Deniaud *et al. Journal of Interaction Science* (2015) 3:1
DOI 10.1186/s40166-015-0005-z

Journal of Interaction Science
a SpringerOpen Journal

RESEARCH Open Access

The concept of "presence" as a measure of ecological validity in driving simulators

Christophe Deniaud[1,2*], Vincent Honnet[2], Benoit Jeanne[2] and Daniel Mestre[1]

Abstract

This pilot study aims to find a way to measure 'presence' as a proxy for ecological validity in driving simulators. The underlying assumption is that a person experiencing a strong sense of presence in the virtual environment will react as if it were real. We measure 'presence' through the 'attention' given to the driving task. We hypothesize that the greater the attention given to the primary driving task, the more the subject will experience spatial presence. 'Attention' was varied by adding a second task and oncoming traffic; we then analyzed behavioral measures of driving performance and subjective 'presence'. The main result is a lack of congruence between subjective and behavioral measures. Although behavioral differences were observed between the various experimental conditions, there was no significant difference in subjective measures of presence. One explanation for this result could be that in all experimental conditions the driving activity did not require high-level cognitive processes, and was instead based on bottom-up attentional processes. Many of the processes involved in driving seem to be automatic, and this study argues for the concomitant use of subjective measures (such as questionnaires) and objective measures to assess presence in driving simulators. Furthermore, the development of a sensitive measure of presence seems to require more challenging scenarios in terms of controlled attention, cognitive involvement and more specifically, the emotions induced by the media. Participants are clearly aware that they are not exposed to any physical danger when using the simulator and the problem of their motivation must be taken into consideration. Another major problem is to establish the extent to which they are absorbed in the simulated driving task. A significant challenge for future research is the emotional validity of driving.

Keywords: *Driving simulator*; *Spatial presence*; *Attention*; *Ecological validity*; *Cognitive involvement*

Introduction

Driving simulation began in the 1960s, when it was used to train specific target audiences such as novice drivers, law enforcement officers and truck drivers [1]. Since then, there have been many advances in terms of computing, visual display and the rendering of vehicle dynamics [4]. Simulators were originally developed to reduce the cost of field studies, provide greater experimental control, and ensure safety in hazardous conditions [2]. By the second half of the twentieth century, they were being successfully applied to aeronautical, rail and maritime operations.

Although there are significant differences, driving simulation has followed progress in flight simulation. Like flying, driving is a dynamic task that involves a set of rapid control maneuvers and critical feedback in order to avoid obstacles and prevent crashes [19]. However, compared to airline pilots, driving involves higher amplitude and higher frequency cues. Motion feedback does not play a key role in most of the slow maneuvers performed by civilian pilots. In fact, there is no evidence that motion-based simulators are more efficient than fixed-base simulators for training commercial pilots [7]. This highlights the stark contrast between driving simulation and civil aviation flight simulation; compared to an airline pilot, the driver needs a higher degree of motion simulation. The higher complexity inherent in the driving task probably explains why flight simulators are widely used for pilot training, while driving simulators are not widely used for driver training [31].

Nowadays, driving simulators are usually designed for two purposes: research and training. The simulator can

---

* Correspondence: deniaud.ch@gmail.com
[1]The Institute of Movement Sciences, University Aix-Marseille II, 163 av. de Luminy, 13009 Marseille, France
[2]PSA Peugeot Citroën Route de Gisy, 78140 Vélizy-Villacoublay, France

constrain driver behavior in order to study distraction and workload, or can be used as a test bed for highway design [26]. The use of a modern, advanced, driving simulator for human factors research has many advantages, including the control of experimental variables, efficiency, expense, safety, and ease of data collection [37]. However, the literature highlights some disadvantages, including simulator sickness, the accurate replication of physical sensations, and most importantly, validity [9].

Towards ecological validity

Driving simulators vary in their degree of sophistication and cost but, despite significant progress it appears that they lack realism [3]. This is a problem because, if they are to be useful as human factors research tools, they must be valid [16] and it is essential to know the extent to which the data that is collected reflect the results that would be obtained in the real world. This multidimensional problem is called simulation validation [5] and it has been a concern for at least the past 25 years.

Blaauw (1982) [5] defined two levels of validity. The first is the physical correspondence between the simulator's features, layout, and dynamics and those of its real-world counterpart. Over the past four decades, simulators have been designed to deliver more and more perceptual cues to the driver in order to reproduce as accurately as possible the experience of driving an automobile. Thus, validity is often assessed in terms of the extent to which a physical variable (visual, audio, and motion feedback) corresponds to its operational equivalent in the real world. The second level is termed behavioral validity; this concerns the correspondence between the behavior of the operator in the simulator and in the real world. Although studies commonly assume that physical validity incorporates behavioral validity, the two are not consistently related [44]. According to Blaauw (1982) [5], the best way to test for behavioral validity is to compare driving in the simulator with driving a real car. Specifically, if the data from the two systems are similar then it is possible to claim 'absolute' validity. An alternative method is to compare performance differences between experimental conditions in the simulator and a real car. In this approach, if the differences that are found between the two systems are in the same direction and have a similar magnitude, then it is possible to claim 'relative' validity [27]. Although absolute validity is obviously the aim of researchers, it seems highly unlikely that there will be an exact correspondence between data from real-world conditions and the simulation. Furthermore, from a methodological point of view there is no 'bad' or 'good' simulator, because researchers are usually interested in the effect of independent variables (the difference between a control condition and other treatments), rather than making numerical measurements.

Godley et al. (2002) [16] argued that relative, but not absolute validity is necessary. Similarly, Törnros (1998) [53] observed that simulation validation should include a description of the research question and how simulators were used to investigate the question. Therefore, each simulator must be validated for a specific use, as each experiment has its own requirements that are related to different aspects of the driving task [13]. Simulation validation has followed developments in technical components such as computers and various display technologies. Over the past four decades, simulators have been designed to deliver more and more perceptual cues to the driver in order to reproduce as accurately as possible the experience of driving an automobile. Thus, simulator validity is often assessed in terms of the extent to which a physical variable corresponds to its operational equivalent in the real world (its physical validity) [29].

As previously discussed, simulation validity is multidimensional. It can be related not only to behavioral and physical dimensions [23], but also to the subjective experience and objective performance. Nevertheless, despite significant progress in validity, studies continue to be criticized for a lack of realism [17]. Specifically, the physical validity of the driving experience appears unable to overcome criticisms concerning the lack of psychological validity [16], defined as the extent to which the risks and rewards of participation in the experiment correspond to real-world risks and rewards [40]. The main problem is that experimental studies cannot provide a motivation that reproduces motivation in the real world. Generally, it appears that the assessment of the validity of the virtual environment involves a comparison with results obtained from studies conducted in real-life situations. However, this comparison is expensive (due to the need for instrumentation) and complex (due to the need to strictly control of all the events occurring in the real-life situation). This is probably why most questions about the validity of simulators are unanswered [42], and why only a few studies have addressed the question.

The concept of presence

This paper develops a new approach. We propose that behavioral similarities between the real and the virtual environment can be explained using the concept of presence. The question of validity does not mean that physical validity should be set against psychological validity. Our approach establishes a methodological tradeoff that is based on both behavioral and psychological considerations, in order to investigate the ecological validity of simulators.

