measurement model of presence includes three levels: performance & behavior, physiology and subjective ratings.

Driving simulators are typically used for a specific purpose. For instance, this may be training or the generation of knowledge about the drivers' interaction with a specific assistance system. Following Sadowski and Stanney (2002), it does not make sense to decouple performance from presence as the utility of that construct depends on performance for most use cases. A research tool that makes drivers feel like being in a car, but performing poorly in the driving task is probably far from being useful. In accordance with this argumentation, performance is included as part of the measurement model of presence. Performance is neither seen as prerequisite of presence nor the other way round. Performance is one measure amongst others to indicate presence.

The term behavior refers to specific action of the drivers that is not in first line necessary for the successful fulfillment of the driving task and mostly an unintended side effect of acting in the virtual environment. The inclusion of this measurement of presence follows the idea of the above mentioned postural responses (Freeman et al., 2000). A vivid example is a motorcyclist on a riding simulator who takes his / her feet from the food pegs and on the floor in standstill. The acquisition of that behavior took place in real-life riding. Then, there was a transfer from the rider's real-riding experience to the laboratory setting. Strictly speaking, there is no rational justification to place the feet on the floor in the simulator, because the simulator will never capsize in standstill. All participants know about this fact. Nevertheless, they do so without actively deciding to. Asked afterwards, they do not even remember this behavior for the most part. The underlying scientific principle is the ground truth paradigm. Behavior that is shown in the virtual environment and obviously transferred from the according task in reality can be interpreted as a hint of increased presence. Not only the aim of an activity is achieved but the people behave in a comparable way to get there. However, it must be noticed that longer exposure to a simulator may lead to simulator-specific acquisition of action-effect associations that overwrite those experiences from the real world. For instance, if the rider notices that there is no need to take the feet from the foot pegs in standstill he / she might change his / her behavior over time.

This ground truth paradigm underpins the inclusion of physiological activity as means of presence, too. The fact that a person's body reacts to specific events in the virtual environment in a comparable way as in reality is another presence indicator (Dillon et al., 2002; Jang et al., 2002; Meehan et al., 2002). For instance, increased heart rate induced by a suddenly appearing car that violates the driver's right of way can be observed as presence measure in a simulator, if this physiological reaction is well-known from reality. Driver behavior and physiology are closely related in terms of their interpretation with regard to presence. Both add additional value to the measurement model of presence as they are not subject to people's consciousness or free will respectively. Therefore, they might be less biased than subjective ratings. For instance, a study compares the levels of presence in a huge hexapod mounted driving simulator with that of a smaller desktop driving simulator. Regardless of possible advantages of the smaller simulator, the impressive appearance of the huge simulator might automatically provoke higher subjective presence ratings. It is important to notice that in this example the rating bias is an artefact of characteristics such as size instead of the experience while driving. Nevertheless, presence is a construct that is dependent on individual impressions (Schubert, 2003). The same driving simulator that provides one specific level of immersion will induce different levels of presence in different drivers. This makes subjective ratings not only useful, but also necessary to paint the whole picture of presence.

Conclusion The proposed presence model for driving simulators consists of a model of perception and action in virtual environments and a measurement model of presence. It combines established technological and psychological approaches to presence. The contribution of specific sensory cues to presence plays an important role. More and contingent sensory feedback leads to higher levels of presence. In line with psychocybernetic models people act in order to control the sensory feedback that is provided by the simulator's display technology.

The better this feedback control works the higher the level of presence. As presence is regarded as a multi-level construct it shall be measured by combinations of physiological, subjective and behavioral respectively performance measures.

4 METHODS

The following chapter summarizes information on study methods. As the contents of this thesis' studies are closely related due to the fact that they address different aspects of the same proposed presence model, a general methods chapter precedes the single study descriptions. The close connections between studies are worked out in the first section 4.1. This section is followed by information on the used motorcycle riding simulator and real motorcycle respectively, panel descriptions, courses and study procedures. Afterwards, the operationalization of the model's contents is clarified in sections on independent and dependent variables. The chapter closes with general remarks on statistical analyses and the resulting general hypotheses.

4.1 Study overview

Five studies were conducted in order to assess different aspects of the presence model for driving simulators (see Figure 7). The technical framework of the motorcycle riding simulator was optimized appropriately according to common criteria from literature (Ambrož et al., 2012; Carsten & Jamson, 2011; Riecke et al., 2009; Welch et al., 1996). It characterizes measurable aspects of the display technology such as framerate, latency, brightness or sound level. These features were kept constant in all studies, as the influence of different display technologies on immersion and presence was not subject to this thesis.

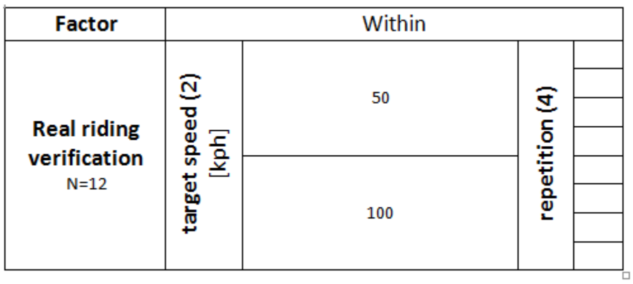
Studies one to three dealt with the investigation of specific links postulated within the model. These studies used different variants of a speed estimation task on a motorcycle riding simulator. The fourth study aimed at replicating the results found in the first three studies in a more complex riding task than speed estimation on a straight rural road. Therefore, a well-known standard experiment on presence in virtual reality was adapted to the riding simulator setup ("the pit"). Study number five used the same speed estimation task as studies one to three, but applied in a real riding experiment. This should deliver insights in the comparability of rider behavior and performance in the simulator and in reality. Summarized, the main research questions were as follows:

- Study I "Video": What is the influence of different sensory cues on presence independent from taking action?
- Study II "Action": Does acting in artificial environments increase presence and how is this connected to the effect of more consistent sensory feedback?
- Study III "Training": How can presence be influenced by training of action and perception in virtual environments?

- Study IV “Generalization”: Are the effects of sensory feedback on presence replicable in a more complex riding task than pure longitudinal control?
- Study V “Real riding”: How do motorcyclists perform regarding speed estimation on a real motorbike compared to the simulator setup?

Factors	Between	Within					
Studies	**Video** N=24	**condition (4)**	visual	**target speed (3) [kph]**	50	**repetition (5)**	
					100		
					160		
			visual & auditory		50		
					100		
					160		
			visual & auditory & proprioceptive		50		
					100		
					160		
			visual & auditory & proprioceptive & vestibular		50		
					100		
					160		
	Action N=24	**condition (4)**	visual	**target speed (3) [kph]**	50	**repetition (5)**	
					100		
					160		
			visual & auditory		50		
					100		
					160		
			visual & auditory & proprioceptive		50		
					100		
					160		
			visual & auditory & proprioceptive & vestibular		50		
					100		
					160		
	Training N=24	**condition (4)**	visual	**target speed (3) [kph]**	50	**repetition (3)**	
					100		
					160		
			visual & auditory		50		
					100		
					160		
			visual & auditory & proprioceptive		50		
					100		
					160		
			visual & auditory & proprioceptive & vestibular		50		
					100		
					160		

Factor	Between	
Generalization N=47	**condition (4)**	visual
		visual & auditory
		visual & auditory & proprioceptive
		visual & auditory & proprioceptive & vestibular



Factor	Within			
Real riding verification N=12	**target speed (2)** [kph]	50	**repetition (4)**	
		100		

Figure 7: Study overview containing panel size and independent variables. The numbers in parentheses indicate the amount of factor levels.

4.2 Simulator description

The DESMORI dynamic motorcycle riding simulator is equipped with a BMW F 800S as mockup, mounted on a 6 dof hydraulic Stewart platform (see Figure 8). The mockup enables the rider to interact with fully realistic controls, such as usual handlebar, brake lever / pedal, clutch, gear selector, etc. that he / she is used to. The manual gear shift uses a sequential six-speed gearbox. An electrical actuator is used to produce a steering torque at the handlebar up to 80 Nm. The rider steers the motorcycle through a combination of steering torque and induced roll torque by shifting his / her weight. The cylindrical screen with a diameter of 4.5 m and 2.8 m of height enables 220° horizontal field of view. The two rear-mirrors are realized by 7 inch TFT-displays while the instrument cluster is represented by a 10 inch TFT-touchscreen containing a speedometer, revolution counter and gear indicator. A helmet with implemented Sennheiser© HD419 headphones (frequency: 20 Hz – 20 kHz, impedance: 32 Ω, sound pressure level: 108 dB) is used for auditory feedback. Moreover, a shaker that is installed below the seat delivers vibrations from the engine and high frequent road roughness between 10 and 50 Hz to the rider. The vibrations and sound files were recorded in the BMW Motorrad laboratories using a four stroke flat twin engine with 1170 cc displacement under various load and rpm combinations. Furthermore, the rider is wearing a customized motorcycle airbag vest (Motoairbag©) with air-filled compartments. It is connected to a rope towing mechanism, so that the rider receives proprioceptive feedback on accelaration, speed and static wind forces by being pulled backwards. Forces up to 300 N can be provided by the electrical actuator. The simulator is running with the simulator control software SILAB. All rider-related inputs (e.g., applied steering torque, induced roll torque, throttle position…) as well as vehicle dynamic parameters (e.g., lateral position on lane, accelaration, velocity…) are logged. Specifically for the ‘Action study’ an interface to the Becker Varioport was used to record physiological measures.

Figure 8: DESMORI dynamic motorcycle riding simulator at WIVW.

Study V: Real riding – test motorcycle

As the DESMORI simulator's motorcycle dynamics model does not correspond to a specific motorcycle, the real riding comparison was conducted with a KTM 1290 Superduke R. This sporty naked bike's engine with a displacement of 1301 cc delivers 127 kW and is using a 6-speed transmission. The test motorcycle was equipped with a CAN-Bus data logger and a GPS mouse (see Figure 9). The motorcycle's position as well as vehicle related data such as speed, gear position or interaction with motorcycle controls was logged. The dashboard was covered so that no information on speed, engine revolutions or gear was available to the riders.

Figure 9: Test motorcycle for the real riding study on speed perception.

4.3 Panel description

All participants were acquired from the WIVW test rider panel. The participating motorcyclists reflect a wide variety of riders (see Table 2). No professional (test) riders took part in the studies. As prior exposure to simulator riding might influence speed perception, all participants in studies one to four were novices in terms of riding a dynamic motorcycle simulator. A lump-sum expense allowance was granted to all subjects. The participants were informed about the actual purpose of the experiments.

Table 2: Panel description: Figures for age and mileage indicate mean values. Standard deviations are given in parentheses.

	N (male/ female)	**Age [years]**	**Mileage last 12 months [km]**	**Total mileage [km]**
Video	24 (24/0)	46 (14)	5,554 (2,660)	99,217 (86,128)
Action	24 (22/2)	31 (12)	8,989 (13,977)	40,310 (38,777)
Training	24 (19/5)	30 (10)	4,991 (4,209)	35,333 (46,699)
Generalization	47 (40/7)	31 (11)	7,048 (10,628)	35,085 (39,738)
Real riding	12 (12/0)	36 (14)	5,400 (6,165)	101,958 (147,493)

4.4 Courses

The courses for all four simulator studies contained different combinations of preprogrammed sections that will be described in the following chapter.

As soon as the participants had to estimate their velocity, the environmental conditions were the same in all studies. Figure 10 displays the standard course for speed estimations. It was a flat rural road with two lanes (4 m lane width each). The surrounding trees' position, height and density were kept constant at all time. The same applies for the weather conditions. The 'Video study' solely used this course section.

Figure 10: Standard course for speed estimations.

The ‘Action’ and ‘Training study’ began with a baseline section in order to familiarize with the simulator and to get physiological and riding baseline measures (see Figure 11 left). The passages for speed estimation started from standstill at a stop sign. The target speed was indicated by a round blue sign with white digits (see Figure 11 right). Both studies used the same sections for the speed estimations as the ‘Video study’. The different speed estimation sections were separated by filling scenarios that should avoid transfer effects. These four scenarios had exactly the same geometry with smooth curves going slightly up- and downhill. The only differences were environmental conditions affecting the road surface condition. The upper four pictures in Figure 12 show the variations neutral asphalt, rain, cobble stone and cobble stone combined with rain. Every speed estimation section was followed by one of the filling scenarios. The order of course sections was permuted in order to avoid sequence effects. The resulting course permutations were similarly used in all simulator studies.

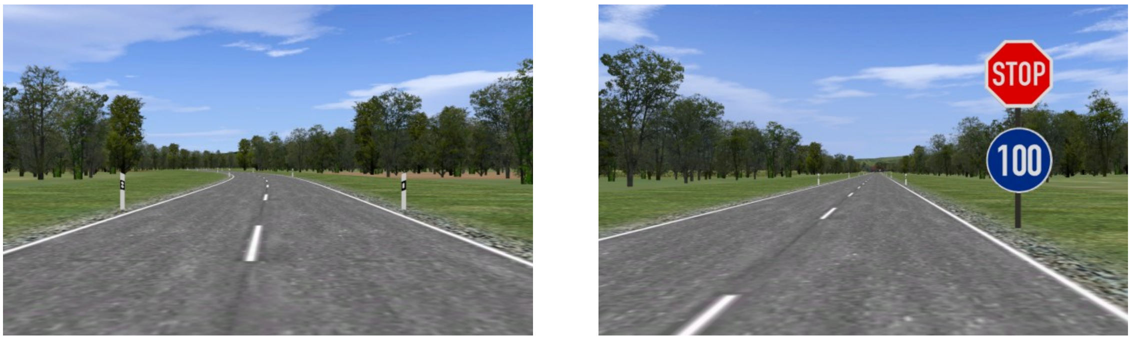


Figure 11: Baseline course on rural road (left) and beginning of speed estimation course for 100 kph target speed (right).

The two lower pictures in Figure 12 display another filling scenario. Participants had to pass a construction site and cross a speed bump. All studies ended on a car parking at the end of a dead end road.

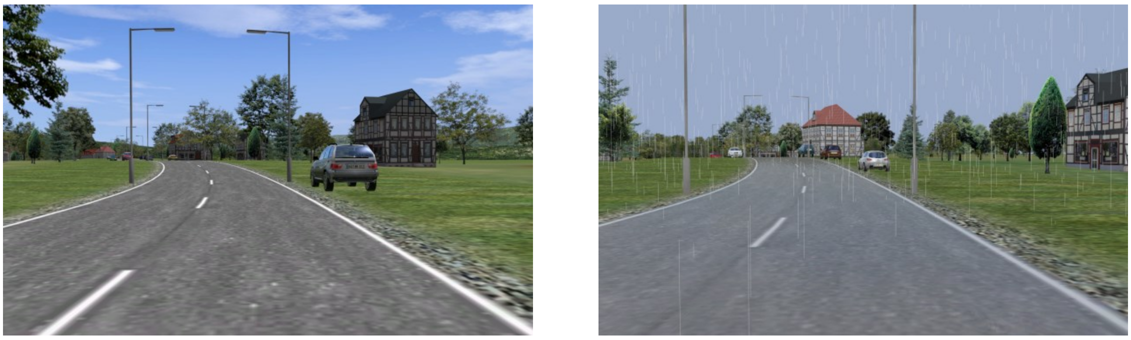


Figure 12: Filling scenarios from upper left to bottom right: neutral, rain, cobble stone, cobble stone and rain, speed bump, construction site following speed bump.

Study IV 'Generalization' focused on one specific situation where the riders suddenly ended up at a deep pit that they had to cross (see Figure 13). As this surprising situation only works once per participant, the section was attached to one of the trials of studies II or III. The total length of the course was 27.19 km without and 28.19 km including the pit.

Figure 13: Entry (left) and passage of pit (right).

Study V: Real riding – test track

The course for the real riding study was a straight road with 4 m lane width and one lane per direction. It had a total length of 700 m. After each trial the riders made a U-turn in order to have the complete length for the next target speed. Estimations of 160 kph were impossible due to the limitation of space. The surroundings resembled the simulator course but had a slightly more urban character with asphalted areas instead of grass and trees in about the same distance and height only on one side.

4.5 Study procedures

An overview of the study procedures is given in Table 3. At the beginning, every participant filled in a privacy statement, a questionnaire on personal data and riding behavior as well as a baseline simulator sickness questionnaire (SSQ). Afterwards, the components of the riding simulator, the study procedure and the upcoming variations were explained to the participants. The following activities, prior to the test trials, were only part of studies II to IV. All participants rode on two courses in order to familiarize with the simulator. The first was a straight rural road without traffic where the focus was on longitudinal control such as accelerating, braking or shifting gears. The second was a curvy rural road with decreasing bend radii targeting lateral control of the virtual motorcycle.

During the training, the participants practiced to accelerate homogenously until an instructed velocity was reached. After keeping the speed constant for a while, a controlled deceleration phase to standstill followed. Beginning and end of every task was indicated by road signs (see Figure 14). In the 'Action study', the rider got equipped with physiological devices afterwards.

Table 3: Simulator studies' procedures with approximate values for duration. Grey shaded activities were not part of the 'Video study'. The dark grey shaded activity was only part of the 'Action study'.

Activity	**Duration [min]**
Introduction	10
Familiarization phase	15
Training	15
Installation of physiological devices	10
1st trial	25
Inquiry	10
2nd trial	25
Inquiry	10
3rd trial	25
Inquiry	10
4th trial incl. the pit	25
Inquiry	10
Final inquiry	5
Total	**155 - 195**

Every participant filled in the SSQ again, before starting with the test trials. Each test trial contained one condition. The conditions were randomly assigned to the trials. Following every test trial, the participants filled in the SSQ and the presence questionnaire. The fourth trial in study II and III ended with the pit, delivering data for the 'Generalization study'. The final inquiry focused on the perceived contribution of the different sensory cues to presence.

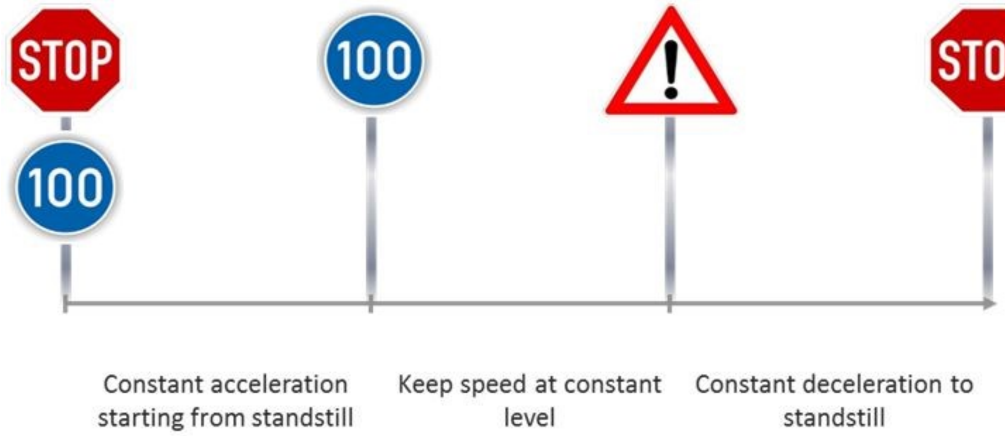
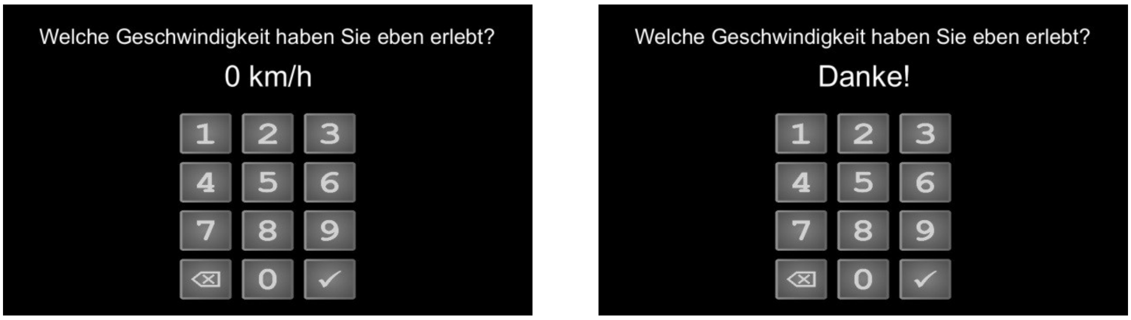


Figure 14: Design of the training course.

In order to avoid breaks in presence, the interaction of rider in the virtual world and experimenter in the laboratory should be minimized (Slater & Steed, 2000). Therefore, the riders in the 'Video study' used the cockpit's touchscreen to type their estimations (see Figure 15).


Welche Geschwindigkeit haben Sie eben erlebt?

0 km/h

Welche Geschwindigkeit haben Sie eben erlebt?

Danke!

Figure 15: Video: HMIs for the speed estimation task appearing automatically after five seconds (left) and after typing the estimated speed (right).

All other studies dealing with speed estimation used the upper beam flash as indicator for the speed estimation. The riders were instructed to accelerate to a certain target speed. When the riders had the impression that they have reached the target speed, they flashed the upper beam once to give their estimation.

Study V: Real riding – procedure

The real riding study began in accordance with the simulator studies. All participants filled in a privacy statement and a questionnaire on personal data and riding behavior. Afterwards, the test riders were informed about the purpose of the experiment and their task. The participants had about five minutes to familiarize with the test motorcycle on urban and rural roads. There were two blocks with four estimations each. Every block focused on one target speed always starting from standstill. The order of target speeds was permuted between participants. In accordance with the simulator studies, the upper beam flash was used to indicate that the participants have reached the target velocity.

4.6 Independent variables

This section describes the independent variables that were varied in the different studies of this thesis. At the beginning of each results section, the relevant independent variables are named.

Condition

The four conditions vary in their amount of sensory feedback that was provided to the participants while riding. This variation was only part of the simulator studies. Due to economic reasons not all possible combinations of the four sensory cues were investigated. In line with the importance of specific cues for simulator driving discussed in literature (see 2.4.1) the following four levels were investigated:

- 1st condition/ condition one: visual
- 2nd condition/ condition two: visual & auditory
- 3rd condition/ condition three: visual & auditory & proprioceptive
- 4th condition/ condition four: visual & auditory & proprioceptive & vestibular

Target speed

The 'target speed' defines the velocity that participants had to estimate without receiving feedback from their speedometer. This independent variable was varied in three steps, whereby the highest target speed was only part of the simulator studies, but not the real riding investigation:

- 50 kph
- 100 kph
- 160 kph

Every combination of condition and target speed was repeated five times in the 'Video' as well as the 'Action study' and three times in the 'Training study'. These repetitions are named 'repetition per target speed and condition' hereinafter.

Method estimation

The 'method estimation' marks the difference between passively experiencing different velocities and actively setting the speed. Thus, this variable had two levels that were relevant for study II 'Action':

- Passive
- Active

Velocity feedback during training

'Velocity feedback during training' states whether participants had an active speedometer during a training phase or not. Those with active speedometer could practice setting specific target speeds with feedback on their performance. They were given the chance to adjust their behavior. The group without feedback completed the same tasks on the motorcycle during the training phase, but did not receive feedback on their speed. The two levels of feedback were relevant for study III 'Training':

- Without feedback
- With feedback

Setting

Study V 'Real riding' delivered a reference point for the riders' speed estimation capabilities in real riding relative to simulator riding. The two levels were named as follows:

- Real riding
- Simulator

4.7 Dependent variables

The following chapter describes which specific means were applied to measure the presence model's dependent variables in the studies.

4.7.1 Performance

The participants' performance in terms of speed estimation was calculated as follows:

$$performance = \frac{estimated\ speed\ [kph]}{target\ speed\ [kph]}$$

Here, the proper terminology is of utter importance: Underestimating the actual speed means that one is riding e.g., at 60 kph (estimated speed), but reports that it feels like the instructed 50 kph (target speed). This results in performance values higher than one. The other way round, an overestimation of actual speed with performance values below one indicates that the rider rides at e.g., 40 kph, but already has the impression of having reached 50 kph (target speed). This relative measure enabled a better comparison across target speeds. Furthermore, the standard deviation of these relative deviations was calculated to indicate the stability of estimates. Another stability indicator was the standard deviation of time taken to estimate the velocity. This reflected whether the behavior shown as acceleration phase from standstill to a certain target speed was more homogeneous in a specific condition.

4.7.2 Behavior

The analyses of behavior focused on spontaneous and non-instructed natural responses of the riders to situations in their virtual surroundings. These were on the one hand measurable with riding data and on the other hand with operator ratings.

The condition of the road surface and weather is typically known to influence motorcyclists' riding behavior as the grip between tire and road may be changed (Schwabe, 2015; Spiegel, 2012). The filling scenarios aimed at investigating under which conditions the motorcyclists show the same adopted riding behavior in the riding simulator. Therefore, each filling scenario was partitioned into three sections. The first 90 m forming a wide bend were disregarded for any analyses as motorcyclists arrived with different velocities depending on the target speed on the prior section. Furthermore, the riders needed some time to react to the 70 kph speed limit sign. The second section contained 674 m of free riding and the third section contained the last 100 m of the filling scenario where the stop sign for the next speed estimation passage could already be seen. All analyses dealing with riding behavior as naturalistic responses contain the first contact situations only. This is due to the fact that not the learning process was of interest but the initial and intuitive behavior of the riders in the given scenario. This type of behavior (e.g., speed adjustment) was available in the objective riding data.

Table 4: Behavioral responses: Categories for the operator rating.

Category	Description
Leaning	The participant changes his or her riding position according to the situation. For instance, more relaxed and upright during slower ridden filling scenarios compared to the acceleration phases for speed estimation. This category includes taking the head down to look over the shoulder for a traffic check.
One-handed riding	The participant rides one-handed to relax during the filling scenarios.
Speaking to the operator	The participant is *not* speaking to the operator while riding. This would be a break in presence and a clear sign that he or she is not completely immersed in the virtual setting.
Taking feet down	The participant takes his or her feet on the ground as soon as he or she has reached stand still.
Duck the head	The participant ducks the head and takes a particularly streamlined position when accelerating in order to avoid wind forces to the head.

Additionally, the pilot study conducted beforehand revealed a certain amount of participants' natural responses to the scenarios. Out of these observations caught by six operators, five behavioral categories were defined that occurred most often and seemed to fit to the studies' content. During the main study, the operators rated the five categories to be present or not during a specific trial. The five revealed behavioral categories are listed and explained in Table 4.

4.7.3 Subjective rating

Subjective ratings were collected in the simulator studies only. These were gathered by means of two well-established questionnaires related to presence and simulator sickness as well as a study-specific final inquiry.

4.7.3.1 Presence-Questionnaire

Subjective measures of presence were taken using a presence questionnaire for virtual driving simulators (Scheuchenpflug et al., 2003). Out of the 51 questions available, 44 were chosen to fit the motorcycle simulator setup as well as the riding task (see 13.1 for the German version). Participants rated each item on a 7-point-Likert scale. Besides analyzing specific items, Scheuchenpflug and colleagues recommend the calculation of three subscales taking items into account that load specifically high on spatial presence, interface quality or involvement. The subscale scores were computed as sums of item responses. The numbers in brackets indicate the possible range of values:

- Spatial presence: 14 items [14-98]
- Quality interface: 8 items [8-56]
- Involvement: 4 items [4-28]

In addition to that, the questionnaire contained the Immersive Tendencies Questionnaire (ITQ). This measures a trait variable how prone a person is to experience high levels of presence (Witmer & Singer, 1998). All participants had to answer these ITQ items only once.

4.7.3.2 Simulator Sickness Questionnaire

Simulator sickness may not be disregarded as it leads to impaired performance in driving simulator tasks (Klüver, Herrigel, Heinrich, Schöner, & Hecht, 2016). This, in turn, will have negative effects on presence. The close connection to presence has been described in chapter 2.4.3.3. Sickness symptoms arising from the virtual ride are therefore measured by the Simulator Sickness Questionnaire SSQ (Kennedy et al., 1993). The SSQ contains 16 symptom variables such as sweating or eyestrain each of which was to be rated on a 4-point scale [0-3]. As dependent variable the aggregate score was computed as the sum of all symptom variable scores. The aggregate score ranges from 0 indicating no sickness at all to 48. The questionnaire translated to German can be found in chapter 13.2.

4.7.3.3 Final Inquiry

The final inquiry aimed at comparing the different sensory cues' contribution to performance and perceived presence. Each sensory cue's influence had to be rated on a 15-point categorical classification scale (Heller, 1985). Furthermore, ranks one to four had to be assigned to the different sensory cues. No ranking could be awarded twice. The final inquiry can be found in chapter 13.3.

4.7.4 Physiology

The record of physiological data contained an electrocardiogram (ECG) delivering the inter-beat interval (IBI), the skin conductance level (SCL) and an electromyogram (EMG). Figure 16 shows the electrode application locations. Cotton pads were taped over the SCL and EMG electrodes to minimize measurement artefacts due to friction of clothes and protective gear. A Becker Varioport was used as physiological measurement device.

Data preprocessing was done using ANSLAB. All physiological data were automatically marked and manually controlled for inconsistencies. The complete course was segmented in different events coding condition, target speed and repetition. In a first step, the mean value of the corresponding physiological parameter was calculated for every event. For example, the mean heart rate on the third 100 kph estimate segment in the visual condition.

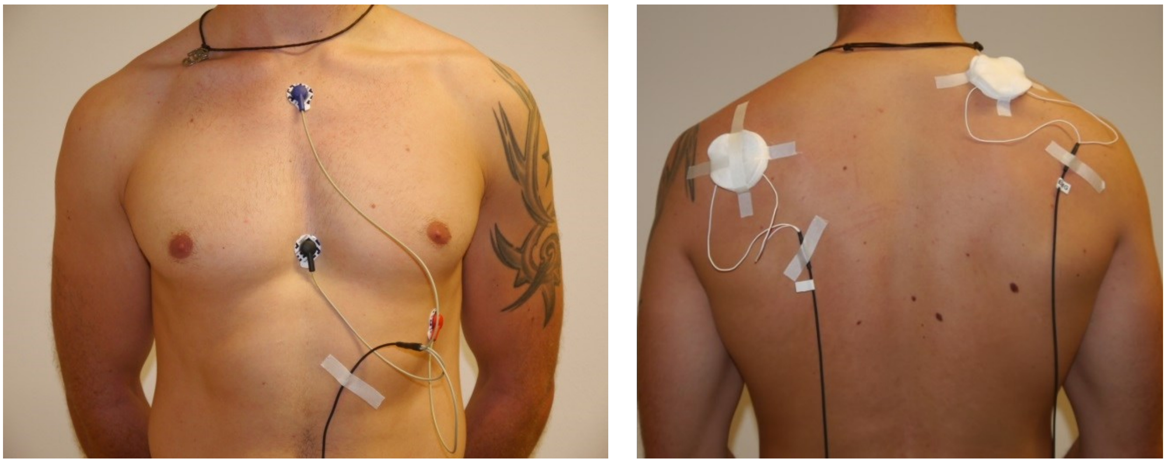


Figure 16: Physiological measurement devices: Applied electrodes for the ECG (left picture) and SCL (left electrodes in right picture) as well as EMG (right electrodes in right picture). The cotton pads were applied to minimize measurement artefacts due to friction of clothes and protective gear.

This was done separately for every subject. In a second step, the values were averaged across repetitions for every rider in every 'condition*target speed' combination. This procedure assured the same weighting for every participant in further statistical analyses. The heart rate was calculated from the inter-beat interval according to the following equation:

$$heart\ rate\ [bpm] = \frac{60.000\ ms}{IBI\ ms}$$

In accordance with the findings of van Dooren et al. (2012), the SCL was measured at the shoulder area. The EMG electrodes were positioned to measure the muscular activity of the trapezoidal muscle. An informal expert interview with motorcycle riding trainers and motorcycle police officers prior to the study revealed the upper back and neck region to be most sensitive for involuntary tension in stressful situations and periods of high concentration.

4.8 Statistical analyses

This chapter gives general information on how the gathered data were analyzed. It starts with data pre-processing for descriptive analyses and ends with specifications of inferential statistics.

In a first step, descriptive statistics were calculated per participant (e.g., mean velocity in a specific condition). Only then, parameters were calculated for the whole panel assuring the same weighting for every participant.

In order to quantify the relationships between the different predictor variables and each continuous dependent variable linear mixed models (LMM) were used (West, Welch, & Galecki, 2007). This modelling approach has certain advantages compared to the traditional analysis of variance (ANOVA) like being less vulnerable to missing data or applying fewer assumptions concerning the variance / covariance matrices. All analyses were conducted using SPSS 23. The model building strategy did not follow sequential iterations, but was retrieved from the hypotheses and compared to the intercept-only model using the Akaike information criterion (AIC). The according Chi-Square statistics based on -2 Log-Likelihoods are reported. The appropriate intercept-only models contained just the intercept for the fixed effect but the same random effects as the model used for prediction. Their comparison therefore indicates to what extend the relevant covariates as fixed effects fit the observed data better than just modeling the noise. There is no literature-driven reason to expect any interactions between the various effects, neither within nor between levels. Nor is there a reason to put additional constrains on the covariance structures. This approach should reduce overfitting tendencies and keep the model simple and interpretable.

Nevertheless, some models failed to converge and it was therefore not possible to obtain proper estimates for the data when e.g., the Hessian Matrix was not positive definite. In this case, the parameter estimates of the last iteration were compared to the results of a subsequently conducted ANOVA using the same data structure and effects. Results of the latter analyses are shown if either approach resulted in the same pattern of statistical effects. The relevant model specifications are given separately at the beginning of each results chapter.

4.9 General hypotheses

The general hypotheses retrieved from the above mentioned considerations on presence are the following:

- **Video**: The pure availability of more consistent sensory cues improves presence independently from taking action in the virtual environment.
- **Action**: Acting in artificial environments increases presence. The positive effect of more consistent sensory feedback on presence remains.
- **Training**: Training action and perception in a virtual environment reduces negative feedback quantifiable as increased presence.
- **Generalization**: The detected presence determinants are not limited to longitudinal control but are also valid in another more complex riding task.
- **Real riding**: The speed estimation performance in a real riding scenario resembles the performance in a sophisticated virtual environment.

In accordance with results from literature (see 2.4), the hypothesized increased level of presence shall be measurable by:

- an improved task performance (more accurate estimates, less variance),
- a higher amount of postural responses,
- more similar behavior between simulator and real riding,
- higher scores on the presence questionnaire,
- less reported sickness symptoms and less drop-outs,
- more similar physiological responses between simulator and real riding.

