

# An experimental exploration of the relationship between subjective impressions of illumination and physical fidelity

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## Abstract

Two experiments were carried out to explore the effect of rendering and interface fidelity on subjective impressions of illumination and perceived presence after exposure to a virtual environment (VE). In particular, a study that compares a real-world task situation to its computer graphics simulation counterpart is presented. The computer graphics simulation was based on photometry data acquired in the real-world space and was displayed on either a Head Mounted Display or desktop display utilising either monocular or stereo imagery and interaction interfaces such as the common mouse and head tracking. 105 participants across five conditions were exposed to the real and computer graphics environment and after completing a spatial task, subjective impressions of the illumination and sense of presence assessments were acquired. Relevant results showed a positive correlation between presence and subjective impressions of lighting (e.g. ‘warm’, ‘comfortable’, ‘spacious’, etc.) for the HMD monocular conditions. For the second study, the computer graphics scenes were rendered in varied levels of shadow accuracy utilising flat-shaded and radiosity rendering and were displayed on a stereo, head tracked Head Mounted Display (HMD). A total of 36 participants across three visual conditions were exposed to the scene and after completing a spatial task, subjective impressions of the illumination and sense of presence assessments were acquired. Relevant results showed a positive correlation between presence and subjective impressions of lighting (e.g. ‘warm’, ‘comfortable’, ‘spacious’, etc.) associated to the high-quality, full-shadow accuracy rendering condition. There was no effect of viewing condition upon subjective impressions of illumination for both studies, because of constant luminance levels. How real-world impressions of illumination could be simulated in a synthetic scene is still an open research question.

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## 1. Introduction

It is not computationally feasible to immerse an observer into an *interactive* artificial environment which mimics the panoply and complexity of sensory experiences associated with a real-world scene. For a start, it is

technologically challenging to control all of the sensory modalities to render the exactly equivalent sensory array as that produced by real world interaction [1–6].

Perceptual fidelity is not necessarily equivalent to physical simulation. The ultimate goal, as often argued, is to create synthetic spaces that are going to induce a sense of ‘presence’ similar to the real world. This goal is not necessarily achieved by accurately simulating the geometry and illumination of real-world spaces. Assembling a Virtual Environment (VE) system to match the

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human perceptual and motor systems is essential. For any given task or for any application that requires a high level of simulation fidelity and mainly targets, for instance, transfer of training in the real world, the ability to induce spatial awareness and impressions of illumination similar to the real world could be essential for a particular task situation.

Light has the obvious function of providing visibility for visual task performance. Flynn [7,8] however, argues that lighting properties should begin with the overall user well being, the visual quality of a room and should not be limited to task visibility. Acquiring subjective impressions of a lighting indicates a move towards assessing lighting designs from an impression point of view rather than a task point of view. One could argue that the presence related research for VE technologies is striving to achieve similar goals: to assess a software platform or a virtual interface generically, not by necessary linking this assessment with task performance even if the relationship between presence and task performance is often considered crucial.

One of the goals of research conducted by Rushmeier et al. [9] on perceptual image quality metrics was to relate subjective impressions of an environment to values computed from measured luminance images. In a more recent study focused on comparability of real and virtual environments for environmental psychology, factor analytic dimensions of evaluation, ambience, privacy and security were similar for both real and flat-shaded simulation of the real-world space, however, a fifth dimension termed arousal was absent in the VE [10]. The studies presented in this paper utilise ratings of impressions of illumination and presence in order to explore the relationship between impressions of illumination and physically-based simulation of computer graphics scenes of varied interface (Study 1) and visual (Study 2) fidelity. It is also valuable to identify whether statistical correlations exist between lighting impressions and perceived presence.

