THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

Defining Reality in Virtual Reality:

Exploring Visual Appearance and Spatial Experience Focusing on Colour

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ABSTRACT

Today, different actors in the design process have communication difficulties in visualizing and predicting how the not yet built environment will be experienced. Visually believable virtual environments (VEs) can make it easier for architects, users and clients to participate in the planning process. This thesis deals with the difficulties of translating reality into digital counterparts, focusing on *visual appearance* (particularly *colour*) and *spatial experience*. The goal is to develop knowledge of how different aspects of a VE, especially light and colour, affect the spatial experience; and thus to contribute to a better understanding of the prerequisites for visualizing believable spatial VR-models. The main aims are to 1) identify problems and test solutions for simulating realistic spatial colour and light in VR; and 2) develop knowledge of the spatial conditions in VR required to convey believable experiences; and evaluate different ways of visualizing spatial experiences. The studies are conducted from an architectural perspective; i.e. the whole of the spatial settings is considered, which is a complex task. One important contribution therefore concerns the methodology. Different approaches were used: 1) a literature review of relevant research areas; 2) a comparison between existing studies on colour appearance in 2D vs 3D; 3) a comparison between a real room and different VR-simulations; 4) elaborations with an algorithm for colour correction; 5) reflections in action on a demonstrator for correct appearance and experience; and 6) an evaluation of texture-styles with non-photorealistic expressions. The results showed various problems related to the translation and comparison of reality to VR. The studies pointed out the significance of inter-reflections; colour variations; perceived colour of light and shadowing for the visual appearance in real rooms. Some differences in VR were connected to arbitrary parameter settings in the software; heavily simplified chromatic information on illumination; and incorrect inter-reflections. The models were experienced differently depending on the application. Various spatial differences between reality and VR could be solved by visual *compensation*. The study with texture-styles pointed out the significance of varying visual expressions in VR-models.

Keywords: Visual appearance, spatial experience, colour appearance, Virtual Reality, Virtual Environment, architectural visualization, light, simulation

PREFACE / ACKNOWLEDGEMENTS

I have carried out my thesis project at the Dept. of Architecture at Chalmers University of Technology. The thesis is based upon three projects:

- The research project *Simulating Colour Appearance in Virtual Environments* (in this thesis referred to as the SCAVE-project). This project was initiated and planned by Dr. Monica Billger at the Dept. of Architecture, Chalmers University of Technology, in 2001. Other institutions that were involved at Chalmers were the Centre for Digital Media and Higher Education, the Dept. of Computer Engineering and the Dept. of Technology Management and Economics. External collaborators were PhD-student Carlo Gatta and Dr. Alessandro Rizzi at the Dept. of Information Technology at the University of Milan. The project was carried out at the Dept. of Architecture at Chalmers University of Technology, 2001 – 2006. The tests with the ACE-algorithm were conducted at the Dept. of Information Technology, University of Milan, in winter 2004.

- The research information project *The Virtual Colour Laboratory* (in this thesis referred to as the VCL-project). This project was initiated and planned by Dr. Monica Billger at the Dept. of Architecture, Chalmers University of Technology, in 2006. The participants in the project were: Dr. Monica Billger, Dr. Karin Fridell Anter, Beata Stahre (Dept. of Architecture, Chalmers University of Technology), Dag Wästberg, Dr. Odd Tullberg and Dr. Michael Connell (WSP Sverige AB). The project was carried out at the Dept. of Architecture at Chalmers University of Technology, 2006 – 2008.
- The research project *Sketching Techniques in Virtual Environments* (in this thesis referred to as the STIVE-project). This project was initiated and carried out by Beata Stahre (Dept. of Architecture, Chalmers University of Technology) and Susanne van Raalte (Vianova Systems Sweden AB). The project was carried out at the Dept. of Architecture at Chalmers University of Technology and at Vianova Systems Sweden AB, 2007 – 2008.

My thesis studies have been financed by the Dept of Architecture, Chalmers University of Technology; and the Lars Erik Lundberg Foundation for Research and Education. I wish to express my gratitude towards both for giving me the financial support I needed to complete the research.

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The part of my studies concerning the test of the ACE-algorithm was conducted in collaboration with Dr. Carlo Gatta and Professor Alessandro Rizzi at the Dept. of Information Technology at the University of Milan. I would like to thank them for our collaboration and for taking care of me during our elaborations in Crema.

