Effects of Presence on Spatial Perception in Virtual Environments

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Abstract. *The influence of the sense of presence on spatial perception in a multi-sided back projection virtual reality system was investigated. Such an influence could diminish the reliability of spatial judgements in virtual environments (VEs), users' presence being only in part controllable. The VE used was a virtual passenger car cockpit. It provided a variety of distance, depth, and size cues. The sense of presence was manipulated by varying a number of technological, content-related, and other contributing factors in four experimental settings. Presence was measured with a questionnaire based on a three-dimensional presence concept (Schubert et al., 1999a). In these four VE settings, seventy-seven participants adjusted the size of the virtual cockpit to the memorized size of a real one. As the main result of the study, regression analyses yielded significant correlations of all three presence dimensions with distance/size estimations. A cognitive mechanism explaining the observed correlations is proposed. An analysis of this mechanism can help enhancing the reliability of spatial judgements in VEs. Effects of the setting variation on mean presence values were notable but weak. Apparently, the systematic influence of the contributing factors on presence was dominated by participants' individual reactions. Finally, systematic variations of mean size judgements across the four settings were found. Those are attributed to direct effects of two contributing factors (frame rate and surface brightness).*

1 Introduction

Understanding spatial perception has been a human endeavour for centuries. The visual perception of the space surrounding us is crucial for our interaction with the environment. An enormous amount of research work addressing this field has been done in the past decades. In comparison, the investigation of spatial perception in VEs has just begun. So far only few results have been reported. For many practical applications of VEs, veridical spatial perception is crucial though. Hence, thorough knowledge about the mechanisms determining spatial perception in Virtual Reality systems is needed.

Another important research topic in the field of teleoperators and VEs is the phenomenon of subjective presence. Research is ongoing in this area as well, be it to further investigate the very nature of the phenomenon, to improve the methods of its measurement, or to analyse its possible effects. In recent years, the analysis of presence-induced effects on cognitive or physiological parameters is increasingly regarded to be important for the understanding and application of virtual reality (see e. g. Stanney et al., 1998; Welch, 1999). Nevertheless, few experimental studies have directly addressed such effects yet (see Welch, 1999, for an overview).

The aim of this study was to investigate possible interactions of these two cognitive phenomena — visual spatial perception and presence. In addition to the academic interest in this question, such an interaction would also have important consequences for practical applications of VEs.

1.1 The objective of this study

For the effective use of VEs for divers tasks as architectural presentations, surgical training, or automobile cockpit development, veridical size and distance perception is a prerequisite. But the way virtual objects are spatially perceived depends on a variety of technological, content-related, personal, and other factors. The influence of some of these factors has already been empirically investigated (see section 1.4).

A possible influence of the sense of presence on spatial perception has not been analysed yet. We thought such an interaction was plausible: The "feeling of being there" in a virtual space is likely to be correlated to the user's spatial perception in that same environment. This should be particularly true for virtual spaces enclosing the user, as it is the case inside a virtual car cockpit, for example.

What would be the practical relevance of such a finding? The degrees of presence users experience — even when receiving identical stimuli — differ strongly due to individual characteristics (their willingness to suspend disbelief, prior media experience etc.; see e. g. Lombard & Ditton, 1997; Regenbrecht, 1999). Consequently, if presence and spatial perception were correlated, users' spatial perception in VEs would also be hardly controllable. *The reliability of product tests, ergonomic analyses etc. performed with virtual prototypes would be diminished.*

This sounds like potentially bad news for VR practitioners. A possible solution to this problem could be found by investigating the mechanisms possibly coupling presence and spatial perception. Thus, the two objectives of this study were to

1. empirically analyse the influence of the sense of presence on visual spatial perception, and to
2. propose a theoretically founded, explaining mechanism if such a correlation is indeed found.

To accomplish this, we used an experimental setting similar to a practical application in an industrial context: a virtual car interior, displayed in 1:1 scale. Such an environment provides a variety of visual stimuli simultaneously, reflecting the ordinary perceptual situation of the visual system. In addition, results can easily be transferred to practical applications.

1.2 Measuring presence

In recent years, the concept of presence has been controversially discussed in the virtual reality and related research communities. This discussion included the very nature and philosophical background of this phenomenon (Heeter, 1992; Held & Durlach, 1992; Loomis, 1992; Sheridan, 1992; Zeltzer, 1992; Slater et al., 1994; Schloerb, 1995; Draper et al., 1998; Flach & Holden, 1998; Witmer & Singer, 1998; Zahorik & Jenison, 1998; Mantovani & Riva, 1999; Schubert et al., 1999a/b; Sheridan, 1999; Slater, 1999) as well as possible methods of measuring it, both being linked.

Different methods of measurement are conceivable, including: (1) physiological measures (see e. g. Barfield et al., 1995); (2) the measurement of intuitive behavioural responses (e.g. Held & Durlach, 1987; Sheridan, 1996); (3) measurements of the user's ability to discriminate real and virtual environments (e.g. Steuer, 1992; Schloerb, 1995; Sheridan, 1996); and (4) subjective user reports (e. g. Heeter, 1992; Barfield & Weghorst, 1993; Slater & Usoh, 1993; Slater et al., 1994; Welch et al., 1996; Witmer & Singer, 1998; Slater, 1999; Regenbrecht, 1999; Schubert et al., 1999a/b; Freeman et al., 2000; Lessiter et al., 2000).

We chose subjective user reports through a post-test questionnaire. Only subjective user reports allow for a differentiation of different facets of the potentially complex construct of presence. Multi-dimensional presence concepts and measurement tools have been proposed by a number of researchers, including Witmer & Singer (1998), Schubert et al. (1999a/b), and Lessiter et al. (2000). In a study like ours, they have an obvious advantage: Spatial perception might be correlated in specific ways to the different aspects/dimensions of presence. The multidimensional concepts enhance the probability to detect these differences.

We decided for a questionnaire developed and tested by Schubert et al. in a sequence of studies (Schubert et al., 1999a/b; Regenbrecht, 1999). These authors suggested to differentiate between spatial presence (highly correlated to the "sense of being there", often considered to be the core concept of presence), involvement, and reality appraisal. All three are thought to be different facets of the sense of presence (Regenbrecht, 1999). Their presence questionnaire is designed to accomplish that.

The original version of this questionnaire features 14 questions. Their respective assignment to the three presence facets has been proven by factor analysis. Minor modifications due to the particular situation of our experiment were necessary, yielding an adapted set of 13 items (seven point Likert scale). Thus, we had to perform another factor analysis with our questionnaire results, see section 3.1. The final questionnaire could be filled out in a few minutes and was used twice within each experimental run (versions "A" and "B", permuted item order). Participants were asked to fill it out while still being immersed.

We consider it important to clearly distinguish the sense of presence from the factors possibly influencing it (see e.g. Regenbrecht, 1999, or Slater, 1999, for a discussion). In our definition, the respective values of these contributing factors establish a situation — modifiable by the developer or operator — which the participant *might* react to by developing a sense of presence depend-ing on stable individual characteristics, changing moods, etc.

1.3 Conceptualizing spatial perception

Among today's research topics in the field of visual perception are the stimulus cues, sensory mechanisms, and neural computations involved, as well as the interrelationship of perceived direction, distance, size, and motion (Loomis, 1996). A major part of this research is focused on observer-centered (egocentric) distance perception: The underlying assumption is that the other properties of spatial layout (e. g. lateral interobject distances, depth[1]) are mainly derived from egocentric distance (see Gillam, 1995, including a discussion of alternative views).