## 2. Background

### 2.1. Subjective responses to lighting

James Gibson has suggested that ‘the optic array from the (real) world can provide the same information without providing the same stimulation. Hence, an artist can capture the information about something without replicating its sensations’ [11]. Flynn [7,8] noted that many lighting systems are designed merely to function in a ‘permissive’ way, i.e. simply to allow performance or participation in an activity that involves vision, without attempting to affect observers’ impressions or behaviour. Many lighting designs, however, especially in a commercial context may intentionally or unintentionally

function more actively as shifting selectively human visual experiences: focusing attention, guiding spatial awareness and route comprehension and generally affecting subjective impressions of a room or task situation. A procedure for investigating the effect of light on impressions and behaviour is based on the use of Semantic Differential (SD) rating scales, including adjectives such as ‘clear-hazy’, ‘pleasant-unpleasant’, etc in [7,8]. Work with such scales has identified several broad categories of impression that can be applied to lighting (Table 1). The categories of impression of particular interest are:

- *Perceptual* categories such as visual clarity, spaciousness, spatial complexity, colour tone, glare.
- *Behaviour* setting categories such as public vs. private space, impressions of relaxing vs. tense space.
- *Overall preference* impressions such as impressions of like vs. dislike or impressions of pleasantness.

Subjective impressions of lighting have proved to be similar when utilising similar light settings in different rooms and with different object arrangements or activity settings indicating that the modifying effect of lighting is consistent across rooms [7]. This reinforces the theory that subjective impressions are more a function of the actual lighting characteristics than the actual environment in question.

Flynn [8] also suggests that visual patterns such as railroad signals and traffic shapes communicate certain categories of information. Visual patterns are used to guide individual and group behaviour and communicate ‘meaning’ without words that affects humans’ sense of place. The specific information and visual content associated with visual stimuli suggest that when generic lighting modes comprising of the patterns of light, shade and colour are altered, the impression or meaning for the typical room occupant or experimental participant is also affected.

Table 1 lists the set of bipolar adjectives related to participants’ subjective impressions of the illumination utilised in Study 1 and 2. The instructions were communicated as follows: ‘The following questions relate to your impression of the 3D room. Please, circle the appropriate step on the scale from 1 to 7, for each question’.

### 2.2. Presence

What sets VE technology apart from its ancestors is that in VE systems users can receive a number of distinct multi-sensory stimuli (i.e., visual, auditory, haptic) which are intended to provide a sensation of natural interaction with the virtual world and, consequently, an illusion of being present in a VE. Presence generally, refers to the sense of being present in time or space in a

Table 1  
List of bipolar adjectives representing subjective lighting impressions

Spacious	1	2	3	4	5	6	7	Confined
Relaxing	1	2	3	4	5	6	7	Tense
Bright	1	2	3	4	5	6	7	Dim
Stimulating	1	2	3	4	5	6	7	Subduing
Dramatic	1	2	3	4	5	6	7	Diffuse
Uniform	1	2	3	4	5	6	7	Non-uniform
Interesting	1	2	3	4	5	6	7	Uninteresting
Radiant	1	2	3	4	5	6	7	Gloomy
Large	1	2	3	4	5	6	7	Small
Like	1	2	3	4	5	6	7	Dislike
Simple	1	2	3	4	5	6	7	Complex
Uncluttered	1	2	3	4	5	6	7	Cluttered
Warm	1	2	3	4	5	6	7	Cold
Pleasant	1	2	3	4	5	6	7	Unpleasant
Comfortable	1	2	3	4	5	6	7	Uncomfortable

particular location (Webster's II Dictionary, 1984). In the world of media and emergent technologies such as video-conferencing, high definition television and home theatre, presence is defined as the perceptual illusion of non-mediation [12]. An illusion of non-mediation occurs when the user fails to perceive the existence of a medium in his/her communication environment and reacts as he/she would if the medium were not there. Presence in VEs can be explained as the participant's sense of 'being there' in a VE; the degree to which the users feel that they are somewhere other than they physically are while experiencing a computer generated simulation [13].

Various methods for assessing or measuring presence have been employed. Loomis [14] observed human responses to events that in the natural world would provoke 'reflex' reactions. For example, if one is sitting in front of a screen and experiences a scene of a car moving towards him/her very fast, then he/she might be 'forced' to turn to the right or left in order to avoid 'collision' responding to the moving image as if it was occurring in reality. A quantitative strategy proposed was based on an observer's inability to discriminate between a real and a VE by adding certain types of noise to a real image until it was impossible to be distinguished from the virtual image [13]. 'Breaks in Presence' could also be reported while a participant experiences a VE simulation [15]. Moreover, physiological measures such as blood pressure and heart rate have been employed [16]. One of the hot open challenges for research is to measure the degree of presence and its operational effectiveness [17].