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Beata Stahre
Gothenburg, January 2009

PUBLICATIONS

Paper A Stahre, B., Hårleman, M. and Billger, M., (2004): *Colour Emotions in Larger and Smaller Scale.* In: Proceedings for AIC 2004 Colour and Paints, Porto Alegre, Brazil, November 2–5, 2004, pp 27-30.

Paper B Billger, M., Heldal, I., Stahre B. and Renström K., (2004): *Perception of Colour and Space in Virtual Reality: A Comparison between a Real Room and Virtual Reality Models.* In: Proceedings for IS&T SPIE 16th annual meeting on Colour Imaging, San José, January 18-22, 2004, pp. 90–98.

Paper C Stahre, B. and Billger, M., (2006): *Physical Measurements vs Visual Perception: Comparing Colour Appearance in Reality to Virtual Reality*. In: Proceedings for CGIV 2006, Leeds, United Kingdom, June 19–22, 2006, pp 146-151.

Paper D Stahre, B., Gatta, C., Billger, M. and Rizzi, A., (2005): *Towards perceptual colour for virtual environments*. In: Proceedings for 10th Congress of the International Colour Association AIC Colour 05, Granada, May 8–13, 2005, pp 219-222.

Paper E Billger, M, Stahre, B. and Heldal, I., (2004): T*he Arbitrary Road from Reaity to Virtual Reality*. Proceedings of 3rd International Congress Arquitectura 3000, The Architecture of In-Difference, Barcelona, Spain, June 30 – July 4, 2004.

Paper F Stahre, B., Billger, M. and Fridell Anter, K., (2007): "To Colour the Virtual World - Difficulties in Visualizing Spatial Colour Appearance in Virtual Environ-ments". *International Journal of Architectural Computing (IJAC). Submitted.*

Paper G Stahre, B, van Raalte, S. and Heldal, I., (2008): *Sketching Techniques in Virtual Environments – Evaluation of texturing styles in an urban planning model.* VSMM '08 – Conference on Virtual Systems and Multi Media, Limassol, Cyprus, October 20 – 26, 2008, pp 230-237

DISTRIBUTION OF WORK

Paper A *Colour Emotions in Larger and Smaller Scale*. Stahre planned and executed, in collaboration with Billger and Hårleman, comparisons between the Swedish part of the *Colour Emotion*-study on colour appearance on colour chips (conducted by Billger and Stahre); and Hårleman's room studies. Stahre and Billger wrote the paper.

Paper B *Perception of Colour and Space in Virtual Reality: A Comparison between a Real Room and Virtual Reality Models*. The experimental data is based on the project initiated and planned by Billger. Stahre and Billger accomplished the technical preparations in relation to the VR-models, with assistance from Renström. Stahre carried out the interviews. Heldal initiated and designed the questionnaire about interactivity and presence. Billger and Stahre analyzed the results regarding colour and light. Billger wrote the paper and Heldal contributed to the outline of the study.

Paper C *Physical Measurements vs Visual Perception.* Billger and Stahre carried out the study. Dr Rejean Barbier at the National Research Council in Canada assisted with calculations and analysis of the measurement data. Professor Ronnier Luo at the University of Leeds provided reflections and comments on the study. Stahre and Billger wrote the paper in collaboration.

Paper D *Towards perceptual colour for virtual environments.* Stahre, Gatta and Billger planned and executed the study in collaboration. Stahre was the main author and co-ordinated the work. Stahre and Gatta performed the tests and analyzed the results. Stahre, Billger and Gatta all contributed to writing the paper.

Paper E *The Arbitrary Road from Reality to Virtual Reality.* Billger planned the study. Stahre carried out the interviews. Heldal initiated and designed the presence and involvement questionnaires. Billger and Stahre analyzed the results regarding colour and light; Heldal analyzed the questionnaires regarding prescence and involvment.

Paper F *To Colour the Virtual World - Difficulties in Visualizing Spatial Colour Appearance in Virtual Environments*. Stahre carried out the elaborations with the textures and Stahre, Billger and Fridell Anter analyzed the results. Stahre, Billger and Fridell Anter wrote the paper in collaboration.

Paper G *Sketching Techniques in Virtual Environments – Evaluation of texturing styles in an urban planning model*. Stahre and van Raalte initiated and planned the study. Stahre developed the textures and the questionnaire. Stahre carried out the analysis in collaboration with van Raalte. Stahre wrote the paper in collaboration with Heldal.