A summary of the specific research question and hypotheses is given at the beginning of each study's results chapter.

5 STUDY I: VIDEO

5.1 Research question

The main goal of this study was to investigate whether more complete multisensory information improves presence independently from taking action in the virtual environment. The focus lay on the presence model components highlighted in Figure 17 that trace back to technological models of presence (see chapter 2.4.1). By changing the active components of the simulator's display technology, the level of immersion changes accordingly. This, in turn, affects the availability of sensory cues. The hypothesis was that the more consistent sensory cues are available, the better the speed estimation performance and the higher the subjective ratings.

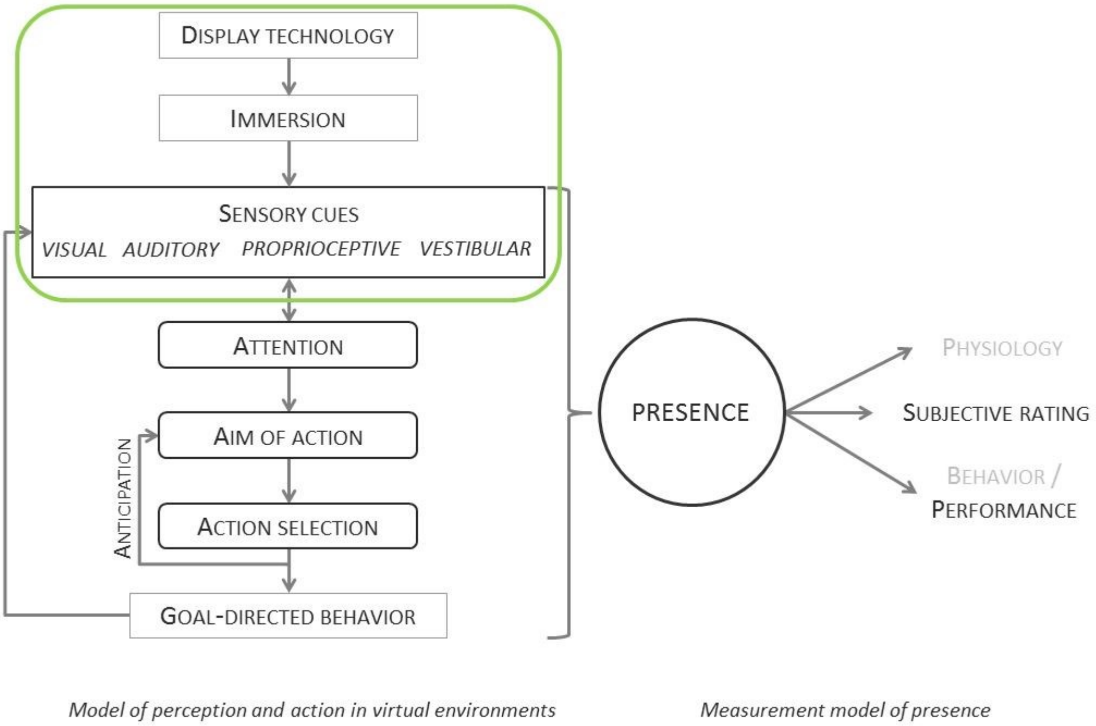


Figure 17: Video: Investigated presence model section (highlighted by the box).

Due to the chosen study design, physiological measures and behavior were not taken into account for the presence measurement.

5.2 Results

The following chapter contains the results of the 'Video study' organized by the type of dependent variables.

5.2.1 Performance

The parametric linear model for repeated measures is conducted with 'condition' (within) and 'target speed' (within) as fixed factors. 'Rider' and 'repetition per target speed and condition' are taken into account as random factors. The combination of a target speed of 160 kph in 'condition four' is used as reference category. The corresponding repeated measures ANOVA takes 'condition' and 'target speed' as within factors.

The participants' performance regarding speed estimation depends on the condition. Estimating speed while receiving visual, auditory, proprioceptive as well as vestibular information leads to statistically significant better performance than estimations based upon pure visual or visual and auditory information. For this longitudinal vehicle control task, the adding of vestibular cues does not improve the performance compared to condition three. Nevertheless, on average, the test drivers misjudge the target speed only by 7.25 % in condition four. Salient is the fact that the velocity is constantly underestimated. As can be seen in Figure 18 (left), the hypothesized general linear mixed model fits the empirical data very well. There is no influence of target speed on the relative deviation of estimated and target speed. Relevant test statistics are given in Table 5.

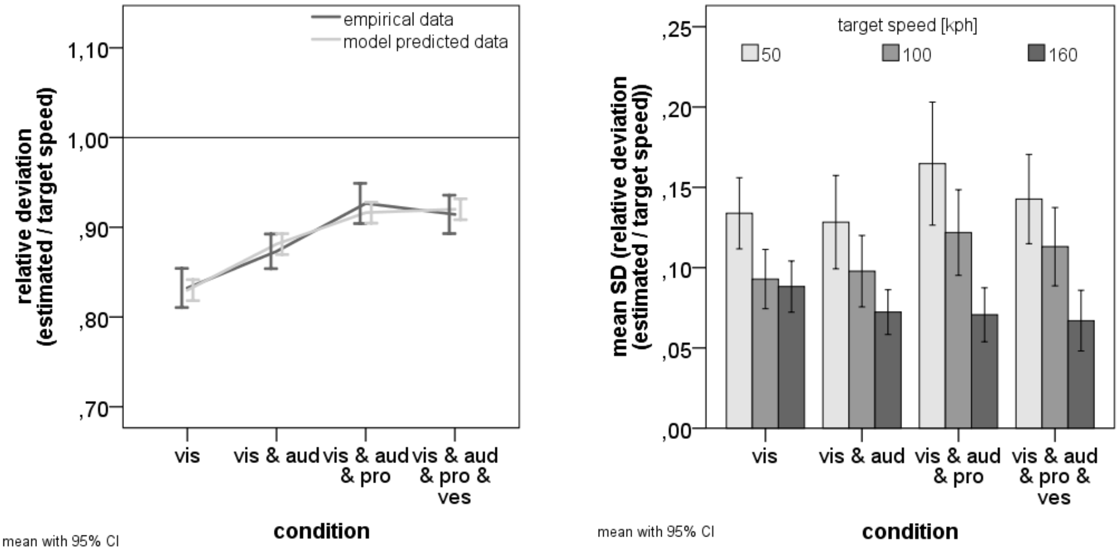


Figure 18: Video: Relative deviation of estimated and target speed for the empirical and model predicted data as a function of condition (left). Stability of estimates indicated by the mean standard deviation of the relative deviation of estimated and target speed as a function of condition and target speed (right).

Statistical analyses do not reveal a dependence of the estimations' stability on the condition ($F(3,21) = 1.26$; $p = .312$; $\eta^2_p = 0.153$). Hence, the variation of estimates is linked to the target speed ($F(2,22) = 29.23$; $p < .001$; $\eta^2_p = 0.727$). The higher the target velocity, the lower the variation of estimates (see Figure 18 right). The interaction does not reach statistically significance ($F(6,18) = 1.78$; $p = .159$; $\eta^2_p = 0.373$).

Table 5: Video: Relative deviation of speed estimation GLMM test statistics.

	GLMM		**Test statistics**
Quality of estimates	Intercept-only model	AIC	-1075.597
	Final model	AIC	-1133.985
		Chi-Square statistics	$X^2(7) = 58.41$; $p < .001$
	Fixed effects	Condition	$F(3,1427) = 35.01$; $p < .001$
		Target speed	$F(2,1427) < 1$

5.2.2 Subjective rating

Presence Questionnaire

In order to assess the effect of condition on the subjectively perceived presence a repeated measures ANOVA is conducted for each subscale. Relevant descriptive statistics are shown in Table 6. The influence of condition on spatial presence reaches a statistically marginal significant effect ($F(3,20) = 2.70$; $p = .073$; $\eta^2_p = 0.288$). With visual input only, participants report a medium high level of spatial presence. Adding one, two or three further sensory cues leads to the same increase in spatial presence compared to the visual condition (see Figure 19 upper left). Furthermore, there is a quite huge variety in between participants' scores. The sub score interface quality is statistically dependent on the condition ($F(3,17) = 30.48$; $p < .001$; $\eta^2_p = 0.843$). Further analyses reveal that riding with visual cues only leads to lower reported interface quality compared to the three other conditions. No statistically significant differences are shown in between condition two to four (see Figure 19 upper right).

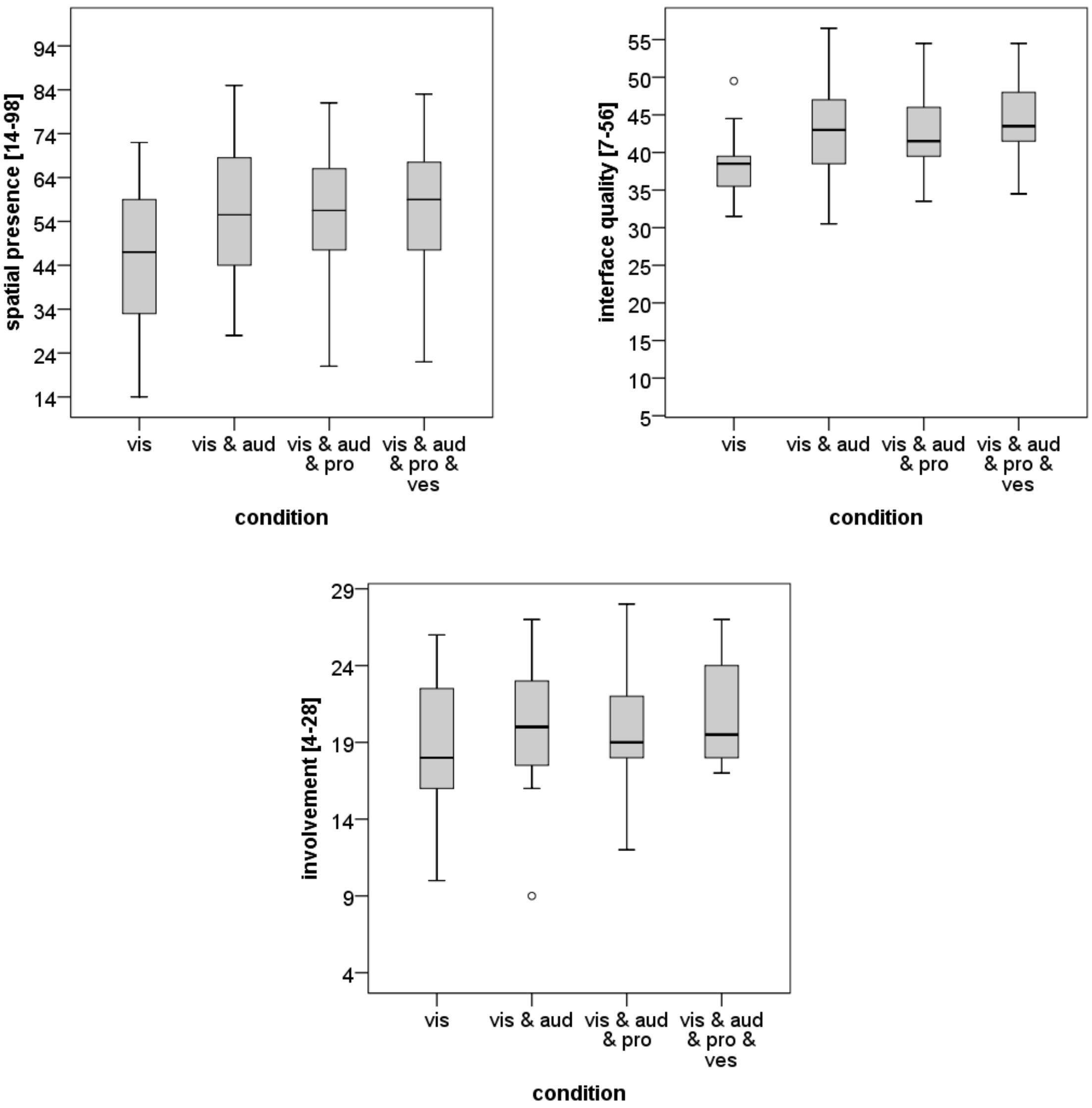


Figure 19: Video: Presence scores on subscales as a function of condition.

There is also a statistically relevant link between condition and reported involvement (*F*(3,18) = 3.17; *p* = .049; η^2_p = 0.346), even if the displayed pattern is slightly different. Riding with auditory as well as auditory, proprioceptive and vestibular information leads to increased involvement scores compared to visual cues only. Condition four shows also a statistically significant increase compared to trials without vestibular information (see Figure 19 bottom center).

Table 6: Video: Descriptive statistics of presence scores on subscales as a function of condition.

		vis	**vis & aud**	**vis & aud & pro**	**vis & aud & pro & ves**
Spatial presence [14-98]	*N*	24	24	24	23
	Min	14	28	21	22
	Max	72	85	81	83
	Mean	46.50	54.63	54.21	56.04
	SD	16.46	15.97	15.56	14.86
Interface quality [7-56]	*N*	21	24	24	23
	Min	31	30	33	34
	Max	49	56	54	54
	Mean	37.90	42.38	42.33	43.83
	SD	4.50	5.86	5.13	5.47
Involvement [4-28]	*N*	23	24	24	22
	Min	10	9	12	17
	Max	26	27	28	27
	Mean	18.96	20.00	19.58	20.95
	SD	4.50	4.02	3.54	3.27

Immersive Tendencies Questionnaire

Figure 20 displays the distribution of the participants' Immersive Tendencies Questionnaire subscales 'emotional involvement' and 'degree of involvement'. Corresponding descriptive statistics can be found in Table 7.

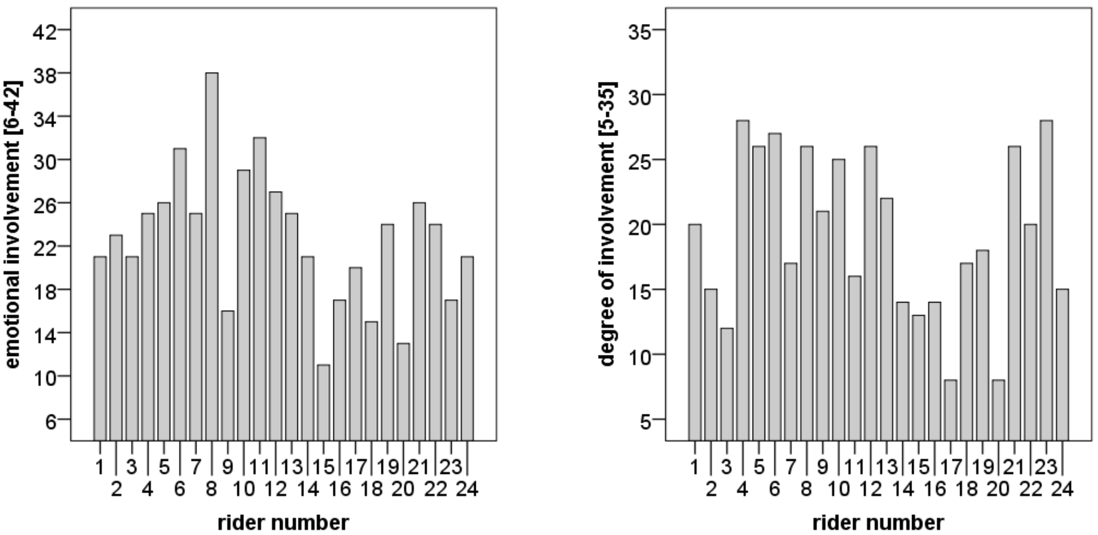


Figure 20: Video: Distribution of participants' emotional involvement (left) and degree of involvement (right) according to the ITQ.

By applying a median split, all participants were divided into two sub groups (low vs. high immersive tendencies) for each subscale separately. The above mentioned ANOVAs were recalculated with an additional dichotomous between factor 'immersive tendencies'. Generally, the group with higher scores on emotional involvement has higher scores on the presence subscales 'spatial presence' ($F(1,21) = 17.89$; $p < .001$; $\eta^2_p = 0.460$) and 'involvement' ($F(1,19) = 7.43$; $p = .013$; $\eta^2_p = 0.281$). Nevertheless, there is no interaction indicating a relation between condition and presence for one of the ITQ sub groups. The median split for degree of involvement reveals no statistically significant effects at all.

Table 7: Video: Descriptive statistics for Immersive Tendencies Questionnaire subscales.

	N	***Min***	***Max***	***Mean***	***SD***
Emotional involvement [6-42]	24	11	38	22.83	6.28
Degree of involvement [5-35]	24	8	28	19.25	6.25

Simulator Sickness Questionnaire

All $N = 24$ subjects finished the study. The sickness symptoms do not vary systematically between the conditions ($F(4,20) < 1$). The computed aggregate scores are on a generally low level with arithmetic means between 2.08 ($SD = 3.08$) for the baseline condition and the highest mean of 2.88 ($SD = 5.00$) for the visual condition. All outliers and extreme values stem from four participants that generally score high across conditions (see Figure 21).

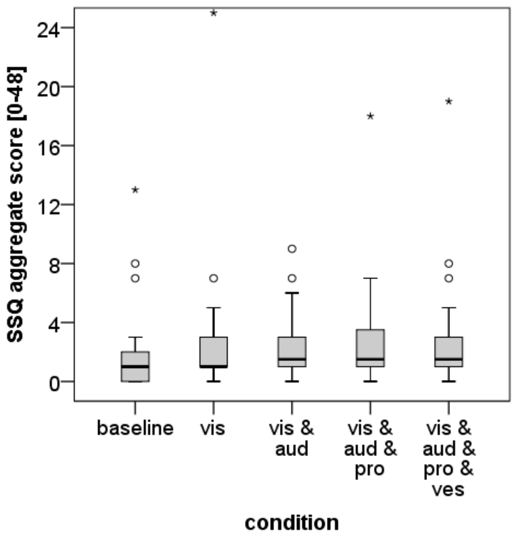


Figure 21: Video: SSQ aggregate scores as a function of condition.

Final inquiry

As part of the final inquiry the participants were asked to report their impression on how much the different sensory cues contributed to their performance in speed estimation on the one hand and to their feeling of presence on the other hand. Repeated measures ANOVAs with condition as within-subject factor were conducted. Data from three participants were missing.

The four sensory cues differ in their subjectively felt contribution to the speed estimation performance ($F(3,21) = 10.73$; $p < .001$; $\eta^2_p = 0.605$). On average, visual cues play the most important role. Their contribution exceeds auditory and vestibular ones.

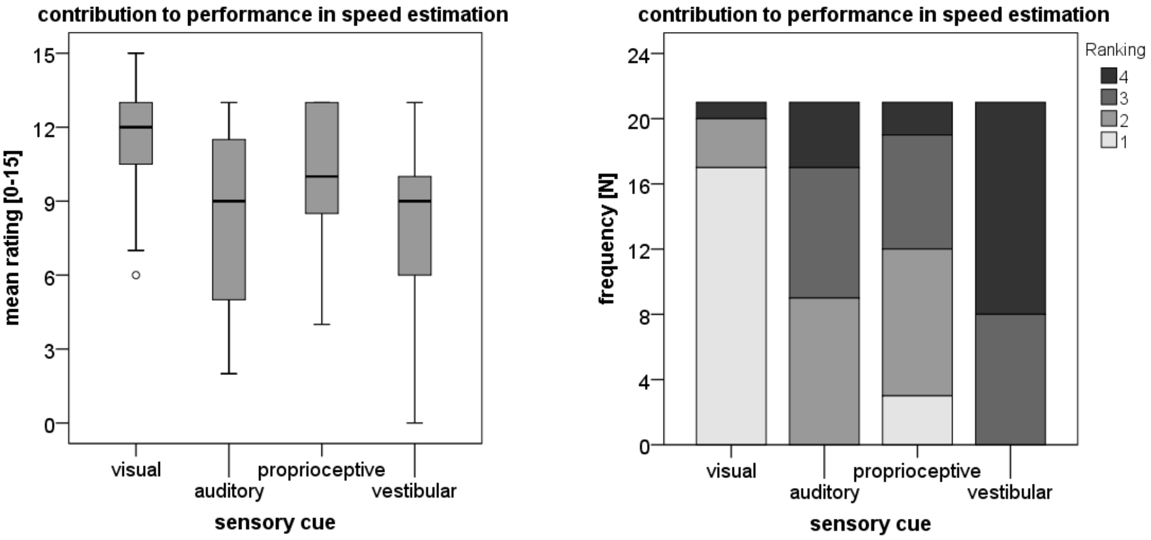


Figure 22: Video: Perceived contribution of different sensory cues to speed estimation performance (left: rating; right: ranking).

Interestingly, proprioceptive information is rated to be of higher importance than auditory and vestibular information, too. Figure 22 (left) shows quite obviously that there is a huge variation in what riders on the simulator experience.

This pattern is mirrored in the rankings that are assigned to each cue (see Figure 22 right). 17 out of 21 participants rank visual cues on the first place. The remaining number one rankings are assigned to proprioceptive cues. The second place is more or less equally assigned to auditory and proprioceptive cues. Vestibular cues are seen to be of least importance concerning speed estimation.

An almost similar effects pattern can be found when looking at the contribution of each sensory cue to subjectively experienced presence by the riders ($F(3,21) = 5.88$; $p = .004$; $\eta^2_p = 0.457$).

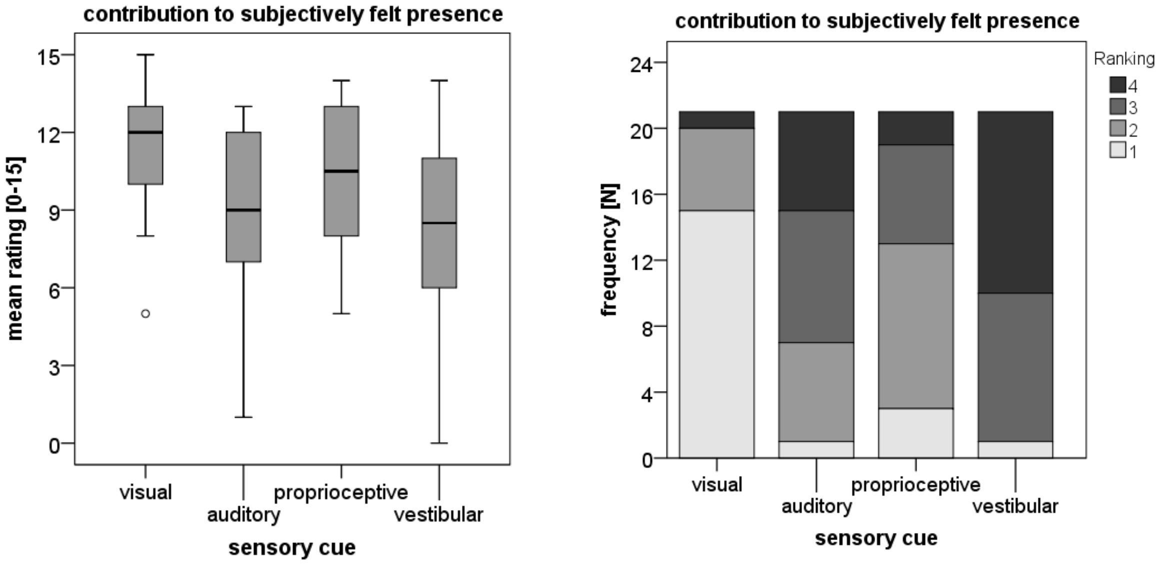


Figure 23: Video: Perceived contribution of different sensory cues to subjectively experienced presence (left: rating; right: ranking).

Once again, visual cues seem almost irreplaceable in order to experience presence. Proprioceptive cues are rated comparably important. Both outperform vestibular cues. Furthermore, auditory cues are rated to be less valuable than visual cues. Figure 23 (left) shows a huge variation between the participants' ratings. Little less dissimilarity can be seen for visual and proprioceptive cues. Taking a look at the assigned rankings shows that visual cues take the lead over proprioceptive ones in terms of rank one assignment (see Figure 23 right). In summary, visual cues are followed by proprioceptive, then auditory and finally vestibular stimulation in terms of participants' rankings for their contribution to subjectively experienced presence. No specific strategies for speed estimation were reported.

5.3 Discussion

In the present study, the influence of different sensory cues on presence was investigated. In a speed estimation task the availability of visual, auditory, proprioceptive and vestibular cues was varied stepwise. To summarize the most important findings, an underestimation of velocities in the motorcycle simulator was observed that decreased with higher target speeds. Visual cues are rated to be the most important contributor to presence, while a further increase of subjectively felt presence occurred as soon as any other additional sensory cue was available. These findings will be discussed more in turn.

The underestimation of speed in driving simulators is a well-known phenomenon (e.g., Ohta & Komatsu, 1991). This has once again been confirmed by the performance measures in this study. As hypothesized more sensory stimulation improved presence in terms of performance. The findings of Hendrix and Barfield (1996) on the importance of auditory cues could be reproduced. Furthermore, the results partly replicate the findings from Ohta and Komatsu (1991). In their study, the participants experienced different velocities passively in a passenger car simulator. Auditory deprivation reduced the riders' performance as well as subjectively experienced presence. Addressing proprioceptive and vestibular senses did not increase presence in terms of performance further. In this study, this was at least the case for vestibular cues. This could be due to the fact that there was no acceleration phase and therefore the hexapod did not deliver that much vestibular stimulation while riding at constant speed. On the other hand, more inconsistent estimations under sensory deprivation of auditory cues have not been found. This might be due to the fact that visual information that plays an especially important role in simulators was always available. An alternative explanation could be that the participants did not even fully notice some sensory deprivations while riding. Sensory cues of one kind can provoke sensory cues of another that are physically not present. In a medical experiment conducted by Biocca, Kim, and Choi (2001) $N = 77$ participants had to eviscerate organs from a human body. Almost 15 % of the participants reported physical resistance when removing the organs. In fact, they had only visual feedback. The imagined haptic feedback unconsciously became part of their perceived action. As the participants were informed about each condition's simulator setup and an inquiry followed each trial, there is probably only a small chance that this might have occurred. Still, it seems worth keeping the possibility in mind.

There was no effect of target speed on performance in terms of the relative deviation between estimated and target speed. This could be expected as threshold values from literature on significantly poorer performance lay below the lowest chosen velocity. Evans (1970) stated that estimations below 25 mph (40 kph) are especially difficult. In this study, 50 kph was the lowest speed to be estimated. Concerning the stability of estimates, as hypothesized, these findings reproduce those of Recarte and Nunes (1996). The higher the velocity, the more stable the estimates. Interestingly, also the performance between both studies is comparable. The underestimation for 100 kph target speed that was included in both studies lies between 10 and 12 %. The decreasing variance of speed estimates with increasing target speed could to some extent be due to a ceiling effect. 160 kph as target speed is close to 186 kph that marks the motorcycle model's high speed. This results in a theoretical maximum overestimation of 26 kph.

Regarding people's subjective ratings one can observe a huge variety in spatial presence values. The marginally significant effect of condition reveals a slight increase of presence as soon as visual stimuli are supported by other sensory cues. Auditory cues in addition to visual cues mitigate the feeling of floating isolated through the virtual environment (Gilkey & Weisenberger, 1995). Proprioceptive and vestibular cues could not enhance ratings of interface quality further. This could also be due to a ceiling effect as ratings for the first condition lay already on a rather high level. Same could hold true for experienced involvement. Even if there is a slightly different pattern, visual cues alone led to a decreased involvement while a simulator setup addressing visual, auditory, proprioceptive as well as vestibular cues led to the higher involvement. Analyzing the ITQ trait variables did not reveal any effects on presence. The group of participants with high immersive tendencies, identified by the ITQ, was not more prone to be affected by the condition. Taking into account that this questionnaire is usually used to assess effects of movies or computer games on people's reactions, the test might not have been sensitive enough for a low emotional and more rational speed estimation task. The data at hand cannot really answer the question regarding the connection between presence and simulator sickness, as the SSQ scores were already on a negligible low level in the first condition (floor effect). Besides confirmation of the highly immersive qualities of the simulator, these generally low ratings could also be a consequence of the very short exposure time per trial (Stanney et al., 2002).

The final inquiry confirmed the subjectively perceived dominance of visual cues for presence (Kemeny & Panerai, 2003). Interestingly, the second most relevance is appointed to proprioceptive cues in terms of performance as well as subjectively perceived presence. This supports the previously expressed relevance of proprioceptive cues to the daily life and the riding task by a couple of research groups (Cole & Paillard, 1995; Mohellebi et al., 2009; Mourant & Sadhu, 2002). In accordance with the increased performance due to proprioceptive cues, the operationalization of proprioceptive information via the rope towing mechanism seems to work as expected. Still, the positive effect on presence could be supported by the nature of this specific task. The presented proprioceptive stimulation contains important information on velocity. Its strength should be proved in further studies with a wider range of riding maneuvers.

Conclusion In sum, the postulated contribution of more consistent sensory information to presence could be confirmed. Yet there seem to be differences with respect to the relevance of specific sensory cues. The importance of the visualization of the virtual world has to be highlighted. Furthermore, additional sensory stimulation especially through auditory and proprioceptive information could increase presence in terms of performance and subjective ratings even more.

6 STUDY II: ACTION

6.1 Research question

The main aim of this study was to figure out whether acting in virtual environments increases presence and how this is connected to the effect of more consistent sensory feedback. As depicted in Figure 24, the influence of addressed senses was still relevant. According to literature, the positive effect of more and consistent sensory feedback on presence should still be noticeable. A second part of the model was relevant for this study that allowed the participants to act instead of purely perceive. Therefore, in contrast to the 'Video study' the production method was applied. Given the correctness of psychocybernetic models of presence (see chapter 2.4.2), acting in the virtual environment should measurably improve presence as compared to the purely passive experience in the 'Video study'.

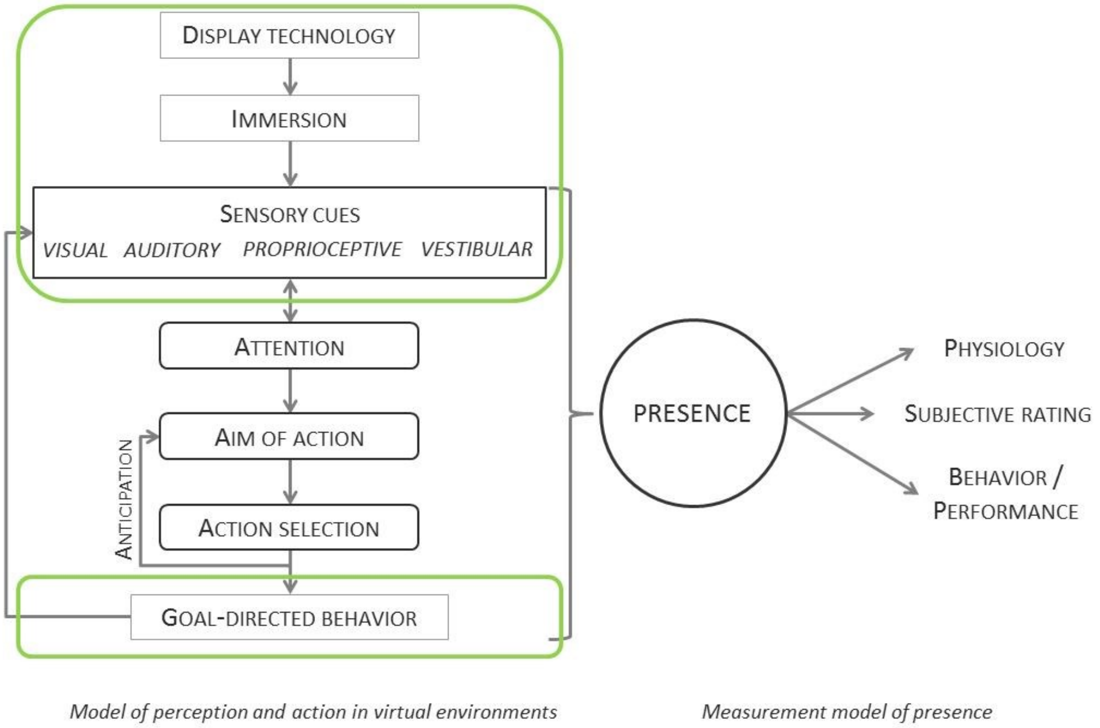


Figure 24: Action: Investigated presence model sections (highlighted by the boxes).

In this study, all dependent variables of the proposed measurement model of presence were included. Compared to the 'Video study', the 'Action study' should reveal better performance and higher subjective ratings of presence. As the characteristics of the sensory cues vary with target speed, the latter was treated as a further variable of interest. According to Recarte and

Nunes (1996) higher target speed should lead to improved speed estimation performance. Physiology and behavior has not been measured in the 'Video study'. Therefore, they were used as indicators of increased presence as a result of changed sensory feedback. In line with prior findings from literature, heart rate, skin conductance level and muscular activity should increase with more sensory stimulation. As physiological parameters are especially sensitive in stressful situations or those phases of higher concentration (Meehan et al., 2002), increased values were expected for the 160 kph target speed condition. If the participants feel more present in the virtual scenario, they should adapt their riding behavior in terms of speed or deceleration according to the road surface conditions. It was hypothesized that these effects occur to an increasing degree during trials with more sensory stimulation. Accordingly, more postural responses as defined in chapter 4.7.2 should be observed.

6.2 Results

The following chapter contains the results of the 'Action study' organized by the type of dependent variables.

6.2.1 Performance

The performance regarding speed estimations was analyzed using a repeated measures ANOVA with 'method estimation' as between-subject factor and 'condition' as well as 'target speed' as within-subject factor. Stability of estimates analyses used a parametric linear model for repeated measures and clustered data with 'method estimation' (between), 'target speed' (within) and 'condition' (within) as fixed factors and 'rider' as random factor assessing variability among individuals. The combination of 'active estimation' at 160 kph in 'condition four' is used as reference category.

Participants in the passive condition underestimate their actual speed (see Figure 25 upper left). Riders that actively set their speed seem to underestimate their velocity accordingly as they overshoot the target speed in the same amount on average (method estimation: $F(1,32) = 26.20$; $p < .001$; $\eta^2_p = 0.450$). The statistically significant effect is a result of the different methods of the 'Video study' and the 'Action study'. In the 'Video study' the participants experience the target speed and give estimations below the target speed on average, because it feels slower to them. In the 'Action study' the participants produce a speed that feels like the target speed and consequently lie above that target speed on average. When accounting for this difference by calculating the mean underestimation instead of a fix relative deviation no difference between passive and active estimation is revealed ($F(1,32) < 1$). This effect is displayed in Figure 25 (upper right).