A multitude of size and distance/depth cues available to the observer have been identified. Cutting & Vishton (1995) and Cutting (1997) described 15 cues proposed by various researchers, including occlusion, relative size and density, linear perspective, relative brightness, motion parallax, retinal disparity, convergence, accommodation, and others. How do they interact to produce a distance perception? How does the visual system react if they provide conflicting distance information? Different theoretical models to analyse this *cue integration process* have been proposed (see e. g. Fine & Jacobs, 1999). As will be further motivated in section 4.2, we base our discussion on the *Modified Weak Fusion (MWF)*-model proposed by Landy et al. (1995). It suggests that the information of different cues is integrated in a linear fashion, the reliability of the individual cues acting as their weights in this process.

1.4 Empirical studies of spatial perception

The amount of empirical evidence concerning *distance and size judgement errors* in real environments is vast. A concise overview is given by Waller (1999). Generally, perceived egocentric distance seems to be compressed relative to distances orthogonal to the line of sight. Studies investigating estimation errors in VEs are less numerous. Some yielded similar results as those in real environments, the results of others differed strongly (see e. g. Henry & Furness, 1993; Lampton, 1995; Witmer & Kline, 1998; Waller, 1999; Hofmann et al., 2001).

Factors affecting size and distance perception in real environments have been subject to intense research for decades, too (see Gillam, 1995, and Cutting & Vishton, 1995, for reviews). Only in recent years, a number of studies has been published on factors affecting spatial perception in VEs. Various system related and cognitive factors have been analysed, including the variation of display type (e. g. Henry & Furness, 1993; Ellis & Menges, 1997; Waller, 1999), texture and stimulus size as well as navigational interface (Witmer & Kline, 1998), scene contrast (Eggleston et al., 1996), field of view (Waller, 1999; and references therein), and error-corrective feedback (Waller, 1999). Few studies have investigated the effects of isolated distance and size cues in VEs or with other imaging displays (e. g. Roscoe, 1984; Surdick et al., 1997; Ellis & Menges, 1998).

The sense of presence has not been among the influencing factors analysed yet. For the mechanism coupling presence and spatial perception we propose in section 4.2, accommodative distance information is an important moderator. Its role in distance perception has been subject to a controversial debate in the context of both real (see e. g. Künnapas, 1968; Semmlow & Hung, 1983; Fisher & Ciuffreda, 1988) and virtual environments (Roscoe, 1984; Roscoe, 1991; Surdick et al., 1997; Ellis & Menges, 1997; Ellis & Menges, 1998).

1.5 Measuring spatial perception

For the measurement of perceived distances, depths, and sizes, different methods have been used (see Loomis, 1996). Among them are estimations of perceived parameters in metrical units as well as comparisons with reference objects. We were particularly interested in comparing participants' perceptions of a real and a corresponding virtual cockpit. Thus, we had participants adjust the size of a virtual cockpit to that of a real reference cockpit seen just beforehand (matching of perceived sizes, see Figure 1).

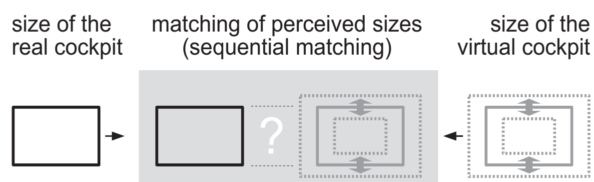

Figure 1. Method used to measure spatial perception in the virtual car cockpit.

2 Method

2.1 Methodological considerations

2.1.1 Twofold data analysis strategy

To analyse effects of presence on spatial perception, participants' sense of presence has to be varied. This can be accomplished by (1) modifying factors supposed to affect presence like frame rate, interactivity etc. (contribut-

1. In this article, the term *depth* is used to describe interobject distances along the direction of sight only. *Distance* is used here to denote the egocentric distances between an object and the observer.

ing factors), or by (2) relying on differences in participants' individual reactions to identical stimuli.

(1) Modification of contributing factors. If one tries to manipulate participants' sense of presence by varying contributing factors, one has to minimize *direct* effects of these factors on the dependent parameter under consideration (here: spatial perception; see Figure 2; compare Draper et al. 1998; Welch, 1999). Thus, the choice of suitable contributing factors is restricted. It is hard to predict if the chosen factors are effective enough to systematically dominate participants' individual reactions. If they do, the proper method to analyse effects of presence on spatial perception is a comparison of the presence and spatial perception means between high and low presence groups.

(2) Relying on individual reactions. It is as hard to predict whether participants' individual reactions to identical stimuli (no contributing factors varied) are strong enough to generate the necessary variations in presence. If they do, the proper data analysis method is a regression analysis (presence vs. spatial perception).

Due to restricted resources we were not able to conduct pre-tests with the necessary sample sizes. To enlarge the likelihood of significant results, we thus employed a twofold strategy: We tried to manipulate presence by varying a set of contributing factors (yielding four different experimental settings), but kept the number of participants large enough to perform regression analysis within each setting (identical stimuli). If the influence of the contributing factors proved to be weak, we could even perform regression analyses with participants from groups experiencing *different values of the contributing factors*. This would further enhance statistical reliability.

2.1.2 General experimental layout

The general layout of our experiment is schematically illustrated in Figure 1. Its main components are the following:

- *Combination of contributing factors.* We decided to combine the effects of different contributing factors to increases the probability of measurable differences in presence.
- *Separation of pictorial realism (PR) factors.* Varying pictorial realism usually involves high labour costs. We were interested in its effects on presence, which are not well understood yet (see also Welch et al., 1996). We thus varied pictorial realism (PR) factors separately from the remaining contributing factors. For brevity, we coined the group of these remaining factors "immersion (IM) factors" (see Witmer & Singer, 1998, and Slater, 1999, for a discussion of the term "immersion").
- *Four settings with uncoupled subject groups.* All IM and PR factors, respectively, were varied simultaneously. This resulted in four settings with low/low, low/high, high/low, and high/high combinations of IM/PR. We assigned four uncoupled groups of participants to these combinations.
- *Measurement of overall size, width and height perception.* Participants perception of overall cockpit sizes, cockpit width, and cockpit height was measured separately. All three cockpit dimensions are relevant parameters in product development.

Due to the high noise expected in both presence and distance/size estimations we decided to use the 0.1 level to judge significance of statistical tests.

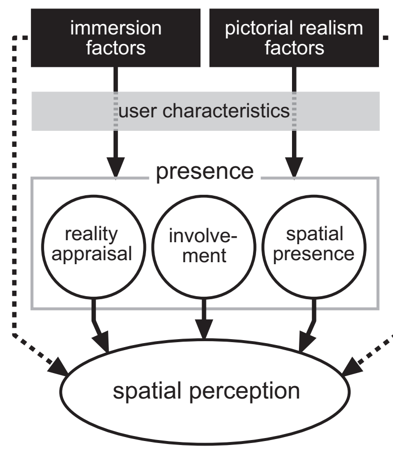

Figure 2. General experimental layout. The dashed lines denote possible direct effects of the contributing factors on spatial perception. The three-dimensional presence concept is adopted from Schubert et al. (1999a/b).

2.2 Participants

Seventy-seven people participated in the study, ranging in age from 20 to 60 years (9 female, 68 male). We mainly recruited passenger car development engineers. We expected them to have a homogeneous educational background concerning the mental representation of spatial structures. This was expected to reduce noise in the spatial perception measurements.

Some of the participants had used virtual reality technologies beforehand, but none of them on a regular basis. The participants' ability of depth perception was tested by assessing their ability to indicate the position of a virtual object in real space. Participants with corrected vision used their glasses or contact lenses during the experiment.

2.3 Apparatus

The virtual vehicle interior was displayed in a cubic-shaped five-sided back projection system (back projection on ceiling, floor, and three walls of the cube). The length of side of the projection planes was 2.5 m. The resolution on each screen was 1020×1020 pixels, the refresh rate 114 Hz. The virtual environment ran on an SGI™ Onyx2™ graphics engine. The participants' head movements were tracked with a six-DOF tracker (MotionStar® by Ascension®), the eye channels were separated using StereoGraphics® CrystalEyes® shutter glasses. For participants' immersive scaling tasks a tubular hand-held interaction device was provided (see section 2.5). Pressing a button on the device and simultaneously rotating it operated the scaling. For the size comparisons, a real cockpit of the corresponding vehicle type was located in a room next to the projection cube.