The most common method for measuring presence is post-experiment self-report. The studies presented here employed questions included in the Slater, Steed, McCorthy, Maringelli 1998 questionnaire [18]. These questions are associated with the notion of presence itself and not with any characteristics of the technology. Hence, they could be applied to the real world as well as

to visual conditions involving displays. For example, the participant rates the extent during the experience that the particular 'space' of the synthetic scene displayed is the dominant reality as well as their level of perceiving the VE as a 'locality' or a 'place' that was visited rather than merely an image seen.

### 3. Study 1: methods

#### 3.1. Participants and visual conditions

Five groups of 21 participants were recruited to participate in this study from the University of Bristol, UK undergraduate and M.Sc. student population and they received course credits for their participation. Eighty percent of the participants in each group were male. A between-subject design was utilised balancing groups for age and gender. Participants were naïve as to the purpose of the experiment. Participants had either normal or corrected-to-normal vision. According to the group they were assigned to, participants were exposed to the environment for 3 min, in one of the following conditions:

1. In reality, wearing custom made goggles to restrict their field-of-view (FoV), allowing for monocular vision; referred to as the *real-world condition*.
2. Using a photorealistic computer graphics simulation on a monocular head-tracked HMD; referred to as the *HMD mono head tracked condition*.
3. Using the same application on a stereo head-tracked HMD; referred to as the *HMD stereo head tracked condition*.
4. Using the same application on a monocular HMD with a mouse interface; referred to as the *HMD mono mouse condition*.

5. Using the same application displayed on a typical monocular desktop monitor with a mouse interface, wearing the same restrictive goggles as in the real-world condition; referred to as the *desktop condition*.

The real environment consisted of a  $4 \times 4 \text{ m}^2$  room (Fig. 1). The computer graphics representation of the real environments was rendered utilising the Lightscape radiosity software. The geometry in the real room was measured using a regular tape measure with accuracy of the order of 1 cm. A photometry instrument (Minolta Spot Chroma meter CS-100) was employed to measure the chromaticity CIE( $x, y$ ) and luminance ( $Y$ ) values of the light and materials in the real room. The Minolta chroma meter is a compact, tristimulus colorimeter for non-contact measurements of light sources or reflective surfaces. The CIE (1931) colour space is based on colour matching functions derived by human experimentation and it incorporates the trichromacy of the human visual system (HVS). The illuminant (light source) was measured by placing a white sheet of paper in a specific position. Most of the materials (walls, objects, shelves, floor, plugframes) were measured at the same position. To ensure accuracy, five measurements were recorded

for each material, the highest and lowest luminance magnitudes were discarded and an average was calculated of the remaining three triplets.

The Lightscape radiosity rendering system uses RGB tristimulus values to describe surface characteristics. The values obtained for the illuminant and surfaces in the scene with the chroma meter needed to be converted from luminance and chromaticity co-ordinates to tristimulus RGB values. Measured chromaticity values were converted to RGB triplets by applying a matrix based on the chromaticity co-ordinates of the monitor phosphors [22]. For the final measurements the illuminant had to be taken into account. Measuring a diffuse surface under a given light source results in  $Yxy$  values including the contribution of the light source itself. Incandescent bulbs are quite orange and fluorescent light is quite green, however, the HVS perceives light in relative values and not as absolute measurements such as the ones out of the chroma meter. The colour constancy attribute of the HVS, generally, corrects for this effect and is responsible for humans perceiving a white sheet of paper as white under a wide range of illumination. If a participant is *immersed* into a synthetic space on a display, theoretically, this should be true as well, however, the small size of the displays and commonly narrow FoV prevents colour constancy from occurring. In relevant calculations for simulating real-world illumination in a synthetic world, therefore, colour constancy needs to be corrected in the rendering process since the HVS does not ‘function’ as in the real world due to the nature of the displays.