At low speeds, the riders underestimate their actual velocity (see Figure 25 bottom center). This tendency seems to shift towards an overestimation at higher velocities. The participants mark a speed of about 152 kph as feeling like 160 kph. Estimating 100 kph seems to work pretty well (target speed: $F(2,31) = 8.34$; $p = .001$; $\eta^2_p = 0.350$). There is no main effect of condition ($F(3,30) < 1$). As a relative deviation of one indicates a perfect performance, the interaction between ‘method estimation’ and ‘condition’ is of interest ($F(3,30) = 4.92$; $p = .007$; $\eta^2_p = 0.330$). This more detailed analysis reveals interesting findings concerning the interpretation of the main effects (see Figure 26). Delivering more sensory feedback led to better performance in the ‘Video study’ indicated by increasing values for the relative deviation towards one. As the participants in the ‘Action study’ start from relative deviations above one, a better performance would be indicated by a decrease in values for the relative deviations towards one. Exactly this is the case. Addressing more senses leads to a better performance in the speed estimation task. Once again, the biggest effect can be seen by adding auditory cues to the pure visual condition. Another interaction that was not foreseen concerns a link between ‘method estimation’ and ‘target speed’ ($F(2,31) = 10.22$; $p < .001$; $\eta^2_p = 0.397$).

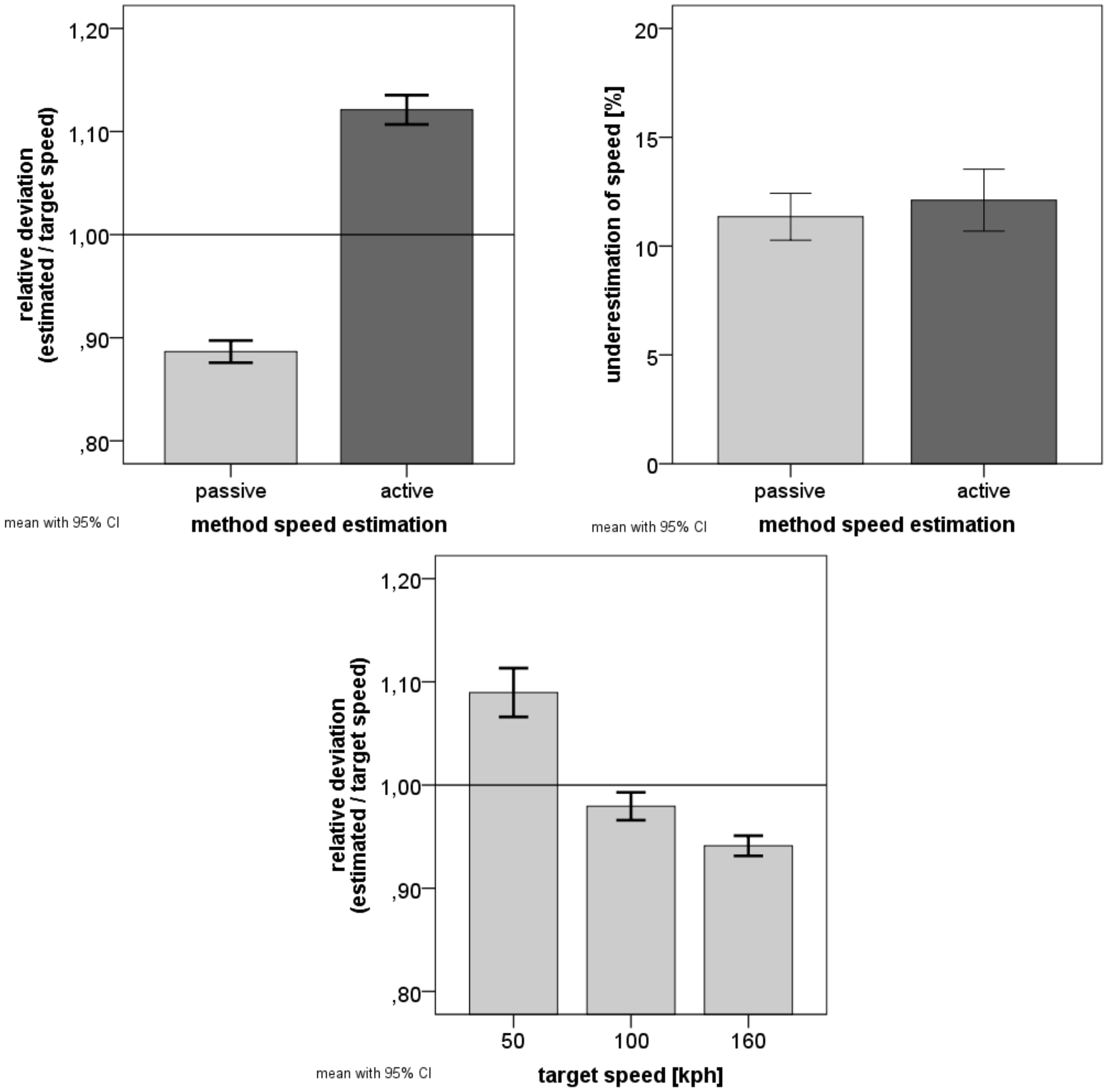


Figure 25: Action: Relative deviation of speed estimation (upper left) and underestimation of speed (upper right) as a function of method speed estimation. Relative deviation of speed estimation as a function of target speed (bottom center).

Participants tend to give estimations independent of target speed when passively experiencing different velocities. This is not the case for active riding. On average the motorcyclists underestimate their actual velocities at low speeds and give pretty good estimations when riding at 100 kph and faster. Due to the different test procedures in the two studies (starting with target speed vs. accelerating to target speed), the comparison of "absolute time taken to estimate" is not meaningful.

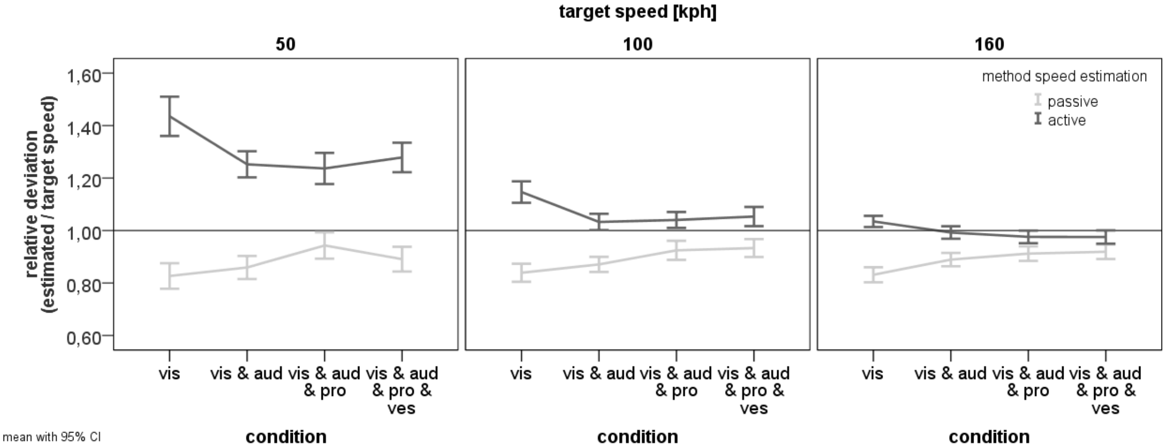


Figure 26: Action: Relative deviation of speed estimation as a function of condition, target speed and method estimation.

While the speed estimates in the passive condition spread noticeably, the participants riding actively are able to reproduce their estimates more constantly under comparable conditions. This effect can be seen in Figure 27 with the dark grey line lying below the light grey line on average. The according effect can be seen with the time taken to estimate the velocities: riding actively leads to more similar durations for the estimation process compared to passive riding. This effect is displayed in Figure 28.

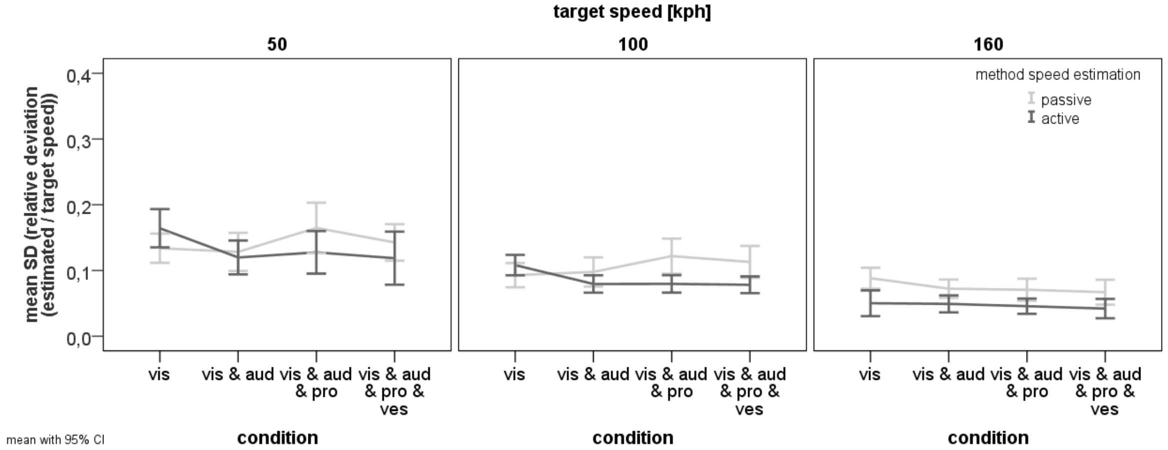


Figure 27: Action: Stability of estimates indicated by the mean standard deviation of the relative deviation of speed estimation as a function of condition, target speed and method estimation.

The estimates also become more stable when higher target velocities are set. The condition shows only a statistically marginal effect, underlining the tendency of more stable estimates with more consistently stimulated senses. Target speed and condition are not systematically linked to the time taken to estimate. All test statistics are summarized in Table 8.

Table 8: Action: Stability of estimates GLMM test statistics.

	GLMM	**Test statistics**	
Stability of estimates	Intercept-only model	AIC	-1621.728
	Final model	AIC	-1759.611
		Chi-Square statistics	$X^2(9) = 137.89; p < .001$
	Fixed effects	Method estimation	$F(1,569) = 14.33; p < .001$
		Condition	$F(3,569) = 2.24; p = .082$
		Target speed	$F(2,569) = 106.88; p < .001$
Stability of duration	Intercept-only model	AIC	2804.155
	Final model	AIC	2785.756
		Chi-Square statistics	$X^2(9) = 18.40; p < .030$
	Fixed effects	Method estimation	$F(1,569) = 24.23; p < .001$
		Condition	$F(3,569) < 1$
		Target speed	$F(2,569) = 1.39; p = .251$

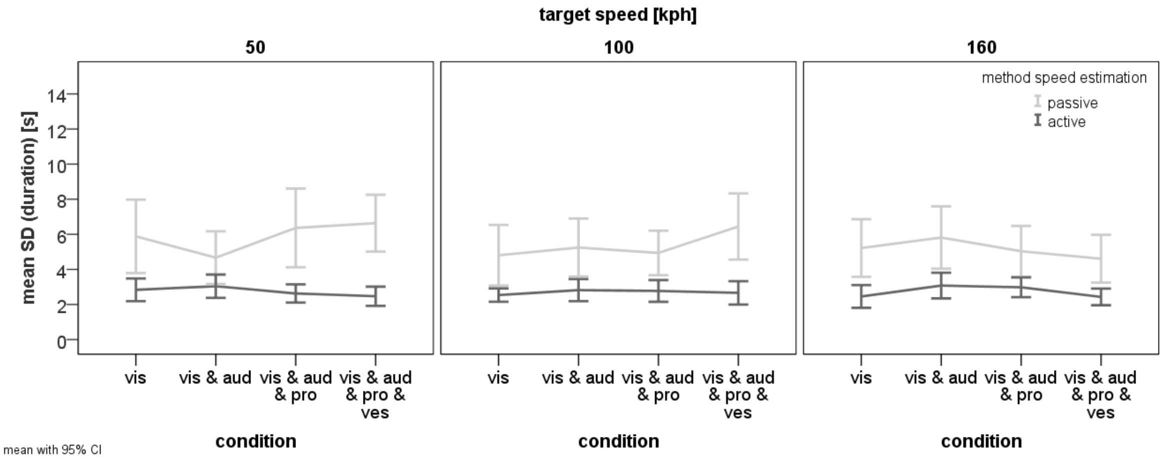


Figure 28: Action: Stability of estimates indicated by the mean standard deviation of time taken to estimate the velocities as a function of condition, target speed and method estimation.

6.2.2 Behavior

A repeated measures ANOVA was conducted using ‘condition’ and additionally ‘filling scenario’ (four levels) as within-subject factors. The statistical analysis for the longitudinal behavior when crossing the speed bump contained only ‘condition’ as within-factor.

The mean velocity during free riding in the filling scenarios differs statistically significant between the different conditions ($F(3,19) = 3.36$; $p = .040$; $\eta^2_p = 0.347$). Especially receiving vestibular feedback, reflecting differences in road roughness, as well as proprioceptive and auditory cues lead to decreased riding speed compared to riding with pure visual feedback. Furthermore, the type of filling scenario has an influence on the participants’ longitudinal control ($F(3,19) = 5.71$; $p = .006$; $\eta^2_p = 0.474$). The mere presence of rain and cobblestone as well as cobblestone alone lead to decreased velocities compared to asphalt and sunshine (neutral) in the simulator. These two effects do not interact ($F(3,13) < 1$). The aforementioned effects are displayed in Figure 29 on the left side.

In accordance with this effect, the riders adjust their velocity to the different conditions when crossing the speed bump ($F(3,21) = 4.61$; $p = .012$; $\eta^2_p = 0.397$). This effect is mainly due to the higher speed in the visual condition compared to the speed reduction in the other three conditions (see Figure 29 right). As speed bumps are commonly used in residential areas a crossing speed between 30 kph and 50 kph was to be expected. All mean velocities are close to 50 kph.

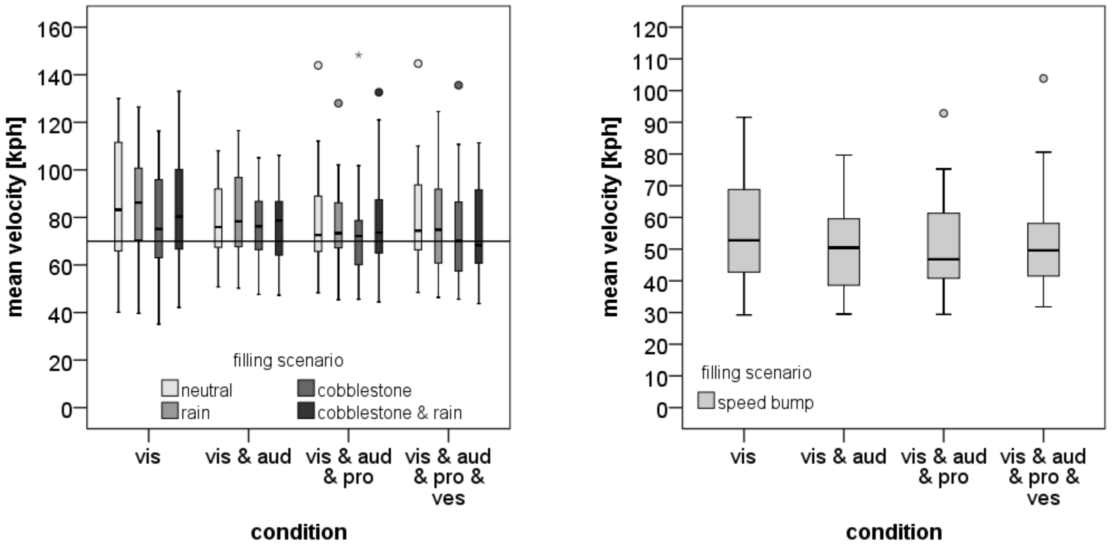


Figure 29: Action: Mean velocities in the different filling scenarios (left) and when crossing the speed bump (right) as a function of condition.

The influence of condition is also present when looking at the maximum throttle position ($F(3,19) = 5.52$; $p = .007$; $\eta^2_p = 0.466$). Once again, delivering sensory cues to all four senses leads to more defensive riding and with that to less maximum throttle positions compared to visual cues only. Furthermore, free riding on cobblestone is characterized by lower values of maximum throttle position compared to riding on neutral roads ($F(3,19) = 3.92$; $p = .025$;

$\eta^2_p = 0.382$). No interaction can be found for the mean velocity (*F*(3,13) < 1). A graphical illustration of these effects is given in Figure 30 (left). Figure 30 (right) displays the minimum longitudinal accelaration, which is the maximum longitudinal deceleration respectively, on the road section 100 m in front of the stop sign. A clear effect of the type of filling scenario can be seen (*F*(3,19) = 56.15; $p < .001$; $\eta^2_p = 0.899$). It is especially the reduced deceleration when riding on cobblestone during rain that differs from the braking behavior shown on asphalt during sunshine.

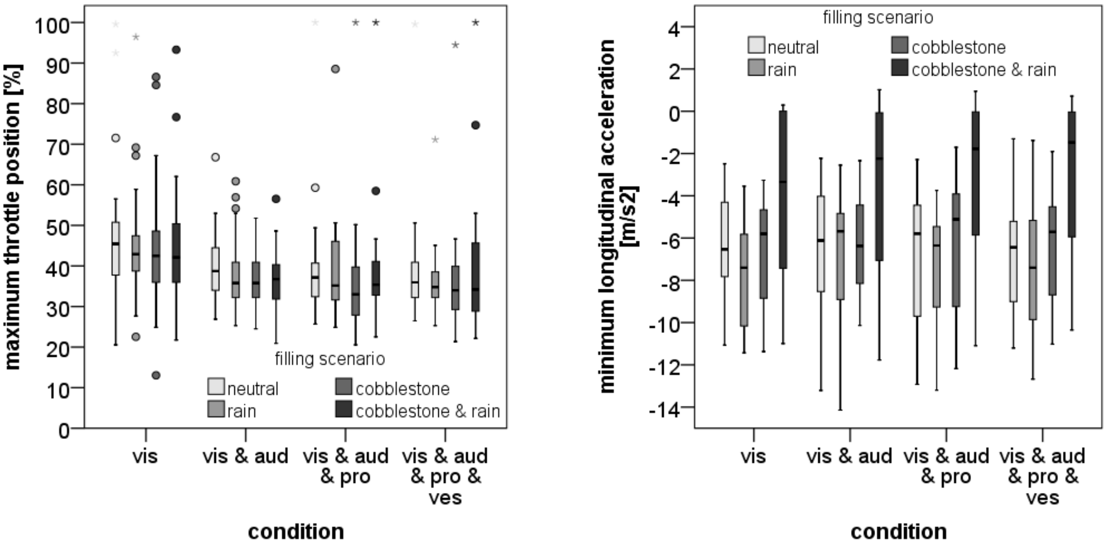


Figure 30: Action: Mean maximum throttle position (left) and minimum longitudinal acceleration (right) in the different filling scenarios as a function of condition.

Neither the main effect ‘condition’ (*F*(3,19) < 1) nor the interaction (*F*(9,13) = 1.21; $p = .368$; $\eta^2_p = 0.455$) were statistically significant.

Another possibility to describe participants’ behavioral response is the operator rating. The dichotomous behavior categories, such as ducking the head at high speeds, were rated as present or not present during a trial. As the frequency of shown behaviors for each category is generally low, only the sum per participant is calculated ranging from zero to five. On average, every participant showed 1.65 of the categorized behaviors per trial. Descriptive analyses are reported as there is a low absolute frequency of observations and differing numbers of participants delivering values for the different conditions. Table 9 displays that there might be a slight tendency of showing more behavioral responses when more sensory cues are addressed.

Table 9: Action: Behavioral responses (operator ratings).

Condition	**vis**	**vis & aud**	**vis & aud & pro**	**vis & aud & pro & ves**
Mean frequency of behavioral responses	1.54	1.62	1.62	1.83
Sum of behavioral responses	37	39	39	44

6.2.3 Subjective rating

This parametric linear model for repeated measures and clustered data was conducted with 'method estimation' (between) and 'condition' (within) as fixed factors and 'rider' (within) as random factor assessing variability among individuals.

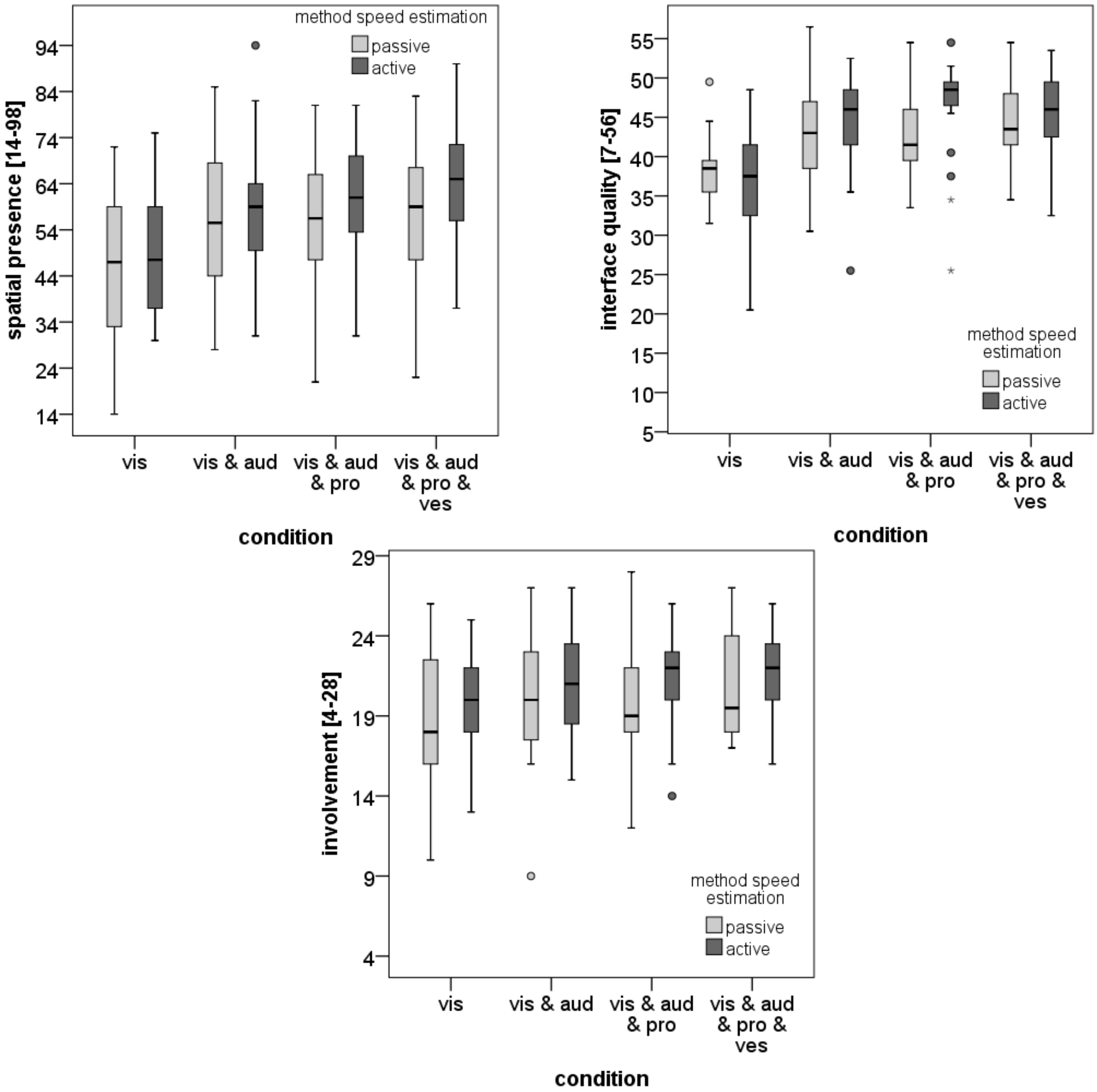


Figure 31: Action: Presence scores on subscales as a function of condition and method speed estimation.

The combination of 'active estimation' and 'condition four' is used as reference category. The corresponding repeated measures ANOVA took 'method estimation' as between and 'condition' as within factor.

Presence Questionnaire

The full models for the three subscales are significantly better than the ones in which only the intercepts are included. Detailed test statistics are given in Table 10.Setting the speed actively does not affect the subjectively felt amount of presence on any of the sub scales while 'condition' does (see Figure 31). Reducing the available sensory cues to visual information only leads to an obvious decrease in spatial presence. Riding with visual and auditory cues results in decreased spatial presence, too. Relatively high variation is observed across all conditions. Condition one leads to medium-low levels of spatial presence that gradually increase to medium-high ratings in condition four on average. Regarding arithmetic means, the same growth pattern across conditions is found for perceived interface quality.

Table 10: Action: Presence questionnaire GLMM test statistics.

	GLMM	**Test statistics**	
Spatial presence	Intercept-only model	AIC	1491.408
	Final model	AIC	1449.498
		Chi-Square statistics	$X^2(6) = 41.92; p < .001$
	Fixed effects	Method estimation	$F(1,186) = 6.69; p = .103$
		Condition	$F(3,186) = 10.88; p < .001$
Interface quality	Intercept-only model	AIC	1151.051
	Final model	AIC	1093.829
		Chi-Square statistics	$X^2(6) = 57.23; p < .001$
	Fixed effects	Method estimation	$F(1,181) = 1.76; p = .187$
		Condition	$F(3,181) = 28.13; p < .001$
Involvement	Intercept-only model	AIC	877.812
	Final model	AIC	853.641
		Chi-Square statistics	$X^2(6) = 24.18; p < .001$
	Fixed effects	Method estimation	$F(1,184) = 2.41; p = .122$
		Condition	$F(3,184) = 8.44; p < .001$

Hence, the deviations are smaller and visual stimulation already results in medium-high ratings that increase to high values for condition four. Experienced involvement is already on a medium-high level for the first condition. Adding more sensory cues subsequently leads to further statistically significant improvements for every level. The complete set of sensory feedback results in enhancements of experienced involvement compared to condition one, two and three.

Immersive Tendencies Questionnaire

In accordance to the 'Video study', all participants were split in two sub groups with 'low vs. high immersive tendencies'. This dichotomous variable was taken as additional between-subject factor and the above mentioned ANOVAs were recalculated. Analyses reveal no statistically relevant effects at all.

Simulator Sickness Questionnaire

Out of the 37 participants that participated in the study in total, $n = 7$ dropped out due to simulator sickness within the first familiarization phase (18.92 %). Five more subjects dropped out due to sickness symptoms within the first two trials, all of them during or after condition one ($n = 1$) or two ($n = 4$).

The aggregate SSQ score reveals a significant sequence effect between trials ($F(5,19) = 5.47$; $p = .003$; $\eta^2_p = 0.590$). Further analyses show that this effect is due to the increase of baseline symptoms compared to all trials. No statistically significant effect that distinguishes between study trials is found. The ANOVA reveals statistically significant main effects for 'method speed estimation' ($F(1,46) = 6.62$; $p = .013$; $\eta^2_p = 0.126$) and 'condition' ($F(4,43) = 6.30$; $p < .001$; $\eta^2_p = 0.369$) as well as a significant interaction ($F(4,43) = 5.02$; $p = .002$; $\eta^2_p = 0.318$). Generally, active speed estimation leads to higher aggregate SSQ scores than passive estimation. Nevertheless, all values are on a reasonable low level. Furthermore, riding the simulator is accompanied by increased SSQ scores independently of condition. Interestingly, the average SSQ aggregate score is on a lower level when riding with all sensory cues available compared to the three remaining test conditions. The highest mean values are achieved when only the visual stimulation is available. The increased sickness scores in the three conditions without vestibular cues are only observed for active speed estimation. It is also true that scores obtained from active estimation lead to an increased variety in participants' ratings. Especially condition one and three include a high range of ratings from different riders. The SSQ aggregate scores are displayed in Figure 32 as a function of condition and method speed estimation.

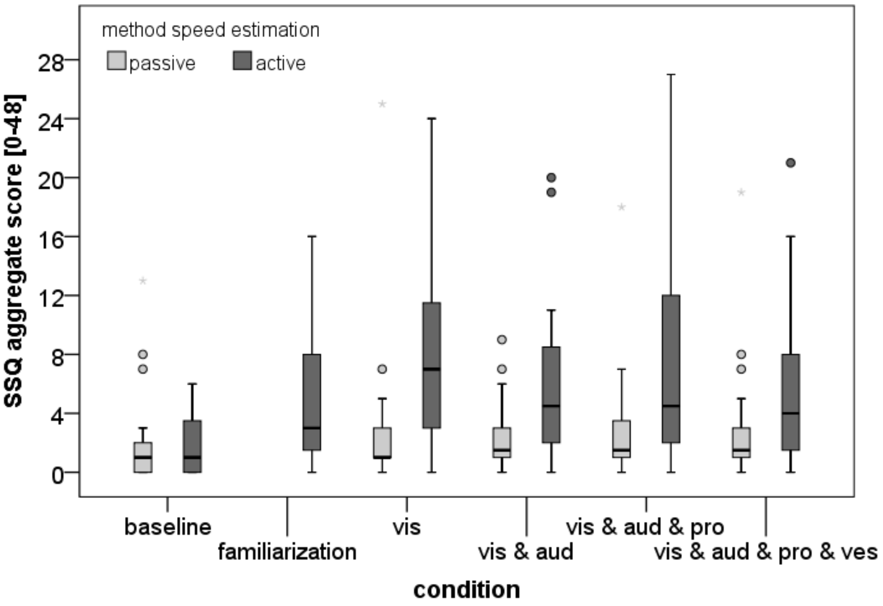


Figure 32: Action: SSQ aggregate scores as a function of condition and method estimation. Due to the study design, 'Video' contained no familiarization phase.

Final inquiry

As part of the final inquiry the participants were asked to report their impression on how much the different sensory cues contributed to their performance in speed estimation on the one hand and to their feeling of presence on the other hand. Repeated measures ANOVAs with 'condition' as within-subject factor and 'method estimation' as between-subject factor were conducted.

Estimating speed passively or actively does not influence the riders' ratings on average ($F(1,46) < 1$). However, the participants' ratings concerning the contribution of each of the four addressed sensory cues to their speed estimation performance differs statistically significant ($F(3,44) = 15.36$; $p < .001$; $\eta^2_p = 0.511$). This effect is displayed in Figure 33 on the left hand side. Further analyses reveal that higher impact is attributed to visual, auditory and proprioceptive cues compared to vestibular ones. The first are also superior to proprioceptive cues. Visual and auditory cues achieve high ratings on average. For proprioceptive and vestibular cues a medium contribution with huge variation between subjects is rated. Interestingly, there is a statistically significant interaction indicating higher scores with less variety in the ratings of auditory cues in the active condition ($F(3,44) = 12.97$; $p < .001$; $\eta^2_p = 0.469$).

The task of assigning ranks to the sensory cues with regard to their contribution to performance in speed estimation almost mirrors the just reported ratings. Figure 33 (right) shows staged bar plots with the rankings of 23 riders as data from one rider were missing. Ranks one and two are almost completely assigned to visual and auditory cues with a slight advantage for the first ones. This is the only obvious difference to the ratings of the 'Video study'. No rider assigns the first rank to auditory cues there. Here, one rider sees proprioceptive feedback to be the most important and four participants assign proprioceptive feedback to rank two.

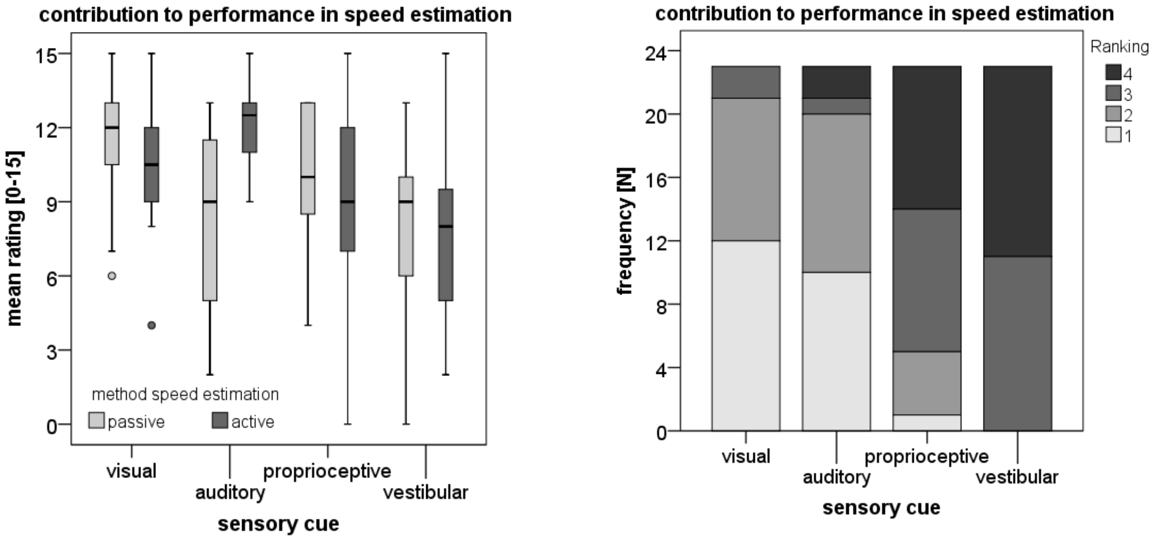


Figure 33: Action: Perceived contribution of different sensory cues to speed estimation performance (left: rating; right: ranking).

Vestibular feedback is assigned to rank three and four. None of the riders assigns rank four to visual cues. This pattern is quite similar to the one found in the 'Video study'.

A statistically marginal significant effect can be seen when the focus lies on the rated contribution of the sensory cues to subjectively felt presence ($F(1,46) = 2.83$; $p = .100$; $\eta^2_p = 0.058$). All sensory cues are rated to be of high importance. But, the participants that had the chance to actively estimate by riding the simulator themselves tend to give higher ratings than the riders that passively experience the velocities. The different sensory cues' contribution to the subjectively felt presence reaches statistically significance again ($F(3,44) = 6.52$; $p = .001$; $\eta^2_p = 0.308$). Visual cues contribute more to the participants' experienced level of presence than all other sensory cues (see Figure 34 left). While some riders have the impression that proprioceptive and vestibular feedback improves their feeling of presence massively, others see almost no influence of these cues. Furthermore, auditory and vestibular stimulation seem to contribute more to the participants' experienced presence, when they ride the motorcycle simulator actively ($F(3,44) = 2.92$; $p = .044$; $\eta^2_p = 0.166$).