2.4 Stimuli

The virtual scene used in these experiments was the front half of a passenger car interior. The 3D model was based on the original data used in the product development process. It was displayed in original size, but scaled during the size estimation task. The virtual model was combined with a real driver's seat and steering wheel. They were introduced to enhance participants' impression of sitting in a vehicle cockpit and to constrain their movements as in a real car. Figure 3 schematically illustrates the relative locations of virtual model, real world props, screens, and the participant's head.

The virtual scene was modified to allow for (1) the differentiation between high and low pictorial realism, and (2) different scaling procedures used in the size estimation task.

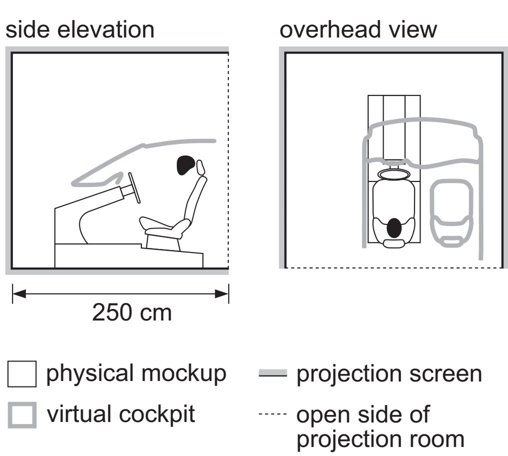

Figure 3. Schematic views of the experimental setup. Participants sat in the driver's seat and could touch the steering wheel. A corresponding real vehicle was located in a room nearby for the size comparisons.

(1) Variation of pictorial realism. The high pictorial realism cockpit featured a high level of three-dimensional detailing and was completely textured in colour. In the low pictorial realism cockpit, most of the three-dimensional detailing not influencing the overall cockpit size impression was removed (switches, instrumentation, safety belts, etc.). No textures were applied, the surfaces were uniformly coloured. Figures 4 (a/b) show views of the two styles approximately from a participant's station point.

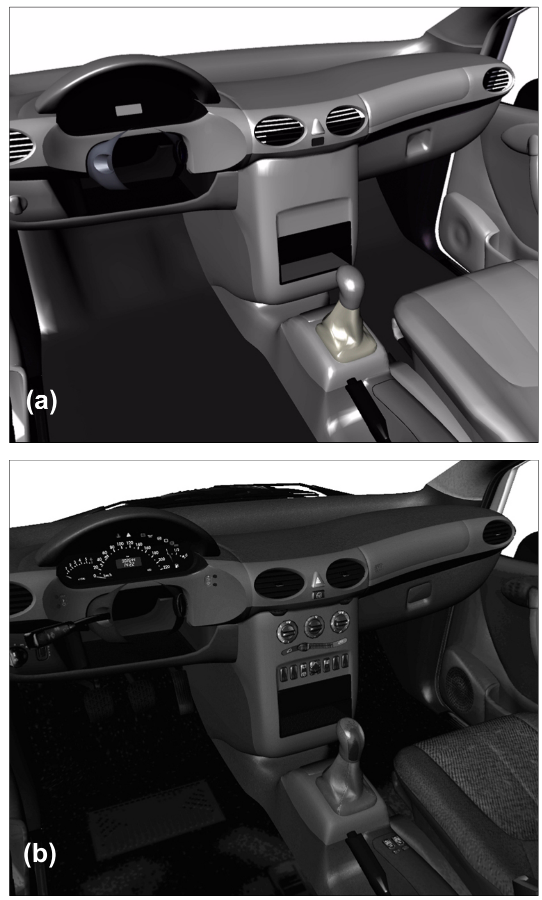

Figure 4. Views of the cockpits used for the (a) low and (b) high pictorial realism settings. Note that the virtual driver's seat and steering wheel were replaced by real ones.

(2) Modifications for different scaling procedures. Participants matched the overall size, width or height of the virtual interior to that of the real interior seen beforehand. For this purpose, the interior was scaled differently in three consecutive sessions (uniform three-dimensional scaling, one-dimensional horizontal scaling, partial one-dimensional vertical scaling; see Figure 5 for details). It was scaled in just indictable steps by factors of $(1 \pm n \times 0.02)$ relative to the original model (n = 1, 2, 3...). For the one-dimensional horizontal scaling all cir-

Table 1: Immersion factors used to influence presence (varied simultaneously)

immersion factor	value for "low"	value for "high"
frame rate	appr. 2 – 2.5 frames/s (for each eye)	appr. 11 – 14 frames/s (for each eye)
interactivity	no immersive interaction	object scaling by immersive interaction
duration of exposure	appr. 8, 3, and 7 min. (sessions 1 – 3)	appr. 11, 6, and 7 min. (sessions 1 – 3)
vividness of scene	no animated objects	animated emergency indicator
mental priming	disillusioning description of experience	illusion-enhancing description
real world ambient light	dim ambient light in real surroundings	only light source was projection
real world background noise	background noise from surroundings	background noises damped
communication w/ instructor	direct addressing of participant	no direct addressing

Table 2: Pictorial realism factors used to influence presence (varied simultaneously)

pictorial realism factor	value for "low"	value for "high"
detailing of 3D model	most 3D details removed	realistically equipped interior
surface textures	no textures applied	realistically textured

cular details were removed, as the transition from a circular to an elliptical shape can easily be recognized. The vertical one-dimensional scaling affected none of the circular details.

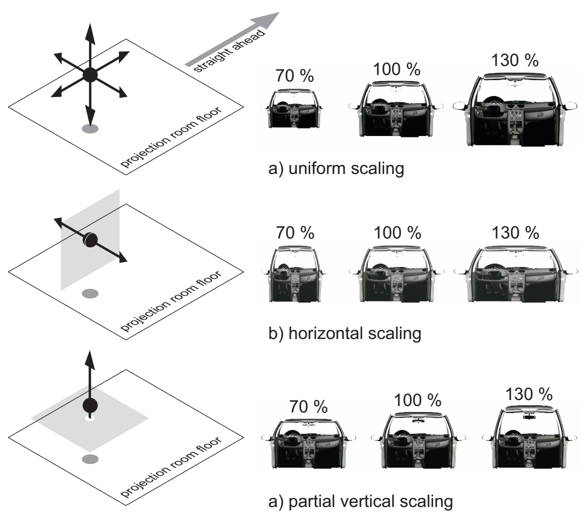

Figure 5. Cockpit scaling styles used in the size estimation tasks (black spheres: participants' station point; grey planes: scaling origin planes; arrows: directions of scaling).

2.5 Choice of contributing factors

Our choice of factors contributing to presence and their respective values followed a compromise strategy: The factors should have minimized direct effects on spatial perception, reflect a realistic application situation, and be effective enough to produce significant differences in presence. Our assessment of their effectiveness was based on a review of previous theoretical and experimental work (e.g. Heeter, 1992; Sheridan, 1992; Held & Durlach, 1992; Slater et al., 1994; Steuer, 1992; Welch et al., 1996; Slater & Wilbur, 1997; Lombard & Ditton, 1997; Witmer & Singer, 1998; Regenbrecht, 1999; Regenbrecht, 2000), and the authors' personal experiences. Tables 1 and 2 summarize the contributing factors finally chosen with their respective values for the "low" and "high" settings.

Direct influences of the selected factors on spatial perception might have been expected for the two pictorial realism factors, interactivity, and frame rate. Added texture or 3D detailing might in general improve the efficiency of some distance/depth cues. There has been no strong evidence for such a correlation in VEs to date though (e.g. Witmer & Kline, 1998).