Historically, driving simulation is an offshoot of virtual reality, where the purpose is to allow one (or more) people to take part in sensorimotor and cognitive activity in an artificial world [28]. The interaction between a person and a virtual world is a transposition of the perception-cognition-action loop in the real world. Immersion in a virtual world cannot be the same as in the real world [22] given that the user has learned how to act naturally in a real and physical world (for instance, without any delay and/ or sensorimotor bias). Thus, depending on the sensorimotor parameters that characterize the simulator, immersion in the virtual environment is a necessary, but not a sufficient condition for performance that is representative of an actual situation [30]. Faced with this problem, in the 1980s a concept emerged from early research into virtual reality, which assesses the issue of the 'ecological' validity of behavior observed in virtual environments. It is known as 'presence' and a wide range of academic disciplines have taken an interest in it, resulting in a range of conceptualizations. For example, Lee (2004, p. 37) defines presence as "a psychological state in which virtual (para-authentic or artificial) objects are experienced as actual objects". This definition is consistent with the general notion of presence, i.e. a "perceptual illusion of nonmediation" [32]. The concept also includes ideas that are at the core of spatial presence, i.e. the experience of being located in the midst of mediated (virtual) objects. In fact, it is sometimes expressed in terms of a common metaphor, i.e. "being there" [32, 51]. The main characteristic of spatial presence is the belief of being located in a mediated environment.

The concept of presence was used for the first time in the field of teleoperations, to designate the operator's subjective sensation of being in the remote environment of the robot they were controlling, rather than their own near physical environment [47, 51, 57]. To have this feeling of presence, the user must be involved in the virtual environment and their tasks, to the point where they are unaware of the mediating technology [33]. Like Slater (2002), Wirth et al. (2007) [56] regarded the state of 'Spatial Presence' as a binary (on/off) experience, during which perceived self-location and in most cases, perceived actions are connected to a mediated spatial environment, and mental capacities are bounded by the mediated environment rather than reality. Some studies [24, 51] have proposed the concept as a tool for assessing driving or railway simulators, but only in situations generating a state of stress.

The main challenge in studies of presence [49, 50, 52] is to arrive at a consensus about its conceptualization, before its operationalization and assessment [48]. Various attempts have been made to describe the concept and despite differences, most authors consider the foundations to rest on attention [41, 46]. Among early attempts to develop a unified approach [56], we decided to base our work on a model developed in 2007 (Fig. 1). The model is made up of two levels: the first involves the construction of an unconscious mental representation of space (the spatial situational model, SSM), which allows, at a second level, a conscious percept of subjective presence (spatial presence). The approach is interesting because the model provided the basis for the 24-item 'Measurement, Effects, Conditions – Spatial Presence Questionnaire' (MEC–SPQ), in which each item corresponds to a major or sub-theme of the model. We decided to base our work on this methodological approach because it is the only model that sets out to explain the emergence and development of spatial presence.

The novelty of this model lies in its description of the subjective processes leading to the emergence of the feeling of presence. Spatial presence is considered to be an experience that only occurs during exposure to a medium, and the model is based on processes of perception and cognition. Higher forms of experience can be constructed on these foundations [8]. Therefore, the MEC model considers spatial presence, attention allocation and the construction of a spatial situation as key concepts for the emergence of presence. The medium affects both short-term orienting responses and more persistent attention allocation [56]. Attention is affected by external sources of information, although user characteristics are also relevant factors as individuals may voluntarily direct their attention towards a medium even if there are no salient stimuli to trigger the behavior.

In most cases, media-induced (involuntary) and user-directed (controlled) attention allocation processes are dependent. While both types of processes may be involved in the development of spatial presence, their relative contribution can vary. Specifically, the model assumes that intentional, focused attention processes are negatively related to the immersiveness of a mediated representation. On the other hand, spatial presence is induced when attention is directed towards the medium, and away from the real environment.

Many media products contain cues that enable attentive users to establish cognitive representations of space. For example, a television broadcast can display white surfaces separated by black lines, which the viewer sees as a room with white walls. Attentive media users process spatial cues and incorporate them into their mental representation of space. Authors call this a Spatial Situation Model (SSM). An SSM is a mental model [25, 43] of the spatial environment that the individual constructs based on (1) spatial cues, and (2) personal spatial memories and cognitions [34]. Media users develop their SSM by integrating spatial cues into their

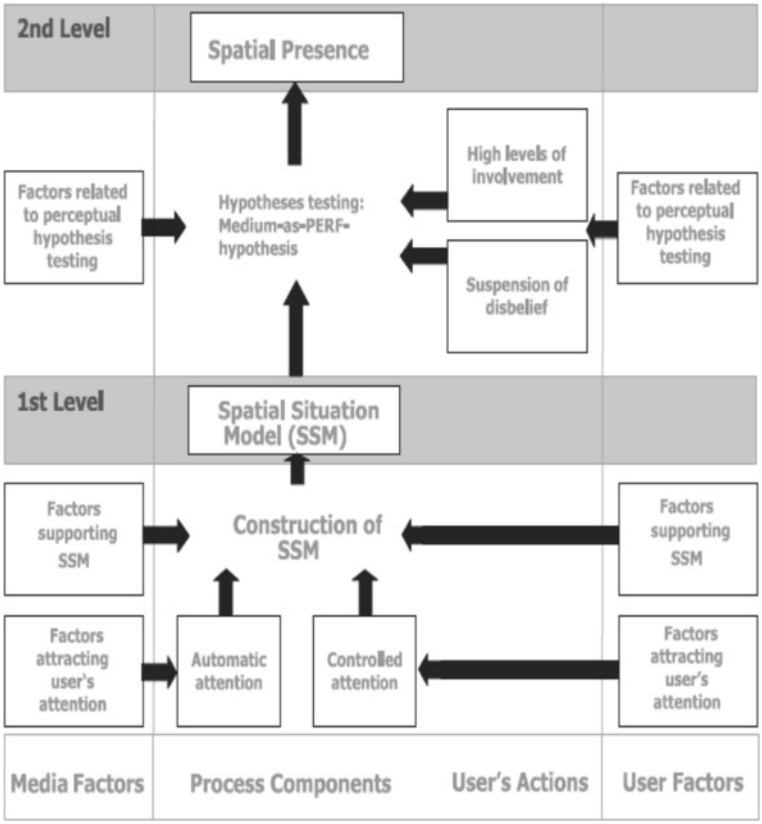

Fig. 1 The Measurement-Effects-Condition (MEC) model of spatial presence

existing spatial knowledge. They may or may not feel as though they are a part of the mediated spatial surroundings represented by the SSM. Additional cognitive and/ or perceptual processes must occur in order for a user to move from an SSM to spatial presence.

The SSM is clearly the result of both automatic and controlled attentional processes. Therefore, our experiment manipulated the cognitive load created by a simulated driving task, in order to generate different attentional states and levels of spatial presence. The independent variables were: 1) a secondary task (the dual-task paradigm) designed to distract the driver from the primary task; and 2) oncoming traffic, designed to focus the driver's attention on the primary task. Our objective was to assess simulator validity based on the two-level spatial presence model [45]. First we evaluated the behavioral dimension (driving performance), based on unconscious cognitive processes. Then we qualitatively evaluate the conscious subjective experience based on MEC–SPQ scores.