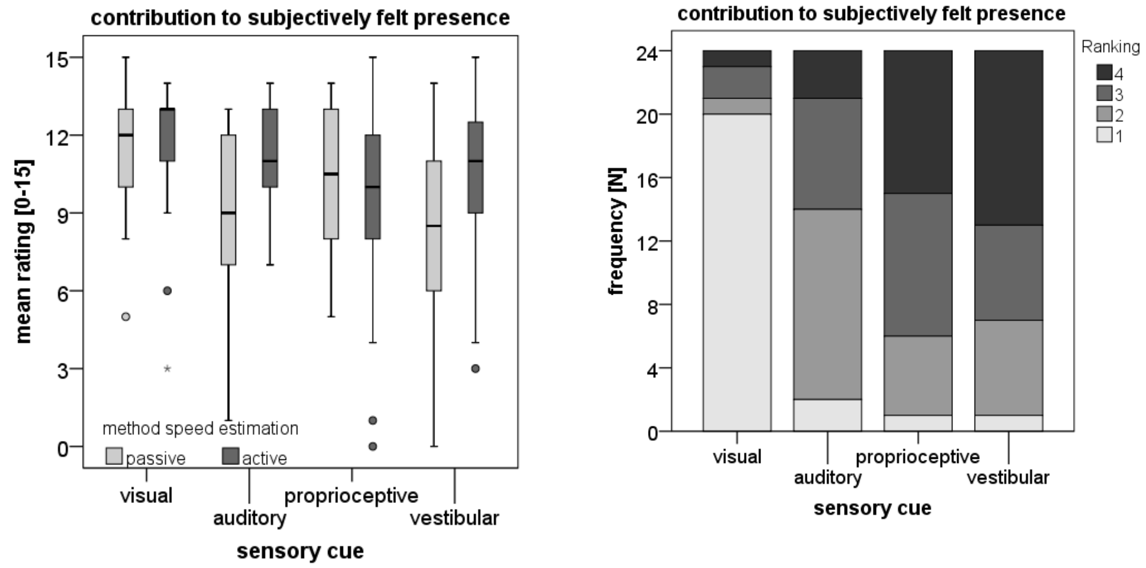


Figure 34: Action: Perceived contribution of different sensory cues to subjectively experienced presence (left: rating; right: ranking).

The staged bar plot in Figure 34 (right) shows the participants' rankings of sensory cues according to their contribution to the amount of subjectively experienced presence. Interestingly, the vast majority (20 out of 24) agrees that visual feedback has highest priority. The assignment of all four ranks to all four sensory cues, at least from one participant, displays major differences in how people experience the impact of different sensory information on presence. This pattern is almost identical with the one of the 'Video study'. The only visible difference is that auditory and vestibular cues are more often ranked in second than in third or fourth place. No specific strategies for speed estimation were reported consistently between participants. Three participants reported to count the seconds that pass between two delineators. Hence, no different effects were visible.

6.2.4 Physiology

This analysis describing the physiological state while emitting the speed estimates contains data from $n = 20$ participants, as data from four subjects were missing. Not every participant contributes to all possible 'condition*target speed' combinations. Test statistics can be found in Table 11.

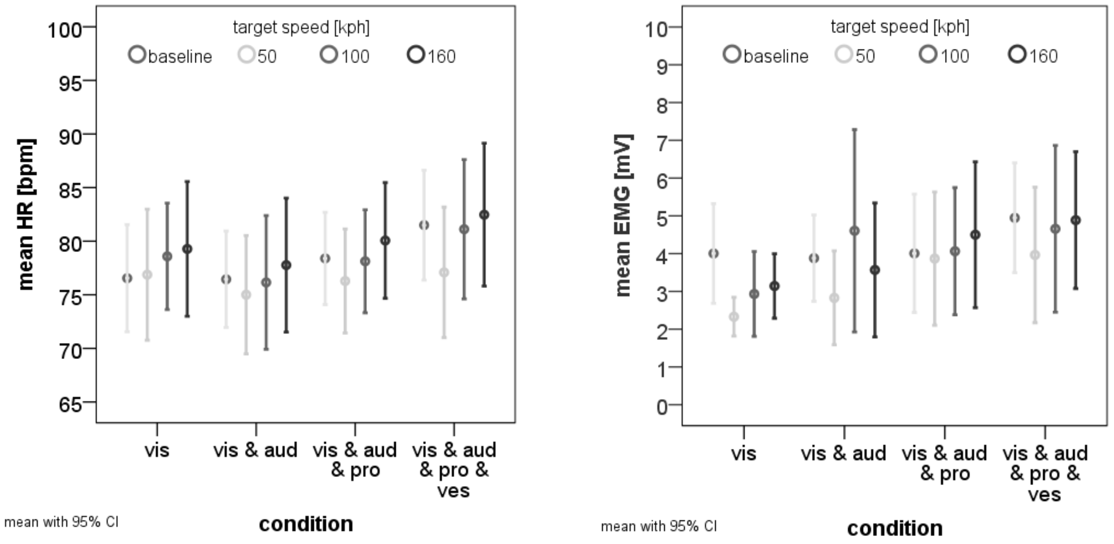


Figure 35: Action: Mean heart rate (left) and electromyogram (right) as a function of condition and target speed.

Riding at high speed leads to an increased mean heart rate (see Figure 35 left). When the participants are to ride at 160 kph their mean heart rate is raised by about 2.99 bpm compared to the 50 kph and 2.59 bpm compared to the baseline condition. The baseline values resemble those of the 100 kph condition on average. The mean heart rate is slightly decreased at lower speeds and increased at higher speeds. Furthermore, there is a statistically significant influence of ‘condition’. If ‘target speed’ is kept at a constant level, addressing all four varied senses results in the highest heart rate. Dropping vestibular feedback decreases the average heart rate by about 2.61 bpm. Without proprioceptive feedback the heart rate descends by 4.38 bpm, which is a statistically significant decrease compared to condition three. Riding with visual cues only reduces the average values by 3.40 bpm compared to the reference category. This effect might also be seen in the varying baseline values between conditions. Generally, confidence intervals with a size of about 10 bpm are observed, independently from different conditions.

The selection of sensory cues significantly influences the mean EMG values, too (see Figure 35 right). Riding with visual sensory feedback or visual and auditory feedback respectively, leads to lower EMG values than riding with additional proprioceptive and vestibular feedback. No difference between the reference category and baseline is found. Moreover, the faster participants ride, the higher muscular tension is measured. However, rather small differences in absolute values are observed compared to the variation of measurements.

Participants’ SCL while estimating speeds is neither influenced by ‘condition’ nor ‘target speed’.

Table 11: Action: Physiology GLMM test statistics.

	GLMM		Test statistics
Mean HR	Intercept-only model	AIC	1721.754
	Final model	AIC	1687.254
		Chi-Square statistics	$X^2(8) = 34.56; p < .001$
	Fixed effects	Target speed	$F(3,254) = 3.67; p = .013$
		Condition	$F(3,254) = 7.24; p < .001$
Mean EMG	Intercept-only model	AIC	1106.756
	Final model	AIC	1093.829
		Chi-Square statistics	$X^2(8) = 19.65; p = .012$
	Fixed effects	Target speed	$F(3,259) = 4.35; p = .005$
		Condition	$F(3,259) = 7.01; p < .001$
Mean SCL	Intercept-only model	AIC	598.434
	Final model	AIC	608.706
		Chi-Square statistics	---
	Fixed effects	Method estimation	---
		Condition	---

6.3 Discussion

In the present study, the main aim was to identify whether acting in virtual environments increases presence and how this is connected to the effect of more consistent sensory feedback. The latter question has been subject to investigation in the 'Video study' in a passive estimation task. The 'Videos study's' results were therefore compared to those of the present study. The underestimation of velocity in the simulator occurred independently of the riders' action whereas higher target speed improved the speed estimation performance in the present study. The positive effect of more consistent sensory feedback on presence was confirmed, too. Besides performance and subjective ratings, spontaneous behavioral responses and physiological measures have successfully been applied. Interestingly, the highest dropout rate due to simulator sickness occurred in the active riding condition with purely visual feedback. These findings will be discussed in the following section in detail.

The performance as presence measure did not reveal a difference between the estimation methods. What was underestimated in the 'Video study' got overadjusted in the 'Action study' on average. This confirms the typically found underestimation of velocities in driving simulators (e.g., Ohta & Komatsu, 1991). Furthermore, the comparable degree of underestimation delivers only weak evidence for sensory attenuation of expected changes in the environment as consequence of the participants' action. This actor-observer bias would result in higher perceived speed for passive riders and lower perceived speed for active riders. From a methodological point of view, the comparison of the studies might be biased as the participants in a between-design did not experience exactly the same speeds. Further research would be needed to clarify this. Hence, the contribution of more sensory feedback is expressed in a statistically significant interaction of condition and method estimation. As soon as auditory cues were available, the performance increased. This confirms the special role of hearing in judgements on speed as found by Evans (1970) in a test track study with a passenger car.

No influence of target speed could be seen in the 'Video study'. On the contrary, an obvious effect was found in this study. The higher the target speed, the better the performance. This interaction has already been reported by Recarte and Nunes (1996). Once again, the performance on speed perception in the simulator is comparable to the performance in the real driving experiment reported by Recarte and Nunes. With a target speed of 100 kph, participants misjudged their speed by about 5 %. The more stable estimates at higher target speeds have already been observed in the 'Video study' and replicate prior results from other researchers (e.g., Recarte & Nunes, 1996; Schleinitz et al., 2015). As pointed out before, the decreasing variance of speed estimates with increasing target speed could be due to a ceiling effect. 160 kph as target speed is close to 186 kph that marks the motorcycle model's high speed. This results in a theoretical maximum overestimation of 26 kph. Otherwise, it could also be an effect of time of exposure. Longer distances are usually driven at 100 kph or faster on rural roads and highways. At least in Germany or rather Europe, this could explain a higher familiarity with the perception of these speeds.

Acting in the virtual environment facilitated the speed estimation which is reflected in more stable estimates. The only inconsistency was the reversed effect of less stable estimates in the visual condition when riding actively. A possible explanation could be that the poorer performance in this condition indicated by higher velocities on average went hand in hand with a higher spread of estimates. Producing the speed actively led also to more consistent durations until the estimations were given. An interpretation supported by psychocybernetic presence models (e.g., Stanney & Hash, 1998) could be that the higher level of user-initiated control provokes higher presence. In this case, presence was measured in terms of more stable estimates as one performance measure. Still, it has to be stated that parts of that effect might be due to the differing study methods of the 'Video' and the 'Action study'. In contrast to the 'Video study' the 'Action study's' production method included an acceleration phase. This takes a certain amount of time if the acceleration capacity of the motorcycle is used consistently.

As discussed in chapter 2.4.2, some psychocybernetic presence theories predict a higher level of presence when people act successfully in the virtual environment. It could be discussed what "successful" in this context means. Is it generally maneuvering the motorcycle appropriately or is it the performance in the instructed speed estimation task? Designing the 'Video study' with a passive rating setup allowed excluding action and investigating the influence of specific sensory cues very well. From a methodological point of view, the study design could have been slightly different when it comes to the comparison with the 'Action study's' results.

Instead of eliminating action completely, one could only eliminate the link between action and effect. This would result in a more comparable setup between the studies as action would be involved in both studies. Nevertheless, the decoupling of action (e.g., accelerating by twisting the throttle grip) and effect (e.g., sensory feedback in terms of optical flow) would impede successful action. As a consequence, the level of presence should decrease compared to the 'Action study' with consequent action-effect coupling. This could be realized by adding an unpredictable time delay between action and produced effect in the simulator. Blakemore, Wolpert, and Frith (2000) conducted a study investigating the influence of such a time delay between action and effect. In general, human beings cannot tickle themselves. The anticipated sensory effects of the self-produced action (tickling) are attenuated. But, by using a kind of robot arm that copies the participant's action with an unpredictable time delay, the sensory effects seem to be more prominent again. The participants could now tickle themselves. As the sensory effects could no longer be anticipated appropriately, no sensory attenuation occurred. Such a study could also deliver insights into the influence of the feedforward part of the model.

The analyses of behavioral responses based on the operator rating could only take a low number of observations into account. The detected tendency supports the hypotheses that more and contingently addressed sensory cues lead to increased presence in this case indicated by spontaneous behavior. This would be in line with results of prior research highlighting the additional value of postural responses (e.g., Bailenson et al., 2004). Nevertheless, for deeper analyses of operator ratings as dependent variable more observations would be necessary. It could be that the behavior categories defined during pilot tests did not cover a sufficient amount of categories or were not fully adequate. Far more interesting were the participants' reactions to the changing sensory feedback in the filling scenarios. Road surface conditions, such as wet cobblestone that are known to be slippery in reality led to lower speed or less deceleration when more senses were addressed. Certainly, there is a relation between velocity and deceleration. If one is riding at lower speed, less deceleration to standstill is needed. Nevertheless, the speed on wet cobblestone was not that much reduced that it could account for the reduced deceleration alone. Following Freeman et al. (2000) this behavior is a clear indicator of presence as more behavior patterns from reality are transferred to the simulator setup. The same effect was observed with the speed bump. A rather high speed bump calls for a careful crossing. The crossing speed was reduced when more than visual stimulation was present. Still, it has to be noticed that the postulated presence model would also have predicted effects of additional proprioceptive and vestibular cues.

Generally, the high ratings for presence are in line with the findings of Slater (2009). He postulates that a high level of presence in terms of place illusion requires sensorimotor contingencies. By giving riders the possibility to interact with the motorcycle in a highly realistically way (real motorcycle controls such as throttle, brakes etc. active in the mixed reality setup of a driving simulator; sensors to measure body movement etc.), presence should be enhanced. This is even reinforced by the fact that the riders see their own body in the virtual world as the mixed reality setup uses a real motorcycle mockup with a projection screen. This may explain the high ratings in this study on all subscales. Nevertheless, the hypothesized increase of presence ratings in the 'Action study' compared to the 'Video study' were not observed. For interface quality and involvement a ceiling effect may be an explanation, as already high scores were achieved without action in the 'Video study'. This was not the case for spatial presence. It seems as if the contribution of sensory stimulation outperforms the contribution of action on subjectively perceived presence. Following Slater's idea, a further improvement of presence would still be possible with regard to the plausibility illusion. All scenarios in this study were scripted without other traffic participants as there was no need for other vehicles with regard to the research question. In fact, they might even have disturbed the task, if participants were not able to adjust their speed voluntarily e.g., due to congestion. Nevertheless, the mutual behavior adaptation between participant and surrounding traffic may be a chance to push presence even more when dealing with other research questions. The comparably high ratings of presence in studies I and II can also be interpreted as supporting proof of the estimation method in the 'Video study'. Minimizing the interaction with the experimenter by typing the estimates directly in to the dashboard screen seems to have successfully avoided breaks in presence (Slater & Steed, 2000).

The significant interactions between 'method estimation' and 'condition' could be explained by the amount of information that the sensory cues contain in the different studies. In the 'Action study' all riders started from standstill and accelerated until the target speed seemed to be reached. This period of accelaration gives the participants the chance to set the engine and wind sound of the target speed in relation to the engine sound in stand still. This additional reference value might help to get a better feeling of how much auditory stimulation is needed and thereby improve the perceived contribution to performance and felt presence. Something comparable might take place with vestibular cues. When riding passively, the hexapod delivers information on road roughness mainly. When riding actively, complementary information is given during the accelaration phase. The hexapod tilts in order to display the pitch angle that is produced by the forces applied to the motorcycle suspensions. This additional information might cause the impression of a higher impact of vestibular cues on presence compared to the 'Video study'. The poorer ratings of vestibular cues concerning performance may be explained by the fact that the movement of the hexapod still contains less information on absolute velocity than engine sound. Once again, the immersive tendencies questionnaire could not reveal differences. However, the high variance of ratings in each condition could be due to differences in the ability to experience presence between individuals.

The dropout of participants due to sickness symptoms within the familiarization phase lies with about 19 % within the typically observed range given by literature (Neukum &

Grattenthaler, 2006). Nevertheless, these values are of course highly dependent on exposure time, previous simulator experience, test course etc. Of higher interest is the increased drop-out of participants in conditions with deprived sensory cues after the familiarization phase. The remaining five participants that quit the study due to sickness did this either in or after condition one or two. No other participant dropped out during or after a condition with at least visual, auditory and proprioceptive stimulation. This might be interpreted as another presence indicator that is supported by the technological approaches to presence (e.g., Akin et al., 1983; Sheridan, 1992b; Steuer, 1992; Witmer & Singer, 1994). Besides dropouts the SSQ values delivered interesting insights. Simulator sickness is related to exposure time (Stanney et al., 2002). Even if a controlled and slightly increased exposure time helps to familiarize with the virtual environment, a negative effect of en bloc exposure time to sickness symptoms is known (Stanney & Hash, 1998). Not surprisingly, higher aggregate simulator sickness scores were found for active speed estimation. Participants in the 'Action study' were riding for about 25 minutes in each condition. Participants in the 'Video study' had the 15 speed estimates per condition divided in 15 separate repetitions lasting for about one minute each. Therefore, it is hard to interpret the findings with regard to the main hypothesis that action reduces sickness. At first glance, the hypothesis cannot be confirmed and the results from Stanney and Hash (1998) could therefore not be replicated completely. Nevertheless, following their further argumentation, the multitude of degrees of freedom might partly explain the negative effect of action. It is too challenging to predict the motorcycle's trajectory correctly as longitudinal and lateral control is completely up to the participants. As a consequence, further improvements of the vehicle dynamics model might be necessary in order to make the motorcycle control more intuitive. Another explanation comes from physiology. Money, Myles, and Naunton (1975) found that stimulating the semicircular canals with angular movement elicits sickness while linear movement stimulation does not. In the passive condition constant speed was displayed and no participant experienced an acceleration phase that goes hand in hand with regular pitch movements. Furthermore, there was no need for filling scenarios which included curvy roads that elicit roll movements of the motorcycle in the 'Video study'. So, the 'Action study's' participants perceived significantly more vestibular stimuli that may be responsible for the sickness symptoms. Yet, this explanation could only hold true for the differences in condition four with an active Stewart platform.

This physiological interpretation leads to the assessment of the bodily responses as indicators of presence. The increasing heartrate with increasing target speed is in line with the findings of Johnson et al. (2011), who compared physiological reactions to stressful surprising events between driving simulator and real driving events. The resembling values of heart rate for baseline and the 100 kph condition might be explained by the fact that the baseline section was a rural road with slight curves. Participants usually rode at about 100 kph on this section as it is allowed by the Highway Code. Thus, this observation might strengthen the link between heart rate and target speed that also occurs in real life. Besides that and according to the hypothesis, the addition of more consistent sensory cues led to an increased heart rate. The same hypothesized effect was observed for the muscular activity. When interpreting the EMG values one has to notice that the EMG baseline values may suffer from a bias due to steering. The speed estimate sections went purely straight while the baseline sections had slight curves. Therefore, riders had to implement a steering torque that influences the muscular activity at the shoulder area. The effect of the condition on the EMG values is reasonable as the rope towing mechanism and balancing on an active motion system lead to more contracted muscles to stay upright in a normal riding position. The use of EMG as presence indicator should be subject to investigation in further studies that avoid the confounding interaction with the independent variable. Neither condition nor target speed had a significant effect on SCL. Generally, SCL is said to be sensitive to risk assessment (Tagliabue & Sarlo, 2015). The chosen speed estimation task did not deal with risky situations. Nevertheless, the SCL was included as dependent variable to check whether tension and concentration, induced through riding at high speeds, influence the SCL comparably. This cannot be confirmed with the available data. Differing from heart rate and muscular activity, skin conductance was also not related to the amount of sensory stimulations.

Conclusion In summary, the present study confirmed the positive effect of action on presence. Furthermore, the importance of sensory cues regarding presence enhancement were demonstrated. Spontaneous behavior as well as physiological measures proved the advantages of the simulator setup with visual, auditory, proprioceptive and vestibular cues. Generally, the simulator sickness increased with longer active riding compared to the passive trials of the 'Video study'. The highest dropouts due to simulator sickness occurred in the purely visual condition indicating the negative effect of sensory deprivation on presence.

7 STUDY III: TRAINING

7.1 Research question

The main aim of this study was to investigate the influence of training on presence. Furthermore, it was explored whether participants make use of a specific sensory cue during the training. The main model components influenced by training are highlighted in Figure 36. In accordance with the control loop paradigm of the model, training action and perception in the virtual environment should reduce negative feedback, quantifiable as increased presence. The training closed the feedback loop in a way that an action aiming at riding at a certain target speed was followed by velocity feedback from the speedometer that was necessary to see if a divergence between actual and ideal speed occurred. This newly possible comparison allowed adjusting prior existing aims of action in the light of evidence. According to the psychocybernetic models (see chapter 2.4.2) this should lead to less perturbations in the feedback loop, more successful action and, as a consequence, higher presence. Participants from the training study should experience higher presence indicated by better performance in the speed estimation task and higher subjective ratings.

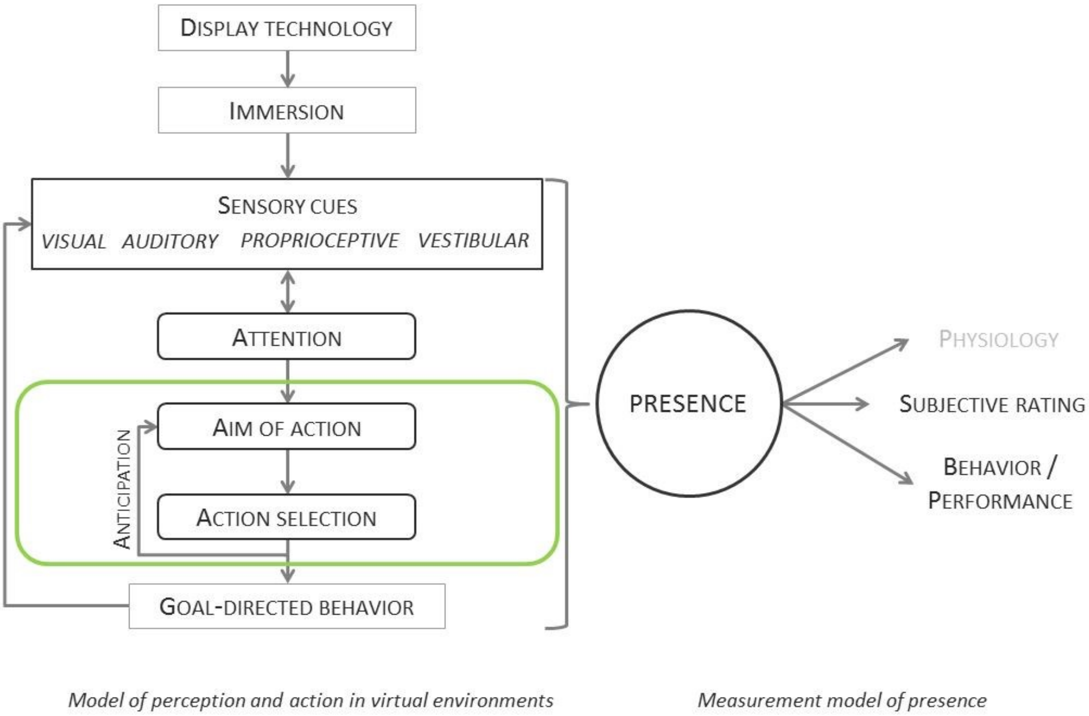


Figure 36: Training: Investigated presence model section (highlighted by the box).

Furthermore, the number of natural responses should be increased. The implemented variation of velocity feedback during training was not related to a specific target speed. Therefore, target speed was treated as random effect. The condition was still of interest as its effect should be independent of training. Training should help for additional improvement compared to the still existing effect of sensory feedback. According to literature there was no reason to expect an interaction between 'velocity feedback during training' and 'condition'. The chosen study design did not include physiological measures.

7.2 Results

The following chapter contains the results of the 'Training study' organized by the type of dependent variables.

7.2.1 Performance

A parametric linear model for repeated measures and clustered data used 'velocity feedback during training' (between) and 'condition' (within) as fixed factors and 'rider' (between), 'target speed' (within) and 'repetition per target speed and condition' (within) as random factors. This analysis takes the different amount of repetitions between the studies into account. The combination of 'training with feedback' in 'condition four' is used as reference category. An ANOVA with 'velocity feedback during training' as between-subject factor and 'condition' as within-subject factor is conducted to analyze the stability of estimates.

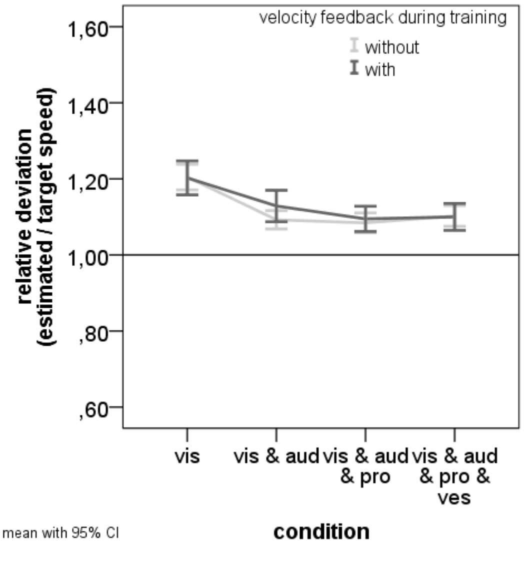


Figure 37: Training: Relative deviation of estimated and target speed as a function of condition and velocity feedback during training.

As can be seen in Figure 37, the participants' performance in the speed estimation task is not influenced by the training phase. The effect of 'condition' is also reflected in the 'Training' data (see Table 12). The riders' estimation performance decreases significantly if sensory feedback is reduced to visual or visual and auditory feedback.

Table 12: Training: Speed estimation performance GLMM test statistics.

	GLMM		**Test statistics**
Quality of estimates	Intercept-only model	AIC	-1693.503
	Final model	AIC	-1751.242
		Chi-Square statistics	$X^2(6) = 57.75; p < .001$
	Fixed effects	Velocity feedback during training	$F(1,2270) < 1$
		Condition	$F(3,2270) = 31.55; p < .001$

Figure 38 shows measures for the stability of estimates. Once indicated by the mean deviation of relative and target speed (left) and once indicated by the time taken to estimate (right). The training phase prior to the experimental trials does not affect the stability of estimates; neither concerning the variation of estimates ($F(1,46) < 1$) nor the time taken to estimate ($F(1,46) < 1$). However, the condition still influences the stability of estimates ($F(3,44) = 6.65$; $p = .001$; $\eta^2_p = 0.312$). Further analysis reveals that the variation of estimates is highest with pure visual feedback compared to all other conditions. No statistically significant interaction can be found ($F(3,44) = 1.10$; $p = .358$; $\eta^2_p = 0.070$). The variability of time participants take to give their estimate, is not linked to the condition ($F(3,44) = 1.71$; $p = .180$; $\eta^2_p = 0.104$). Here again the interaction is not statistically significant ($F(3,44) < 1$).

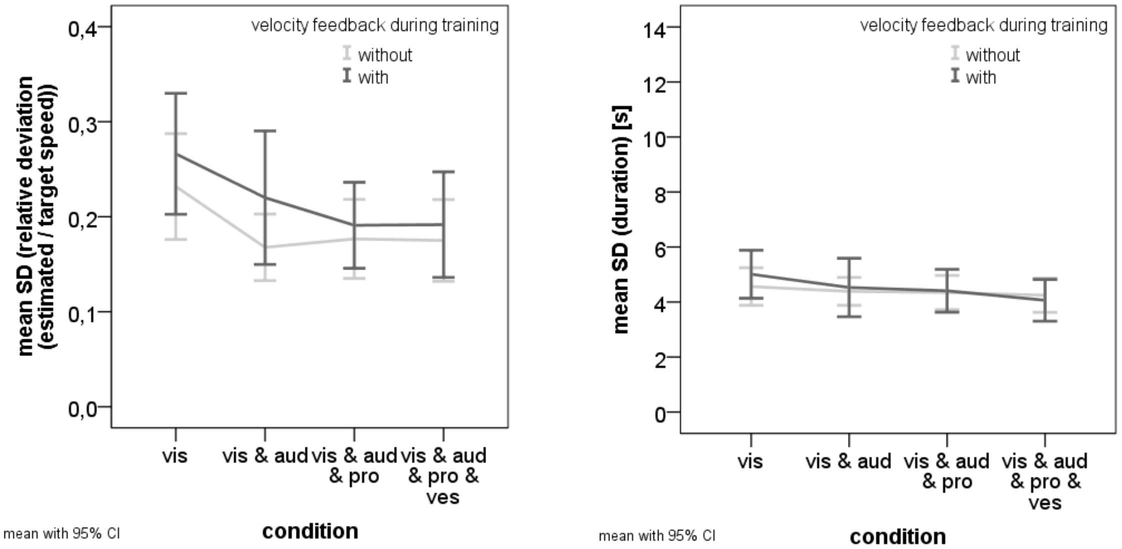


Figure 38: Training: Stability of estimates indicated by the mean standard deviation of the relative deviation of estimated and target speed (left) and time taken to estimate the velocities (right) as a function of condition and velocity feedback during training.

7.2.2 Behavior

The spontaneously shown behavioral responses of the riders are once again categorized and descriptively displayed in Table 13. Compared to the 'Action study' the numbers are generally on a lower level. The pattern between the conditions within training differs, too. Whereas conditions one, three and four are rather comparable, there is a higher frequency of behavioral responses in the combined visual and auditory condition.

Table 13: Training: Behavioral responses (operator ratings).

Study	**Condition**	**vis**	**vis & aud**	**vis & aud & pro**	**vis & aud & pro & ves**
Action	Mean frequency of behavioral responses	1.54	1.62	1.62	1.83
	Sum of behavioral responses	37	39	39	44
Training	Mean frequency of behavioral responses	1.17	1.46	1.17	1.21
	Sum of behavioral responses	28	35	28	29

7.2.3 Subjective rating

This parametric linear model for repeated measures and clustered data was conducted with 'velocity feedback during training' (between) and 'condition' (within) as fixed factors and 'rider' (within) as random factor assessing variability among individuals. The combination of 'condition four' and training with velocity feedback is used as reference category. The corresponding repeated measures ANOVA took 'velocity feedback during training' as between and 'condition' as within factor.

Presence Questionnaire

Results concerning the presence questionnaire are visualized in Figure 39. Corresponding test statistics are given in Table 14. The participants' subjective experience of spatial presence, interface quality as well as involvement is not influenced by the velocity feedback which they have received during the training phase. Huge differences between the participants' ratings are remarkable. This holds especially true for the spatial presence scores. The average level of ratings given by riders of the 'Training study' is comparable to those of the 'Action study' on a mid to high level for the three sub scores. A statistically significant influence of the condition on the experienced presence still exists. Stimulation of all four varied sensory cues leads to the highest scores compared to stimulation with visual feedback only. Adding auditory cues already leads to a constant high level for the perceived interface quality that is not increased through the stimulation of further sensory cues.

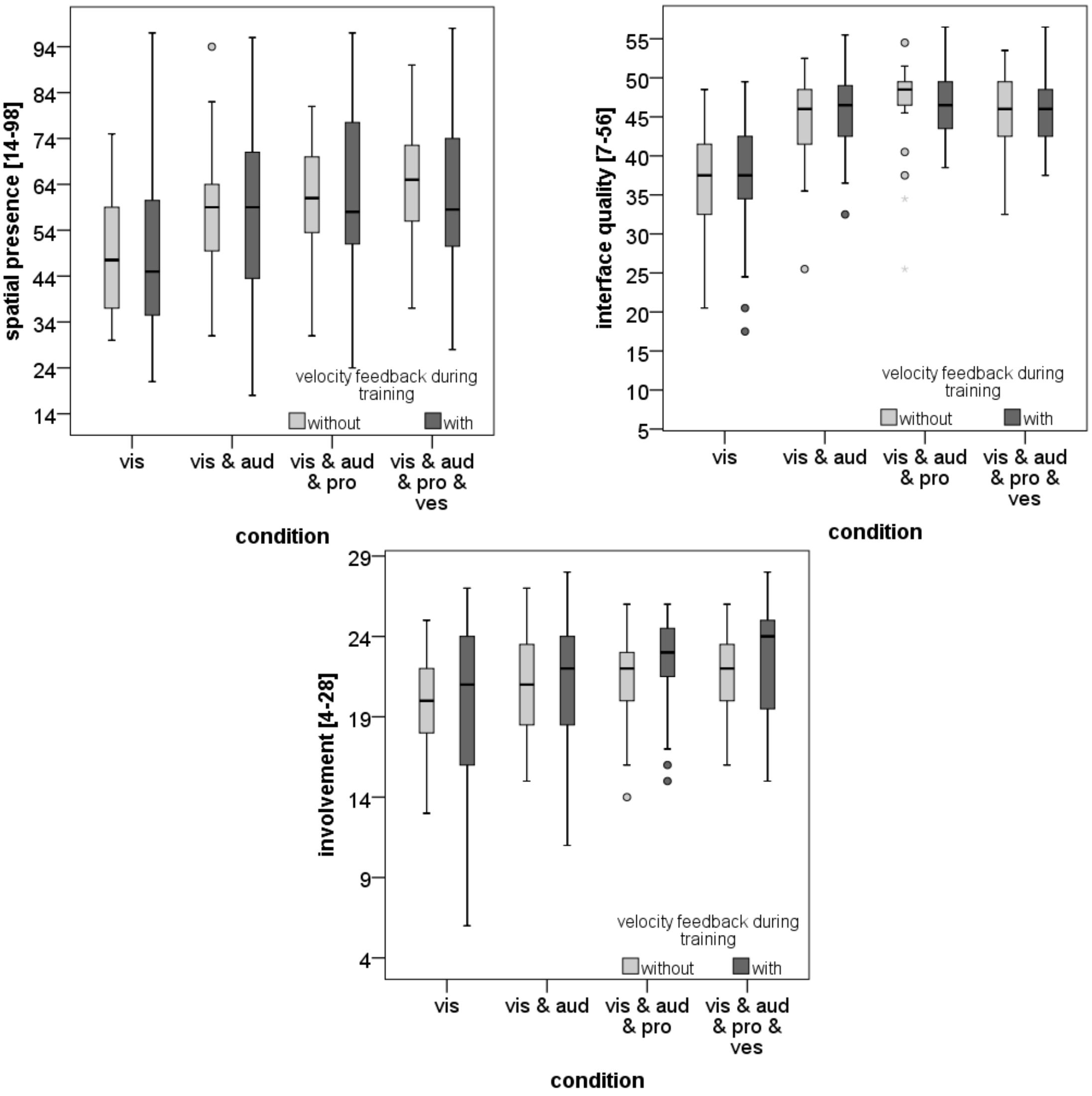


Figure 39: Training: Presence scores on subscales as a function of condition and velocity feedback during training.