The principles explained above are quite complex issues related to colour vision and how the brain deals with perceptual constancies and are not fully understood. In Study 1, the illuminant in the real room as measured with a white sheet of paper was taken into account when converting the CIE( $x, y$ ) co-ordinates to RGB for all the materials measured in the real experimental room. The colour of the illuminant in RGB values was set as (1,1,1) for the radiosity rendering, e.g. white. All the displays were gamma corrected [15].

The computer graphics application was displayed on a Kaiser Pro-View 30 head tracked HMD and the application was driven by a PC with an average-cost graphics card. The Field-of-View (FoV) of this display is  $30^\circ$  diagonal.

### 3.2. Procedures

The Inter Pupillary Distance (IPD) of each participant was measured prior to exposure and the stereo application’s parallax (where applicable) was adjusted accordingly. The visual viewpoint was set in the middle of the room and participants could rotate horizontally on a full circle around that viewpoint and vertically approxi-



Fig. 1. The real and virtual environment.

mately on a half circle. The FoV and resolution was the same across the technological conditions. The exposure time was 3 min across conditions. The room where the experiment was taking place was kept dark during exposure. After completing a spatial task, subjective impressions of the illumination and sense of presence assessments were acquired.

A record of each participant's navigational patterns was monitored with the help of a digital compass placed on the swivel chair participants were sitting on. Whilst this information is not at a high enough resolution to be useful in determining the time spent looking at each object in the room, the amount and location of participants' idle time was monitored so as to ascertain that it was similar across visual conditions [19].

### 3.3. Study 1: Results

Lighting impressions and presence data were analysed using a comparison of means before carrying out an analysis of variance (ANOVA) across conditions [20]. ANOVA is a powerful set of procedures used for testing significance where two or more conditions are used. Significance decisions involve rejecting or retaining the null hypothesis which claims that groups are identical. The null hypothesis is rejected when the probability that a result occurring under it is less than 0.05. In addition to this generic analysis and to avoid the theoretical problem of ordinal data, a binomial regression analysis was employed. This method verified the results related to significant differences identified by the generic ANOVA analysis.

There was no significant effect of visual condition upon the illumination impressions and presence dataset. The relevant means are shown in Table 2. This is not a surprising result since the computer graphics rendering was the same across conditions with the navigation interface varied. The photometry measurements acquired from the real world space ensured that illumination was simulated as accurately as possible between the real world and the computer graphics rendering.

A significant positive correlation was revealed between the lighting impressions dataset and the presence dataset for the HMD mono head tracked condition

( $r = 0.47$ , Spearman's correlation,  $p < 0.05$ ) and for the HMD mono mouse condition ( $r = 0.37$ , Spearman's correlation,  $p < 0.05$ ). Interestingly, according to these correlations a high level of perceived presence resulted in a high rating of 'comfort', 'warmth', 'spacious' or 'relaxing' impression associated with subjective responses to lighting for these HMD conditions. Lighting ratings are structured in a somewhat reverse way to the presence questionnaire since high ratings for presence indicate a high level of perceived presence, however, low assessments for subjective responses to lighting results in a 'radiant', 'warm', or 'pleasant response'.

## 4. Study 2: methods

### 4.1. Participants and visual conditions

Three groups of 12 participants were recruited from the University of Sussex, UK postgraduate population. Eighty percent of the participants from each group were male. A between-subject design was utilised balancing groups for age and gender. Participants were naïve as to the purpose of the experiment. Participants had either normal or corrected-to-normal vision. According to the group they were assigned to, participants were exposed to the environment for 45 s, in one of the following conditions:

1. Using an interactive radiosity computer graphics simulation of an office on a stereo head-tracked Head Mounted Display (HMD); referred to as the *high-quality condition* (80% radiosity iterations).
2. Using an interactive radiosity computer graphics simulation of the same office on a stereo head-tracked HMD; referred to as the *mid-quality condition* (40% radiosity iterations).
3. Using a low quality, interactive flat shaded computer graphics simulation of the same office on a stereo head-tracked HMD; referred to as the *low-quality condition*.