Our four hypotheses were:

MEC–SPQ scores:

H1: Traffic in the virtual world is a positive predictor of MEC–SPQ scores
H2: A secondary task is a negative predictor of MEC–SPQ scores

Driving performance:

H3: Traffic in the virtual world is a positive predictor of driving performance
H4: A secondary task is a negative predictor of driving performance

Method

In this section, we describe the methodology used to carry out the study. More specifically, it deals with the presentation of the exprimental setup, the procedure and the measures (spatial presence questionnaire and driving performance).

Experimental setup

Twenty car drivers (14 men and 6 women), with at least five years' experience took part in the experiment. Each participant drove an average of 16,000 km per year. Their ages ranged from 22 to 45 (mean = 32.8 years;

standard deviation = 6.45). Recruits were students and staff at the Faculty of Sport Sciences at Marseille University, France. Only healthy participants with normal or corrected vision, who did not suffer from motion sickness, were selected. All volunteers signed an informed consent form. They were divided into four experimental groups designed to test the two independent variables, namely whether a secondary task was performed (or not), and the presence of oncoming traffic (or not).

The experiment used the SIM^2-IFSTTAR fixed-base driving simulator equipped with an ARCHISIM object database [12]. The projected display (at 30 Hz) offered a 150° horizontal and 40° vertical field of view. The cockpit (see Fig. 2) contained a microcontroller managing a force feedback steering wheel, 3 pedals (accelerator, brake, clutch), a gear box, display dials (speedometer, tachometer) and various switches (windscreen wipers, lights, etc.). Driving performance was recorded online for offline analysis.

A high-end Windows XP desktop computer powered the simulator. It was equipped with a 3.0 GHz Intel Core 2 Extreme CPU, and 4.0 GB of 2000 MHz DDR3 RAM. Two NVidia Geforce 8800 Ultra graphics cards were used for video output, either in standard or parallel processing (SLI) mode depending on the display configuration. The simulator's hardware provides a full range of sensory cues and stimuli to the driver who in turn, controls the simulation model that is represented in software. Modular subsystems provide simulator functionality. These subsystems include the visual system, auditory cue generation, data collection, scenario generation and control.

Procedure

We used a digital model of the Versailles Satory runway (see Fig. 3), which is a closed 3.7 km loop with long straight stretches and corners with different radii of curvature.

The first independent variable was whether there was bidirectional traffic (or not), which varied the level of attention (see Fig. 4). A bidirectional traffic system divides drivers into two streams of traffic that flow in opposite directions.

The second was the introduction of a second task (or not). This required the participant to launch a digital hourglass by double-clicking the mouse of a laptop positioned so that the driver had to avert their gaze from the main scene. This task had to be carried out every minute. One group performed this task in oncoming traffic, while the other group carried it out in no-traffic conditions. It is important to note that the secondary task was not used to measure performance, which is why reaction times were not recorded. In all experimental conditions, each participant had to complete 10 laps of the track at a maximum speed of 110 km/h, while respecting the Highway Code.

Table 1 shows the four experimental groups, each of five subjects.

MEC (Measurement, Effects, Conditions) Spatial presence questionnaire

We administered an adapted version of the MEC Spatial Presence Questionnaire (MEC–SPQ) after each session [54]. The questionnaire uses a 5-point Likert scale ranging from 1 ('I do not agree at all') to 5 ('I fully agree'). The six dimensions were tested using 4-item scales. At the first level, Visual Spatial Imagery (VSI) is assessed with questions such as, "When someone describes a space to me, it's usually very easy for me to imagine it clearly"; "I dedicated my whole attention to the medium" (for Attention Allocation); and "I was able to imagine the arrangement of the spaces presented in the medium very well" (for the Spatial Situational Model). At the second level, cognitive involvement (CogInv) was assessed with items such as "I thought most about things having to do with the medium"; and "I didn't really pay attention to the existence of errors or inconsistencies in the medium" (for Suspension of Disbelief, SoD). Finally, spatial presence was measured and analyzed using the self-location dimension (e.g., "I felt as though I was physically present in the environment").

Internal reliability coefficients (alpha) were computed for each of the six dimensions. Alphas were high, ranging from 0.94 (Attention Allocation) to 0.76 (Suspension of Disbelief). Others were: Spatial Situational Model α = 0.91;

Fig. 2 The driving simulator

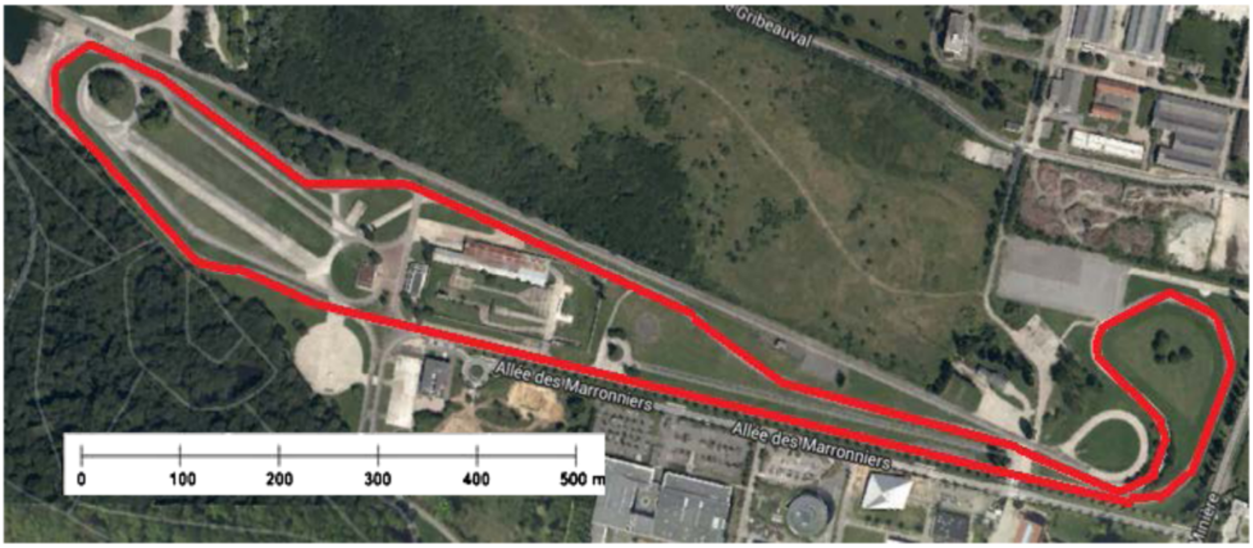

Fig. 3 The versailles satory runway

Cognitive Involvement α = 0.86; Suspension of Disbelief α = 0.76; and Self-location α = 0.86.

Driving performance

We analyzed four behavioral variables of driving performance, namely the mean and standard deviation of speed and lateral position. These indicators were selected as mean speed and variation in speed are frequently used in studies of driving behavior [11]. Several studies [38, 39] have found that visual distractions decrease speed; the driver is assumed to slow down in order to cope with the visual input. Speed variation can be voluntary, due to the environment and interactions with other road users, while involuntary changes are due to loss of control [38]. Mean speed can also be used as a metric of driver response in situations requiring a change in speed [39].