ADDITIONAL PUBLICATIONS BY THE AUTHOR

Heldal, I.; Bråthe, L. and Stahre, B., (2008): *The Influence of Visualization Technologies on Estimating Object Sizes and Colours*. In: Proceedings for VSMM '08 – Conference on Virtual Systems and Multi Media, Limassol, Cyprus, October 20 – 26, 2008. pp 43-48.

Heldal, I.; Stahre, B.; Spante, M. and Billger, M., (2008): *The influence of the applied technologies on estimating graphical representations*. In: Proceedings for Architectural Inquiries - Theories, methods and strategies in contemporary nordic architectural research, Göteborg, Sweden, April 24–26, 2008.

Stahre, B. and Billger, M., (2006): *Colour Meaning in Different Settings: Example from the fine arts and experimental colour studies*. In: Proceedings for AIC South Africa 2006, Misty Hills, Gauteng, South Africa, October 24–27, 2006. pp 58-61.

Stahre, B. (2006). *How to Convert Reality into Virtual reality: Exploring Colour Appearance in Digital Models,* Licentate Thesis, Dept of Architecture, Chalmers University of Technology, Göteborg, Sweden, 2006.

Ou, L-C., Luo, M.R., Cui, G., Woodcock, A., Billger, M., Stahre, B., Huertas, R., Tremeau, A., Dinet, E., Richter, K. and Guan, S., (2005): *The Effect of Culture on Colour Emotion and Preference*, In: Proceedings for AIC Granada, Spain, May 8 – 13, 2005. pp 259-262.

Stahre, B.; Hårleman, M. and Billger, M., (2004): "Färg i stor och liten skala", *Färgnotiser*, (76), 2005.

Billger, M.; Stahre, B. and Konradsson; Y., (2002): *Colour Emotions in Sweden,* In: Proceedings for the *International Conference on Colour Emotion Research and Application*, Bangkok, Thailand, July 5–7, 2002. pp 1-3.

ABBREVIATIONS

2D	Two-dimensional
3D	Three-dimensional
3Ds max®	3D Studio max, Discreet®
ACE	Automatic Color Equalization
CAVE™	Cave Automatic Virtual Environments
CIE	Commission Internationale de l'Eclairage; International Commission on Illumination
CRT	Cathode Ray Tube
Dvmockup	Division Mock-Up dVise 6.0.
GUI	Graphical User Interface
HDR	High Dynamic Range
HDRI	High Dynamic Range Imaging
HVS	Human Visual System
IES	Illuminating Engineering Society
IPT	Immersive Projection Technology
K	Kelvin
L	Luminance; Candela/m^2
L*a*b	L=lightness, a=green/red, b=blue/yellow
LCD	Liquid Crystal Display
LDR	Low Dynamic Range
Lightscape™	Autodesk Lightscape™, Release 3, 2
NCS	Natural Colour System
NPR	Non-Photorealistic Rendering
OSGExp	Open Source Exporter from 3Ds max® to OpenSceneGraph
RGB	Red Green Blue
SPD	Spectral Power Distribution
VR	Virtual Reality
VE	Virtual Environment

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The colour of the object illuminated partakes of the colour of that which illuminates it.

- Leonardo da Vinci

Artists can colour the sky red because they know it's blue. Those of us who aren't artists must colour things the way they really are or people might think we're stupid.

- Jules Feiffer

If you know exactly what you are going to do, what is the point of doing it?

- Pablo Picasso

1. INTRODUCTION

This thesis deals with how *Virtual Reality (VR)*[1] can be developed as an architectural visualization tool in the communication between the architect and the client and user. The focus of the work is the *visual appearance*[2], especially regarding *colour*[3]; and the *spatial experience*[4] of architectural VR visualizations, with the starting point in the real world visual appearance and spatial experience. The thesis provides an insight into how different aspects of an architectural spatial VE, especially light and colour, affect the spatial experience, and thus contributes to a better understanding of the prerequisites for visualizing believable spatial VR models. It is important to point out that, by combining many different methods, the whole of the spatial setting is investigated.

The target groups for the thesis are VR developers, researchers working with visual aspects of VR, and professional users working with architectural and spatial VR models. From my experience, both professionals and researchers within this group often have an extensive knowledge in aspects of VR concerning e.g. usability, interaction and technology (soft- and hardware development), and much research has been undertaken within these areas. However, knowledge about how we perceive and experience the whole complexity of a spatial real world setting is not equally considered in research on spatial VR. With this thesis I wish to convey the importance of, and the problems associated with, the simulation of real world correspondent spatial colour appearance in VR; and furthermore highlight the importance of the whole complex spatial experience in VR, in the design of architectural VR visualizations.