Spatial presence and involvement in condition two, on the other hand, are still lacking behind the ratings of condition four. Adding proprioceptive and vestibular cues leads to further increased subjective ratings.

Immersive Tendencies Questionnaire

In accordance with ‘Study I: Video’ and ‘Study II: Action’, all participants were split in two sub groups with low vs. high immersive tendencies. This dichotomous variable was taken as an additional between-subject factor and the above mentioned ANOVAs were recalculated. However, there is no interaction between ‘condition’ and ‘low vs. high immersive tendencies’, indicating higher values for the latter group. Furthermore, no effects showed that people with high immersive tendencies could make better use of the training.

Table 14: Training: Presence questionnaire GLMM test statistics.

GLMM		Test statistics	
Spatial presence	Intercept-only model	AIC	1513.180
	Final model	AIC	1464.119
		Chi-Square statistics	$X^2(6) = 49.07; p < .001$
	Fixed effects	Velocity feedback during training	$F(1,186) < 1$
		Condition	$F(3,186) = 15.02; p < .001$
Interface quality	Intercept-only model	AIC	1125.978
	Final model	AIC	1059.438
		Chi-Square statistics	$X^2(6) = 66.55; p < .001$
	Fixed effects	Velocity feedback during training	$F(1,178) < 1$
		Condition	$F(3,178) = 35.78; p < .001$
Involvement	Intercept-only model	AIC	940.510
	Final model	AIC	917.022
		Chi-Square statistics	$X^2(6) = 23.50; p < .001$
	Fixed effects	Velocity feedback during training	$F(1,184) < 1$
		Condition	$F(3,184) = 8.14; p < .001$

Simulator Sickness Questionnaire

Out of the 39 participants that were invited for the study in total, $n = 8$ dropped out due to simulator sickness within the first familiarization phase (20.51 %). Five more subjects dropped out with sickness symptoms within the first two test trials and two after trial three; one of them during or after condition one and each three during or after condition two and four. The simulator sickness dropouts within condition four occurred immediately in the first trial, while sickness symptoms were already high after the familiarization phase.

The ANOVA reveals a statistically significant main effect for 'condition' ($F(5,42) = 6.75$; $p < .001$; $\eta^2_p = 0.445$), but no influence of 'velocity feedback during training' ($F(1,46) < 1$) and a marginal significant interaction ($F(5,42) = 2.10; p = .084$; $\eta^2_p = 0.200$).

In both studies, riding the simulator is accompanied by increased sickness scores compared to the baseline measurement (see Figure 40). Once again, the aggregate scores are on a reasonable low to mid-level. All extreme values and outliers can be attributed to four out of the 48 riders.

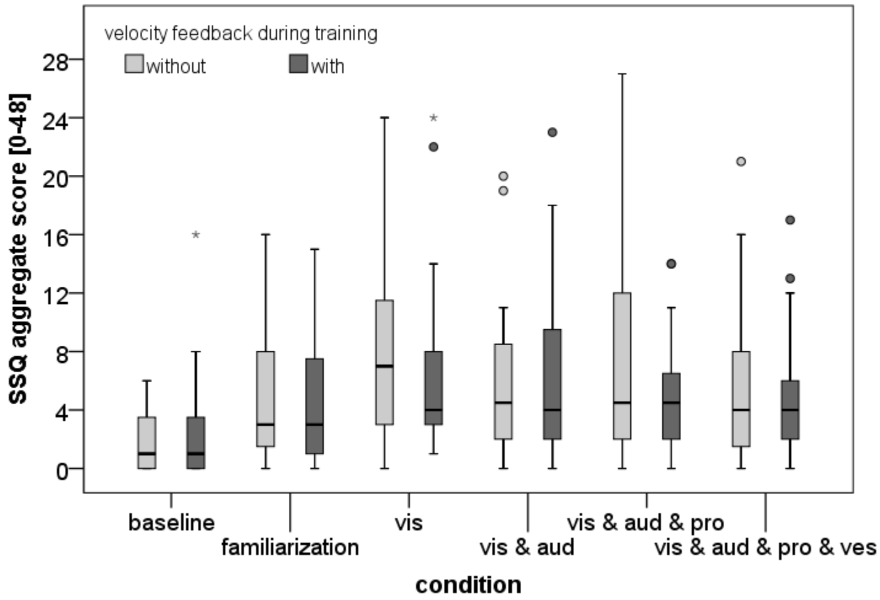


Figure 40: Training: SSQ aggregate scores as a function of condition and velocity feedback during training.

While the shorter familiarization trials lead to slightly increased values, the highest ratings are achieved in the visual condition. Noticeable, participants' ratings vary strongly in this condition and also when riding without vestibular feedback only. Comparing the simulator configuration four to the three conditions without vestibular cues shows higher values for the latter. The only difference between riding without or with feedback during the familiarization phase can be seen in a lower mean aggregate score in the visual condition for the latter.

Final inquiry

Repeated measures ANOVAs with 'condition' as within-subject factor and 'velocity feedback during training' as between-subject factor were conducted.

Figure 41 (left) contains a visualization of the rated contributions of the different sensory cues to performance in the speed estimation task. The fact that half of the participants received feedback on their velocity during the training phase while the other half did not, did not affect the rated contribution of sensory cues to their performance level ($F(1,46) < 1$). Once again, a strong influence of 'condition' on the ratings was seen ($F(3,44) = 21.02$; $p < .001$; $\eta^2_p = 0.589$). The contribution of visual and proprioceptive cues was on a comparable high level even if the variance is considerable. The ratings on auditory cues show less variance and the statistically significant highest ratings. Vestibular cues rank fourth on a medium level. Here again, the riders vary extremely in their assessments. There is no interaction between 'velocity feedback during training' and 'condition' ($F(3,44) < 1$).

Figure 41 (right) shows the equivalent rankings. In the 'Training study' the auditory cues are placed on rank one from the majority of the participants. Proprioceptive cues are ranked first in almost a quarter of the rankings. These are four more than in the 'Action study'. Additionally, there are now three riders that see the contribution of visual cues as most unimportant. That is the second difference to the 'Action' ratings. For vestibular cues the fourth rank is dominant.

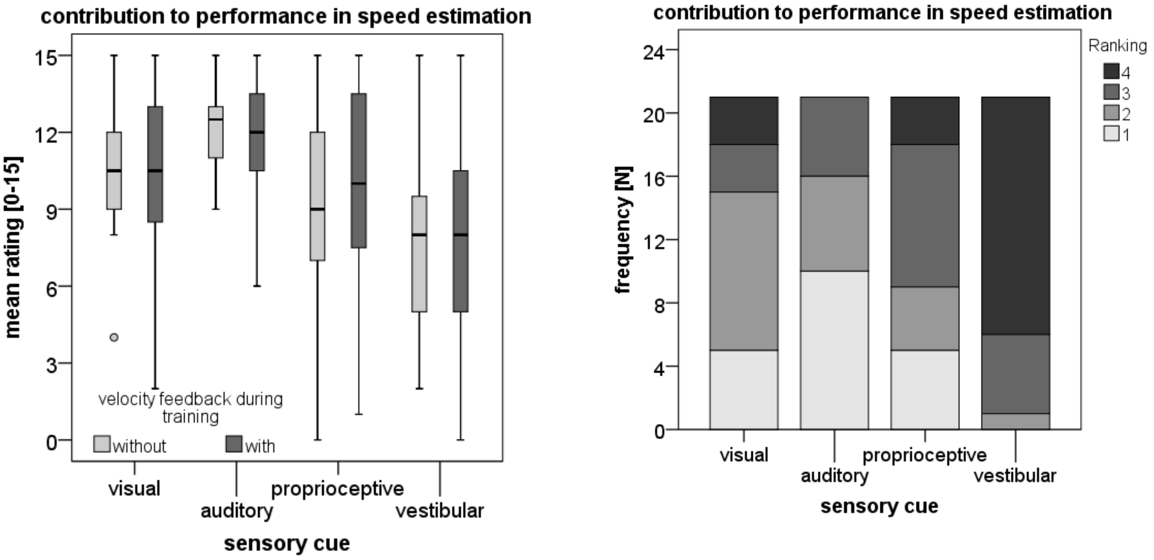


Figure 41: Training: Perceived contribution of different sensory cues to speed estimation performance (left: rating; right: ranking).

Figure 42 (left) displays the ratings on perceived contribution of the sensory cues to the level of experienced presence.

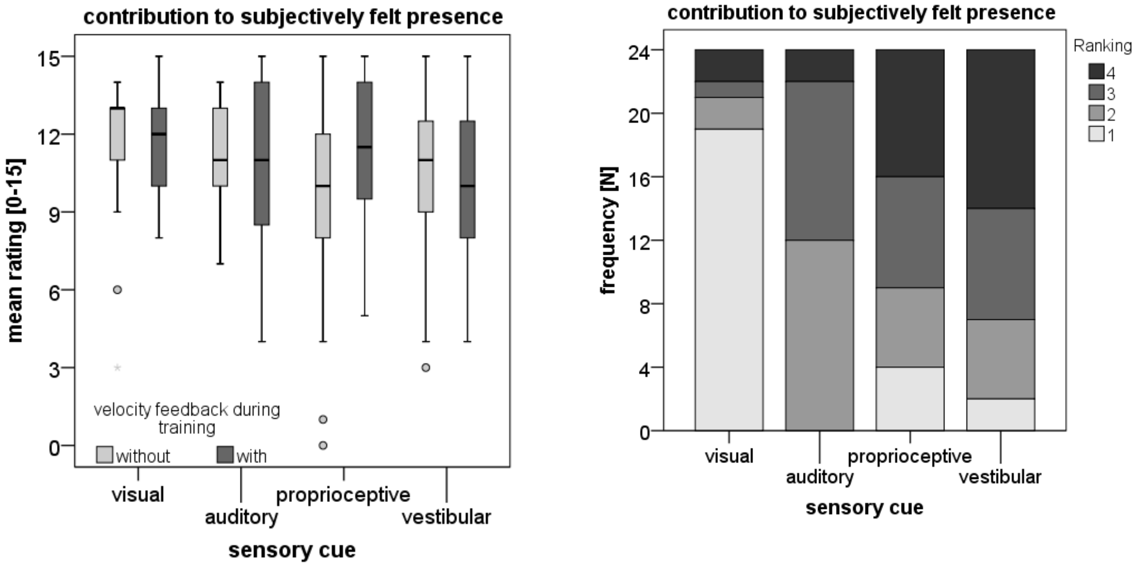


Figure 42: Training: Perceived contribution of different sensory cues to subjectively experienced presence (left: rating; right: ranking).

Participants of the 'Action study' and the 'Training study' do not differ in their ratings ($F(1,46) < 1$). The condition shows a statistically marginal difference between the sensory cues ($F(3,44) = 2.62$; $p = .063$; $\eta^2_p = 0.152$). There is a tendency that visual cues are rated superior to proprioceptive and vestibular ones. No statistically significant interaction is found ($F(3,44) = 2.07$; $p = .119$; $\eta^2_p = 0.123$).

Figure 42 (right) contains the rankings assigned to the different sensory cues in relation to their contribution to the level of subjectively experienced presence. The perceived level of experienced presence is clearly dominated by visual impressions with 19 out of 24 riders ranking visual cues first. None of the riders assigns rank one to auditory cues. Besides that, there is a high variability between participants, as all four ranks are assigned to proprioceptive and vestibular cues. This general pattern corroborates the outcomes of the 'Action study'. No specific strategies to estimate the velocity were reported.

7.3 Discussion

In the present study, the effect of training on presence was subject to investigation. The hypothesis according to the psychocybernetic background of the model was that velocity feedback during a training phase helps to adjust action-effect associations and thereby increases presence. In summary, neither a positive nor negative effect of training on presence could be identified. The pattern reflecting the different sensory cues' contribution to presence remains unchanged compared to the 'Action study'.

The positive effect of sensory stimulation on presence is still preserved. Independently from the training phase, the speed estimation performance is better and more stable if at least three senses are addressed. It has to be stated that the training phase with velocity feedback contained all four varied sensory cues (condition four). A learning process in order to tune the expectations of produced effects could therefore generally be available for all four senses. However, the data showed no adaptation process. Not even in condition four that matched the training condition. It seems as if the underlying processes that shall enhance presence were not affected by the training variation. Usually, a specific action of the driver goes along with the expectation of according effects. In this case the vehicle's reaction (Neukum, Krüger, & Schuller, 2001). The ideomotor principle postulates that every action effect coupling has to be learned first. So, the question arises what can be seen as effect of one's action. Findings from literature explain that unintended effects of one's action are not automatically part of the action-effect coupling but may need a stronger saliency (Stock & Stock, 2004). Maybe, the participants did not pay enough attention to relevant sensory cues. The availability of velocity feedback - so called knowledge of result - could have led to an unnaturally high attentional focus on the instrument cluster. Thereby, the sensory feedback provided by the virtual environment is partially neglected (Swinnen, Schmidt, Nicholson, & Shapiro, 1990). The riders' activity is more or less adjusted by the speedometer and the action-effect relations are not learned accordingly. One possibility to get rid of this effect could be to switch on the speedometer only in some trials of the training phase. So that in repetitions of the same condition the participants can allocate their full concentration on how this specific velocity "feels" in terms of sensory feedback. A possibility to control whether this distraction effect occurs could be the use of eye tracking.

Taking the research of Herwig and Horstmann (2011) into account, another explanation could be the external implementation of aims of action especially during the training phase. The authors claim that action-effect learning only works for endogenously driven action. That is, if the aims of action are set intention-based instead of stimulus-based. This degree of freedom shall be of highest importance during the acquisition phase. Assuming that this controversially discussed effect exists (Pfister, Kiesel, & Hoffmann, 2011), one could have let the participants choose their target speed freely during the training phase. If they decided to aim at a target speed of 65 kph instead of being told by the road signs to go for 100 kph, a bigger effect would have been expected. However, several findings from cognitive research deal with a laboratory setting that includes rather arbitrary action-effect associations such as button presses that produce a certain tone or light signal (Elsner & Hommel, 2004; Herwig, Prinz, & Waszak, 2007; Pfister et al., 2011). These are often completely new to the participants. The motorcycle riders instead started with baseline knowledge about the action-effect contingencies. For instance, turning the throttle leads to changed visual feedback in terms of higher optical flow. This fact might make the direct comparison a bit more difficult.

The low effect of training might also be due to the short duration of training. The process of adjusting an aim of action, so to set new perceptions as reference value might simply take longer. All participants have never ridden a motorcycle riding simulator before. Therefore, one has to assume that they make use of the reference values that have been acquired within years of riding a real motorcycle. It seems plausible, that these aims of action are not overwritten within minutes of riding a simulator. A counter-argument could be that the training is only used to re-calibrate the existing action-effect association what has to be separated from building or training new associations. Other traffic psychological studies suggest that well-known control loops such as those assumed while steering a car can be adjusted very quickly. For instance, drivers learn to go straight ahead with a 30° rotated steering wheel within milliseconds (Schneider, 2016). Therefore, a training duration of 10 minutes should be sufficient.

Another possible explanation for the missing effect of training is a ceiling effect with regard to the performance. Without any feedback from the speedometer average estimation errors of about 10 % were observed in condition four (the training condition). Maybe, this already high performance could not be improved by the velocity feedback during the training phase.

The frequency of behavioral responses did not increase from the 'Action' to the 'Training study'. A possible explanation could be that the feedback during the training phase was specifically related to velocity (speedometer visible). The behavioral responses, in turn, are not only evoked by speed perception but, for example, also by lateral vehicle control. Furthermore, counting the frequency of such behaviors is maybe insufficient. The quality of the riders' reactions could also be of interest. A participant that tries to be more streamlined at higher speeds maybe shows more behavioral responses than a rider that just takes his head down constantly and independent from speed or condition. This could be an improvement of this dependent variable, even if it might be difficult to exactly define the quality of behavioral responses.

Presence in terms of subjectively rated spatial presence is not influenced by the training variation. Prior studies have shown that spatial presence can be positively influenced by visual and auditory stimuli (e.g., Hendrix & Barfield, 1996; Kemeny & Panerai, 2003; Riecke et al., 2009). This was also the case in this study. The effects of an improved model of action and perception usually point to improved interaction with the virtual environment (Draper et al., 1998). This might explain the missing improvement of spatial presence. The rated interface quality and immersion, on the other hand, start from an already high level in the 'Action study' so that the training's effects might not really be noticed. As to the condition visual and auditory cues contributed to high ratings. The first might be explained by the immersive visualization with a huge cylindrical screen that does not recognizably limit the field of view in the virtual world. The latter confirms the dominance of auditory sensory information on presence (e.g., Gilkey & Weisenberger, 1995; Murray et al., 2000; Sanchez-Vives & Slater, 2005). Therefore, a ceiling effect may also explain that proprioceptive and vestibular information did not increase the ratings further. As already discussed for the 'Action study', the ITQ did not proof useful to detect possible differences as a function of the experimental conditions.

The dropout due to simulator sickness is on a comparable level to the 'Action study'. Given the assumption that the exposure duration plays an important role, this is comprehensible (Stanney et al., 2002). Both studies required rides of about 20 to 30 minutes per trial. The rather small amount of dropouts makes it hard to generalize these findings. Four more dropouts occurred during or after condition one and two. This pattern has also been observed in the 'Action study' and it points into the same direction that deprived sensory feedback increases dropouts and thereby decreases presence. This time, three more participants quit the study early after riding in condition four. This would contradict the previously given explanation. Given the fact that these three participants already had high SSQ ratings after the familiarization phase but still wanted to continue relativizes this effect. No influence of the training on the SSQ ratings was observed. Prior studies mainly revealed exposure time, unsynchronized sensory stimulation etc. as main contributors to simulator sickness (e.g., Neukum & Grattenthaler, 2006; Stanney & Hash, 1998). These factors were not influenced by the variation between the studies. It might be that their effect is confirmed once more and that the SSQ as presence measure was not sensitive to the training variation.

With regard to the subjectively experienced importance of the sensory cues to performance, the auditory cues were rated higher compared to the 'Action study'. However, the participants could not enhance their performance more than in the 'Action study' when auditory information was available. The subjectively perceived contribution of different sensory information to felt presence was not modulated by the velocity feedback during training. As the proposed presence model does not predict an interaction between the effects of sensory stimulation and training on presence, this is in line with the expectations.

Conclusion The present study could not demonstrate the hypothesized positive effect of training on presence. None of the presence indicators revealed changes compared to the 'Action study' which did not contain a training period with feedback. The positive influence of more consistent sensory feedback on presence can be regarded as a stable effect as the main results of both 'Video' and 'Action study' were replicated.

8 STUDY IV: GENERALIZATION

8.1 Research question

In the previously reported studies the contribution of different sensory cues to presence was subject to investigation. All participants of the 'Action' and 'Training study' faced an unexpectedly appearing deep pit at the end of their last experimental trial on speed perception. The goal of this study was to investigate whether the effects of sensory cues on presence can be generalized and occur in a more complex riding task than longitudinal vehicle control, too. The inclusion of a pit was the attempt to transfer the above mentioned virtual reality pit experiment that included a walking participant (Meehan et al., 2002), to motorcycle riding.

As the pit did not include a specific task, classical performance measures could not be taken. Concerning behavioral measures, the increased presence through more consistent sensory feedback should become manifest in more hesitation before entering the pit and a more defensive riding style in terms of acceleration and speed while crossing. Given the stressful situation of facing the deep pit, increased physiological activity with more sensory feedback was hypothesized. Due to the typical delay in physiological responses, this was expected to occur after crossing the pit. The effect of the condition should also be expressed in the participant's subjective evaluation of the situation.

8.2 Results

The following chapter contains the results of the 'Generalization study' organized by the type of dependent variables. For in-depth analyses the pit was partitioned into three sections (entry, passage, and exit) that were of special interest. The first section contained the pit approach on a straight rural road, where the pit could already be seen but not yet entered (40 m). The second section contained the first contact of the participants with the steepest slope (5 m), whereas the third part included the exit from the bottom of the pit and the almost straight even rural road afterwards (355 m). It is very important to keep these different section lengths in mind when interpreting e.g., mean values.

8.2.1 Behavior

An ANOVA with 'condition' as between factor was conducted for $N = 47$ valid subject data sets. Relevant pit sections were assessed separately as the variation within sections was of interest.

All participants stop in front of the pit. Analyzing the duration people are spending on the pit edge reveals a statistically marginal significant effect ($F(3,43) = 2.38$; $p = .083$; $\eta^2_p = 0.142$). Participants tend to hesitate longer before entering the pit when more senses are addressed. With visual cues alone, the riders spend about 10 sec before daring to move on. Figure 43 (left) reveals a difference of about 5 sec on average when auditory cues are available in addition to the visualization. An active rope towing mechanism and hexapod do not increase the hesitation period further.

The maximum throttle position, describing the participants' input on a behavioral level, reveals no statistically significant difference between the conditions when passing the pit ($F(3,43) = 1.14$; $p = .345$; $\eta^2_p = 0.073$). The hypothesized more defensive riding style as a measure of raised presence cannot be found here.

The velocity when entering the pit passage is marginally higher with visual cues only ($F(3,43) = 2.67$; $p = .059$; $\eta^2_p = 0.157$). This finding is in line with the previously discussed results of hesitation before entering the pit. Having a reduced set of sensory cues available is linked to a higher velocity when beginning to pass the pit. Once again, conditions two to four seem to be on a comparable level as to the entering velocity. The riders enter the steep slope slower (see Figure 43 right).

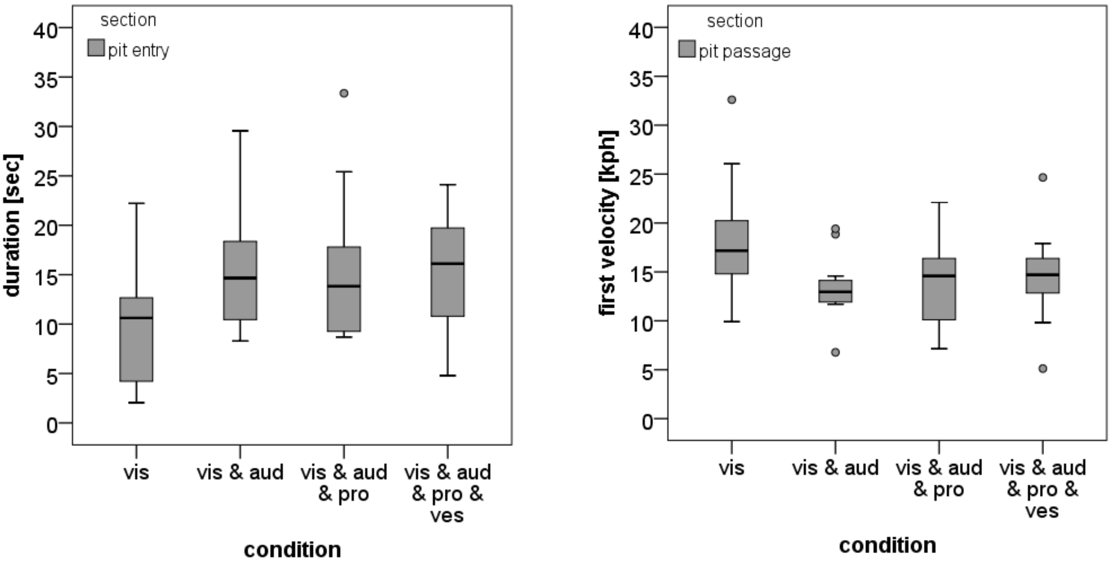


Figure 43: Generalization: Duration of hesitation on pit edge (left) and first velocity value while passing the pit (right) as a function of condition.

Figure 44 shows the results of a more detailed descriptive analysis of the speed profiles. These are given exemplarily for conditions one and four. The graphs display the bandwidths of velocities ranging from the slowest to the fastest rider at every road section. It can be seen that participants approach the pit at higher speeds when less sensory cues are addressed (0 – 40 m). The second dip of velocities occurs when the riders are back on the straight road (90m). Almost all participants decelerate significantly and take a rest following the successful crossing. After that, all participants accelerate again, but more homogeneously when visual, auditory, proprioceptive and vestibular cues are addressed.

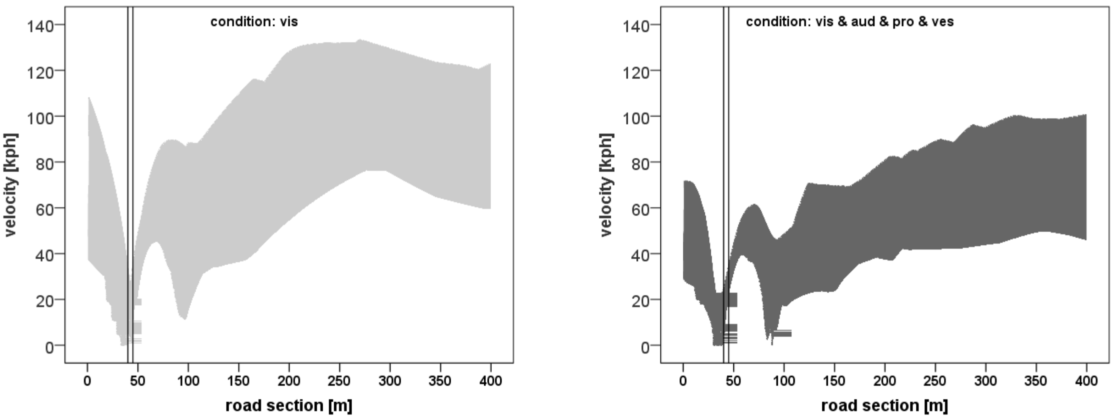


Figure 44: Generalization: Bandwidths of velocities as a function of road section and with reference to condition one (left) and four (right). The vertical lines indicate the boundaries between the three sections.

During the long exit section, sensory deprivation leads to higher variation and higher absolute velocities.

8.2.2 Physiology

This parametric linear model for repeated measures and clustered data was conducted with 'condition' (between) and 'pit section' (within) as fixed factors and 'rider' (within) as random factor assessing variability among individuals. The combination of 'condition four' and 'pit exit' is used as reference category to keep this in line with the other analyses that do not reference to a baseline. Test statistics are displayed in Table 15.

These analyses, describing the riders' physiological state during the pit experiment, contain data from *N*= 23 participants, as data from one subject of the 'Action' study was missing. Besides 'condition', the pit section (three levels: entry vs. passage vs. exit) was taken into account as an additional fixed within effect 'section'.

Even if higher mean values for the heart rate are found in condition four compared to the three remaining conditions, only the effect of the 'pit section' turns out to be statistically significant. Leaving the pit results in a higher mean heart rate than entering (4.60 bpm), respectively passing (3.18 bpm) it. Compared to baseline activation an even stronger increase by about 8.30 bpm is found. Constantly high variations can be seen across all conditions and pit sections.

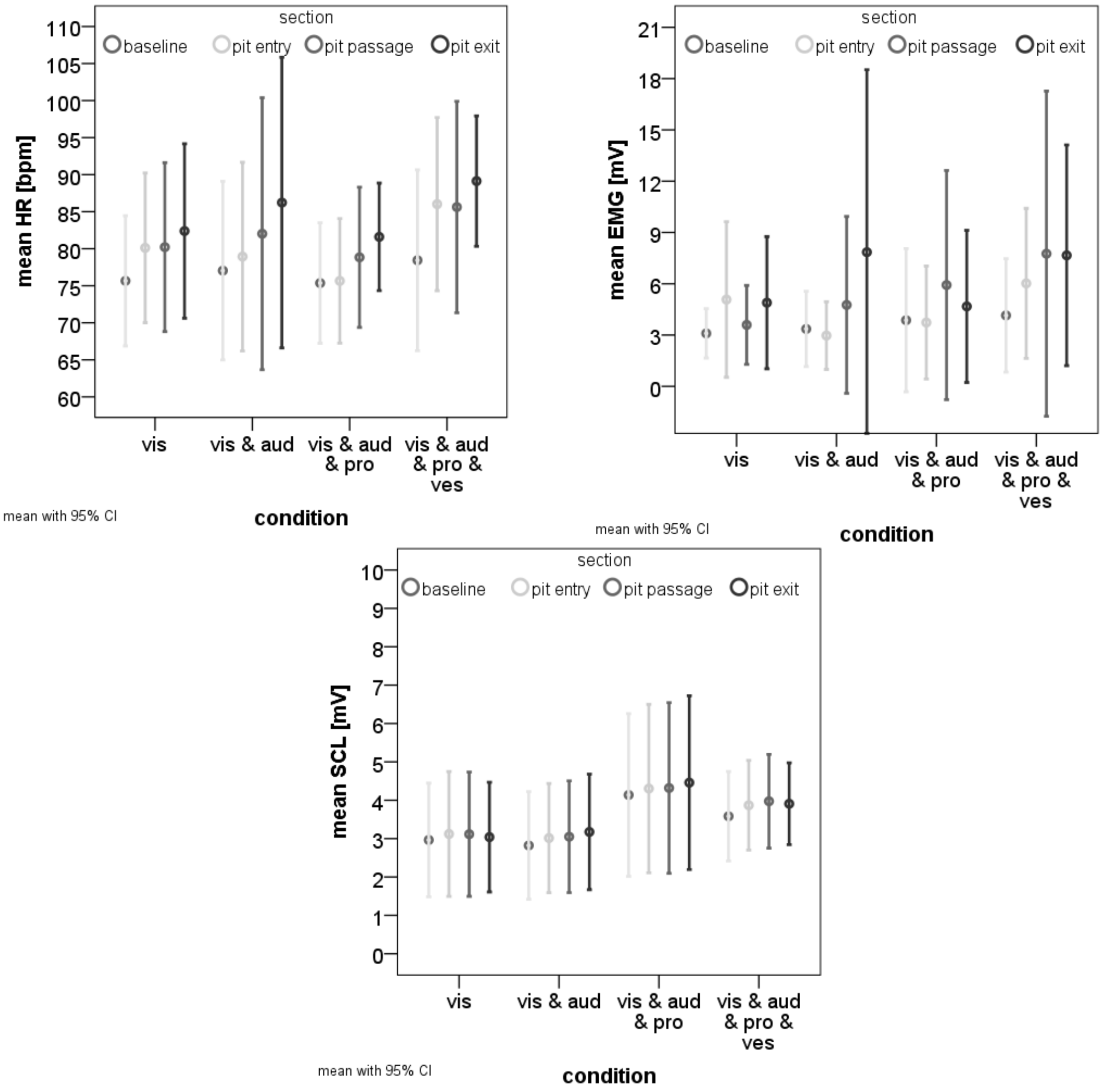


Figure 45: Generalization: Mean heart rate (upper left), EMG (upper right) and SCL (bottom center) as a function of condition and section.

A link between 'condition' and the recorded EMG values is not found. Entering, passing and exiting the pit leads to more muscular tension in the shoulder area than the baseline ride. The different pit sections do not differ from each other. Though, one must clearly state that once again participants vary strongly in their response to the sections. Especially, high variations occur when passing and exiting the pit. The same pattern of slightly increasing average values in the three pit sections compared to baseline is reflected in the SCL. However, there is no difference in between the sections. The differences between conditions do not reach statistically significance even though in condition three means and confidence intervals seem to increase slightly.

Table 15: Generalization: Physiology GLMM test statistics.

	GLMM	**Test statistics**	
Mean HR	Intercept-only model	AIC	631.343
	Final model	AIC	580.362
		Chi-Square statistics	$X^2(10) = 48.74; p < .001$
	Fixed effects	Section	$F(3,85) = 11.06; p < .001$
		Condition	$F(3,85) < 1$
Mean EMG	Intercept-only model	AIC	501.676
	Final model	AIC	448.353
		Chi-Square statistics	$X^2(10) = 63.91; p < .001$
	Fixed effects	Section	$F(3,84) = 5.24; p = .002$
		Condition	$F(3,84) < 1$
Mean SCL	Intercept-only model	AIC	66.222
	Final model	AIC	31.651
		Chi-Square statistics	$X^2(10) = 32.34; p < .001$
	Fixed effects	Section	$F(3,84) = 8.99; p < .001$
		Condition	$F(3,84) = 1.04; p = .382$

8.2.3 Subjective rating

As the pit was a comparably short section at the end of the last trial belonging to either the 'Action' or 'Training study', the standardized presence questionnaire was not specific to the pit scenario. In order to get detailed information on how the riders experienced this particular event they were questioned during the final inquiry.

Summarizing the comments, the pure visualization of the steep slope projected on the huge cylindrical screen already led to high arousal across conditions. None of the riders entered the pit without decelerating to standstill and investigating what is lying in front of him or her. One participant from condition three even referred to his fear of heights when watching the pit entry. He seriously struggled to proceed but did so in the end. The reports that stand out were those of the participants in condition four. They told that they had in mind the pitch and roll motion of the motorcycle while riding. Furthermore, they had already experienced the hexapod's reaction when crossing the speed bump. What almost all of the participants reported was that they imagined what their motorcycle might do when crossing the pit, before they entered. At that moment – and also while riding through it – they stated that they fully forgot about the laboratory and just concentrated on the riding task without falling. Something they reported to do in challenging scenarios in real riding, too. Fading out what is irrelevant to the successful riding task completion. On the contrary, participants that were in the visual condition stated that it felt kind of unreal as if they flew through the pit. This became better with auditory cues. The statements of these participants resembled those of condition one, but did not include this feeling of being detached from the virtual riding task. Crossing the pit with active visualization, sound and rope towing mechanism did not lead to other statements in the final inquiry.

8.3 Discussion

The present study investigated the generalizability of the previously conducted studies on the influence of sensory cues on presence. In order to achieve a high level of controllability the previous studies focused on longitudinal vehicle control in terms of speed estimation. The present study chose a more complex riding task with the crossing of an unexpectedly appearing deep pit. To summarize the most important findings, a trend towards higher presence with more sensory information available was observed as to behavioral and subjective measures. In contrast, physiological measures responded to the crossing itself but independently of the condition. These findings will be discussed in turn.