Changes in lateral position can be caused by tracking errors, which make it difficult to maintain a consistent line. Increased variation in lateral position is usually associated with reduced lateral control [6, 11]. Mean lateral position is used as a driving strategy metric, reflecting the driver's desire to follow a safe path [15].

Results

This study validated the spatial presence model, and more specifically characterized spatial presence using behavioral indicators. We analyzed subjective and behavioral measures, based on MEC–SPQ scores and driving performance respectively.

MEC spatial presence questionnaire

Means were computed for each group for the six dimensions of the MEC–SPQ (see Table 2). Overall, scores were high. The "Attention Allocation" scale had the highest mean score (4.2, SD = 0.70), while the "Cognitive Involvement" scale had the lowest (3.33, SD = 0.95).

We tested our hypotheses using a generalized linear model, based on a 2 × 2 factorial design and independent

Fig. 4 Bidirectional traffic

Table 1 Experimental design

	Dual task	Traffic
Group 1	No	Yes
Group 2	Yes	Yes
Group 3	No	No
Group 4	Yes	No

groups. A multivariate analysis of variance (MANOVA) assessed interactions between the independent variables.

The MANOVA analysis shows that there was no interaction between the traffic and dual task conditions (see Table 3). Contrary to expectations, none of the experimental conditions had a significant effect on MEC–SPQ scores (H1 and H2 were rejected).

We computed nonparametric Gamma correlations between scales for traffic and no-traffic groups. No significant correlation was found for either group between Attention Allocation and SSM scores or between the VSI and SSM scores. Furthermore, neither group had a significant correlation between CogInv and Self-location scores (no-traffic group: 0.57, $p = 0.03 < 5\ \%$; traffic group: 0.68, $p = 0.01 < 5\ \%$). However, there was a significant correlation in the no-traffic group between SoD and Self-location scores (0.70, $p = 0.008 < 1\ \%$) and SSM and Self-location scores (0.73, $p = 0.008 < 1\ \%$). It therefore seems that in the no-traffic condition, SSM, SoD and CogInv are positive predictors of Self-location. In other words, drivers who do not have to navigate traffic report a greater subjective sense of presence. However, the predicted first-level correlations with Attention Allocation, VSI and SSM are not observed.

Driving performance

The analysis of lateral position and speed looked at the mean and standard deviation for each subject for each lap.

Table 3 MANOVA RESULTS

	Dual Task	Traffic	Dual Task*Traffic
Attention Allocation	F = 0.24	F = 0.09	F = 0.01
	P = 0.63	P = 0.77	P = 0.92
Spatial Situation Model (SSM)	F = 0.58	F = 4.13	F = 0.26
	P = 0.48	P = 0.06	P = 0.62
Cognitive Involvement (CogInv)	F = 0.36	F = 0.20	F = 1.11
	P = 0.56	P = 0.66	P = 0.31
Suspension of Disbelief (SoD)	F = 0	F = 0.17	F = 0.17
	P = 1	P = 0.69	P = 0.69
Visual Spatial Imagery (VSI)	F = 4.48	F = 1.68	F = 0.01
	P = 0.05	P = 0.21	P = 0.95
Spatial Presence: Self-Location	F = 1.48	F = 0.46	F = 0.02
	P = 0.24	P = 0.51	P = 0.89

* statistical significance set at p<0.05

Lateral position

Lateral position (LP) is the distance between the center of the car and the center of the lane. As Fig. 5 shows, there is an interaction between the secondary task and traffic conditions (F = 28.827, $p < 1\ \%$). The mean lateral positions of Groups 1 (1.35 m) and 2 (1.39 m) who were exposed to traffic are higher than those of Groups 3 (0.92 m) and 4 (0.19 m) who were not exposed to oncoming traffic (F =164.43, $p < 1\ \%$).

In the no-traffic condition, the secondary task had an effect. Group 3, which did not have a secondary task had a higher mean lateral position (0.92 m, F = 35.27, $p < 1\ \%$) than Group 4 (0.19 m). This effect was not observed in the traffic condition.

Speed

Figure 6 shows the dual task effect (F = 2.33, $p < 1\ \%$). Over ten laps, Groups 1 and 3 (single task) drove faster than Groups 2 and 4 (dual task).

Table 2 Mean (M) and standard deviation (SD) of MEC spatial presence questionnaire scores

	Group 1	Group 2	Group 3	Group 4
Attention Allocation	M = 4.07	M = 4.27	M = 4.20	M = 4.33
	SD = 0.72	SD = 0.28	SD = 0.93	SD = 0.91
Spatial Situation Model (SSM)	M = 3.6	M = 3.53	M = 4.27	M = 3.93
	SD = 0.28	SD = 0.73	SD = 0.64	SD = 0.60
Cognitive Involvement (CogInv)	M = 3.07	M = 3.80	M = 3.33	M = 3.13
	SD = 1.19	SD = 0.80	SD = 1.10	SD = 0.80
Suspension of Disbelief (SoD)	M = 3.80	M = 3.67	M = 3.80	M = 3.93
	SD = 0.65	SD = 0.75	SD = 0.90	SD = 0.55
Visual Spatial Imagery (VSI)	M = 3.05	M = 3.85	M = 3.55	M = 4.30
	SD = 0.74	SD = 1.29	SD = 0.51	SD = 0.55
Spatial Presence: Self-location	M = 3.50	M = 4	M = 3.30	M = 3.7
	SD = 0.71	SD = 0.18	SD = 1.31	SD = 0.69

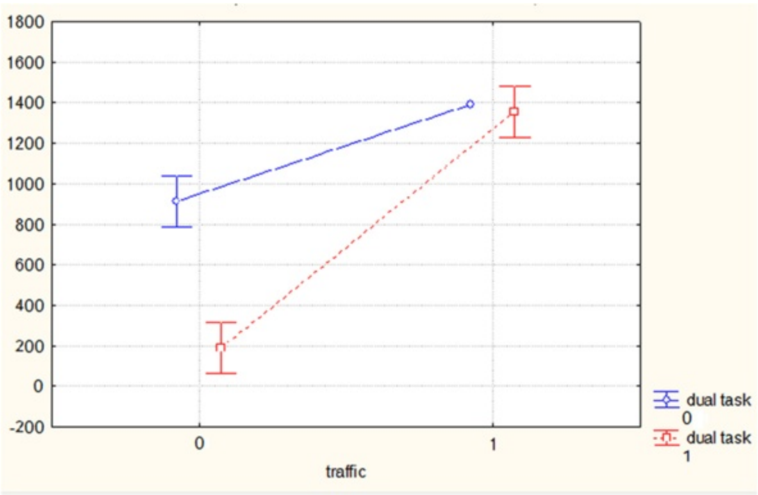

Fig. 5 Mean lateral position depending on traffic and dual task variables

Figure 7 shows that there was an interaction between task and traffic conditions (F = 24.5, $p < 1$ %). The mean speed of Groups 3 and 4 (no-traffic) was higher (31 m/s) than Groups 1 and 2 (traffic) (27.50 m/s, F = 103.45, $p < 1$ %). Furthermore, the mean speed of Group 3 (no-traffic, single task) was higher (31.53 m/s) than Group 4 (no-traffic, dual task) (30.4 m/s, F = 4.94, $p < 5$ %).