Concerning interactivity, a direct influence could not have been excluded if the interactivity was an integral part of the task evaluated. For this reason, we introduced a second ("placebo") task in the high immersion settings that was not related to the size estimation task and was not evaluated. Participants were asked to alter the scaling of cockpit parts and scale them back to their original sizes by means of an immersive interaction. Figure 6 shows the interaction type used. The placebo task was easily and quickly learnable and proved to be involving in preliminary experiments.

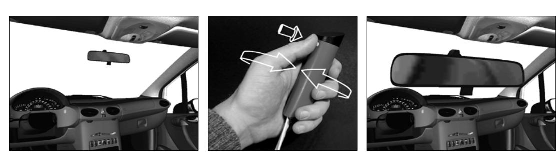

Figure 6. "Placebo" interaction.

A factor presumably strongly influencing presence is the frame rate. But due to the temporary distortions caused by a low frame rate (or high system lag), varying the frame rate might affect spatial perception as well. We decided to use the frame rate as a contributing factor, but checked for possible direct effects on spatial perception in a parallel experiment (see Hofmann et al., 2001).

2.6 Procedure

Participants' task was to memorize the size/proportions of the *real* vehicle interior and to subsequently choose the *virtual* interior scaling that fitted their memory of the real interior best. This procedure was repeated twice for each participant, employing a different scaling technique in each session. She or he was informed of the type of scaling currently employed. Participants were shown the real interior prior to each VE session to refresh their memories. Upon entering the VE, the virtual cockpit scaling was off the correct size (randomized). It was then judged by the participant (too big/wide/high, too small/narrow/low, just right). The judgement was given aloud and the operator immediately adjusted the size by one step in the indicated direction. This procedure was repeated until the participant judged the size (proportions) to be correct. Participants were asked not to use parts of their body for measuring distances to assist their estimations.

Just after completion of the estimation tasks in the first and third session, participants were asked to fill out presence questionnaires A and B, respectively. Doing so they remained seated, the virtual cockpit was still displayed, and they were still wearing the shutter glasses. Following the third session, each participant was asked to complete another questionnaire inquiring the occurrence of simulator sickness, prior use of VEs and related technology, and personal data.

Participants were randomly assigned to the four experimental settings ($n_{low/low} = 18$, $n_{low/high} = 15$, $n_{high/low} = 21$, $n_{high/high} = 21$, for immersion/pictorial realism). Two participants had to be excluded from data analysis as they did not complete presence questionnaire B ($n_{tot} = 75$). Prior to each experimental run participants' interocular distances were measured and the projected images accordingly adjusted (Towa Medical Instruments® PD-82II® digital pupillometer).

2.7 Calibration

The aim of the calibration process was to determine the "actually projected" size of the virtual cockpit in real space. For this purpose, characteristic distances within the cockpit were measured using a transparent real ruler. The reading was done repeatedly (n = 10) for each distance. The estimated reading error was 0.5 cm, the standard deviation within the 10 readings ranged between 0.3 and 0.9 cm.

Different degrees of distortion were measured along the various distances and directions probed. We grouped and averaged those distortions relevant for size estimations in the respective scaling situations. These means were used to calibrate the zero lines of the estimation errors reported below.

3 Results

3.1 Factor analysis of presence questionnaire results

The results of questionnaires A and B were subject to separate but equally structured factor analyses (75 cases, all 13 questionnaire items used, main component analysis, Varimax rotation). In each case, the suitability of the data was checked using the measure of sampling adequacy (MSA) criterion (see e. g. Backhaus et al., 1996).

The results of questionnaire A did not proved to be suitable for factor analysis according to the MSA test (MSA value = 0.76 < 0.8). In addition, the analysis yielded factor loadings that only in part corresponded to the structure intended by the authors of the original questionnaire (Schubert et al., 1999a). We were not able to interpret them in an alternative sound way and thus excluded these results from further analysis. We assume that due to the employment of this questionnaire only a few minutes after their first VE exposure, it was too early for many participants to relate their own impressions to the way the questionnaire requested to express them.

As described in section 1.2, the items of questionnaire B were identical to those in A, but presented in a different order. Its results proved to be suitable for factor analysis according to the MSA criterion (MSA value = 0.81). It yielded three factors with eigenvalues > 1. Numerically, the questionnaire items could unambiguously be assigned to these three factors using a 0.5 threshold for loadings to be considered high (one loading was slightly below 0.5).

Regarding their content-related evaluation, the high loading items allowed a straightforward interpretation of the three factors that corresponded very well with that of the original authors (Schubert et al., 1999a). This could not be taken for granted due to our slight adjustment of the questionnaire. We coined the three factors reality appraisal, involvement, and spatial presence after Schubert et al. (1999a) (they used the term "realness" for the first factor).

For the variance and regression analyses reported below, each participant was assigned her or his respective factor values (extracted by regression) for reality appraisal, involvement, and spatial presence. The factor values were normalized (to a mean of zero and a variance of one).

3.2 Mean presence values

The factor values for the participants within each of the four IM/PR settings were averaged separately, enabling a comparison of the mean values of each factor across settings. The mean values were subject to separate variance analyses. As an overall result, the influence of the setting variation on presence values was notable but weak. Details are published elsewhere (Hofmann & Bubb, 2001). *Here, the findings of this analysis will be used to support the interpretation of the results of sections 3.3 and 3.4.*

Hofmann and Bubb (2001) found significant influences in the following cases only: For reality appraisal, the variance analyses yielded significant differences of the means between the low and high IM settings for high PR at the 0.1 (and 0.05) level ($F(1, 34) = 5.133$, $p = 0.030$, higher reality appraisal for high IM) and between the low and high PR settings for low IM at the 0.1 level ($F(1, 31) = 3.041$, $p = 0.091$, higher reality appraisal for low PR). For involvement, a significant difference of the means was found between the low and high IM settings for low PR ($F(1, 37) = 3.999$, $p = 0.053$, higher involvement for high IM). For spatial presence, the variance analyses yielded no significant differences of the means, with α-error probabilities ranging between 0.57 and 0.94.

3.3 Mean size estimations

As for the factor values, participants' size estimations within each of the four settings were averaged separately and were subject to separate variance analyses. Figures 7 (a-c) show the mean *estimation errors EE* for uniform scaling, horizontal scaling, and partial vertical scaling. The *estimation error* is defined as the ratio of the chosen size/scaling of the virtual interior S_{choice} and that of the real one the former was compared to (S_0):

$$EE\ [\%] \equiv \left[\frac{S_{choice}}{S_0} - 1 \right] \times 100\ .$$

The estimation error describes differences in linear dimensions. Note that a positive estimation error indicates an underestimation of the size or scaling of the virtual cockpit. As a more intuitive measure, we defined the *relative size perception SP_r* as

$$SP_r\ [\%] \equiv \frac{S_0}{S_{choice}} \times 100 = \frac{1}{1 + EE/100} \times 100\ .$$