Each environment varied considerably with regard to shadows. The flat-shaded environment did not include any. Radiosity algorithms, however, display view-independent diffuse interreflections in a scene assuming the conservation of light energy in a closed environment (Fig. 1). All energy emitted or reflected by every surface is accounted for by its reflection from or absorption by other surfaces. The result of a radiosity solution is an interactive three-dimensional representation of light energy in an environment allowing for soft shadows and colour bleeding that contribute towards a photo-realistic diffuse image. No specular reflections were computed. The luminance level of the scene (brightness) was constant across conditions (Fig. 2).

Table 2  
Study 1: overall means for presence and lighting impressions across visual conditions

	Presence	Lighting impressions
Real	4.27	4.20
Desktop	3.73	4.01
HMD mono head tracked	3.48	4.04
HMD mono mouse	3.64	3.90
HMD stereo head tracked	3.51	4.14



The environment of the mid-quality condition was a result of 40% radiosity iterations. The environment of the high-quality condition was a result of 80% of available radiosity iterations. In all cases, a single ceiling mounted light source was used. The basic model construct was identical and the contents and room layout remained unchanged across conditions.

The computer graphics application was displayed on a Kaiser Pro-View 30 head tracked HMD and the application was driven by a PC with an average-cost graphics card. The FoV of this display is 30° diagonal. The experimental space consisted of a room, represent-

ing an academic's office including various objects (Fig. 2). The radiosity rendering process described above resulted in three distinct models of varying polygon count. The viewpoint was set in the middle of the virtual room and navigation was restricted to a 360° circle around that viewpoint and 180° vertically (rotation). Participants were sitting on a swivel chair during exposure.

Due to the increased polygon count, the high-quality radiosity environment placed a greater computation demand, therefore, it could not be rendered and displayed in real-time as rapidly as either the mid- or low-quality versions. In order to maintain parity with regard to the display and update speed of each environment given the differing levels of computational load, the maximum frame-rate of the high-quality environment was ascertained via the use of a simple frame-rate counter, at 12 frames per second (fps). The frame rate was kept constant across conditions. A simple subsystem calculated the actual frame rate the selected environment was running at, compared this to the desired 12fps and paused the simulation for the amount of time corresponding to the differential in frame-rate. This subsystem was run by the simulation once every frame, thus maintaining a constant 12fps regardless of the complexity of the scene. Each of the three environments was presented in stereoscopic 3D by employing a dual channel video subsystem.

#### 4.2. Procedures

The inter pupillary distance (IPD) of each participant was measured prior to exposure and the application's parallax was adjusted accordingly for each individual. This had an impact on the achievable frame-rate since each polygon position must be calculated twice, once based upon the view direction detected via the head tracker and again based upon the same information plus the parallax differential. The results of such techniques are visibly impressive, but may contribute to the average frame-rate (12fps) that was observed during the experimental simulation which, however, was considered adequate.

After completing a spatial task, subjective impressions of the illumination and sense of presence assessments were acquired. The visual viewpoint was set in the middle of the room and participants could rotate horizontally on a full circle around that viewpoint and vertically approximately on a half circle. The room where the experiment was taking place was kept dark during exposure. Participants were led to believe that this was just a test phase of the main experiment, therefore, they were not aware of the experimental task prior to exposure.

Although this study did not include systems necessary to track eye movement, a record of each participant's



Fig. 2. Flat-shaded rendering (above), mid-quality radiosity rendering (middle) and high quality radiosity rendering (bottom).

head movement was monitored through software. Whilst this information is not at a high enough resolution to be useful in determining the time spent looking at each object in the room, the amount and location of participants' idle time was monitored so as to ascertain that it was similar across visual conditions. A measurement was taken once every 4 frames, providing 3 measurements every second across all conditions.

#### 4.3. Study 2: Results

Illumination impressions and presence data were analysed using a comparison of means before carrying out an ANOVA across conditions [20]. Significance decisions involve rejecting or retaining the null hypothesis which claims that groups are identical. The null hypothesis is rejected when the probability that a result occurring under it is less than 0.05. In addition to this generic analysis and to avoid the theoretical problem of ordinal data, a binomial regression analysis was employed. This method verified the results related to significant differences identified by the generic ANOVA analysis.