In the traffic condition, the mean speed of Group 1 (single task) was higher (29.74 m/s) than Group 2 (dual task) (25.25 m/s, F = 85.06, $p < 1$ %).

Standard deviation of lateral position (SDLP)

Figure 8 shows that for each group the standard deviation of the lateral position did not significantly change over laps. There was no interaction between groups and laps (F = 0.60, $p = 0.94$)

However, the standard deviation of the lateral position of Group 4 (no-traffic, dual task) was higher than other groups (1.47 m). This compares to 0.83 m and 0.84 m for Groups 1, 2 and 3 respectively (F = 156.39, $p < 1$ %) (H4 is confirmed). There were less significant differences (based on the Bonferroni post-hoc test) between Groups 2 and 3 ($p = 0.02 < 5$ %), and Groups 2 and 1 ($p < 5$ %) (H3 is validated), but not between Groups 1 and 3 ($p = 1$).

Standard deviation of speed

Figure 9 shows that there was no interaction between group and lap variables (F = 0.60, $p = 0.93$). However, there was a significant interaction between group and the SD of speed (F = 41.02, $p < 1$ %). This confirms H4.

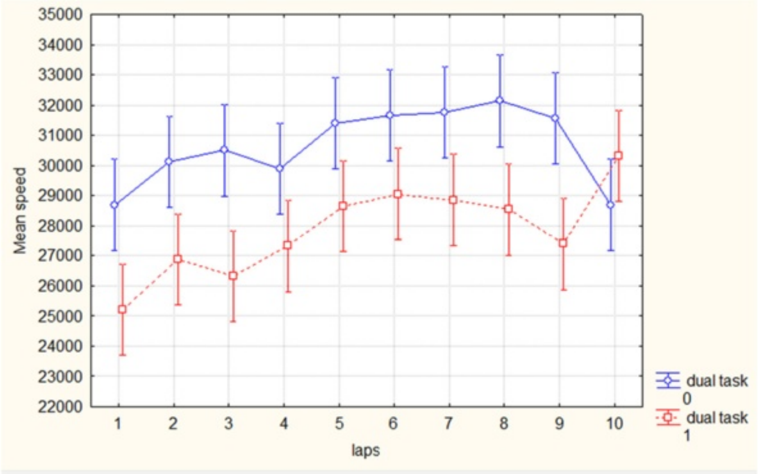

Fig. 6 Mean speed as a function of laps and dual task variables

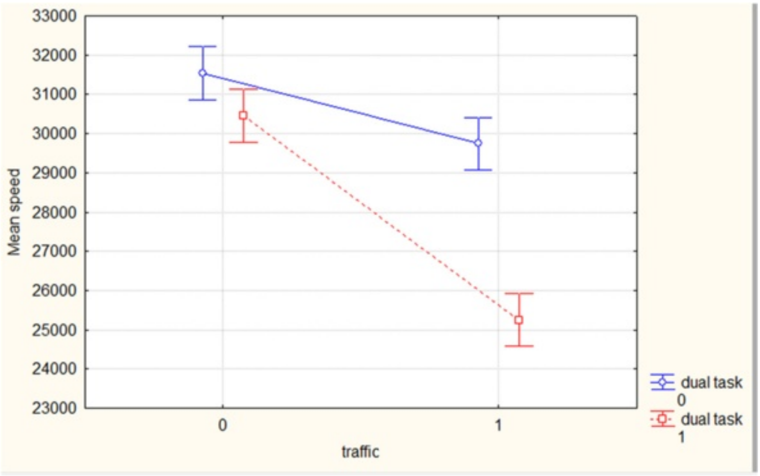

Fig. 7 Mean speed as a function of traffic and dual task variables

The standard deviation of speed was significantly lower for Group 2 (1.99 m/s) than Group 1 (14.08 m/s), Group 3 (11.85 m/s) and Group 4 (12.73 m/s) (F = 41.02, $p < 1$ %). There were less significant differences between Groups 1 and 3, and Groups 1 and 4.

Figure 10 shows that the mean standard deviation of speed over the ten laps was significantly different (F = 2.81, $p < 1$ %).

However, we note that from the fifth lap to the ninth lap there was no significant difference (F = 0.13, $p = 0.97$).

Linear regressions

Linear regressions were carried out between MEC–SPQ scores and driving parameters. Only two main results emerged.

A negative linear regression was found between SoD scores and the standard deviation of the lateral position in curves (linear effect: $\beta = -0.91$, $p < 5$ %). The higher the SoD score, the lower the standard deviation of the lateral position, which suggests improved driving performance.

A negative linear regression was also found between VSI scores and the standard deviation of the lateral position over 10 laps (linear effect: $\beta = -0.98$, $p < 1$ %). Higher VSI scores correlated with a decrease in the standard deviation of the lateral position, which also suggests improved driving performance.

Discussion

The simulation of driving in research into road safety and the design of assistance systems raises the problem of the

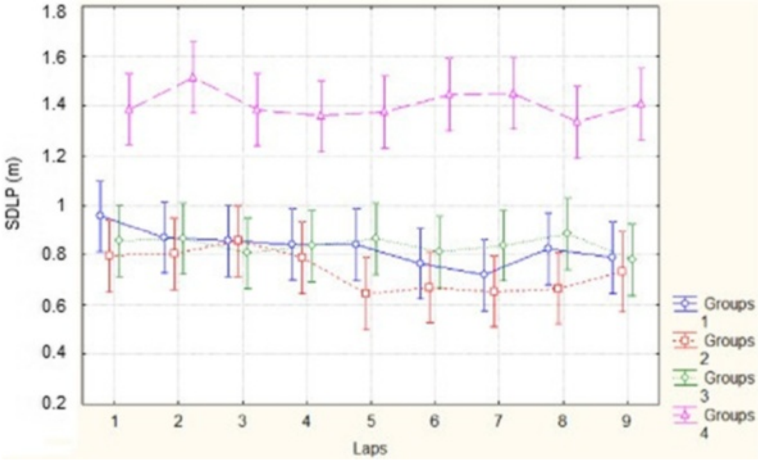

Fig. 8 Standard deviation of lateral position as a function of laps and group

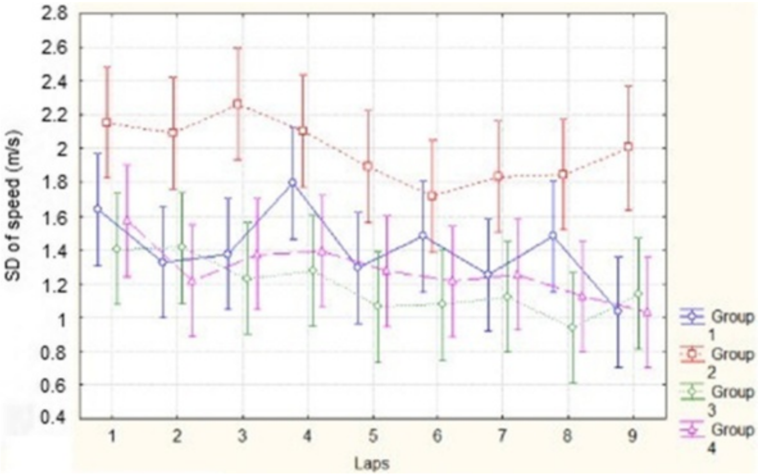

Fig. 9 Mean standard deviation of speed over the 10 laps for each group

validity of the results. In theory, virtual environments offer a unique opportunity to carry out experiments using a replica of physical space, but to what extent can behavior be transposed from the virtual to the real world?