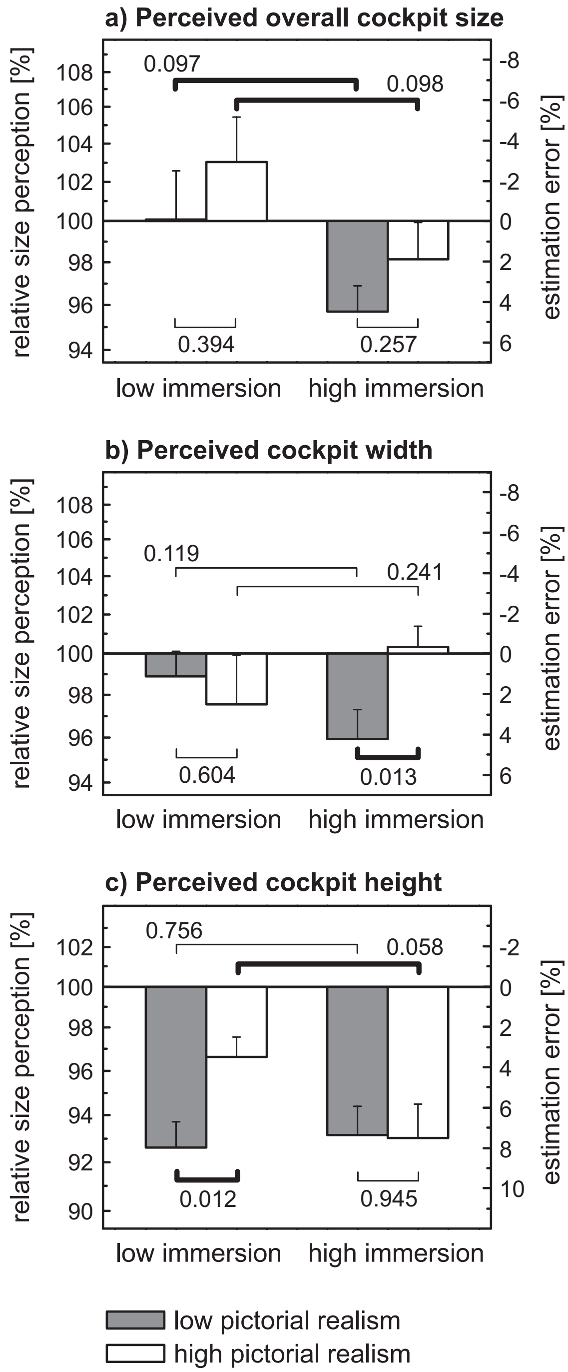

Figure 7. Mean size estimation errors (and corresponding relative size perception) means in the four experimental settings (and standard errors of the means). (a) uniform scaling, (b) horizontal scaling, and (c) partial vertical scaling. Positive estimation errors denote underestimation of the virtual cockpit size. The brackets denote the results of the variance analyses (thick bracket: significant difference of the means at 0.1 level; thin bracket: not significant difference; numbers: α-error probabilities). The statistical analysis is valid for the estimation error only (not for the relative size perception). For a relative size perception < 100 %, a correctly projected virtual cockpit was perceived too small.

SP_r gives the percentage of the actually displayed size[1] that the cockpit has been perceived with ($SP_r > 100$ %: overestimation; $SP_r < 100$ %: underestimation). All statistical tests were performed using the estimation errors (due to the non-linear correlation between SP_r and the raw data S_{choice}). The zero lines in Figures 7 (a-c) were calibrated as described in section 2.7.

For *uniform three-dimensional scaling*, the variance analyses yielded a significant difference of the means between the low and high IM settings for low PR ($F(1, 36) = 2.905$, $p = 0.097$) and high PR ($F(1, 34) = 2.887$, $p = 0.098$). For *horizontal one-dimensional scaling*, the variance analyses yielded a significant difference of the means between low and high PR settings for high IM ($F(1, 39) = 6.741$, $p = 0.013$). For *partial vertical one-dimensional scaling*, we found a significant difference of the means between low and high IM for high PR ($F(1, 34) = 3.835$, $p = 0.058$) and between low and high PR for low IM ($F(1, 31) = 7.105$, $p = 0.012$). No other significant differences were found (see Figure 7 for error probabilities).

3.4 Correlation of presence values and size estimations

As our measurements of both presence values (i. e., factor values) and size estimations were metrical, regression analysis could be used to investigate possible correlations. We used linear regression, as no theoretical considerations suggested higher level regression functions. In sections 3.4.1 and 3.4.2, we report the results of two successive stages of this analysis, keeping either one setting variable (IM or PR) or both constant within the analysed samples (“combined samples” or “separate samples”, see Figure 8). The validity of the regression analysis of the combined samples will be discussed in section 4.1.

3.4.1 Regression analyses of combined samples

As can be seen in Figure 8, we constructed four combined samples. For these samples, all possible combinations of estimation errors (using one of the three scaling procedures) and the three presence facets were analysed for correlations.

The α-error probabilities p reported below denote the probability to erroneously assume an actually not existing linear correlation. b is the regression coefficient, $b_{95\%}$ denotes the interval that contains the true slope of the regression function with a probability of 95 %. The regression analyses yielded significant linear dependencies of size estimations on presence values in four cases:

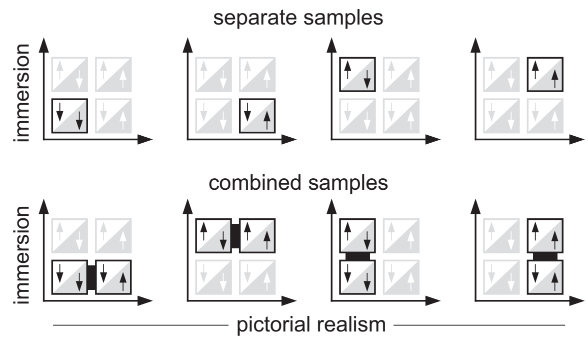

Figure 8. Different sample types used in the regression analyses. The arrows denote low or high values of immersion and pictorial realism. In the lower row, participants of two groups are combined to form a larger sample. See section 4.1 for a discussion of the validity of the regression analyses performed with these combined samples.

- estimation error (uniform scaling) vs. *reality appraisal* for low IM ($F(1, 31) = 5.000$, $p = 0.033$, $b = 3.57$, $b_{95\%} = [0.31, 6.82]$, PR varied) and for low PR ($F(1, 36) = 4.118$, $p = 0.050$, $b = 2.63$, $b_{95\%} = [0.02, 5.27]$, IM varied),
- estimation error (partial vertical scaling) vs. *involvement* for low IM ($F(1, 31) = 3.143$, $p = 0.086$, $b = -1.53$, $b_{95\%} = [-3.28, 0.23]$, PR varied), and
- estimation error (uniform scaling) vs. *spatial presence* for high IM ($F(1, 39) = 5.335$, $p = 0.026$, $b = -2.58$, $b_{95\%} = [-4.84, -0.32]$, PR varied).

Figures 9 (a-d) show the respective scatter plots, including the linear regression functions. Note the different slopes of the regression functions: *for an increase of involvement and spatial perception, the cockpit is perceived larger; for an increase of reality appraisal, it is perceived smaller*.

Two additional significant correlations were found, but the corresponding scatter plots suggested that the low error probabilities were caused by single data points (outliers).

3.4.2 Regression analyses of separate samples

Within the separate samples (both setting variables kept constant), effects of immersion or pictorial realism are ruled out. The samples are smaller than those used in 3.4.1. The probability of statistically confirming an existing correlation is decreased, and statistical evidence found is less reliable. Hence, the regression analyses of the separate samples are only used to confirm (or rebut) the results of the previous section. The following significant correlations were found:

1. The “actually displayed size” was measured by *direct* comparison of real and virtual objects, see section 2.7.

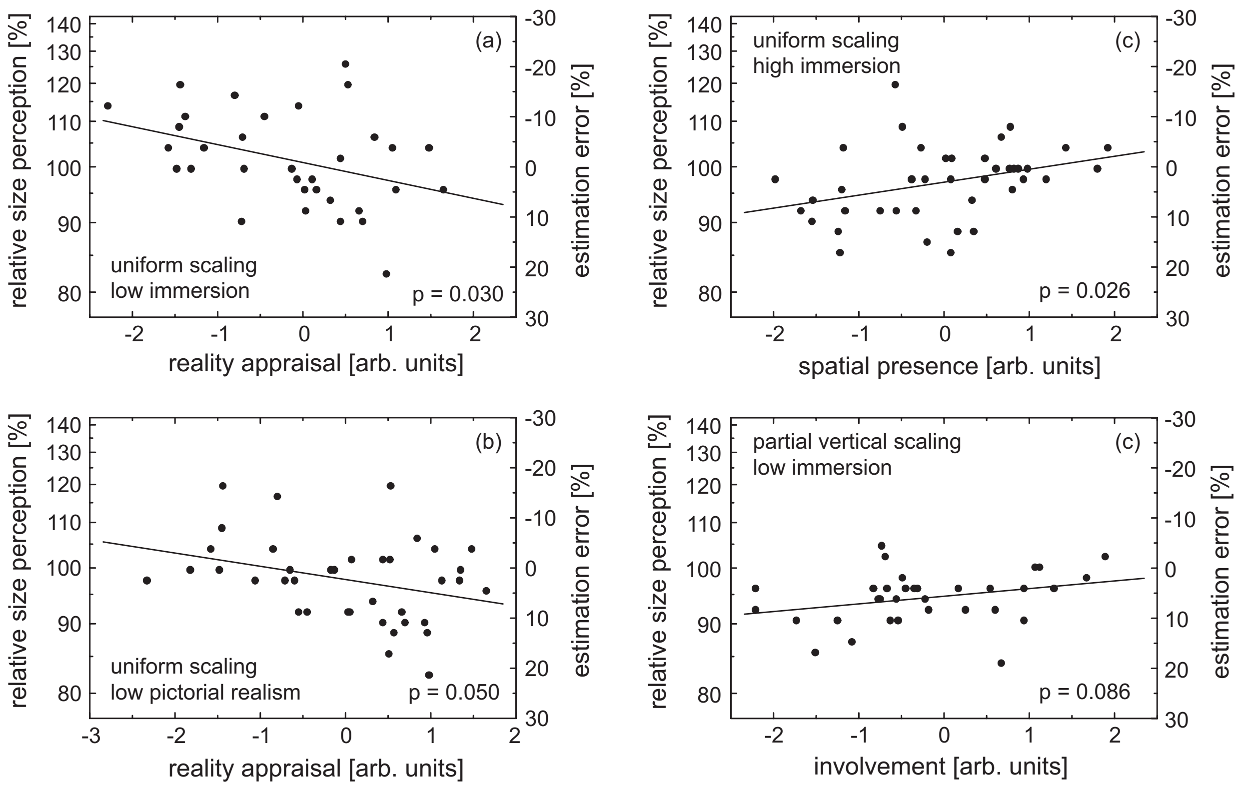

Figure 9. Significant linear correlations of estimation error vs. presence facet for combined samples (either immersion or pictorial realism constant). Significant correlations were found for all three presence facets. Each data point represents the values of a single participant. Plots of the linear regression functions are included, p is the respective α-error probability. Positive estimation errors denote underestimation of the virtual cockpit size. The corresponding relative size perception values give a more intuitive understanding of the results: For a relative size perception < 100 %, a correctly projected virtual cockpit was perceived too small.

- estimation error (uniform scaling) vs. *reality appraisal* for low IM and low PR ($F(1, 16) = 3.451$, $p = 0.082$, $b = 4.13$, $b_{95\%} = [-0.58, 8.85]$),
- estimation error (partial vertical scaling) vs. *involvement* for low IM and high PR ($F(1, 13) = 4.023$, $p = 0.066$, $b = -1.72$, $b_{95\%} = [-3.57, -0.13]$), and
- estimation error (uniform scaling) vs. *spatial presence* for high IM and low PR ($F(1, 18) = 6.316$, $p = 0.022$, $b = -2.81$, $b_{95\%} = [-5.15, -0.46]$).

These three cases coincide with the four that showed significant correlations in the previous section regarding participants (subsamples of those in the previous section), scaling technique used, and presence facet under consideration. They show the same directions of dependence. *Thus, they support the validity of the correlations found in the combined samples.*

Two other numerically significant correlations were found within the separate samples:

- estimation error (horizontal scaling) vs. *spatial presence* for low IM and high PR ($F(1, 13) = 6.816$, $p = 0.022$), and
- estimation error (uniform scaling) vs. *involvement* for low IM and low PR ($F(1, 16) = 6.058$, $p = 0.026$, $b = -5.42$, $b_{95\%} = [-10.09, -0.75]$).

A scatter plot of the former correlation does not support the assumption of a linear correlation. The latter does not coincides with any sample combination showing a significant correlation in section 3.4.1, but shows the same direction of dependence on involvement as reported above.

4 Discussion

In section 2.1, two statistical methods to investigate effects of presence on spatial perception have been outlined: (1) comparisons of mean differences of presence and spatial perception among the four setting, and (2) regression analyses. Due to the weak systematic influence of the setting variation (i. e., immersion and pictorial realism variation) on presence, method (1) cannot be effectively employed.

The results of the regression analyses are promising though, *showing significant correlations of all three presence facets with spatial perception*. What remains to be clarified is the following: Was it justified to analyse the combined samples, with immersion or pictorial realism acting as a *moderator variable* within these samples? This will be looked at in section 4.1.

Having done that, we will propose an explanation for the observed correlations of presence facets and spatial perception. The influence of the scaling technique on the observability of significant correlations is discussed next. We proceed by addressing the mean differences in spatial perception between settings, proposing a direct influence of two contributing factors. Finally we discuss the magnitude of the estimation errors and practical implications of our findings. Details of the effects of immersion and pictorial realism on presence are discussed elsewhere (Hofmann & Bubb, 2001).

4.1 Overestimation of correlations in the combined samples?

Participants within a combined sample experienced different values of either immersion or pictorial realism. IM or PR might have acted as *moderator variables*: Differences of the means in presence values and/or spatial perception *between the two groups within the combined sample* can lead to an over- or underestimation of the actual correlations by those calculated in the regression analysis (Bortz, 1999):

1. An *overestimation* can occur if the means of a presence facet *and* spatial perception differ significantly within the same combined sample.
2. If only the means of a presence facet *or* spatial perception differ significantly, an *underestimation* of the correlation between the presence facet and spatial perception is possible.

A comparison of the results of sections 3.2 (presence means) and 3.3 (spatial perception means) showed that an overestimation according to (1.) *can be ruled out in all cases with significant correlations* in the combined samples. An underestimation of correlations according to (2.) might have taken place in a number of cases. The enhanced statistical reliability due to the enlarged samples by far outweighs this possible disadvantage though.

4.2 Effects of presence on spatial perception: a coupling mechanism

We found statistical evidence for presence-related effects on spatial perception in four instances, including all three presence facets. But what might be the mechanism causing these correlations?

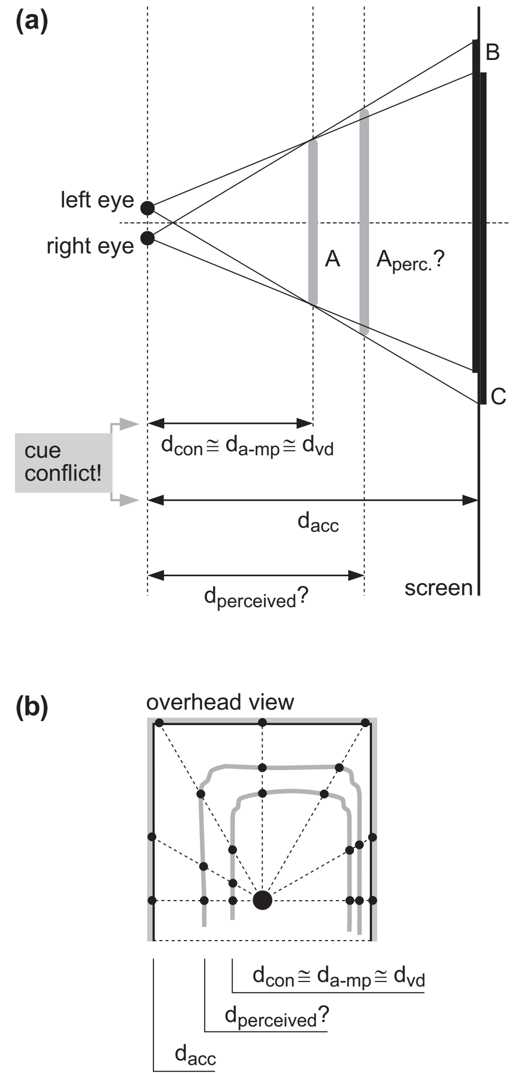

Figure 10. (a) accommodation-related cue-conflict in the distance perception of a virtual object A in a projection system (see text). The distance information d_{acc} provided by accommodation differs from that given by other distance cues (convergence (d_{con}), vertical disparity (d_{vd}), motion perspective ($d_{a\text{-}mp}$), and possibly others), as the user focuses on the double image B/C on the screen. (b) The effect of the perceptual situation from (a) in the setup used in the experiments reported here.