This work touches on different research fields; however the viewpoint is constantly that of architectural research. The studies are based on the knowledge and perspective of the research fields that I have as an architect, with my base in the field of colour research. This approach has shaped the structure of this thesis and the way more basic concepts are explained.

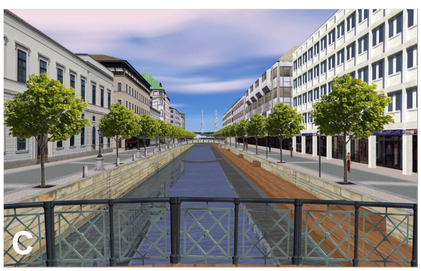
[1] *Virtual Reality (VR)* has no absolute definition, but in this thesis I refer to a computer-generated 3D-world that allows the user to feel present and interact with the world, i.e. move around in it, move objects etc. See Section 2.1. for more details.

[2] *Visual appearance* is a part of the more complex concept of spatial experience. It is in this thesis used to describe the impression of light, colour and other visual aspects of a spatial setting.

[3] *Colour appearance* is here referred to as a general concept for the perceived colour of a surface.

[4] By *spatial experience* I refer to the whole complex experience of a spatial setting, and the factors affecting it.

1.1. Identifying the problem area



Figures 1.1.A,B,C,D.
Example of the use of VR in planning and design of the urban built environment (Image courtesy of Roupé, M., and Johansson, M. Construction Management, Chalmers University of Technology, 2009).

Today's design processes involve many participants and demand new methods of communication. Architects, clients and users sometimes have communication difficulties when it comes to visualizing and predicting how the yet unbuilt environment is going to be experienced. Using VR as a design tool is becoming increasingly common and the advantages of using this new medium for communicating ideas are many. Traditional representations, e.g. plans, perspectives and sections, are usually, due to their abstract nature, difficult for laymen to correctly interpret (Dorta and Lanlande, 1998; Hornyánszky Dalholm, 1998). VR can be used as a tool that can reproduce the planned reality more accurately than traditional design tools are able to (see Figures 1.1.A-D). VR also makes it possible to feel presence in an alternative environment (Riva, 1999), which is an advantage when planning what is not yet built, and it can enhance perception with regard to space and depth (Sik-Lányi et al, 2003). Among architects, VR is above all used as a tool for visualization for the communication of ideas (Setareh et al, 2005). Virtual models that facilitate an accurate understanding of a design project could make it easier for these actors to participate in the planning process. If different visual qualities could be correctly reproduced in virtual modeling, VR could be used as an effective design tool for predicting real world appearance, especially in colour and lighting design, in the later stages of a design.

Depending on which stage of the design project plans are in, there is a need for more or less abstraction and detailing in the visualizations. Often the elements that contribute towards realism are decided in the final stages of a design process[5] (Hannibal et al, 2005), and reliable realism with high detailing levels in the visualizations is therefore necessary. However, today's technologies still create a somewhat simplified realism in interactive modeling, which has caused users to be caught in the visual expression of the visualization, rather than focusing on what the visualization is intended to show. The strive for photorealism in the models, and for geometrical exactness, also create issues regarding how to visualize what is not yet fully decided upon in a project design. If a visualization could be better adjusted to the spatial conditions in VR, VR could be used as an effective design tool for demonstrating real world appearance.

1.1.1. Conveying visual reliability

The visualization of real settings in VR is difficult due to the different prerequisites in VR compared to reality. The problems are connected both to the specific prerequisites for reproducing colour appearance in VR and to more general issues regarding the design of a virtual world in terms of realism and spatial experience.

To predict how a colour will be experienced in a room is difficult. A colour appears different on a small sample than it does in a room, where the visual appearance is strongly affected by spatial factors, e.g. light, as well by human perception. The perceived colour in a room is affected mainly by the spectral properties of the coloured surface, the spectral distribution of light in the room, the observer's adaptation level and the influence between adjacent areas of different colours (Liljefors, 2006, p. 250).

The problem of creating illumination realism is central when translating reality into VR (Slater et al, 2002, p 73-77). The reproduction of colour is very closely connected to the reproduction of illumination. Today's VR-technology enables the creation of very realistic models from a geometric point of view and scenes can be created that are almost impossible to distinguish from reality. However, it is often not necessary to be physically accurate in a scene when it comes to light transportation. For many applications it is enough that the scene looks 'appealing' and 'believable'. Still, reliable simulations of light are important when it comes to architecture and lighting design, for example when predicting the lighting conditions in a building (Ulbricht et al, 2005). The presentation of colour is a crucial factor for the understanding and interpretation of a virtual setting (Urland, 2004).