In general, the presence model components dealing with the effects of sensory stimulation could be confirmed by this more complex riding situation, too. The effect pattern was comparable to the one observed in the 'Action study'. The visual condition seems to stand out again. Participants' behavior in this condition was less defensive than it was suspected to be facing such an extreme maneuver. They did not hesitate that much before entering the pit and were faster when they did so. The bandwidth of velocities may be interpreted as a replication of the effect of the other three studies on speed estimation. Sensory deprivation led to higher ridden velocities. Assuming that the participants had no reason to ride faster in conditions with reduced sensory feedback, this finding could be interpreted as another indicator of speed underestimation. Furthermore, it can be seen that the different participants behave more homogeneously when more sensory cues are addressed. To paint the whole picture, one must emphasize that all participants showed strong signs of being present in the virtual environment. Every rider had the clear instruction to go ahead until reaching the parking lot. Nevertheless, everybody stopped on the pit edge and hesitated with the crossing. The speed limit on that section of rural road was 100 kph. None of the riders exceeded 33 kph while passing the pit. They were cautious. In accordance with Slater (2009) the participants seemed to accept the virtual environment as the environment they are actually acting in. The riders seemed to experience place as well as plausibility illusion by the strong connection between their action (accelerating to enter the pit) and sensory feedback (e.g., tilting motorcycle when crossing the pit edge).

Physiological parameters such as heart rate or skin conductance level are well known to respond with a certain delay. Taking into account that the pit entry and passage were rather short sections, this could be one possible explanation for the fact that moderately low effects of the pit crossing on the physiological measures were found. On the one hand, the results were in line with the expectations. The pit obviously induced some kind of involvement and presence, as physiological parameters rose in this situation compared to baseline riding. This is in line with the original pit study's findings (Meehan et al., 2002) and also other simulated driving studies that deal with even more fearful stimuli such as tunnel drives with tunnel-fearful patients (Mühlberger, Bülthoff, Wiedemann, & Pauli, 2007). It is of special interest as physiological effects as compliment to other measures of presence are not subject to the participants' free will. On the other hand, this effect could not be enhanced by giving more sensory feedback what has previously been hypothesized. The section's effect of more physiological activity while passing and leaving the pit could - besides the before mentioned natural delay - be a consequence of the riding task itself. But this should only be true for condition four, when the riders felt a high pitch angle. Visual, auditory and proprioceptive cues have also been available in a comparable amount during baseline ride and pit entry.

The interview as part of the final inquiry brought up very interesting statements. Some participants reported about "fully forgetting the laboratory and concentrating on the riding task in order not to fall". This report met the core element of presence. The participants accepted the virtual world as relevant to their action and ignored the laboratory setting. This replicates the findings from the original pit study (Meehan et al., 2002). Adding auditory cues seemed to help, accepting the virtual world and the riding task the participants had to fulfill. The rope towing mechanism did not really intensify this impression. This might be due to the fact that all riders decelerated to standstill and crossed the pit at pretty low speeds without intense acceleration or deceleration. The requirements of the system to produce high noticeable effects were therefore not met. Strong effects were reported from those riders that crossed the pit with an active hexapod. The steep slope led to high pitch angles which produced severe vestibular stimulation. When investigating the relation between sensory stimulation on the one side and presence on the other, these statements show pretty well how important it is to pay attention to the setting. The speed estimation tasks may not have been the perfect setup for vestibular cues to show their contribution to presence. It might be the case that these cues are of high relevance if stimulation is more intense. Regarding driving simulators in general this could, for example, be lateral control but also longitudinal control on courses with more changing height profile.

As said before, the pit could only be faced once by every participant. Paying tribute to this a between-subjects design resulted with eleven to twelve participants per condition which is a rather low value for each cell. This could be one possible explanation to the fact that only statistically marginal significant effects were found for the riding data. More in-depth analyses would call for a higher number of participants to confirm the relation between the number of sensory cues addressed and presence measured by these behavioral variables.

Conclusion The present study transferred a well-known standard experiment of presence research from a walking participant, unexpectedly facing a deep pit in the virtual world, to a corresponding motorcycle riding task. The importance of diverse and consistent sensory stimulation with regard to presence was shown. Yet not all presence indicators demonstrated the same effect. Behavioral measures as well as subjective ratings delivered positive effects as soon as at least visual and auditory cues were available. Physiological presence indicators did not respond to the different available sensory information. The findings show that it is important to interpret presence as multi-level construct and to not rely on single indicators.

9 STUDY V: REAL RIDING

9.1 Research question

This study aimed at delivering a reference frame for the observed speed estimations in the simulator setup. Great effort has been made to construct a sophisticated virtual environment including relevant sensory stimulation for the speed estimation task. Therefore, it was hypothesized that the speed estimation performance in a real riding scenario resembles the performance on the motorcycle riding simulator. On the one hand, performance between real riding and simulator riding was compared. On the other hand, the riders' behavior in terms of comparable strategies to achieve this performance was analyzed. The hypothesis was that the induced level of presence in the 'Action study' is sufficient to yield comparable behavior in both settings.

9.2 Results

A quite fair comparison of the real riding estimations can be made with those estimations from the 'Action study' in condition four, where all senses were addressed. The results section's focus lies on descriptive statistics as the amount of participants and conditions differs clearly between the two studies. Nevertheless, a parametric linear model for repeated measures and clustered data was conducted with 'setting' (between) and 'target speed' (within) as fixed factors and 'rider' (between) as random factor. Values for the target speed of 100 kph in real riding are used as reference category. The corresponding repeated measures ANOVA took 'setting' as between and 'target speed' as within factor. Alpha is set to .20 in order to implicitly decrease Beta as the equivalence between the groups is of interest. This shall help to give an impression of possible differences and similarities between simulator and real riding.

9.2.1 Performance

First of all, a tendency for the underestimation of speed in the simulator condition can be seen (see Figure 46 left). However, this general effect occurs for real riding, too. From a statistical point of view, there seems to be no difference concerning the riders' speed estimation performance in the simulator compared to real riding. Aiming at a target speed of 100 kph improves the performance on average compared to a target speed of 50 kph.

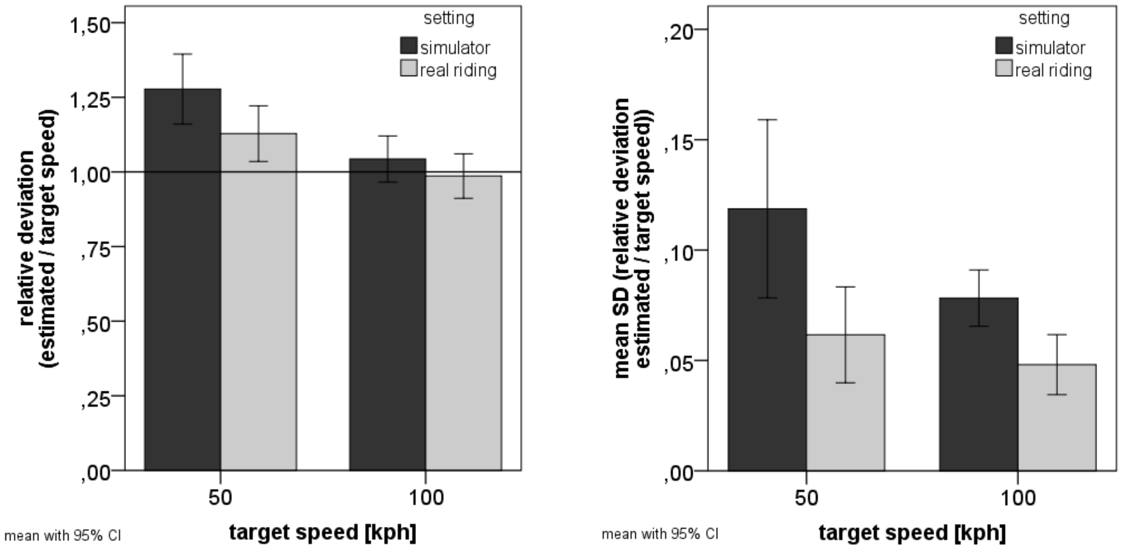


Figure 46: Real riding: Relative deviation of speed estimation as a function of target speed and setting (left) and stability of estimates as a function of target speed and setting (right).

Interestingly, this holds true for simulator- as well as real riding (see Table 16). On average, the speed estimates are very good in the 100 kph target speed condition. However, estimating velocities on a real motorcycle leads to more stable estimates compared to the riding simulator ($F(1,34) = 7.02$; $p = .012$; $\eta^2_p = 0.171$). The corresponding graph can be found in Figure 46 (right). Once again, one should always keep in mind that twice as much participants delivered estimates in the simulator study compared to the real riding investigation. A trend towards more stable estimates while targeting 100 kph can equally be seen for simulator- and real riding ($F(1,34) = 3.91$; $p = .056$; $\eta^2_p = 0.103$). No interaction between 'setting' and 'target speed' occurs ($F(1,34) < 1$). Table 17 shows descriptive statistics of the participant's performance. The difference between simulator and real riding regarding the mean velocity estimations and stability of estimates is rather low in absolute values. In contrast to that, there are obviously higher deviations of maximum estimates on the simulator. The worst estimate is more than twice as high as the target speed (114.28 kph for a target speed of 50 kph).

Table 16: Real riding: Riders' speed estimation performance GLMM test statistics.

	GLMM		Test statistics
Performance	Intercept-only model	AIC	-10.297
	Final model	AIC	-33.895
		Chi-Square statistics	$X^2(4) = 23.61; p < .001$
	Fixed effects	Setting	$F(1,69) < 1; p = .338$
		Target speed	$F(1,69) = 49.07; p < .001$

Those huge mistakes cannot be seen in the real riding data. Nevertheless, it has to be stated that motorcyclists' performance concerning speed estimation is also far from perfect in reality. For instance, the velocity estimates are spread across a range of about 47 kph in the 100 kph target speed condition.

Table 17: Real riding: Descriptive statistics concerning velocity estimations.

	Simulator		**Real riding**	
Target speed [kph]	**50**	**100**	**50**	**100**
Mean velocity estimation [kph]	63.87	104.33	56.42	98.62
Mean *SD* of velocity estimations [kph]	5.93	7.82	3.08	4.81
Minimum velocity estimation [kph]	40.35	61.69	43.56	79.46
Maximum velocity estimation [kph]	114.28	148.51	70.01	126.12

9.2.2 Behavior

The following chapter compares the number of different gears while estimating a given target speed, between the simulator and the real riding condition. A rider that estimates the 100 kph in every trial by using the fourth gear is assigned a 'number of gears' one. If he once uses the fifth gear, he will be assigned a two and so on. As both data sets vary significantly in terms of engine power of the motorcycle models that were used, number of participants and number of trials per target speed etc., only descriptive statistics are given. It is therefore not of interest whether 100 kph trials are e.g., estimated in the fifth gear in both settings. Due to these limitations, other potentially interesting action patterns, such as throttle position over time or development of velocity, are not considered.

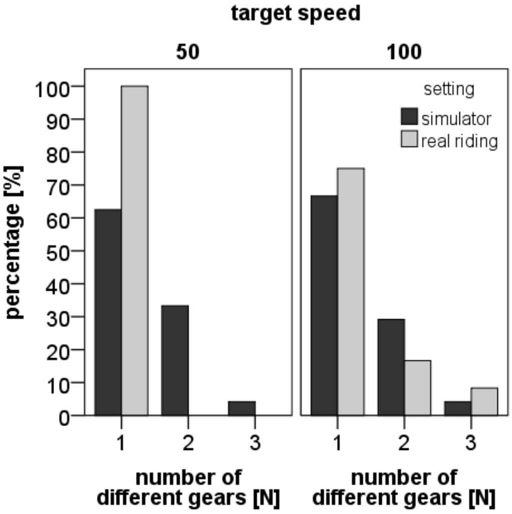


Figure 47: Real riding: Number of different gears per target speed and setting.

While riding the simulator, about 65 % of the riders estimate a specific target speed by using the same gear in every trial. 31 % of the riders use two gears and 4 %, that is one rider, uses three different gears in the same condition. This pattern seems to be independent of target speed in the simulator. In real riding, a similar pattern can be seen for the 100 kph condition. However, when 50 kph target speed has to be reached, all riders use the same gear. Generally, one can see the tendency that the majority of riders estimate an instructed target speed by using the same gear in the simulator as well as in the real riding setting (see Figure 47).

9.3 Discussion

The present study focused on the comparability of riders' speed estimation in simulator and real riding. To conclude, no substantial differences in speed estimation performance occurred.

A point of criticism that simulator studies often have to take is the poor or biased speed perception. The studies I to III confirmed these velocity underestimation tendencies – especially for lower speeds. Hence, the important question in this discussion should not be how close the simulator comes to a perfect performance, but how close one can get to the real riding performance. This study revealed that this divergence is not that tall. While there were more extreme outliers and higher variation in the simulator data, a comparison of mean values revealed no substantial differences in performance between simulator and real riding.

As the above displayed stability of estimates is calculated from a different number of subjects and estimates, it shall not be compared in absolute numbers. Having the double amount of participants in the simulator study compared to real riding influences the standard deviation of course. Noticeably, a lower standard deviation in real riding was observed despite the smaller sample size. This might indicate even more stable estimates in real riding which should be subject to further investigation. Nevertheless, this study's results should help to properly integrate the findings of the previously reported experiments. The 'Action study' revealed more stable estimates for a target speed of 100 kph compared to 50 kph. The same tendency can be seen in the real riding results. Interestingly, this effect contradicts the findings of Ohta and Komatsu (1991) who found that higher target speeds correlate with higher overestimations and that this effect is even stronger in simulators. This may partly be explained by one of their own reported findings, namely the high importance of visual cues in driving simulator settings. Ohta and Komatsu have chosen a TV screen for visual cues in the simulated environment and observed poor speed perception performance. The motorcycle riding simulator in this study used a huge cylindrical screen with 220 ° field of view that comes close to naturalistic conditions. Another difference between the studies that might account for variance in data is the activity of the participants. Ohta and Komatsu had all participants driving as passenger and passively experiencing the velocities. This thesis' study applied the production method that involves active behavior of the participants.

Taking a look at the selected gear during the estimation phase should deliver insight into the riders' normal action patterns. The specific chosen gear cannot be compared as the motorcycle specifications vary strongly between simulator and real motorcycle (different displacement, gear ratio, engine power…). Nevertheless, within each setting one can compare if a certain effect (e.g., target speed 100 kph) is linked to a constant action (e.g., choose gear X) to achieve this effect. This is generally the case for the simulator setting as well as the real riding. Only the pattern for a target speed of 50 kph while real riding differs in a way that all riders always use the same gear in each trial. This might be due to the fact that the test vehicle provided had very high engine power so that every rider changed the gear only once after initial acceleration to the second gear and stayed there. A proper task specific validation of speed estimation in a riding simulator compared to real riding would require the same motorcycle as the engine power is related to the task of longitudinal control. Furthermore, a within-subject design could minimize the variation coming from inter-individual differences.

These findings are of special interest, because driving simulators in general are said to suffer from problematic speed estimations. At least for motorcycling and this specific motorcycle riding simulator, the study suggests that proper speed estimation might be comparably easy or difficult in both environments. Discussing this further leads to the widely discussed topic of simulator validity (see e.g., Buld et al., 2014; Jamson, 2000; Wade & Hammond, 2000) and away from the original topic of presence. To conclude, the study aimed at delivering a reference frame for the chosen task of speed estimation and it should help to better integrate the performance findings in the previously reported studies.

Conclusion Despite higher variability the mean speed estimation performance between simulator and real riding was comparable ensuring reasonable validity of the results from the simulator studies.

10 SYNOPSIS

In the present thesis, a presence model for the application in driving simulator setups was developed. Empirical tests of the model's predictions were conducted in a series of five experiments. The postulated positive effect of diverse and contingent sensory feedback on presence was demonstrated. The general importance of visual cues in a driving simulator was highlighted. Additionally, acting in virtual environments improved presence. In contrast, the hypothesized positive influence of training on presence did not occur. Finally, different measures of presence have been applied and their sensitivity to presence in the different studies has been discussed. Therefore, a slightly adapted presence model for driving simulators is shown in Figure 48 that contains a visualization of the summarized major findings. A more detailed synopsis follows in turn.

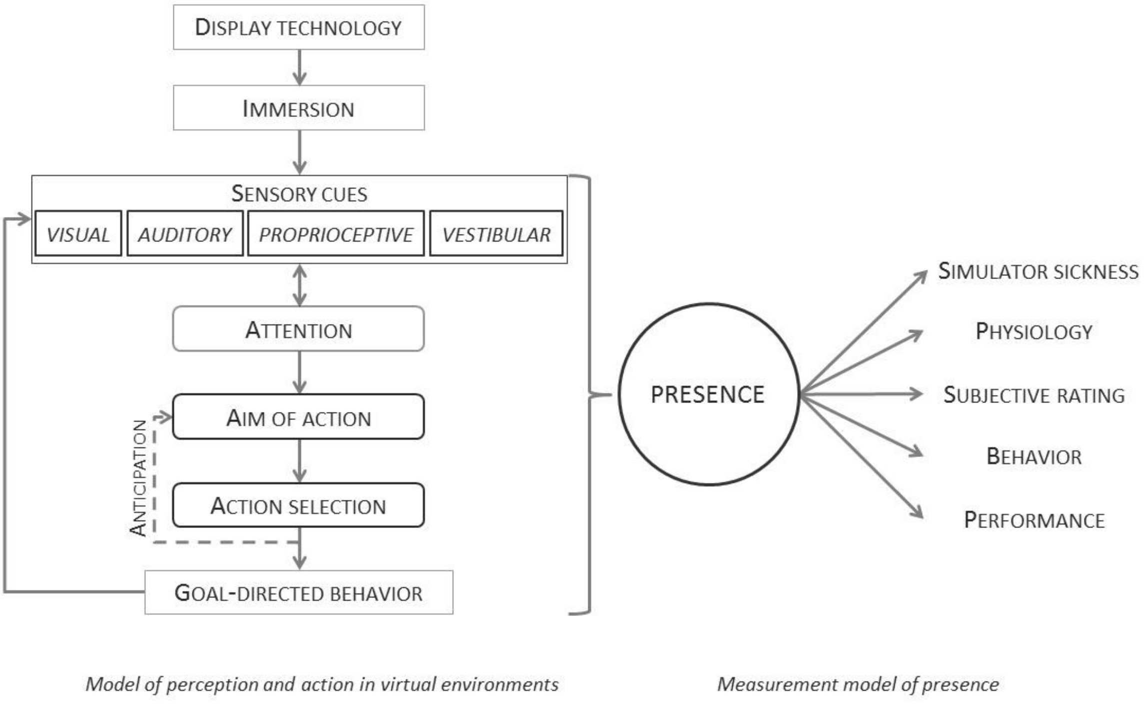


Figure 48: Revised presence model for driving simulators.

The previously postulated relation of display technology affecting immersion and thereby the sensory stimulation provided to the driver remains unchanged. Hence, the studies I to III showed different effects of the different sensory cues. Visual cues alone were already able to create a remarkable baseline level of presence. Adding more sensory cues could nevertheless enhance presence significantly. However, the different presence measures revealed variously strong effects of the other sensory cues. There was no linear increase in presence when more sensory cues were added stepwise. To take this into account, the sensory cues are now displayed in separate boxes. Generally, it would be possible to expand the model if other senses become relevant. The postulated influence of attention was not specifically subject to investigation up until now. The scenarios and independent variables were planned in a way that the attention attribution on the available sensory information was more or less unavoidable. For instance, auditory cues coming from headphones within the helmet will be noticed by a rider. Nevertheless, it remains unclear whether specific sensory information is actively processed.

The feedforward loop in the lower part of the model is now included with dashed lines, indicating that study III could not reveal a positive effect of training. The riders' behavior and positive performance in the 'Action study' without training suggests that action-effect associations were applied that have been acquired in real life. The training period in the simulator did just not help to improve this any further. More specifically, the model postulates that a selected aim automatically triggers the anticipation of the related effects. This feedforward process should make actions more efficient as the anticipation allows quick control and, if necessary, adjustment of actions. The existence and role of these feedforward processes have been shown in experiments on basic motor control (Desmurget & Grafton, 2000) and it has to be assumed that they occur in driving simulator scenarios, too. Nevertheless, no specific investigations on the role of feedforward in driving simulator settings have been conducted up until now. For instance, it could be interesting to investigate whether corrective actions occur while setting the position of the throttle twist grip before sensory feedback changes accordingly. The manifest goal-directed behavior closes the loop as it changes perceived sensory feedback.

The following conclusions were drawn with regard to the measurement model. As previous research already revealed, different measures of presence do not always point into the same direction (Freeman et al., 1999; IJsselsteijn et al., 2000). For instance, the active hexapod in the 'Generalization study' led to high subjective ratings of the importance of vestibular cues. Hence, this effect could not be seen in behavioral measures, such as a more defensive riding style when crossing the pit, or physiological measures, such as an increased heart rate. This has two consequences. Firstly, presence seems to be a multi-level construct that calls for different measures. There is not one single reliable presence indicator. Secondly, it is therefore recommended to select different possible indicators prior to study conduction with regard to the given driving task. If one aims at investigating presence in a driving simulator that shall later be used for the assessment of distraction induced by different secondary tasks in a highway scenario, heart rate or skin conductance may not be the first choice. On the other hand, if presence in a race car simulator shall be measured, physiological measures could be a promising indicator based on the ground truth paradigm. This diversity in the presence measures' sensitivity led to a further development of the model. The previously summarized measure "Behavior / Performance" is now separated as a consequence of the studies' results. Furthermore, it is obvious that participants who drop out during a simulator ride due to sickness symptoms can not feel present in the virtual environment. The constant surveillance of sickness symptoms showed results that were on average in line with other measures of presence. Following this experience and recommendations from literature (e.g., Stanney et al., 2002), it could make sense to explicitly take simulator sickness into account in the presence model.

Simulator sickness would be seen as a consequence of action and perception in virtual environments and therefore belong to the measurement model of presence in the proposed model. An inverse connection between simulator sickness and presence is postulated. What should be kept in mind is that simulator sickness, in turn, can be measured by different means such as subjective ratings as well as physiological reactions.

No new model components have been added. Due to the missing influence of a personal trait in relation to presence, as measured by the ITQ in studies I to III, no individual trait factor was included. Furthermore, there are still no dedicated situational components of the virtual environment included in the model for the following reason: For instance, the action that is necessary to drive at 100 kph (effect) will obviously differ between different types of cars. A light passenger car with small engine might call for another gear and another throttle position than a huge powerful SUV. Consequently, various actions might lead to the same effect depending on the simulated vehicle. A decision for one specific action could be triggered by situational cues (in this case e.g., the simulated vehicle a participant is driving). Yet an argument against the inclusion of a situational factor could be the following: The situation is already included in the aim of action. The set of sensory cues which determines an action's aim does not become manifest on a general level, such as "drive at 100 kph" but on a lower level such as "drive at 100 kph in a powerful SUV". This idea is close to the postulation of action preparing event files by Hommel (2009). These files are regarded as networks of codes that may also include situational activation conditions. Still the question remains how specific the action-effect associations can be and what is part of it when certain information is not available during the learning process. These questions could lead to further investigations digging deeper into fundamental research.

From a psychological point of view, this thesis' results paved the way to further research questions that might help understanding the phenomenon of presence even more. The knowledge about the importance of specific sensory cues to presence is highly relevant for improvements of presence in existing or newly designed simulators. For instance, the replacement of static wind forces in reality by a rope towing mechanism that produces proprioceptive stimulation in the simulator clearly showed its strength. Hence, these findings pose new questions that could be subject to further investigations: What specific information is transported via a certain sensory cue that people include in their aim of action? For instance, the results of the simulator studies pointed out that auditory cues helped the participants to improve their speed estimation performance. One question that still remains open is, for example, whether riders aim at adjusting the rpms of the engine to a specific level or whether they aim at adjusting the wind noise to a certain level. Further research could therefore make use of a paradigm called "test for the controlled quantity" (Powers, 2005). Thereby, potentially relevant information within the sensory feedback is varied on a subliminal level – a disturbance is applied - and it is observed whether the participants adjust their behavior. Working on speed perception, one could create a task where the riders are instructed to keep a constant velocity without information from the dashboard. What the participants would not know is that their velocity is automatically kept constant while e.g., the rpms of the engine are smoothly increased without changing the wind noise. If the participants' aim of action contains a specific engine sound as effect of their action, one should observe adjustments of the throttle position (goal-directed behavior). If the rider input does not change, there is probably other information coded in the auditory cues that is relevant for the participants' action.

The contribution of more consistent sensory stimulation to presence was confirmed in the different studies. Hence, it seems as if there is not the simple linear correlation in terms of providing one more sensory cue leads to the same increase in presence, regardless of already existing sensory feedback. The four chosen sensory cues have been varied stepwise. From a methodological point of view, this was a useful and efficient operationalization to gain insight into the effects of sensory deprivation on presence. Nevertheless, in doing so it was accepted that, for instance, proprioceptive cues have never been experienced by the riders without auditory cues. The potential of the first to compensate for the latter could not be examined. Especially with regard to these compensating abilities of specific cues, it might be interesting to replicate the studies with a complete mixed design for the 'condition' factor levels. Thereby, one could investigate in more detail the pure contribution of sensory information as well as possible interactions. Another study design to reveal the specific sensory contributions could be to include the use of these cues in the instruction. For instance, the rider could get the task to produce the sound of 100 kph. Different measures of presence could then be interpreted more specifically.

The above presented results were obtained from studies conducted on a motorcycle riding simulator. For sure, this entails some special characteristics such as the rope towing mechanism for proprioceptive stimulation imitating wind forces. Nevertheless, the rope towing mechanism is just one possible operationalization of proprioceptive stimulation. An according operationalization in a car driving simulator could be an active seat belt that tightens while braking. This could imitate the feeling of being retained by the seat belt while decelerating. Further research would have to prove whether the results can be generalized to each level of sensory feedback, as stated in the model, or whether the positive effect of addressing proprioceptive cues is due to this specific operationalization. Research from the automotive sector supports the proposed model of presence as positive effects of sensory feedback were found in different modes of operationalization (e.g., Mourant & Sadhu, 2002; Reymond et al., 2001).

All reported studies have more or less defined the aim of action externally by means of instruction by the experimenter. According to Herwig and Horstmann (2011) this may have led to the low effects of training, because according to these authors intrinsically set aims are of special importance for the learning of action-effect associations. Nevertheless, this instruction defines only an aim on a certain hierarchical level such as driving at 100 kph (Powers, 2005). The translation of this aim into aims of lower levels is still up to each person. For instance, some people might include more visual and some more auditory information as reference frame on a lower level. The decision to include one or the other can be regarded as an intrinsically motivated process. A possible interpretation is that every externally set aim will be transferred into intrinsically motivated aims of action at some level. Thus, it can be assumed that it might make no difference where the aim of action is originally defined. Many other studies found action-effect associations with forced choice tasks (e.g., Pfister et al., 2011). Yet the presented studies cannot answer the question whether completely intrinsically motivated control loops work differently. Further studies would be needed to deliver insights into this motivational part of the model.

Another aspect that has not been part of this thesis is the investigation of the underlying mechanisms of how perception and action are cognitively represented and whether there is the need to distinguish action and perception in virtual environments from action and perception in the real world. This is, for instance, an ongoing discussion among supporters of the perceptual control theory (PCT) or theory of event coding (TEC) such as Hommel (2009). This open question is of high interest to more fundamental research, as it helps to understand action and perception in general.

In conclusion, the main components of the presence model for driving simulators were maintained. A summary of the main results and an outlook will be given in the following chapter.

11 CONCLUSION & OUTLOOK

The research in this thesis investigated postulated connections between components of a newly developed presence model for driving simulators. It could be seen that the diversity of sensory feedback positively influences presence. Acting in the virtual environment could further enhance presence, but it is no necessary precondition for presence to occur, as shown in the 'Video' and 'Action study' on speed perception. Further confirmation came from a study that investigated the same independent variables in a new context - the pit. A positive effect of training on presence with regard to the speed estimation task was not observed. Results from a real riding study on speed perception delivered a reference frame for the simulator performance. It could be seen that the performance in the simulator condition with complete sensory stimulation is not that different from the performance on a real motorcycle.

In summary, presence may be interpreted as a quality measure of perception in virtual environments. This quality can be enhanced by more and consistent sensory feedback as well as successful action. The latter is interpreted as the control of perception following psychocybernetic approaches. In other words, a high level of presence can be achieved if the participants know the associations between their action and the corresponding change in the environment. The proposed model delivers a scale to evaluate existing driving simulators in their ability to produce presence. Furthermore, implications for the design of new simulators can be retrieved.

Latest developments in the entertainment industry could push research and development processes in the field of driving simulation forwards. In 2016, Samsung© introduced its Entrim 4D headphones which use galvanic-vestibular simulation to deliver vestibular cues appropriately matching visual input from a head mounted display. If this technology proves to maintain stable operation without increasing simulator sickness, it could quite easily be adapted to driving simulation enhancing presence in a new manner. The proposed presence model could then deliver the theoretical framework to investigate the effect of such new promising technologies on presence.

Recent advancements in the motorcycle sector, such as advanced rider assistance systems or navigation systems, call for cognitive ergonomic assessment in order to avoid distraction and to enhance safety. This thesis' findings could help to develop proper research tools for the assessment of these human-machine interfaces in the motorcycle sector and thereby contribute to powered two wheelers' safety. Moreover, this is also valid for other types of simulators.

Even though more research is certainly needed, the evidence delivered in this thesis closes a gap in traffic psychological research and is potentially useful in generating questions and methods in accordance with the theoretical framework that will hopefully lead to further insights into the construct of presence.

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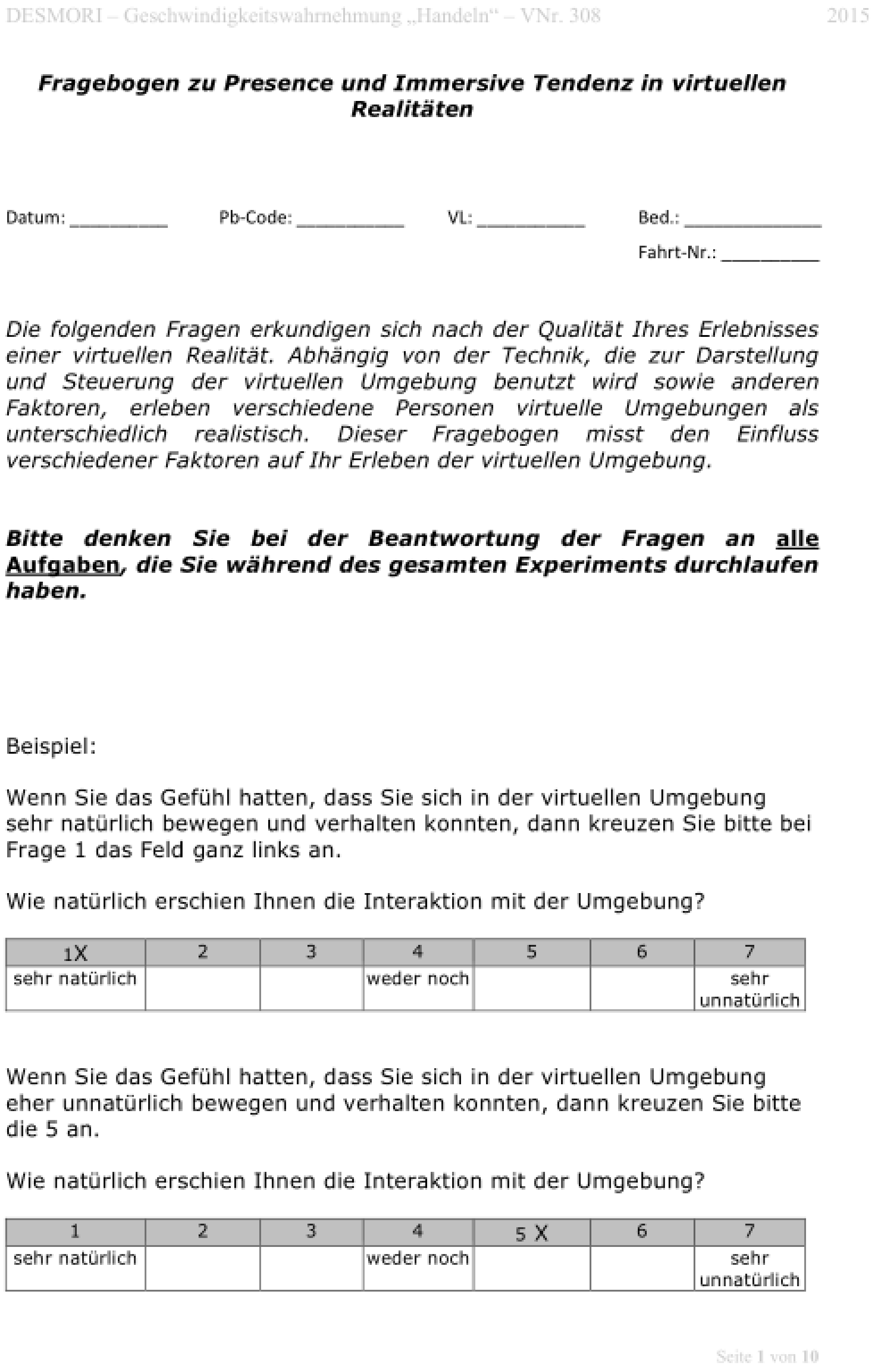
13 APPENDIX

The study material is displayed in the version used for the ‘Action study’. Generally, the same material was used for ‘Video’ and ‘Training’. No further questionnaires were used for ‘Generalization’ and ‘Real riding’. For reasons of legibility no distinction is made between male and female word forms.

13.1 Presence questionnaire

Pages five to six contain the Immersive Tendencies Questionnaire (ITQ) that was filled in just once, aiming to measure a stable personal trait. The presence questionnaire of the 'Video study' did not contain the items 4, 7, 10, 11, 13 and 15 as these were meaningless when just being passive.



Fragebogen zu Presence und Immersive Tendenz in virtuellen Realitäten

Datum: __________ Pb-Code: __________ VL: __________ Bed.: __________

Fahrt-Nr.: __________

Die folgenden Fragen erkundigen sich nach der Qualität Ihres Erlebnisses einer virtuellen Realität. Abhängig von der Technik, die zur Darstellung und Steuerung der virtuellen Umgebung benutzt wird sowie anderen Faktoren, erleben verschiedene Personen virtuelle Umgebungen als unterschiedlich realistisch. Dieser Fragebogen misst den Einfluss verschiedener Faktoren auf Ihr Erleben der virtuellen Umgebung.

Bitte denken Sie bei der Beantwortung der Fragen an alle Aufgaben, die Sie während des gesamten Experiments durchlaufen haben.