Our explanation is based on the distance/depth cue integration model by Landy et al. (1995). In short, we suggest the following mechanism: *Firstly, the distance information provided by accommodation differed strongly from that of the other cues available, causing a cue conflict. Secondly, the weight of the accommodative information in the distance cue integration process was modified by the observer's degree of presence. Hence, the overall perceived distance (and therefore the perceived size of the cockpit, see below) depended on the degree of* *presence.* We motivate and detail this explanation in five steps.

Step 1: Dominant role of distance perception. Participants could estimate the overall size of the cockpit in two ways: either by judging the *size* of those parts of the cockpit positioned in their current direction of sight, or by judging the *absolute distances* to these parts and the cockpit shell. The perception of object sizes is generally thought to depend on their perceived distance though (see e. g. Gillam, 1995). The perception of *depth* between cockpit parts might have been used by the visual system to assist distance perception. If this kind of integration of depths to an absolute distance perception actually happens, is an unresolved matter (compare Loomis, 1996). Thus, participants impression of absolute distances is the parameter to look at here.

Among the cues providing absolute distance information are convergence (Fisher & Ciuffreda, 1988; Gillam, 1995), accommodation (Fisher & Ciuffreda, 1988; Ellis & Menges, 1998), absolute motion parallax (Sedgwick, 1986), and possibly vertical disparity (Gillam, 1995). Cues like horizontal disparity, relative motion parallax, relative size etc. provide only depth information (see e. g. Cutting & Vishton, 1995).

Step 2: Accommodation-related cue-conflict. In VEs, a sharp picture can only be perceived in the picture plain. If a virtual object is projected to be perceived in front or behind the picture plain, the accommodative distance information d_{acc} differs from that provided by convergence (d_{con}), absolute motion parallax ($d_{a\text{-}mp}$), vertical disparity (d_{vd}) and possibly others (see Figure 10). The latter cues can — to a first approximation — be regarded to carry similar distance information. This *cue conflict* caused by accommodation was constantly present in our experiments. The virtual surfaces whose distances should be estimated were located in front of the projection screens (Figure 11).

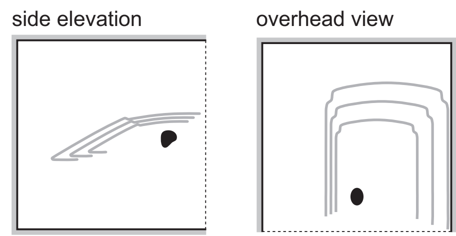

Figure 11. Relative locations of virtual cockpit surfaces and projection screens for scaling factors of 80, 100, and 120 % of the original size (uniform scaling).

Step 3: Cue integration and perceptual weights. How did the visual system deal with this cue conflict? How was the information from the different cues integrated? Landy et al. (1995) proposed a weighed linear integration model for the process of distance and depth perception (*Modified Weak Fusion*-model; see Figure 12). According to Landy et al., a distance map is established for each cue individually. Cues might interact in this process. In a second step, a reliability map is assigned to each cue. These reliability maps determine the weight α_i of each cue in the integration process. The perceived distance d_p for a point in space can be approximated by

$$d_p = \sum_i \alpha_i d_i ,$$

d_i being the distance information of cue i for this point (see Landy et al., 1995, for details; simplified). Landy et al. (1995) as well as Fine & Jacobs (1999) gave examples for the applicability of this model.

After Landy et al. (1991), the reliability assigned to a cue is reduced if its information strongly conflicts with that of others that provide consistent information. This was the case for the accommodative cue in our experiments. Convergence, absolute motion parallax, and possibly vertical disparity provided similar distance information: they confirmed each other. Thus, *the weight α_{acc} of the accommodative cue could be regarded as the smallest among the cues available*.

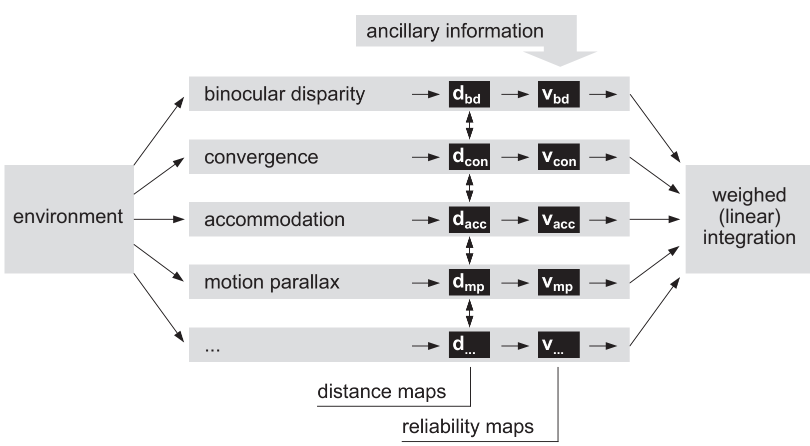

Figure 12. *Modified Weak Fusion*-model for depth and distance cue integration, after Landy et al. (1995; diagram adapted). See the text for details.

Step 4: Enhanced relevance of accommodation. Several mechanisms might have enhanced the weight of the accommodative distance cue though. (1) The distance information provided by (blur-driven) accommodation is thought to influence convergence. It causes the point of vergence to shift towards the accommodative demand ("accommodative vergence"; see Semmlow & Hung, 1983; Fisher & Ciuffreda, 1988). This process might have amplified the influence of the accommodative information on perceived distance. (2) In the low-light conditions of our experiment, participants' pupils dilated, yielding a relatively small depth of focus and thus an enhanced accuracy of d_{acc}. (3) The accuracy of d_{acc} might have been further enhanced and possibly α_{acc} increased by the visibility of the projection screen edges. They provided additional accommodative stimulus.

To sum up steps 1 through 4, we expect participants to perceive the cockpit *slightly, but notably larger* when the perceptual weight of the accommodative distance cue is *enhanced* (compare Figure 10). Finally, it remains to be answered why presence — or more precisely its three facets analysed here — interact with the cognitive cue integration process. We propose two ways of interaction. We cannot provide proof for any one of the two, but consider both to be reasonable:

Step 5a: Influence of spatial presence and involvement. In real space, the accommodative distance information is usually similar or equal to that given by other cues. Upon entering a VE, this is often not true any longer, resulting in the described cue-conflict. We suggest that the perceptual system initially reacts to this unfamiliar situation or *new perceptual rule* inherent in the virtual space by suppressing the weaker, conflicting cue (i. e., further reducing its weight). The weakest cue was the accommodative one in our case.