The key objective in most studies is that the participant's behavior in the virtual world is as similar as possible to the real world. However, for too long the design of virtual environments has focused on engineering considerations [14], and this technocentric approach to immersion and interaction has become outdated. It is being replaced by a new, anthropocentric approach where operators see themselves as fully-fledged users of the virtual environment. The user perceives and interacts with physical entities and other elements of the virtual world in ways that do not necessarily require sensorimotor physical activity. This prevents them from assimilating the virtual reality as a simple copy of the real world. Immersion is a necessary, but not a sufficient condition for an accurate representation of the actual driving situation [37].

Faced with this problem, the concept of 'presence' emerged in the 1980s from early work into virtual reality. Presence addresses the issue of the 'ecological' validity of observed behavior. Various attempts have been made over the past decade to develop a unified approach to the concept, and we decided to base our work on a model developed in 2007. This 'spatial presence' model consists of two levels [46]: the first involves the construction of an unconscious mental representation of space; while the second concerns the conscious experience of subjective presence. Consequently, presence depends on the development of both unconscious and

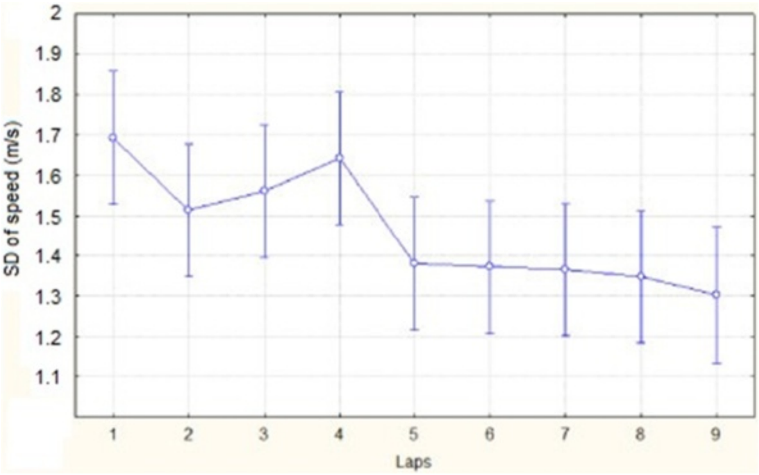

Fig. 10 Mean standard deviation of speed over the ten laps (all subjects)

conscious cognitive processes. The dynamic is modulated by interaction between the immersive characteristics of the virtual environment and user characteristics. This is a rare example of a model that can explain the processes involved in the emergence of presence. Moreover, although it may appear to reduce presence to its spatial dimension, the final conceptualization is the result of immersion, interaction and other factors internal to the user.

Our study is based on the work of [45, 46]. We measured presence in terms of direct subjective experience (verbalized by the participant), and indirect behavioral indicators (driving parameters). The objective was to assess the validity of the driving simulation through the concept of presence. The underlying assumption was that psychological validity is a positive predictor of behavioral validity. More specifically, we hypothesized that a person who has a strong sense of presence in the virtual environment will react as if they were in a real environment.

Overall, our results showed no significant differences between the four experimental conditions. In the virtual world, neither the addition of traffic nor a secondary task was a positive predictor of MEC–SPQ scores. Although the addition of a second task did not have an effect on subjective measures of presence it did affect behavioral measures. [55] argue that low standard deviation (SD) for speed and lateral displacement indicate good control, and stable and consistent driving. In our experiment, the SD of speed (in the traffic condition) and the SD of the lateral displacement (in the no-traffic condition) were both higher in the dual task than the single task condition. The no-traffic, dual task group tended to drive in the middle of the road (they had the lowest mean lateral position). While this could be interpreted as an efficient driving strategy, it is not particularly consistent with the Highway Code. Similarly, the dual-task, traffic group compensated for the conditions by slowing down. Unfortunately, an increase in the SD of speed indicated that their driving became unstable and that overall driving performance was impaired.

Concerning the MEC–SPQ, the only strong positive correlation was between SSM and Self-location in the no-traffic groups. It is also interesting to note that these were the only groups where CogInv, SSM and SoD scores were positive predictors of Self-location. This result suggests that the model was more effective in the no-traffic groups, and that these groups were more involved in the subjective experience. However, if the second level of the model appears to show higher levels of presence for the no-traffic groups, no significant correlations were observed for the first level, which involved Attention and VSI linked to the SSM. We argue that this lack of congruence between the two levels is that, as [46] propose, subjective measures from questionnaires assess spatial presence as a cognitive feeling, but fail to reveal the temporal dynamics of attention allocation and more globally the development of the spatial situation model. Our results use response time to a simple dual task, which seems to emphasize that physiological measures could be more relevant for the assessment of first-level dimensions.

Finally, the results of the linear regressions between MEC–SPQ scores and the standard deviation of vehicle parameters supports the idea that a reduction of variability is positively correlated with higher scores for items at the second level of the MEC model. None of the first-level dimensions (e.g. Attention Allocation or SSM) are correlated to behavioral variables. This result suggests that the first-level dimensions of the model fail to capture the dynamics of driving behavior.

The main outcome of our study was that behavioral measures revealed significant effects of the manipulated variables (traffic and task) on driving performance. However, these effects were not confirmed by subjective reports. One explanation could be that despite the experimental conditions, driving did not involve high-level, conscious, cognitive processes. Despite the high MEC–SPQ scores, it is likely that driving was based on a set of procedures or routines. Our experimental conditions might have been insufficient to create distinct levels of attention, involvement and suspension of disbelief, leading to distinct levels of presence (see Fig. 1). As the MEC model suggests [46], internal factors (such as emotional arousal) are key elements in the emergence of a sense of presence based on controlled attentional processes. Thus, high levels of self-reported presence (positively correlated with behavioral measures) might be required to develop more challenging scenarios, in terms of controlled attention, cognitive involvement and more specifically emotions created by the media. Participants in driving simulations are clearly aware that they are not exposed to any physical danger, and according to [23], the main problem to be solved is how to simulate conditions that engage them.

Conclusion

This study seems to confirm the pertinence of the two MEC levels. However the SPQ failed to demonstrate the structural relevance of the model's first level. Our results suggest that subjective measurements based on questionnaires fail to report significant behavioral effects. Here, this was observed in the dual task condition involving the unconscious aspects of the attentional dimension. The more dynamic first-level dimensions suggest that it is more relevant to promote the use of behavioral measures as 'on line' measures for their assessment. Subjective measures seem to be more relevant to evaluate second-level dimensions, which illustrate the subjective experience of presence. The analysis of vehicle parameters clearly showed that the experimental groups adopted different, but more-or-less automated procedures and strategies. Given the high degree of automation in cognitive processes related to driving [28], we argue for the use of both subjective (such as questionnaires) and objective (e.g. physiological) measures to assess presence in driving simulators. [36] points out that there has been much debate about the best way to measure presence. Researchers need to find a reliable, valid, sensitive, and objective way to measure subjective judgments of psychological states or responses. Until this is found, it remains unclear exactly what participants are responding to, and how their responses are affected by the need to continuously assess their experience. More generally, presence questionnaires are administered after the event, and cannot reflect ongoing changes in the participant's state of mind during the experience [48].