Beispiel:

Wenn Sie das Gefühl hatten, dass Sie sich in der virtuellen Umgebung sehr natürlich bewegen und verhalten konnten, dann kreuzen Sie bitte bei Frage 1 das Feld ganz links an.

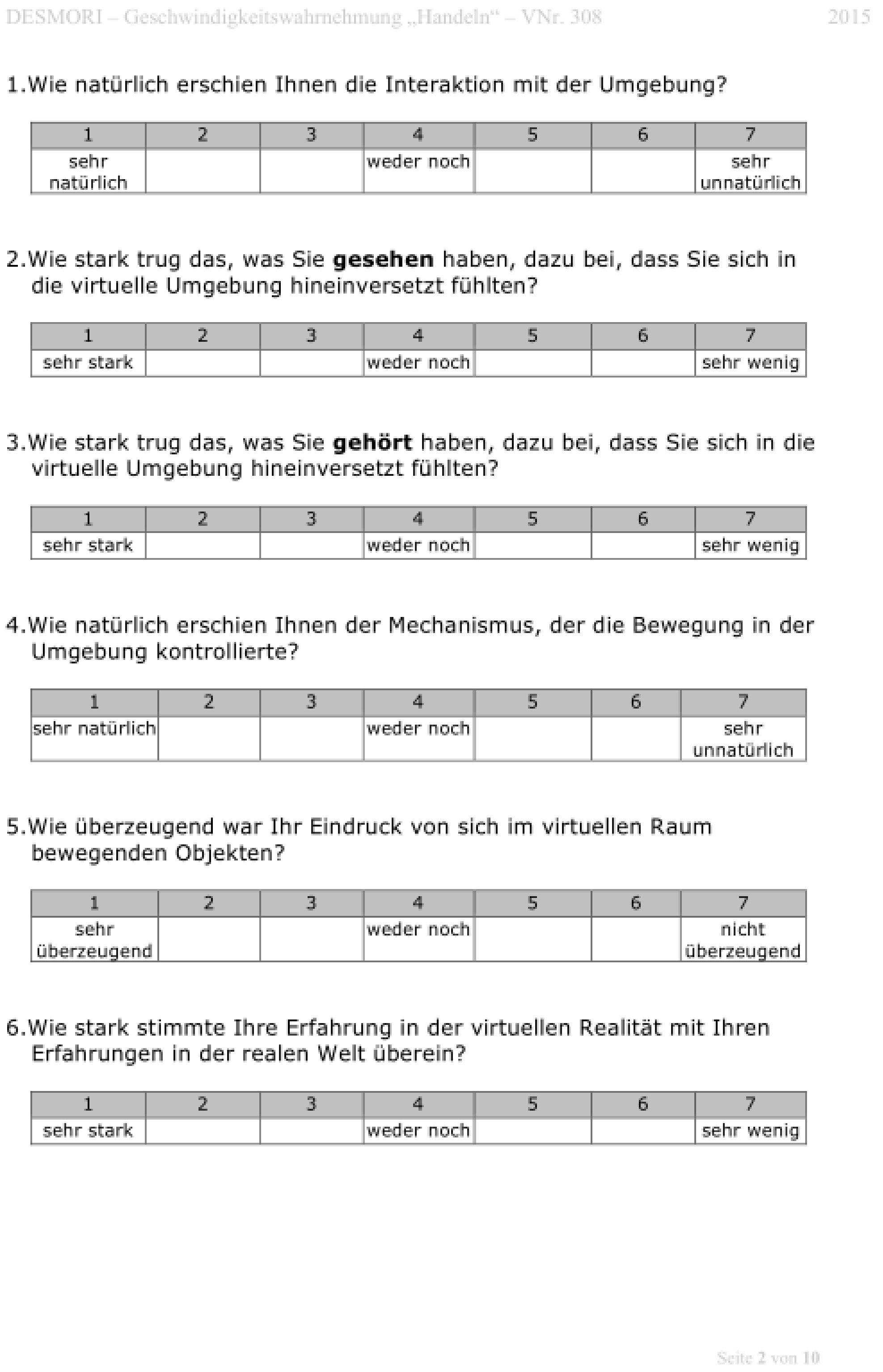
Wie natürlich erschien Ihnen die Interaktion mit der Umgebung?

1X	2	3	4	5	6	7
sehr natürlich			weder noch			sehr unnatürlich

Wenn Sie das Gefühl hatten, dass Sie sich in der virtuellen Umgebung eher unnatürlich bewegen und verhalten konnten, dann kreuzen Sie bitte die 5 an.

Wie natürlich erschien Ihnen die Interaktion mit der Umgebung?

1	2	3	4	5 X	6	7
sehr natürlich			weder noch			sehr unnatürlich



DESMORI – Geschwindigkeitswahrnehmung „Handeln“ – VNr. 308 2015

1.Wie natürlich erschien Ihnen die Interaktion mit der Umgebung?

1	2	3	4	5	6	7
sehr natürlich			weder noch			sehr unnatürlich

2.Wie stark trug das, was Sie **gesehen** haben, dazu bei, dass Sie sich in die virtuelle Umgebung hineinversetzt fühlten?

1	2	3	4	5	6	7
sehr stark			weder noch			sehr wenig

3.Wie stark trug das, was Sie **gehört** haben, dazu bei, dass Sie sich in die virtuelle Umgebung hineinversetzt fühlten?

1	2	3	4	5	6	7
sehr stark			weder noch			sehr wenig

4.Wie natürlich erschien Ihnen der Mechanismus, der die Bewegung in der Umgebung kontrollierte?

1	2	3	4	5	6	7
sehr natürlich			weder noch			sehr unnatürlich

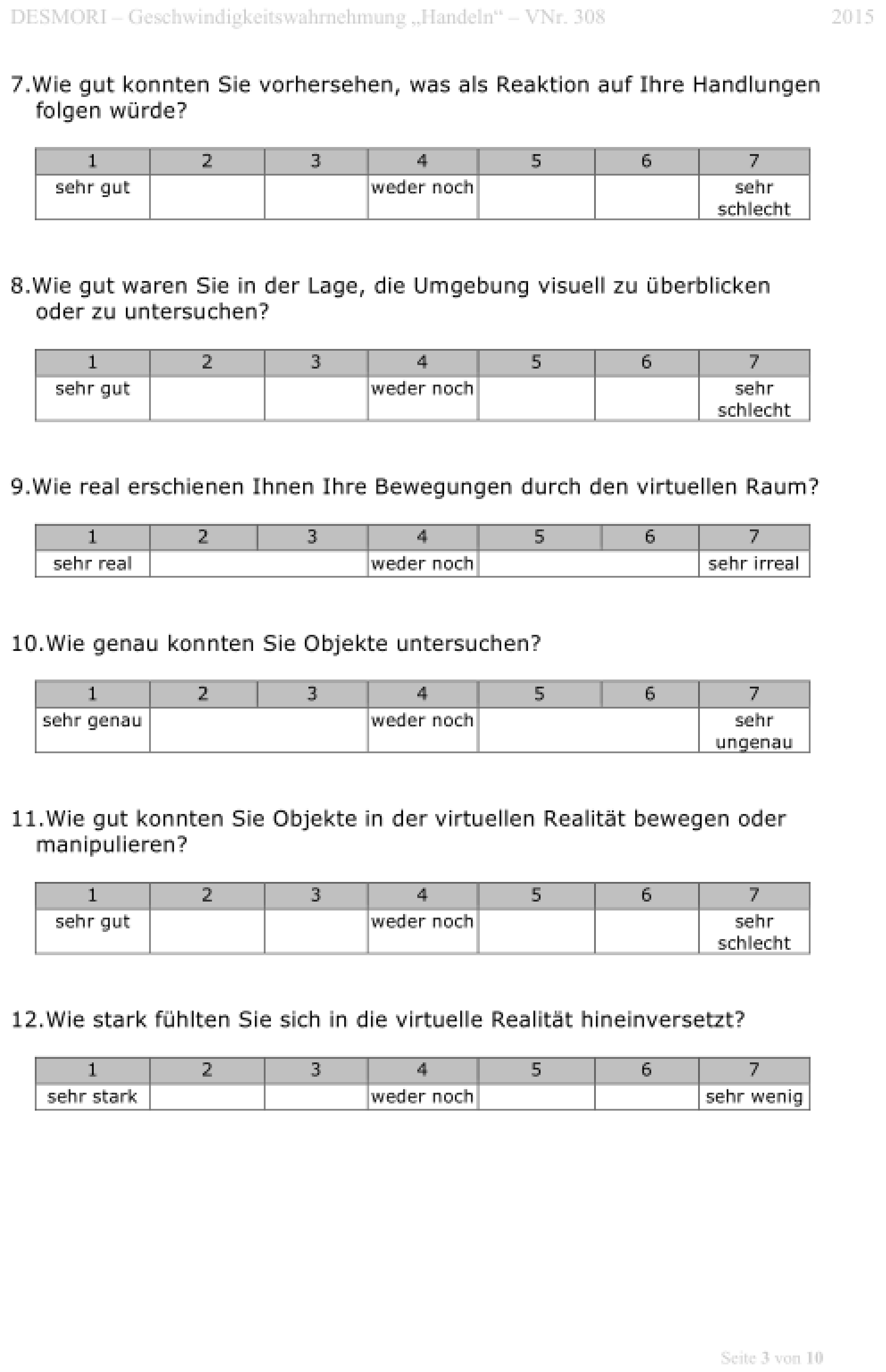
5.Wie überzeugend war Ihr Eindruck von sich im virtuellen Raum bewegenden Objekten?

1	2	3	4	5	6	7
sehr überzeugend			weder noch			nicht überzeugend

6.Wie stark stimmte Ihre Erfahrung in der virtuellen Realität mit Ihren Erfahrungen in der realen Welt überein?

1	2	3	4	5	6	7
sehr stark			weder noch			sehr wenig

Seite 2 von 10



DESMORI – Geschwindigkeitswahrnehmung „Handeln“ – VNr. 308 2015

7.Wie gut konnten Sie vorhersehen, was als Reaktion auf Ihre Handlungen folgen würde?

1	2	3	4	5	6	7
sehr gut			weder noch			sehr schlecht

8.Wie gut waren Sie in der Lage, die Umgebung visuell zu überblicken oder zu untersuchen?

1	2	3	4	5	6	7
sehr gut			weder noch			sehr schlecht

9.Wie real erschienen Ihnen Ihre Bewegungen durch den virtuellen Raum?

1	2	3	4	5	6	7
sehr real			weder noch			sehr irreal

10.Wie genau konnten Sie Objekte untersuchen?

1	2	3	4	5	6	7
sehr genau			weder noch			sehr ungenau

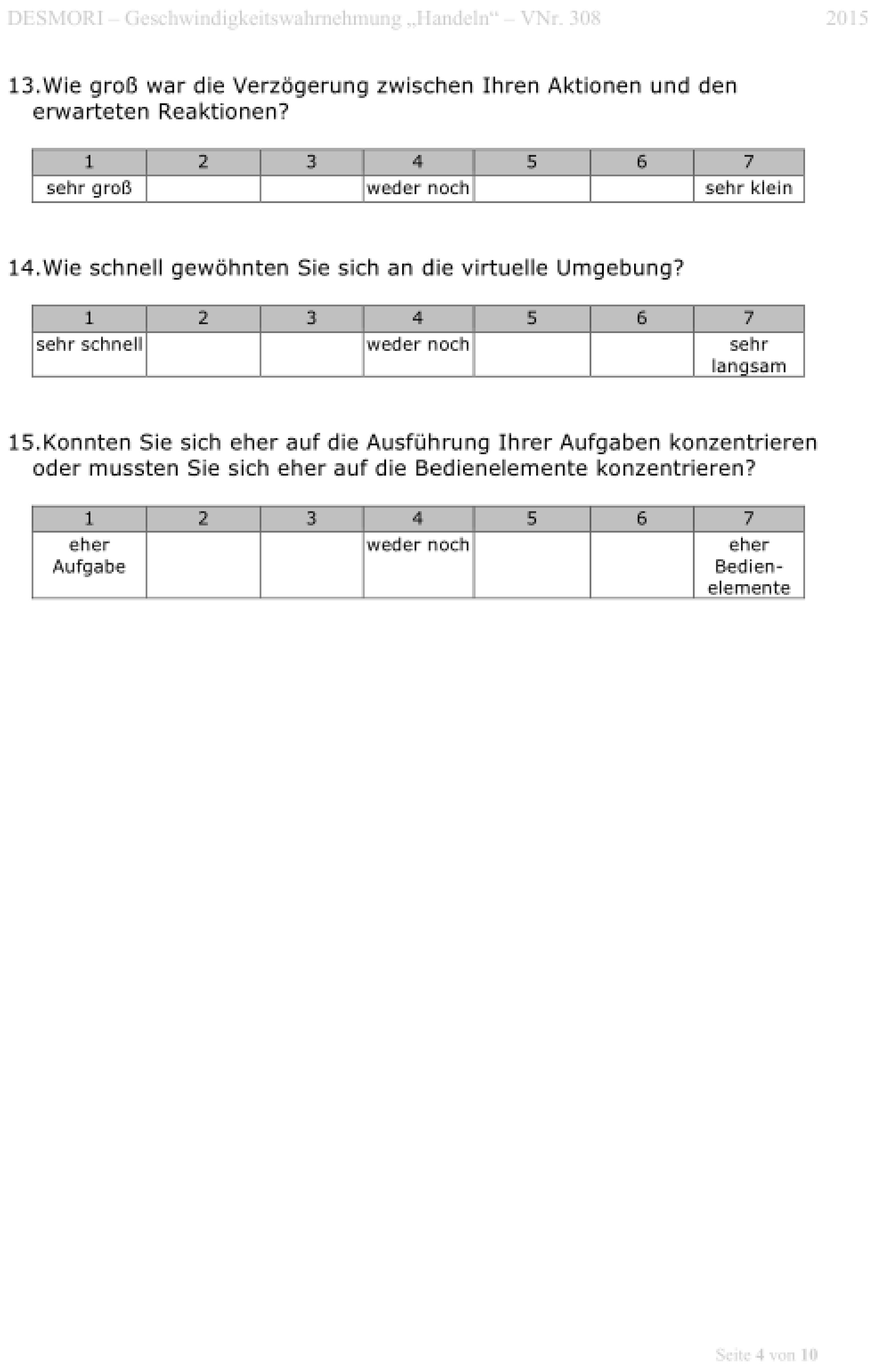
11.Wie gut konnten Sie Objekte in der virtuellen Realität bewegen oder manipulieren?

1	2	3	4	5	6	7
sehr gut			weder noch			sehr schlecht

12.Wie stark fühlten Sie sich in die virtuelle Realität hineinversetzt?

1	2	3	4	5	6	7
sehr stark			weder noch			sehr wenig

Seite 3 von 10



13. Wie groß war die Verzögerung zwischen Ihren Aktionen und den erwarteten Reaktionen?

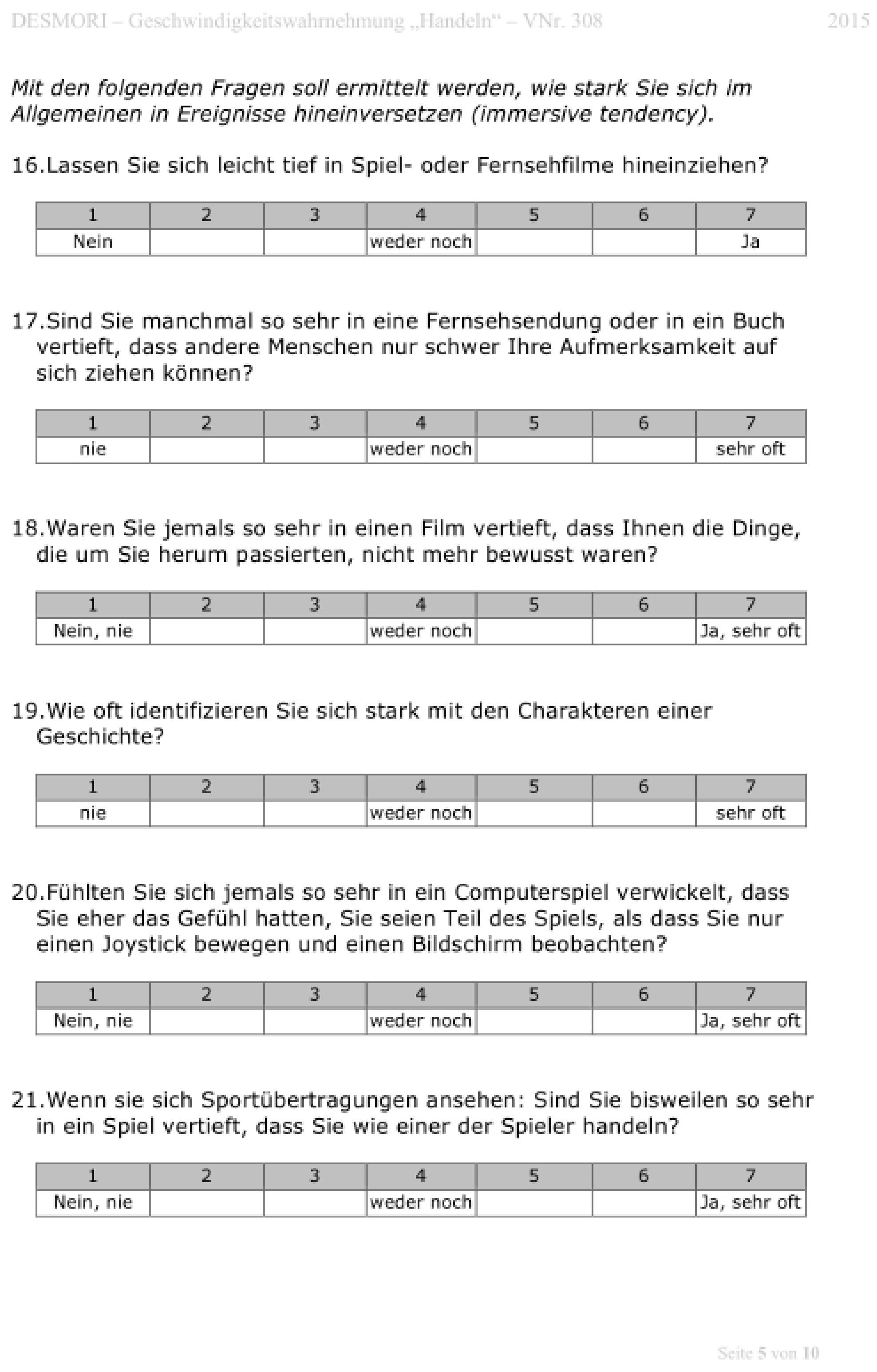
1	2	3	4	5	6	7
sehr groß			weder noch			sehr klein

14. Wie schnell gewöhnten Sie sich an die virtuelle Umgebung?

1	2	3	4	5	6	7
sehr schnell			weder noch			sehr langsam

15. Konnten Sie sich eher auf die Ausführung Ihrer Aufgaben konzentrieren oder mussten Sie sich eher auf die Bedienelemente konzentrieren?

1	2	3	4	5	6	7
eher Aufgabe			weder noch			eher Bedien-elemente



Mit den folgenden Fragen soll ermittelt werden, wie stark Sie sich im Allgemeinen in Ereignisse hineinversetzen (immersive tendency).

16. Lassen Sie sich leicht tief in Spiel- oder Fernsehfilme hineinziehen?

1	2	3	4	5	6	7
Nein			weder noch			Ja

17. Sind Sie manchmal so sehr in eine Fernsehsendung oder in ein Buch vertieft, dass andere Menschen nur schwer Ihre Aufmerksamkeit auf sich ziehen können?

1	2	3	4	5	6	7
nie			weder noch			sehr oft

18. Waren Sie jemals so sehr in einen Film vertieft, dass Ihnen die Dinge, die um Sie herum passierten, nicht mehr bewusst waren?

1	2	3	4	5	6	7
Nein, nie			weder noch			Ja, sehr oft

19. Wie oft identifizieren Sie sich stark mit den Charakteren einer Geschichte?

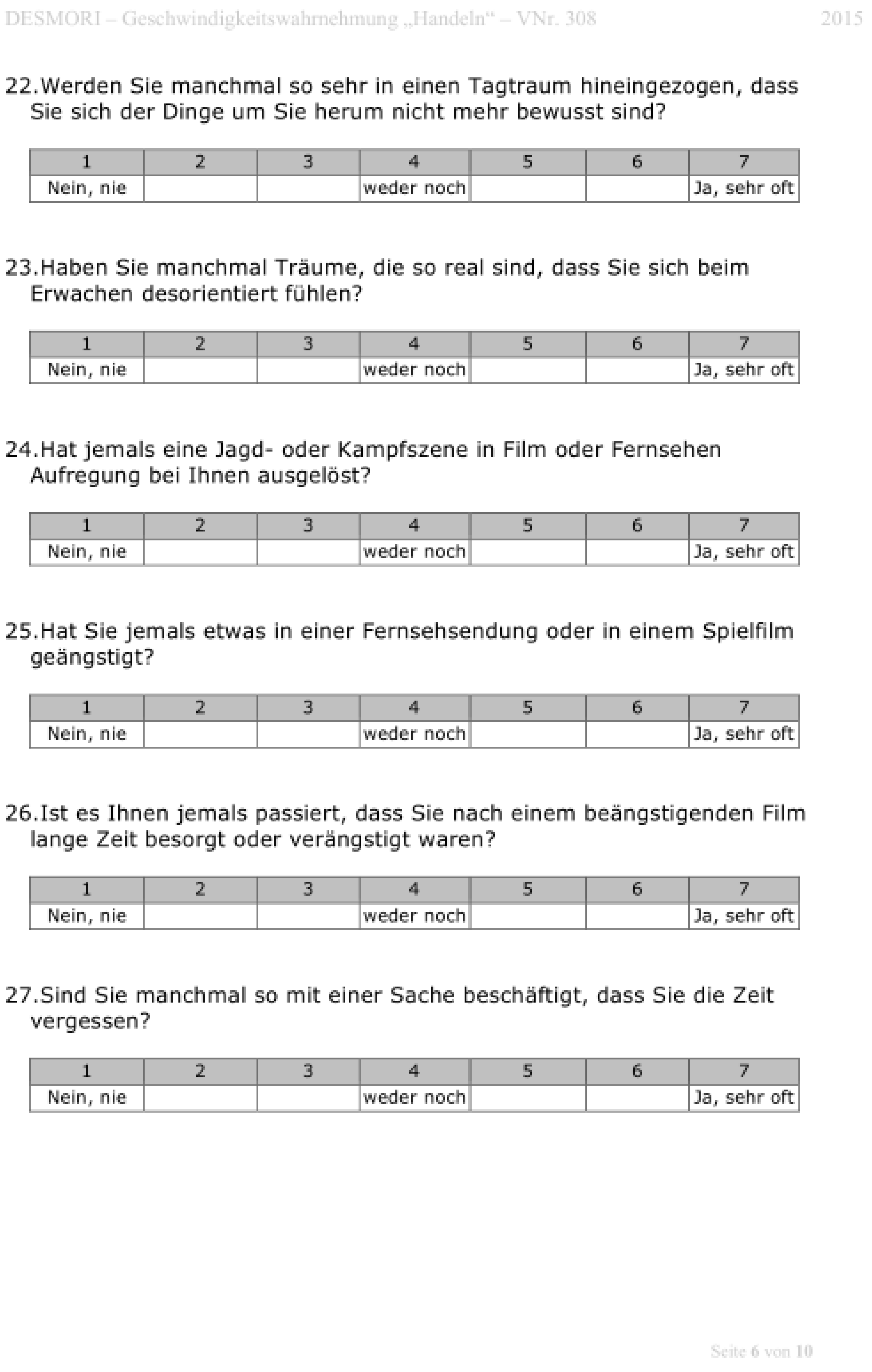
1	2	3	4	5	6	7
nie			weder noch			sehr oft

20. Fühlten Sie sich jemals so sehr in ein Computerspiel verwickelt, dass Sie eher das Gefühl hatten, Sie seien Teil des Spiels, als dass Sie nur einen Joystick bewegen und einen Bildschirm beobachten?

1	2	3	4	5	6	7
Nein, nie			weder noch			Ja, sehr oft

21. Wenn sie sich Sportübertragungen ansehen: Sind Sie bisweilen so sehr in ein Spiel vertieft, dass Sie wie einer der Spieler handeln?

1	2	3	4	5	6	7
Nein, nie			weder noch			Ja, sehr oft



22. Werden Sie manchmal so sehr in einen Tagtraum hineingezogen, dass Sie sich der Dinge um Sie herum nicht mehr bewusst sind?

1	2	3	4	5	6	7
Nein, nie			weder noch			Ja, sehr oft

23. Haben Sie manchmal Träume, die so real sind, dass Sie sich beim Erwachen desorientiert fühlen?

1	2	3	4	5	6	7
Nein, nie			weder noch			Ja, sehr oft

24. Hat jemals eine Jagd- oder Kampfszene in Film oder Fernsehen Aufregung bei Ihnen ausgelöst?

1	2	3	4	5	6	7
Nein, nie			weder noch			Ja, sehr oft

25. Hat Sie jemals etwas in einer Fernsehsendung oder in einem Spielfilm geängstigt?

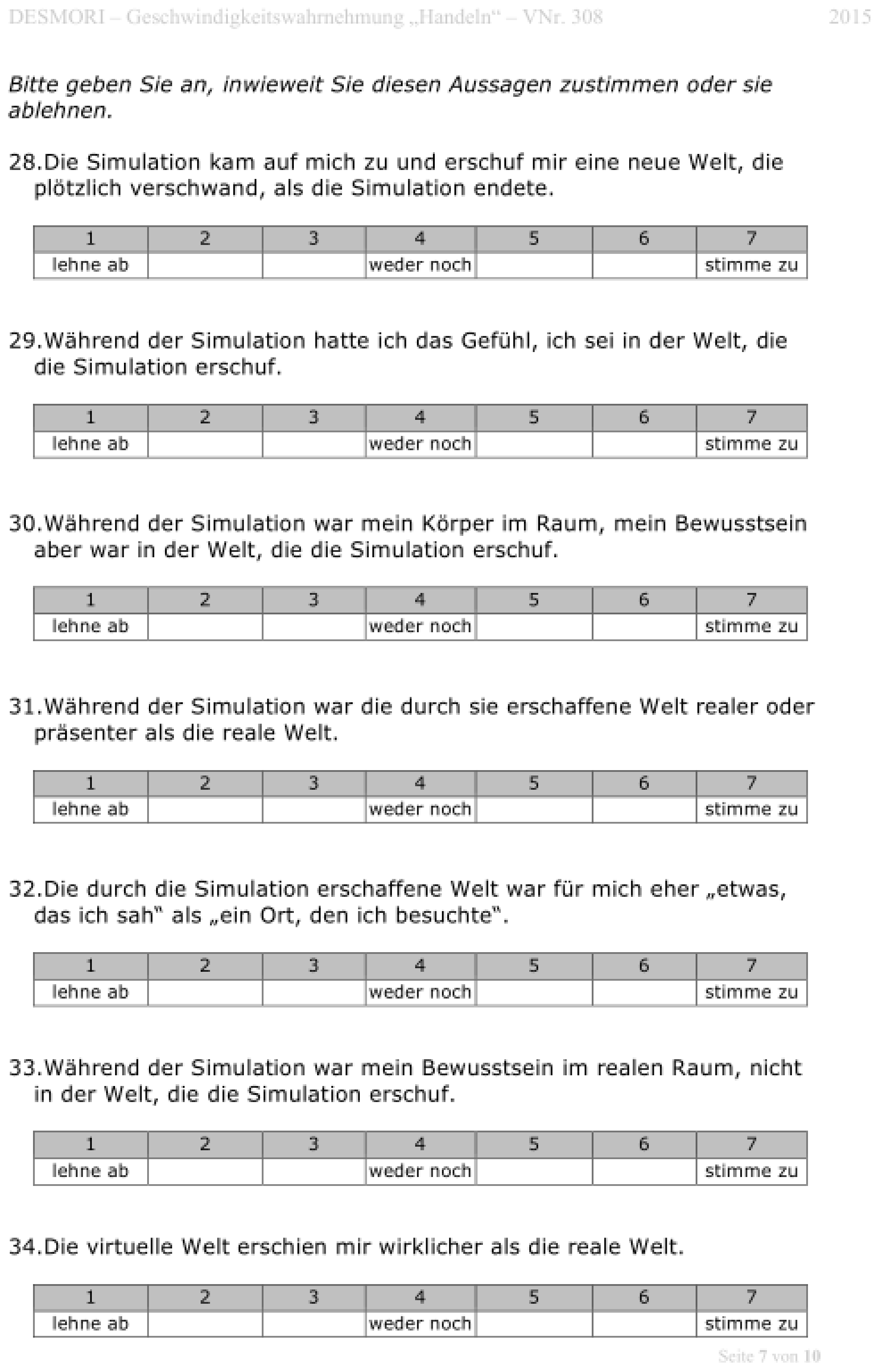
1	2	3	4	5	6	7
Nein, nie			weder noch			Ja, sehr oft

26. Ist es Ihnen jemals passiert, dass Sie nach einem beängstigenden Film lange Zeit besorgt oder verängstigt waren?

1	2	3	4	5	6	7
Nein, nie			weder noch			Ja, sehr oft

27. Sind Sie manchmal so mit einer Sache beschäftigt, dass Sie die Zeit vergessen?

1	2	3	4	5	6	7
Nein, nie			weder noch			Ja, sehr oft



Bitte geben Sie an, inwieweit Sie diesen Aussagen zustimmen oder sie ablehnen.

28. Die Simulation kam auf mich zu und erschuf mir eine neue Welt, die plötzlich verschwand, als die Simulation endete.

1	2	3	4	5	6	7
lehne ab			weder noch			stimme zu

29. Während der Simulation hatte ich das Gefühl, ich sei in der Welt, die die Simulation erschuf.

1	2	3	4	5	6	7
lehne ab			weder noch			stimme zu

30. Während der Simulation war mein Körper im Raum, mein Bewusstsein aber war in der Welt, die die Simulation erschuf.

1	2	3	4	5	6	7
lehne ab			weder noch			stimme zu

31. Während der Simulation war die durch sie erschaffene Welt realer oder präsenter als die reale Welt.

1	2	3	4	5	6	7
lehne ab			weder noch			stimme zu

32. Die durch die Simulation erschaffene Welt war für mich eher „etwas, das ich sah“ als „ein Ort, den ich besuchte“.

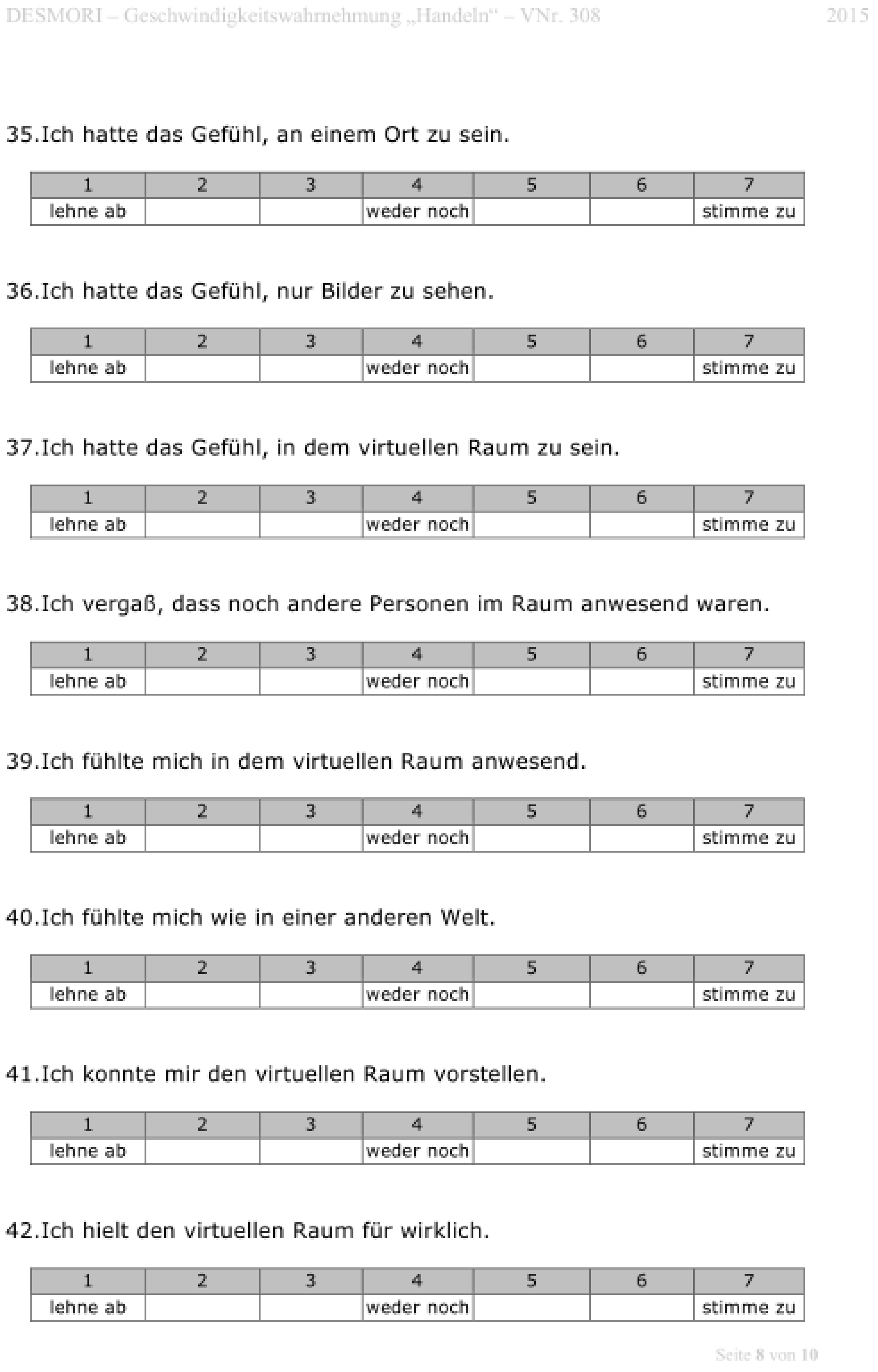
1	2	3	4	5	6	7
lehne ab			weder noch			stimme zu

33. Während der Simulation war mein Bewusstsein im realen Raum, nicht in der Welt, die die Simulation erschuf.

1	2	3	4	5	6	7
lehne ab			weder noch			stimme zu

34. Die virtuelle Welt erschien mir wirklicher als die reale Welt.

1	2	3	4	5	6	7
lehne ab			weder noch			stimme zu



35. Ich hatte das Gefühl, an einem Ort zu sein.

1	2	3	4	5	6	7
lehne ab			weder noch			stimme zu

36. Ich hatte das Gefühl, nur Bilder zu sehen.

1	2	3	4	5	6	7
lehne ab			weder noch			stimme zu

37. Ich hatte das Gefühl, in dem virtuellen Raum zu sein.

1	2	3	4	5	6	7
lehne ab			weder noch			stimme zu

38. Ich vergaß, dass noch andere Personen im Raum anwesend waren.

1	2	3	4	5	6	7
lehne ab			weder noch			stimme zu

39. Ich fühlte mich in dem virtuellen Raum anwesend.

1	2	3	4	5	6	7
lehne ab			weder noch			stimme zu

40. Ich fühlte mich wie in einer anderen Welt.

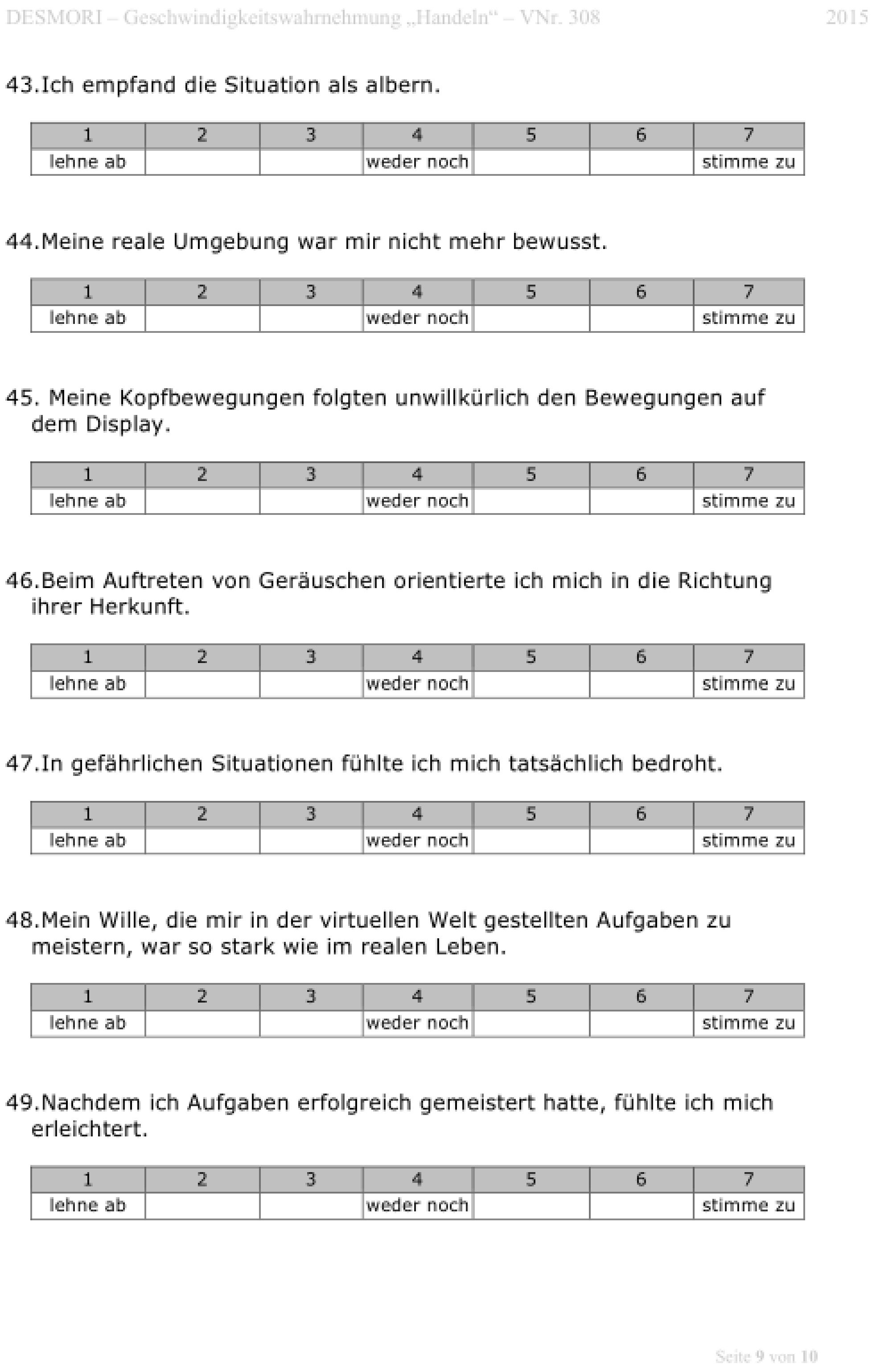
1	2	3	4	5	6	7
lehne ab			weder noch			stimme zu

41. Ich konnte mir den virtuellen Raum vorstellen.

1	2	3	4	5	6	7
lehne ab			weder noch			stimme zu

42. Ich hielt den virtuellen Raum für wirklich.

1	2	3	4	5	6	7
lehne ab			weder noch			stimme zu



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43.Ich empfand die Situation als albern.