When it comes to the reproduction of colour appearance it is possible to calculate a highly realistic scene where each pixel has physically correct colourimetric data. However, there has been significantly less investigation into how to apply this data in order for the colour appearance to correctly correspond to reality. In order to create visually realistic simulations according to how we perceive our surrounding world, it is not enough to base the computations on physical measurements of colour and light in the real world. Instead, we need to include our *perception* of reality in the computations, and program various sorts of visual phenomena into the software. (Maloney, 2001, pp 388-416)

[5] *The design process* is a wide concept with many interpretations. In this thesis I consider it to be roughly divided into four phases: the early design phases of pre-conception (e.g. associative imagery) and sketching/design, and the later phases of presentation and management. It is important to point out that the concept will be referred to in this thesis, but is not the focus of my studies.

1.1.2. Conveying believable experiences

Computer generated visualizations can in some ways increase the distance between the designer and the representation of the design ideas (Brown, 2003), which is connected to how we experience and interpret the visualizations.

Most of today's interactive spatial models aim for a photorealistic appearance. The strive for photorealism in visualizations can sometimes lead to unwanted side effects. It can be argued that a photorealistic expression in the visualizations can be misleading regarding how finished the design plans depicted are, when on the other hand, the photorealistic level in architectural VR-models is often unsatisfactorily low. Too much detail and visual realism in visualizations at the initial stages of a design is often not necessary and can even be misleading, since that information will not be decided on until later on (Neto, 2003). A high level of realism could then lead to a too definite and non-negotiable expression in a visualization, and suggest that the project plans cannot be changed (Richens and Schofield, 1995; Hannibal et al, 2005).

On the other hand, spatial differences in VR compared to reality tend to create an imbalance or disturbance in the experience and visual expression of a VR model. This problem is also connected to the use of photorealism in textures[6], combined with a simplified geometry and lack of realistic interactive light. This sometimes unsettles users when experiencing a model, i.e. the model is trying to look realistic but does not look realistic enough.

The spatial differences in VR compared to reality affect the experience of the *virtual environment (VE)*[7]. However well made it is, a virtual setting can never offer the sense of real presence in a spatial context. For example, our movements are different in a virtual model (depending also on which type of VR system we are using) compared to reality, and our attention is not drawn by the same means. A virtual setting consists mainly of sight impressions which thus restrict active investigation. To make a user observe a specific detail or a certain phenomenon can therefore be difficult. In order to improve the believability of the experience of a spatial VR model, spatial differences between reality and VR affecting the experience need to be considered.

For the creation of believable VEs in the process of forming a design idea, there is a need for different expressions and levels of representation. According to Brown (2003), different types of representations appear to fit different phases of a design, and one challenge is how to integrate

[6] A *texture* refers in this thesis to a 2D image, e.g. a bitmap- or a TGA-file. This image is projected on a surface in a 3D model and consequently determines the surface's appearance and character. In 3D modelling, the method texture mapping is used in order to add detail, surface texture, or colour to a model.

[7] *Virtual Environments (VEs)* is another term with no absolute definition. I consider it to be interior or exterior environments in a computer-generated 3D-world. See Section 2.1. for more details.

different computer generated representations into the process. The visualizations have to be able to interpret some issues exactly e.g. (Drettakis et al, 2007), while just sketching others (Lange, 2005). In the early stages of a design process it is important to allow a certain amount of vagueness in order for the correct perception of the design idea to be communicated. For this, the value of traditional sketches needs to be considered.

1.2. Aims

How can the visual appearance and the spatial experience of a VR model be improved so as to better support the understanding of space, colour and lights? The overall goal for my PhD project is to develop the knowledge on how different aspects of the VE, especially light and colour, affect the spatial experience, and thus contribute to a better understanding of the prerequisites for visualizing believable spatial VR models. The aims with this thesis are:

1) To identify problems and test solutions for simulating spatial colour and light in VR. This aim concerns issues connected to visual appearance and software technology.

2) To develop knowledge of the spatial conditions in VR required to convey believable experiences, and to evaluate different ways of visualizing spatial experiences. This aim concerns issues connected to spatial experience.