Physiological measures could be an interesting alternative to overcoming the problems encountered in the traditional questionnaire approach. The objective approach to measuring presence attempts to measure automatic responses that are nevertheless meaningfully correlated with the medium's properties and/or content [21]. Potential measures include physiologic processes such as heart rate, respiration, skin resistance, skin temperature and peripheral brain wave activity. This assumes that as the sense of presence in a virtual environment increases, physiological responses to the environment will mirror those exhibited in a real environment [20]. Another advantage of physiological measures is that they are continuous, and can be used to assess the characteristics of presence over time.

Unfortunately, there are only a few studies that examine the relationship between presence and physiological responses [10, 18, 55], but nevertheless some interesting results have been obtained. [35] successfully used physiological measures (heart rate and skin conductance) as a surrogate for presence. Similarly, Guger et al. [18] showed that heart rate reflects the physiological state of the participant. Cardiovascular activity and psychophysiological measures related to the skin (temperature and conductance) are often associated with emotional experience, hedonic valence, the orienting response to novelty, and defensive responses [29]. Similarly, [29] suggested that both automatic and controlled attention play an important role in presence, which can be measured by cardiac indicators. Phasic heart rate deceleration has been suggested as a measure of automatic attention, and respiratory sinus arrhythmia as a measure of controlled attention. Further investigation into the subjective rating of presence and physiological measures are clearly required in order to understand its dynamics more fully.

Finally, the main limitation of our study is the small cohort size, which requires a cautious interpretation of the validity and reliability of our results. Future work should be based on a larger sample to adequately detect between-group differences.

Competing interests

The authors declare that they have no competing interests.

Authors' contribution

All authors were involved in the planning, design, conduct, writing and reviewing of this paper. All authors read and approved the final manuscript.

Acknowledgments

We would like to thank the simulation team at the Mediterranean Center for Virtual Reality who made a substantial contribution to the experiment's design and data acquisition, but who do not meet the criteria for authorship.

Received: 24 October 2014 Accepted: 16 June 2015

References

1. Allen, RW, & Jex, HR. (1980). Driving simulation – Requirements, mechanization and application. *SAE Technical Paper Series Paper number, 800448*, 1–12.
2. Allen, RW, & McRuer, DT. (1977). *The effect of adverse visibility on driver steering performance in an automobile simulator". 1977 SAE Transactions (Vol. 86, pp.1081-1092; SAE Paper 770239)*. Warrendale, PA: Society of Automotive Engineers.
3. Allen, RW, Mitchell, DG, Stein, AC, & Hogue, JR. (1991). Validation of real-time man-in-the-loop simulation". *VTI Rapport, 372A, 4*, 18–31.
4. Allen, RW, Stein, AC, Aponso, BL, Rosenthal, TJ, & Hogue, JR. (1990). A low cost, part task driving simulator based on microcomputer technology". *Transportation Research Record, 1270*, 107–113.
5. Blaauw, GJ. (1982). Driving experiments and task demands in simulator and instrumented car". *Human Factors, 24*, 473–486.
6. Brookhuis, KA, de Vries, G, & de Ward, D. (1991). The effects of mobile telephoning on driving performance". *Accident Analysis and Prevention, 23*(4), 309–316.
7. Bürki Cohen, J, & Go, TH. (2005). *The effect of simulator motion cues on initial training of airlines pilots"*. San Francisco, CA: AIAA-2005-6109. Proceedings of the American Institute of Aeronautics and Astronautics Modeling and Simulation Technologies Conference.
8. Darken, RP, Allard, T, & Achille, LB. (1998). Spatial orientation and wayfinding in large-scale virtual spaces: An introduction. *Presence: Teleoperators and Virtual Environments, 7*(2), 101–107.
9. De Winter, J., Van Leuweeen, P., & Happee, P. (2012, August). Advantages and Disadvantages of Driving Simulators: A Discussion. In *Proceedings of Measuring Behavior* (Eds.), AJ Spink, F. Grieco, OE Krips, LWS Loijens, LPJJ Noldus, and PH Zimmerman (pp. 47–50). Utrecht, The Netherlands.
10. Dillon, C., Keogh, E., Freeman, J., & Davidoff, J. (2000). Aroused and immersed: the psychophysiology of presence. Presence 2000 – 3rd International Workshop on Presence. (Eds.), Goldsmiths College/ Independent Television Commission. (UK) London.
11. Engström, J, Johansson, E, & Östlund, J. (2005). Effects of visual and cognitive load in simulated motorway driving. *Transportation Research Part F, 8*(2), 97–120.
12. Espié, S, Gauriat, P, & Duraz, M. (2005). Driving simulators validation: The issue of transferability of results acquired on simulator. In *National advanced driving simulator, university of Iowa (Eds) proc. Driving simulation conference DSC north-America'2005, november 30th – october 2nd* (pp. 149–156). Orlando, FL: Center for Advanced Transportation Systems Simulation.
13. Fisher, D. L., Rizzo, M., Caird, J., & Lee, J. D. (Eds.). (2011). *Handbook of driving simulation for engineering, medicine, and psychology*. CRC Press. Boca Raton, Fla, USA
14. Garrott, W. R., Mazzae, E. N., & Goodman, M. J. (2005, June). NHTSA'S National advanced driving simulator research program. In *Proceedings: International Technical Conference on the Enhanced Safety of Vehicles* (Vol. 2005, pp. 9p-9p). National Highway Traffic Safety Administration. Washington, DC.
15. Gibson, JJ, & Crooks, LE, (1938). A theoretical field-analysis of automobile-driving. The American journal of psychology, LI (3), 453–471.
16. Godley, ST, Triggs, TJ, & Fildes, BN. (2002). Driving simulator validation for speed research". *Accident Analysis and Prevention, 34*(5), 589–600.
17. Goodman, M, Bents, FD, Tijerina, L, Wierwille, WW, Lerner, N, & Benel, D. (1997). *"An investigation of the safey implications of wireless communications*

in vehicles" (DOT HS 808 635). Washington, DC: National highway Traffic Safety Administration, US Department of Transportation.