1	2	3	4	5	6	7
lehne ab			weder noch			stimme zu

44.Meine reale Umgebung war mir nicht mehr bewusst.

1	2	3	4	5	6	7
lehne ab			weder noch			stimme zu

45. Meine Kopfbewegungen folgten unwillkürlich den Bewegungen auf dem Display.

1	2	3	4	5	6	7
lehne ab			weder noch			stimme zu

46.Beim Auftreten von Geräuschen orientierte ich mich in die Richtung ihrer Herkunft.

1	2	3	4	5	6	7
lehne ab			weder noch			stimme zu

47.In gefährlichen Situationen fühlte ich mich tatsächlich bedroht.

1	2	3	4	5	6	7
lehne ab			weder noch			stimme zu

48.Mein Wille, die mir in der virtuellen Welt gestellten Aufgaben zu meistern, war so stark wie im realen Leben.

1	2	3	4	5	6	7
lehne ab			weder noch			stimme zu

49.Nachdem ich Aufgaben erfolgreich gemeistert hatte, fühlte ich mich erleichtert.

1	2	3	4	5	6	7
lehne ab			weder noch			stimme zu

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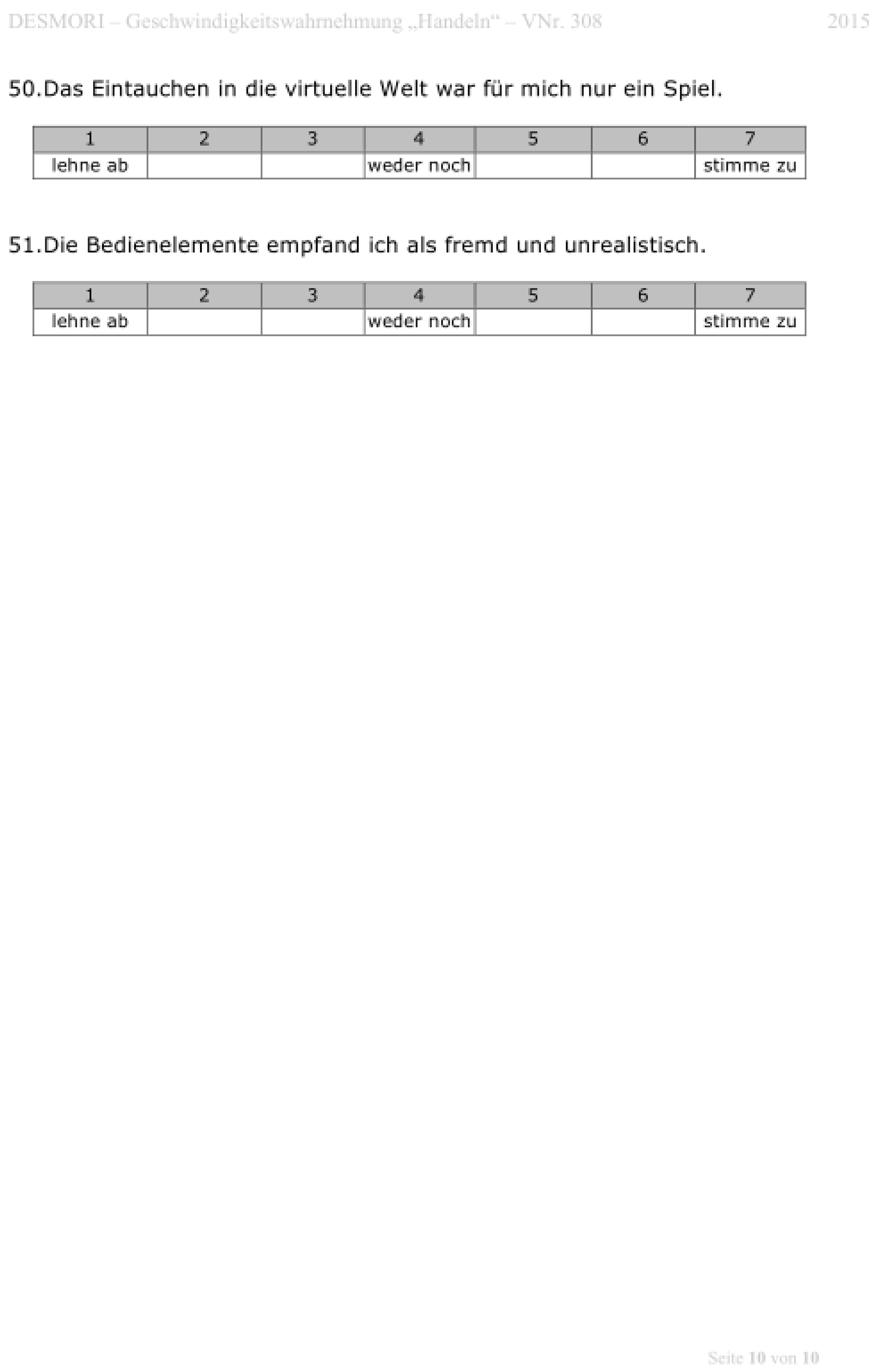

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50. Das Eintauchen in die virtuelle Welt war für mich nur ein Spiel.

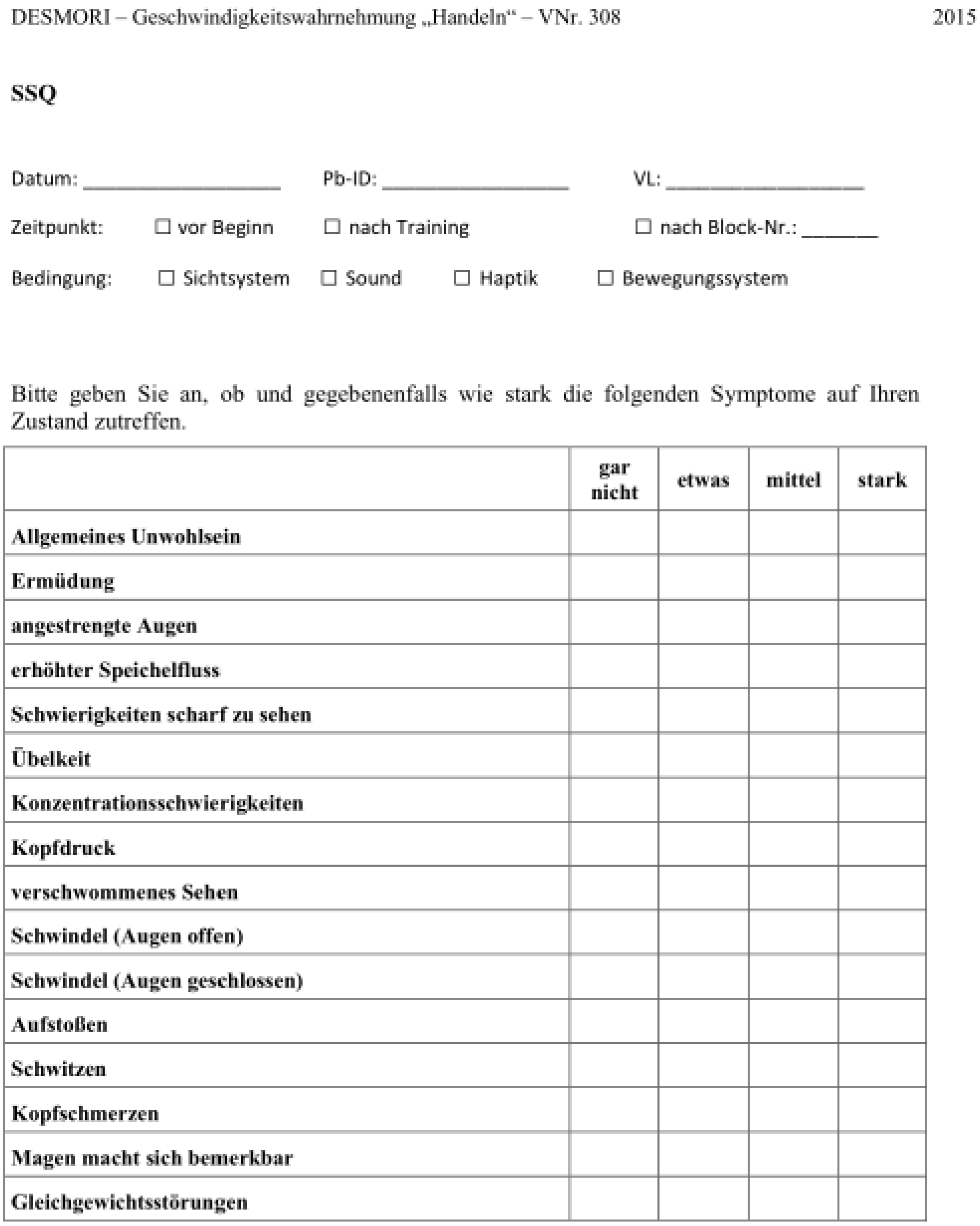
1	2	3	4	5	6	7
lehne ab			weder noch			stimme zu

51. Die Bedienelemente empfand ich als fremd und unrealistisch.

1	2	3	4	5	6	7
lehne ab			weder noch			stimme zu

Seite 10 von 10

13.2 Simulator Sickness Questionnaire



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SSQ

Datum: ____________________ Pb-ID: ____________________ VL: ____________________

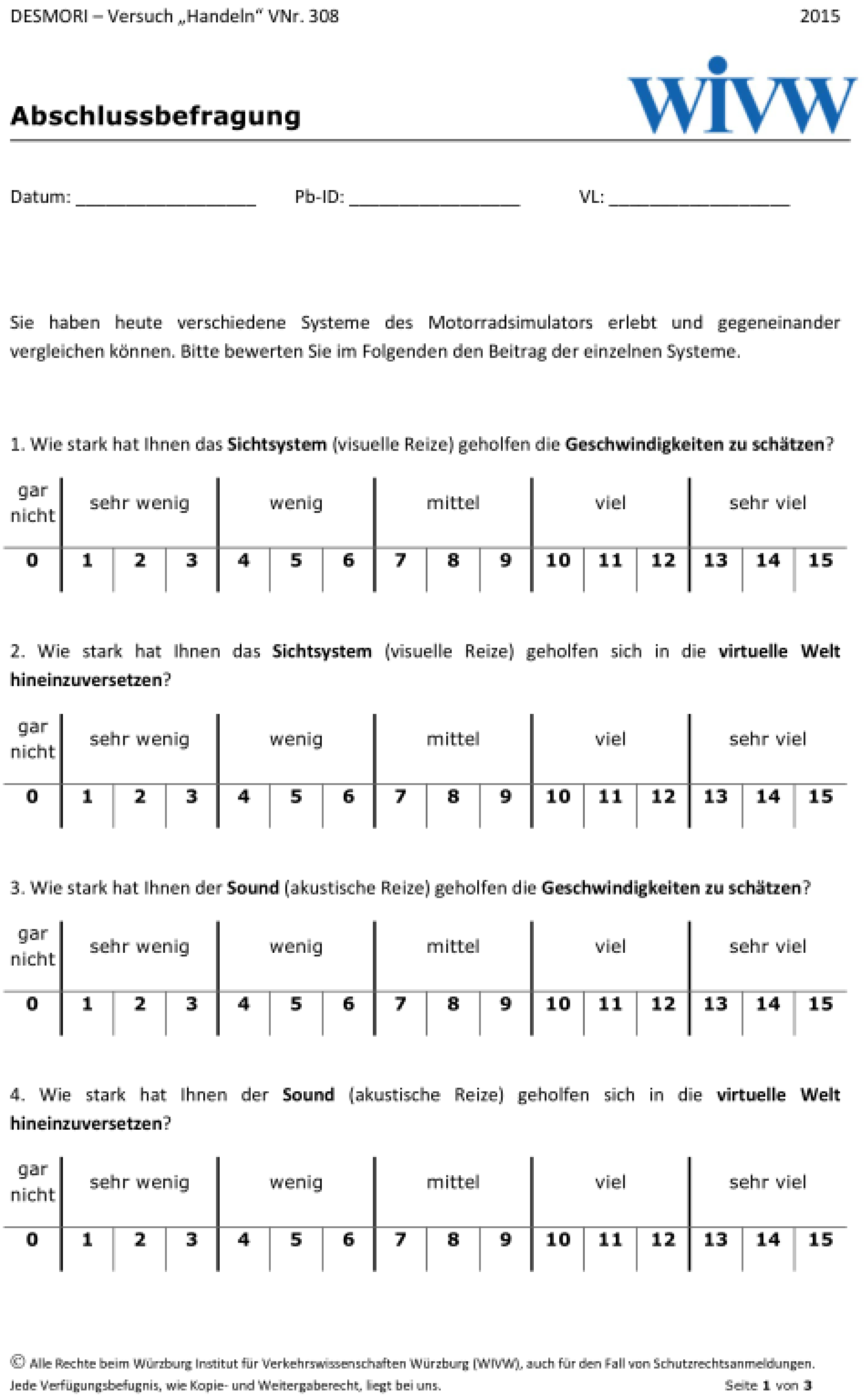
Zeitpunkt: ☐ vor Beginn ☐ nach Training ☐ nach Block-Nr.: _______

Bedingung: ☐ Sichtsystem ☐ Sound ☐ Haptik ☐ Bewegungssystem

Bitte geben Sie an, ob und gegebenenfalls wie stark die folgenden Symptome auf Ihren Zustand zutreffen.

	gar nicht	**etwas**	**mittel**	**stark**
Allgemeines Unwohlsein				
Ermüdung				
angestrengte Augen				
erhöhter Speichelfluss				
Schwierigkeiten scharf zu sehen				
Übelkeit				
Konzentrationsschwierigkeiten				
Kopfdruck				
verschwommenes Sehen				
Schwindel (Augen offen)				
Schwindel (Augen geschlossen)				
Aufstoßen				
Schwitzen				
Kopfschmerzen				
Magen macht sich bemerkbar				
Gleichgewichtsstörungen				

13.3 Final inquiry



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Abschlussbefragung

Datum: ________________ Pb-ID: ________________ VL: ________________

Sie haben heute verschiedene Systeme des Motorradsimulators erlebt und gegeneinander vergleichen können. Bitte bewerten Sie im Folgenden den Beitrag der einzelnen Systeme.

1. Wie stark hat Ihnen das **Sichtsystem** (visuelle Reize) geholfen die **Geschwindigkeiten zu schätzen**?

gar nicht	sehr wenig			wenig			mittel			viel			sehr viel		
0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**

2. Wie stark hat Ihnen das **Sichtsystem** (visuelle Reize) geholfen sich in die **virtuelle Welt hineinzuversetzen**?

gar nicht	sehr wenig			wenig			mittel			viel			sehr viel		
0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**

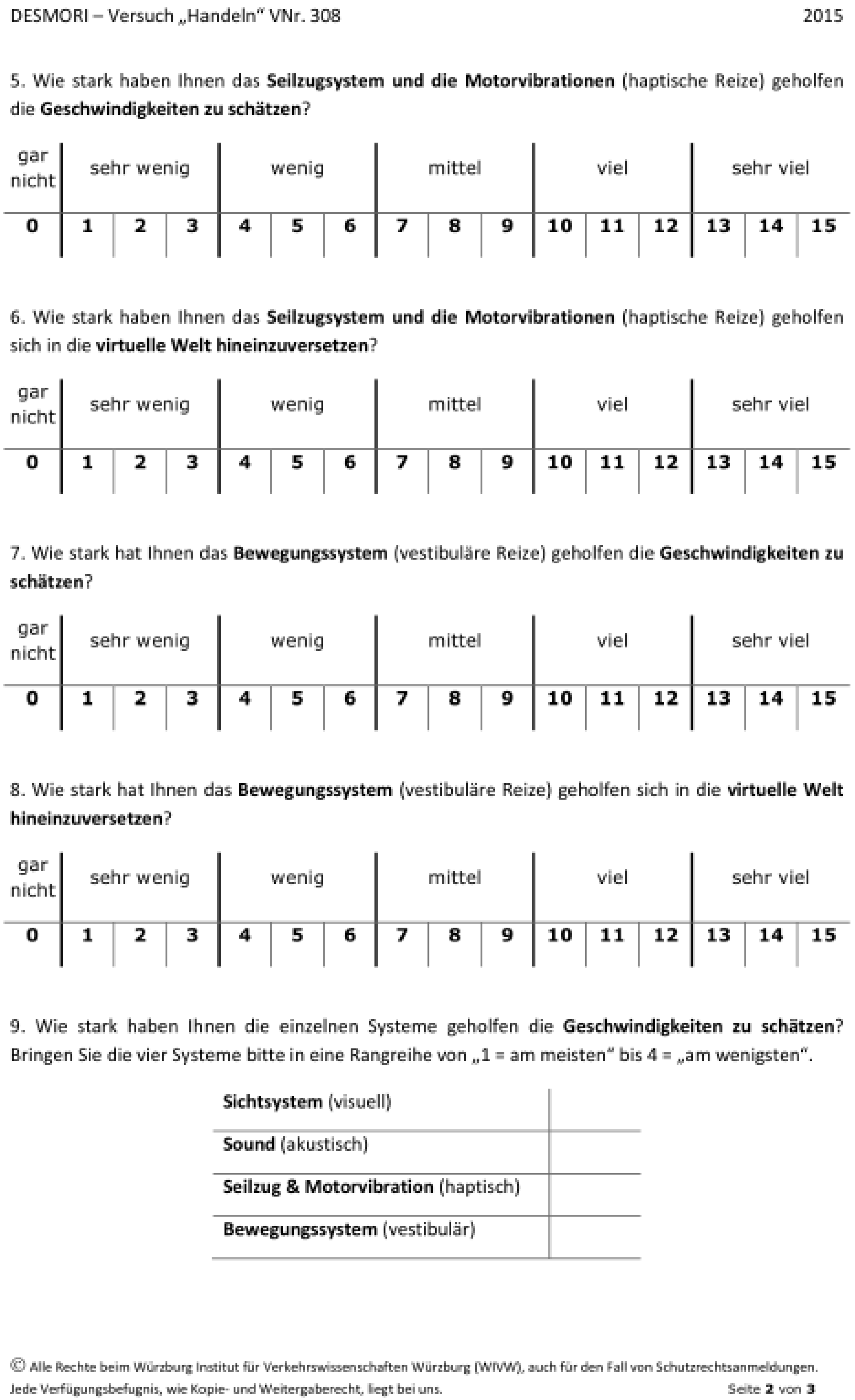
3. Wie stark hat Ihnen der **Sound** (akustische Reize) geholfen die **Geschwindigkeiten zu schätzen**?

gar nicht	sehr wenig			wenig			mittel			viel			sehr viel		
0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**

4. Wie stark hat Ihnen der **Sound** (akustische Reize) geholfen sich in die **virtuelle Welt hineinzuversetzen**?

gar nicht	sehr wenig			wenig			mittel			viel			sehr viel		
0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**

Seite **1** von **3**



5. Wie stark haben Ihnen das **Seilzugsystem und die Motorvibrationen** (haptische Reize) geholfen die **Geschwindigkeiten zu schätzen**?

gar nicht	sehr wenig			wenig			mittel			viel			sehr viel		
0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**

6. Wie stark haben Ihnen das **Seilzugsystem und die Motorvibrationen** (haptische Reize) geholfen sich in die **virtuelle Welt hineinzuversetzen**?

gar nicht	sehr wenig			wenig			mittel			viel			sehr viel		
0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**

7. Wie stark hat Ihnen das **Bewegungssystem** (vestibuläre Reize) geholfen die **Geschwindigkeiten zu schätzen**?

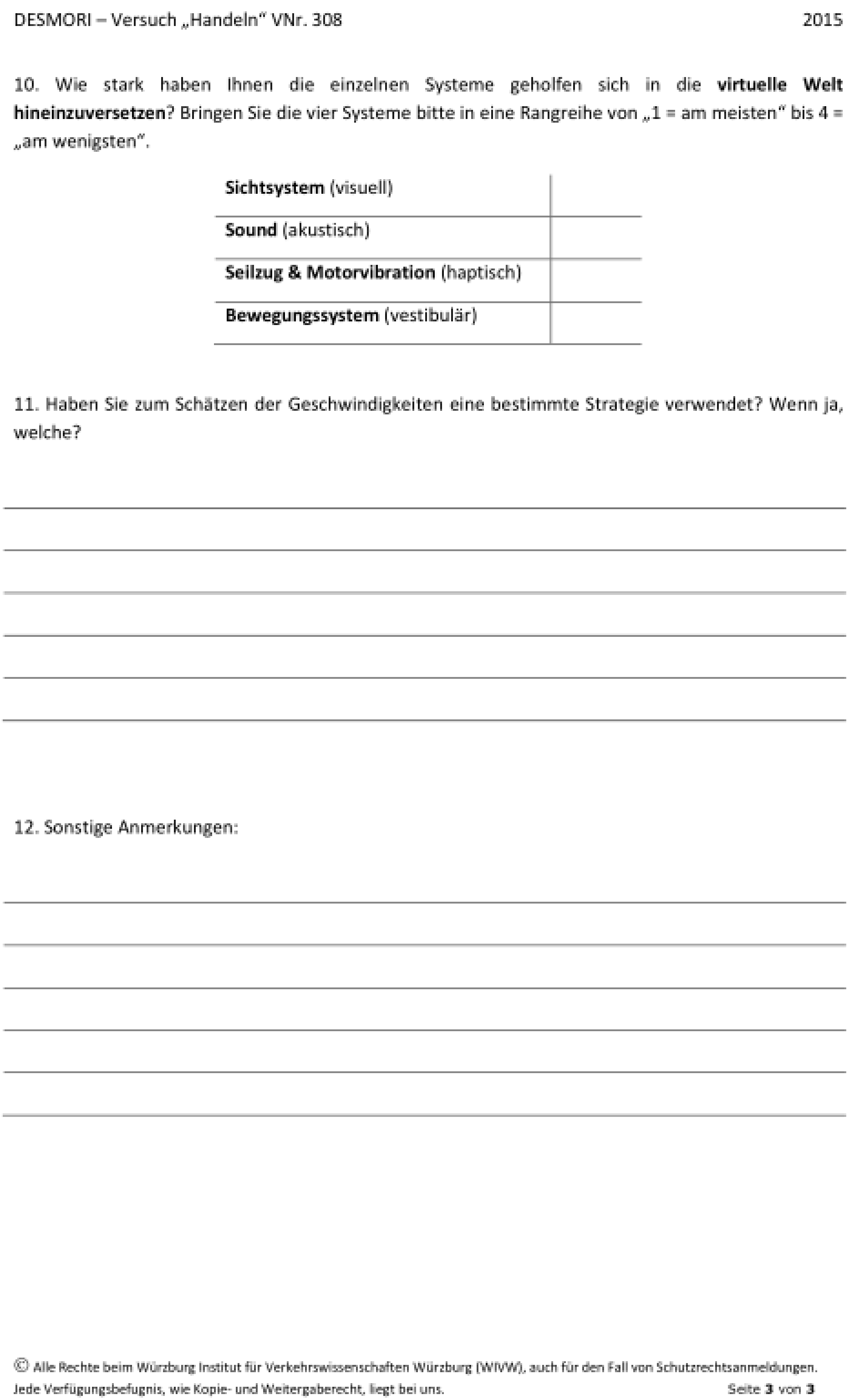
gar nicht	sehr wenig			wenig			mittel			viel			sehr viel		
0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**

8. Wie stark hat Ihnen das **Bewegungssystem** (vestibuläre Reize) geholfen sich in die **virtuelle Welt hineinzuversetzen**?

gar nicht	sehr wenig			wenig			mittel			viel			sehr viel		
0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**

9. Wie stark haben Ihnen die einzelnen Systeme geholfen die **Geschwindigkeiten zu schätzen**? Bringen Sie die vier Systeme bitte in eine Rangreihe von „1 = am meisten“ bis 4 = „am wenigsten“.

Sichtsystem (visuell)	
Sound (akustisch)	
Seilzug & Motorvibration (haptisch)	
Bewegungssystem (vestibulär)	



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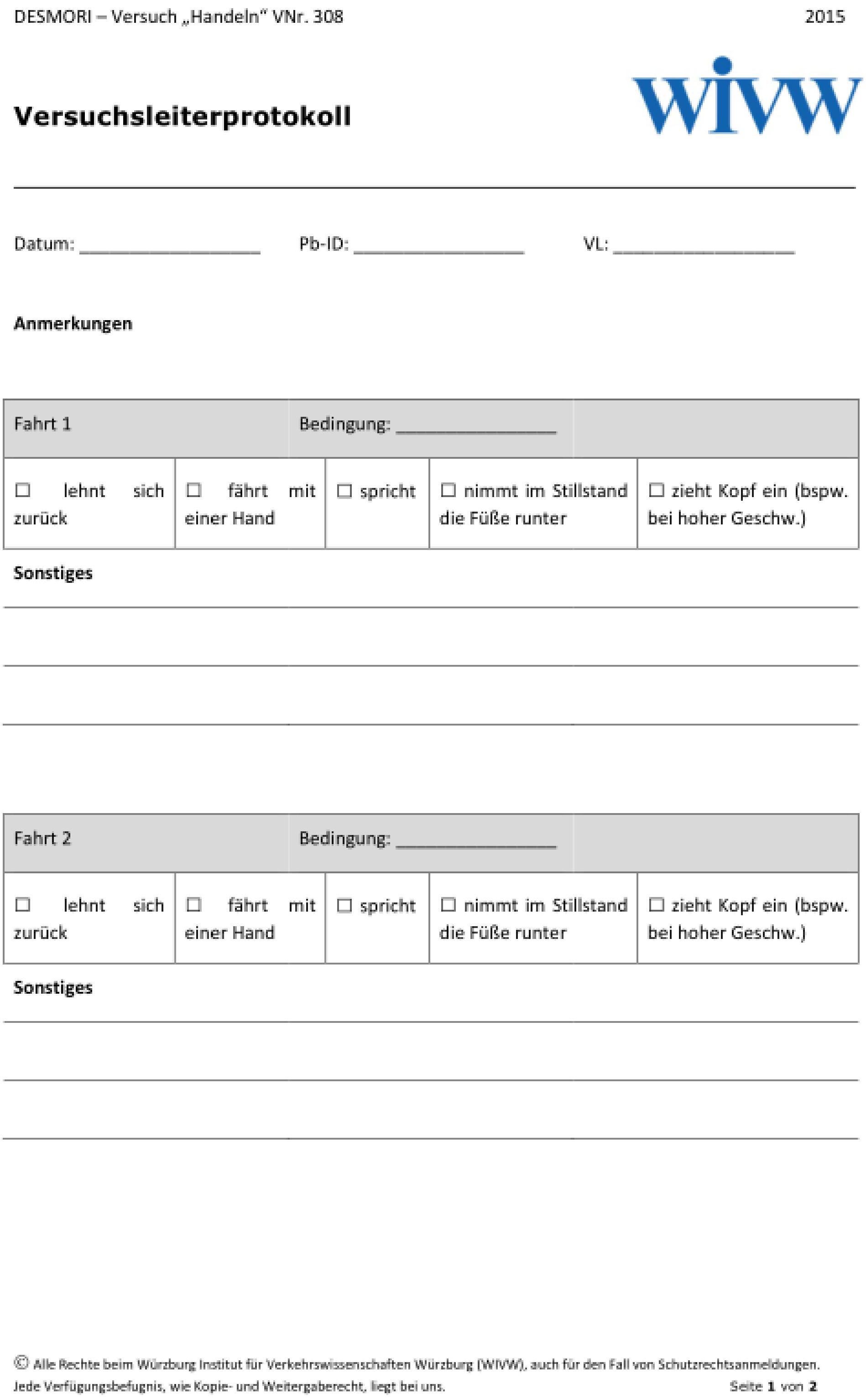
10. Wie stark haben Ihnen die einzelnen Systeme geholfen sich in die **virtuelle Welt hineinzuversetzen**? Bringen Sie die vier Systeme bitte in eine Rangreihe von „1 = am meisten“ bis 4 = „am wenigsten“.

Sichtsystem (visuell)	
Sound (akustisch)	
Seilzug & Motorvibration (haptisch)	
Bewegungssystem (vestibulär)	

11. Haben Sie zum Schätzen der Geschwindigkeiten eine bestimmte Strategie verwendet? Wenn ja, welche?

12. Sonstige Anmerkungen:

13.4 Investigator protocol



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Versuchsleiterprotokoll

Datum: ____________________ Pb-ID: ____________________ VL: ____________________

Anmerkungen

Fahrt 1		Bedingung: ________________		
☐ lehnt sich zurück	☐ fährt mit einer Hand	☐ spricht	☐ nimmt im Stillstand die Füße runter	☐ zieht Kopf ein (bspw. bei hoher Geschw.)

Sonstiges

Fahrt 2		Bedingung: ________________		
☐ lehnt sich zurück	☐ fährt mit einer Hand	☐ spricht	☐ nimmt im Stillstand die Füße runter	☐ zieht Kopf ein (bspw. bei hoher Geschw.)

Sonstiges

Seite 1 von 2

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Fahrt 3	Bedingung: ________________			
☐ lehnt sich zurück	☐ fährt mit einer Hand	☐ spricht	☐ nimmt im Stillstand die Füße runter	☐ zieht Kopf ein (bspw. bei hoher Geschw.)

Sonstiges

____

____

____

Fahrt 4	Bedingung: ________________			
☐ lehnt sich zurück	☐ fährt mit einer Hand	☐ spricht	☐ nimmt im Stillstand die Füße runter	☐ zieht Kopf ein (bspw. bei hoher Geschw.)

Sonstiges

____

____

____

Allgemeines

____

____

____

____