After a while, to the extent the user *accepts the VE as her or his current direct environment and focuses her or his attention on it*, the perceptual system might adapt to these new rules. It therefore accepts the conflicting distance information and stops suppressing the accommodative cue. Consequently, the perceived distance would increase with enhanced acceptance and/or attention. But acceptance of the VE as the current environment ("the sense of being there") and directing one's focus from real to virtual are just what spatial presence and involvement, respectively, are all about. *Hence, the cockpit was perceived larger with increasing involvement and spatial presence.*

Step 5b: Influence of reality appraisal. The explanation we suggest for the reality appraisal-related effect is similar, but opposite in direction. We suppose that judging the current (virtual) environment to be "real" — i. e. to be very similar to the environment that the user normally experiences — might diminish the acceptance of the perceptual rules inherent in the VE, but unfamiliar in the real environment. Judging the virtual environment to be real might be coupled to the dominance of perceptual processing used in real situations. As it would probably happen in a real environment, the conflicting, weaker (accommodative) cue is suppressed. *This results in a decrease of perceived distance with increased reality appraisal.*

The mechanism proposed in this section is suitable to explain all presence-related effects on spatial perception we found in our experiments.

4.3 Influence of the scaling techniques

We found the majority of presence-related effects on spatial perception when the uniform scaling technique was employed. For one-dimensional horizontal scaling, no significant (and optically trustworthy) correlation was found. What is the reason for this selective occurrence?

(1) Presence effect active, but not measurable. During the one-dimensional scaling procedures the cockpit was distorted. Apparently, participants were able to detect even slight distortions. If a correctly displayed cockpit was perceptually enlarged by the presence effect, participants were expected to choose a narrower/lower cockpit to account for that. But doing so, the cockpit was distorted. Thus, their scaling choice probably followed a compromise strategy: compensating for the presence effect vs. minimizing distortions. This most likely has attenuated the detectability of the presence effect.

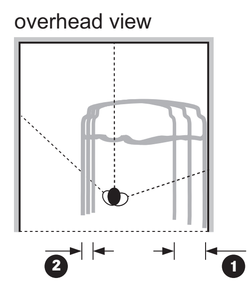

Figure 13. Effects of cockpit scaling (scaling origin at the location of the observers head, horizontal scaling). The strongest scaling effects were observable when looking to the right (1).

(2) Presence effect not active. In the viewing direction featuring the strongest scaling effects for horizontal scaling, the virtual surface was located only few centimetres in front of the projection screen, thus $d_{acc} \approx d_{con}$ (right cockpit side, see Figure 13). When this scaling technique was used, participants were observed to mainly look into this direction for their judgements. Thus, the distance in-

formation provided by accommodation was very similar to that provided by the other cues; variations of the perceptual weight of the accommodative cue had little or no effect on the perceived distance in the horizontal scaling task.

4.4 Direct influence of contributing factors on spatial perception

Due to the weak effects of the IM/PR-setting variations on presence values, the mean size perception differences between settings (section 3.3) can hardly be attributed to variations in presence. We rather suggest that two of the *contributing factors* varied between the settings had *direct effects* on participants spatial perception: frame rate (immersion factor) and surface texture/brightness (pictorial realism factor). *Taking two exceptions into account, they explain the complete structure of spatial perception means* (Figure 7).

4.4.1 Frame rate effect

In three out of six cases of IM-variation, we found a significant increase of perceived cockpit sizes with the transition from high to low immersion (in a fourth case significance was approached, $p = 0.119$). This was probably caused by the variation of the frame rate: we found a similar effect in a size estimation experiment *where only the frame rate was varied* (see Hofmann et al., 2001, for a detailed discussion; compare section 2.5). In the remaining two of the six cases, variation of the frame rate had no influence (Figure 7).

Mechanism. In a nutshell, the explanation proposed by Hofmann et al. (2001) is as follows: For low frame rates, a virtual object "follows" the user's head movements (and thus the line of sight) before its virtual position is adapted by the system. Generally users focus their attention on those parts of the virtual object the line of sight is currently moved to. Hence, those parts seem to be temporarily enlarged, resulting in a cognitive averaging process of motion-dependent size cues.

Exception one. For horizontal scaling and high PR, the effect was not detectable. Here, participants judged the cockpit size mainly by looking to their right (Figure 13). When turning their heads to the right, for low frame rates the cockpit moved mainly *parallel*, not *perpendicularly* to their line of sight. This type of temporary movement is harder to detect, as sensitive depth perception is necessary. Additionally, in the high PR cockpit brightness and contrast were reduced. This might have resulted in a deterioration of depth perception. Thus, the temporal shifts were only partly perceived.

Exception two. For partial vertical scaling and low PR, the frame rate effect is disabled, too (Figure 7). Here, only the upper part of the cockpit was scaled. It is conceivable that participants used a compromise strategy again for their size estimations, trying to balance distortions and overall size impression (compare section 4.3).

4.4.2 Brightness effect

In two cases, the cockpit was perceived significantly smaller with the transition from high to low pictorial realism settings. We attribute this effect to the higher surface brightness of the low PR model, which might result in surfaces being perceived closer (see e. g. Nagata, 1991; Cutting & Vishton, 1995; Surdick et al., 1997). Similar, but not significant differences of the means were observed in two other cases of PR-variation (see Figure 7). The remaining two cases coincide with the exceptions explained in section 4.4.1 and are likely to have the same cause.

4.5 Magnitude of the mean estimation errors

The magnitude of the mean estimation errors found in our experiments did not exceed 8 %. This is in the same order of magnitude that studies of other researchers yielded (e. g. Henry & Furness, 1993; Ellis & Menges, 1998; Waller, 1999; but see also Witmer & Kline, 1998). Direct comparisons provide limited insight though, as experimental conditions generally differed with regard to various aspects.

4.6 Practical implications

What is the impact of our research on practical applications of VEs? Presence is thought to be strongly influenced by individual user characteristics (see e. g. Regenbrecht, 1999). Our results further support this notion. In section 1.1, we argued that a correlation of presence and spatial perception is therefore likely to *diminish the reliability of spatial judgements* made in VEs. We found such a correlation in the experiments reported here.

To control the influence of presence on spatial perception in VEs, an analysis of the coupling mechanism we proposed might be helpful. Two ways of control are conceivable. One is obvious, but difficult to accomplish: Try and keep your users' sense of presence on a homogeneous level. A second possibility is to *eliminate the cue conflict* caused by accommodation. To accomplish this, one could locate virtual objects exclusively near the focus plain. In many types of applications, this is not feasible though. Another way to eliminate the cue conflict would be this: *automatically and dynamically adapt the optical distance of the focus plane to the distance of the virtual object currently looked at*. This sounds promising to us, but might prove to be technically demanding. No existing device we know of is adaptable in this way.

5 Conclusion

In this paper we investigated the effects of three facets of the sense of presence on spatial perception in a VE. The environment used was similar to a practical application in an industrial context. It provided a variety of cues to spatial perception.

As the main result of this study, we found statistically significant correlations of all three presence facets with spatial perception. An explanation was suggested that accounts for all linear correlations found in our experiments. It is based on the assumption that the sense of presence affects the way the visual systems reacts to a distance cue conflict typical for VEs. Spatial presence and involvement exhibited an effect opposing that of reality appraisal, the third component included in the presence concept assumed here. This suggests that further research is needed to investigate the mutual relation of the presence facets and their integration into a single presence concept.

The observed effects of presence could diminish the reliability of spatial judgements in VEs. This is underlined by the second result of our study: In our experimental setup — designed to closely resemble a practical application — immersion and pictorial realism variations had a notable, but overall weak influence on presence. Presence, and consequently spatial perception, proved to be strongly influenced by individual user characteristics. But by analysing the mechanisms coupling presence and spatial perception proposed here, ways might be found to control spatial perception in VEs more reliably.

Knowledge about both spatial perception and presence-related effects in VEs is being gathered by a growing number of researchers. However, a far more detailed as well as coherent picture of the mechanisms involved is needed. Only on that basis can we design virtual environments that successfully enter industrial, therapeutical, and other practical application areas.

Acknowledgments

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