18. Guger, C., Edlinger, G., Leeb, R., & Pfurtscheller, G. (2004). Heart-rate variability and event-related ecg in virtual environments. In Presence 2004: The 7th Annual International Workshop on Presence, pp. 240-245, 2004.
19. Hancock, PA. (2008). The future of simulation". In D Vicenzi, J Wise, M Mouloua, & PA Hancock (Eds.), *Human factors in simulation and training* (pp. 169–188). Boca Raton, FL: CRC Press.
20. IJsselsteijn (2004). *Presence in Depth*. Ph.D. Thesis. Eindhoven University of Technology.
21. IJsselsteijn, W. A. (2004). Presence in depth. (Unpublished doctoral dissertation). Eindhoven University of Technology, Eindhoven; The Netherlands.
22. Jamson H. (1999) Curve Negotiation in the Leeds Driving Simulator: The Role of Driver Experience. In Engineering in Psychology and Cognitive Ergonomics, Vol. 3, (Ed.), D. Harris, Ashgate, Aldershot, (pp. 351–358).
23. Jamson, SL, & Jamson, AH. (2010). The validity of a low-cost simulator for the assessment of the effects of in-vehicle information systems". *SAFETY SCI, 48*, 1477–1483.
24. Johnson, MJ, Chahal, T, Stinchcombe, A, Mullen, N, Weaver, B, & Bedard, M. (2011). Physiological responses to simulated and on-road driving". *International Journal of Psychophysiology, 81*(3), 203–208.
25. Johnson-Laird, PN, & Bara, BG. (1984). Syllogistic inference. *Cognition, 16*(1), 1–61.
26. Kantowitz, B.H., 2001. Using microworlds to design intelligent interfaces that minimize driver distraction. In: Proceedings of the International Driving Symposium on the Human Factors in Driver Assessment, Training, and Vehicle Design. Aspen, CO.
27. Kaptein, NA, Theeuwes, J, & Van der Horst, R. (1996). Driving simulator validity: some considerations". *Transportation Research Record, 1550*, 30–36.
28. Kemeny, A, & Panerai, F. (2003). Evaluating perception in driving simulation experiments. *Trends in Cognitive Sciences, 7*(1), 31–37.
29. Laarni, J., Ravaja, N., & Saari, T. (2003, October 6-8). Using eye tracking and psychophysiological methods to study spatial presence. Paper presented at the 6th International Workshop on Presence, Aalborg, Denmark.
30. Lee, KM. (2004). Presence, explicated". *Communication Theory, 14*(1), 27–50.
31. Lee, AT. (2005). *Flight simulation"*. Aldershot, United Kingdom: Ashgate.
32. Lombard, M, & Ditton, T. (1997). At the heart of it all: The concept of presence. *Journal of Computer-Mediated Communication, 3*, 2.
33. Lombard, M, Snyder-Duch, J, & Bracken, CC. (2002). Content analysis in mass communication: Assessment and reporting of intercoder reliability. *Human communication research, 28*(4), 587–604.
34. McNamara, TP, Hardy, JK, & Hirtle, SC. (1989). Subjective hierarchies in spatial memory. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 15*(2), 211.
35. Meehan, M. (2000). An Objective Surrogate for Presence: Physiological Response. Presence 2000-3rd International Workshop on Presence. [online]. Available: http://www.presence-research.com/ (May 29, 2001).
36. Meehan, M, Razzaque, S, Insko, B, Whitton, M, & Brooks, FP, Jr. (2005). Review of four studies on the use of physiological reaction as a measure of presence in stressfulvirtual environments. *Applied psychophysiology and biofeedback, 30*(3), 239–258.
37. Nilsson, L., 1993. Behavioural research in an advanced driving simulator-experiences of the VTI system. Proceedings of the Human Factors and Ergonomics Society 37th Annual Meeting *37*(1), 612–616.
38. Östlund, J. Carsten, O., Merat, N., Jamson, S., Janssen, W., & Brouwer, R., et al. (2004). Deliverable 2—HMI and safety-related driver performance. Human Machine Interface And the Safety of Traffic in Europe (HASTE) Project, Report No. GRD1/2000/25361 S12.319626, Institute for Transport Studies, Leeds, UK.
39. Patten, CJ, Kircher, A, Östlund, J, & Nilsson, L. (2004). Using mobile telephones: cognitive workload and attention resource allocation. *Accident analysis & prevention, 36*(3), 341–350.
40. Ranney, TA, Simmons, LA, Boulos, Z, & Macchi, MM. (2000). Effect of an afternoon nap on nighttime performance in a driving simulator". *Transportation Research Record, 1686*, 49–56.
41. Regenbrecht, H, & Schubert, T. (2002). Real and illusory interaction enhance presence in virtual environments". *Presence: Teleoperators and Virtual Environments, 11*, 425–434.
42. Reimer, B, D'Ambrosio, LA, Coughlin, JE, Kafrissen, ME, & Biederman, J. (2006). Using self -reported data to assess the validity of driving simulation data". *Behavior Research Methods, 38*(2), 314–324.
43. Sanford, AJ, & Garrod, SC. (1982). Towards a processing account of reference. *Advances in psychology, 8*, 100–110.
44. Santos, J, Merat, N, Mouta, S, Brookhuis, K, & De Waard, D. (2005). The interaction between driving and in-vehicle information systems: Comparison of results from laboratory, simulator and real-world studies. *Transportation Research Part F: Traffic Psychology and Behaviour, 8*(2), 135–146.
45. Schubert, T. (2004). The sense of presence in virtual environments: A three-component scale measuring spatial presence, involvement, and realness". *Zeitschrift für Medienpsychologie, 15*, 69–71.
46. Schubert, TW. (2009). A new conceptualization of spatial presence: Once again, with feeling". *Communication Theory, 19*, 161–187.
47. Schuemie, MJ, Van Der Straaten, P, Krijn, M, & Van Der Mast, CA. (2001). Research on presence in virtual reality: A survey. *CyberPsychology & Behavior, 4*(2), 183–201.
48. Slater, M. (1999). Measuring presence: A response to the Witmer and Singer presence questionnaire". *Presence: Teleoperators and Virtual Environments, 8*, 560–565.
49. Slater, M. (2002). Presence and the sixth sense. *Presence: Teleoperators and Virtual Environments*, 11(4), 435-439.
50. Slater, LD, & Lesmes, D. (2002). IP interpretation in environmental investigations. *Geophysics, 67*(1), 77–88.
51. Slater, M, Lotto, B, Arnold, MM, & Sanchez Vives, MV. (2009). How we experience immersive virtual environments : the concept of presence and its measurement". *Anuario de Psicologia, 40*(2), 193–210. Meeting *37*(1), 612–616.
52. Steuer, J. (1992). Defining virtual reality: Dimensions determining telepresence. *Journal of communication, 42*(4), 73–93.
53. Tichon, JG. (2007). Using presence to improve a virtual training environment". *CyberPsychology & Behavior, 10*(6), 781–787.
54. Törnros, J. (1998). Driving behaviour in a real and a simulated roadtunnel—a validation study. *Accident Analysis and Prevention, 30*(4), 497–503.
55. Vorderer, P, Wirth, W, Saari, T, Gouveia, FR, Biocca, F, Jäncke, L, Böcking, S, Schramm, H, Gysbers, A, Hartmann, T, Klimmt, C, Laarni, J, Ravaja, N, Sacau, A, Baumgartner, T, & Jäncke, P (2004). Development of the MEC Spatial Presence Questionnaire (MEC-SPQ). Unpublished report to the European Community. Project Presence: MEC (IST-2001-37661).
56. Wiederhold, BK, Davis, R, & Wiederhold, MD. (1998). The effect of immersiveness on physiology. In G Riva & MD Wiederhold (Eds.), *Virtual environments in clinical psychology and neuroscience*. Amsterdam: IOS Press.
57. Wirth, W, Hartmann, T, Böcking, S, Vorderer, P, Klimmt, C, Schramm, H, & Jäncke, P. (2007). A process model of the formation of spatial presence experiences. *Media psychology, 9*(3), 493–525.
58. Witmer, BG, & Singer, MJ. (1998). Measuring presence in virtual environments: A presence questionnaire. *Presence: Teleoperators and virtual environments, 7*(3), 225–240.