The overall means for lighting impressions and presence are shown in Table 3. The rendering quality did not prove to have a significant effect upon the subjective impressions of lighting dataset. This is not a surprising result since the luminance level of the scene was constant across conditions, despite the varied shadow accuracy.

An overall effect of condition was not revealed for the perceived presence dataset. This is in accordance with similar results in previous studies [5,6,21]. The presence measuring device employed either failed to pick up an effect of condition upon presence or there was not an effect of condition across conditions. Only a concrete understanding of presence, in a way that will allow formal assessments of its perceived level in experimental studies such as this one (if this is ever possible or desirable) will aid towards forming relevant conclusions.

A statistically significant positive correlation was revealed, however, between the subjective responses to lighting dataset and the presence dataset for the high quality radiosity condition ( $r = 0.54$ , Spearman's correlation,  $p < 0.05$ ). According to this correlation a high level of perceived presence resulted in a high rating of 'comfort', 'warmth', 'spacious' feeling and 'relaxing'

feeling associated with subjective lighting impressions, for the high-quality condition. For this phenomenon to be verified and fully explained, a study that would focus on validating these results should be designed.

#### 5. Discussion

A theory for lighting design as discussed above argues that light cues signal subjective associations or impressions and that the direction of these impressions is somewhat independent of the room in which the light cues are viewed [7,8]. It could be hypothesised that by accurately simulating the illumination in the real world to match the illumination in a synthetic space, subjective responses to lighting may vary depending on the accuracy of the computer graphics rendering and the fidelity of the VE (display, field-of-view, tracking, system design). However, such subjective reports might be independent of physics-based simulations.

For Study 1, the computer graphics rendering was retained the same across varied displays and navigational interfaces (desktop monitor vs. a HMD, a mouse interface vs. head tracking and mono vs. stereo computer graphics rendering). Theoretically, if the participants' response is similar across conditions for the same interactive computer graphics scene, this could be a step towards validating the metric that could be subsequently used for assessing subjective responses when varied lighting fixtures or rendering quality scenes are utilised. There was no effect of condition upon subjective impressions of illumination, because of constant luminance levels. Interestingly, in this study, the perceived level of presence correlated positively with feelings of warmth, comfort, simplicity, uniformity and spacious space for the monocular conditions displayed on the HMD including either a common mouse or head tracking as interaction interfaces. This indicates that participants with a high sense of presence communicated a high level of subjective impressions such as comfort, warmth, spaciousness, etc. The display, in this case, the HMD, proved to be a factor for this significant correlation.

For Study 2, the effect of the quality of rendering and in particular, shadow accuracy employing the radiosity algorithm was investigated. There was no effect of condition upon the lighting impressions and the presence datasets indicating that shadow accuracy did not affect participants' level of comfort, warmth, etc. related to their subjective impressions of the illumination and sense of presence. It is worth noting here, that the luminance level was retained the same across visual conditions, despite the varied quality of rendering. The constant luminance levels in Study 1 and 2 proved to be the deciding factor that would yield significant effects of viewing condition. Further experimental exploration of

Table 3  
Study 2: overall means for presence and lighting impressions across visual conditions

	Presence	Lighting impressions
Low quality	2.77	4.00
Mid quality	2.86	3.47
High quality	2.66	3.46

this conjecture should be conducted in the future. There was a positive correlation between presence and feelings of comfort and warmth associated only with the high-quality rendering. This indicates that when participants reported a high (low) level of presence, they similarly reported a high (low) level of positive subjective impressions to the lighting as expressed by the set of bipolar adjectives administered. This correlation was only observed for the high-quality condition.

How real-world responses related to subjective impressions of illumination and presence could be incorporated into a computer graphics simulation in addition to the simulation of geometry and illumination, is still an open research question. Factor analytic insights related to categories of lighting impressions as described in Section 2.1 could in future work identify sub-category variations. Identifying ways to induce reality rather than simulating the physics of reality is a significant research challenge.

## References

- [1] Billinghamurst M, Ellis SR, Mania K, Steed A. Usability evaluation techniques for virtual reality technologies: human factors issues, course notes. IEEE Virtual Reality 2002, Orlando, USA.
- [2] Biocca F, Brooks Jr FP, Ellis SR, Mania K, Slater M, Steed A, Whitton M. Understanding virtual environments: immersion, presence, and performance. ACM Siggraph 2002 course notes, San Antonio, USA, full-day course.
- [3] Mania K. Simulating perceptual processes and cognition with interactive virtual environments. IEEE Conference on Systems, Man and Cybernetics 2004, in special session titled 'Human-Centred Fidelity Metrics for Virtual Environment Simulations', IEEE Computer Society, 2004.
- [4] Mania K, Adelstein B, Ellis SR, Hill M. Perceptual sensitivity to head tracking latency in virtual environments with varying degrees of scene complexity. In: Proc. ACM Siggraph Symposium on Applied Perception in Graphics and Visualization, ACM Press, 2003; 39–47.
- [5] Mania K, Chalmers A. The effects of levels of immersion on presence and memory in virtual environments: a reality centred approach. *Cyberpsychology and Behavior* 2001;4(2):247–64.
- [6] Mania K, Troschianko T, Hawkes R, Chalmers A. Fidelity metrics for virtual environment simulations based on human judgments of spatial memory awareness states. *Presence, Teleoperators and Virtual Environments* 2003;12(3):296–310.
- [7] Flynn JE. A study of lighting as a system of spatial cues. In: EDRA-6 Workshop on the Psychological Potential of Illumination, University of Kansas, 1975.
- [8] Flynn JE. A study of subjective responses to low energy and nonuniform lighting systems. *Lighting Design and Applications Journal* 1977; 6–15.
- [9] Rushmeier H, Ward G, Piatco C, Sanders P, Rust B. Comparing real and synthetic images: some ideas about metrics. *Proc. EGRW* 1995.
- [10] Kort Y, Ijsselstein W, Koojman J, Schuurmans Y. Virtual laboratories: comparability of real and virtual environments for environmental psychology. *Presence, Teleoperators and Virtual Environments* 2003;12(4):360–73.
- [11] Gibson J. The information available in pictures. *Leonardo*, vol. 4. Great Britain: Pergamon Press; 1971. p. 27–35.
- [12] Lombard M, Ditton T. At the heart of it all: the concept of presence. *JCMC* 1997;3(2).
- [13] Shloerb DW. A quantitative measure of telepresence. *Presence, Teleoperators and Virtual Environments* 1995; 4(1):64–80.
- [14] Loomis JM. Presence and distal attribution: phenomenology, determinants and assessment. *SPIE vol. 1666: human vision, visual processing and digital display III*, 1992. p. 590–5.
- [15] Slater M, Steed A. A virtual presence counter. *Presence, Teleoperators and Virtual Environments* 2000;9(5):413–34.
- [16] Meehan M. An objective surrogate for presence: physiological response. 3rd International Conference on Presence, ISBN 9-386-1571-X, 2001.
- [17] Brooks Jr FP. What's real about virtual reality. *IEEE Computer Graphics and Applications* 1999; 16–27.
- [18] Slater M, Steed A, McCarthy J, Maringelli F. The influence of body movement on subjective presence in virtual environments. *Human Factors* 1998;40(3):469–77.
- [19] Mania K, Randell C. Monitoring navigational strategies and idle time in real and virtual environments: an experimental study. 8th International Conference on Virtual Systems and Multimedia (VSMM 2002, Korea), Kiwisoft Company Ltd., 2002. p. 327–35.
- [20] Coolican H. Research methods and statistics in psychology, 3rd ed. Hodder & Stoughton; 1999.
- [21] Usuh M, Catena E, Arman S, Slater M. Using presence questionnaires in reality. *Presence, Teleoperators and Virtual Environments* 2000;9(5):497–503.
- [22] Travis D. Effective color displays. New york: Academic Press; 1991.