The following questions will be considered:

Questions concerning visual appearance: Will a simulated room look the same as the real one? If not, how do reality and the simulation differ? Are the colours correctly reproduced? If not, in what way do they differ? Is the relationship between the colours correct? How is the illumination perceived with regard to light level, light distribution, perceived colour of light? How can we compare different spatial settings with regard to visual appearance, when we can only be in one setting at a time?

Questions concerning software technology: Providing that a room is modeled with the information on physical conditions available before it is built, how well does the software meet the demands? What are the limitations of the parameters of the software concerning colour and light? How can we convert real paints to digital colours and how can we evaluate the reliability of appearance?

Questions concerning spatial experience: How does the spatial experience differ in VR compared with reality? How do we relate to the model, e.g. movements and impression of size and scale? How can different visual expressions in architectural VR-models contribute to a better understanding of a visualization? How can we compare different spatial settings with regard to spatial experience, when we only can be in one setting at a time?

1.3. Research approach

My research approach consists of a combination of different methodologies, with emphasis on a qualitative and an experimental approach. Most of the applied methods are connected to simulation and modeling research (Groat and Wang 2002, pp 275-300). My studies are based on the viewpoint of architectural research. When using an architectural perspective, aspects other than purely technical or scientific ones need to be considered. The studies are mainly based on a qualitative approach, which has proved more important than quantitative aspects as regards obtaining a meaningful result on colour. The full complexity of the context in enclosed spaces has been considered as a guiding feature for the studies of colour appearance in rooms. Room size, materials, colours, light and other spatial conditions have all been considered as part of the whole. The methods used are means to deepen the understanding of how spatial conditions affect colour appearance.

The different spatial conditions in virtual settings compared to reality have been the starting point for the studies on spatial pre-requisites of VR. The complexity of factors affecting the spatial experience in desktop VR has been considered, focusing on the visual expression of the models. The research approach has been primarily design based (my own elaborations, reflections and evaluations combined with group discussions in the research team) in combination with user evaluations of a demonstrator. The methods have been applied in order to investigate problems when visualizing spaciousness in VR, as well as to gain knowledge of the effects of different visual expressions in a model.

The applied methods can be divided into two main groups: *literature reviews* and *empirical studies*. Literature reviews have been conducted in order to assess the state of the art, i.e. the different aspects and research fields of this thesis, based on my questions and perspective.

The empirical studies were the following:

- ***A comparison between two existing studies on small colour samples and real rooms.*** The results of an international project on the experience of small colour chips were compared to a study on spatial colour experience in full scale rooms (see Paper A).
- ***Experimental study on real rooms vs virtual rooms.*** Sequential comparisons between real rooms and different VR simulations were conducted in order to map out problems of making realistic models in VR (see Papers B and C).
- ***Elaborations with an algorithm for improving the colour appearance in the virtual rooms.*** Elaborations with an algorithm were conducted as a possible solution to the stated problems of making visually realistic models in VR (see Paper D).
- ***Reflections in action on a demonstrator for an accurate visual appearance and spatial experience.*** To investigate the spatial differences in VR compared to reality, reflections in action on a virtual demonstrator for colour phenomena were conducted (see Paper F). A design based, abductive (Reichertz, 2004) research approach was applied. Elaborations with the visual expression of the model were alternated with inter-reflections and group discussions.
- ***Evaluation of texture styles with non-photorealistic expressions in an urban planning model.*** To investigate a possible solution to spatial problems in VR, non-photorealistic texture styles were developed and evaluated in a usability study with professional VR users through a questionnaire (see Paper G).

The thesis is based on the following projects:

- ***Simulating Colour Appearance in Virtual Environments: A comparison of the experience of colour and light in real and virtual rooms (SCAVE)***, which is an interdisciplinary research project aiming to investigate the accuracy of the simulations regarding colour, light and spatial experience in commercial software (see Papers B-E). The PhD project was originally formulated within the frames of this project.
- ***The Virtual Colour Laboratory (VCL)*** which is a popular science project aiming at pedagogically showing research results on colour appearance in a VE (see Paper F).

- ***Sketching Techniques in Virtual Environments (STIVE)***, which is a research project aiming to investigate the need for different visual expressions of a VR-model, adjusted to different phases in the planning process (see Paper G).

The methods will be presented in detail in Chapter 4. It has not proved possible to be locked in one methodological approach, due to the ever changing circumstances and knowledge gained during the studies. Instead, a constant adaptation to the circumstances has been necessary, and consequently questions and perspectives have been somewhat revised.

1.4. The development of the thesis project

This work has developed through two phases. The first phase focuses on VR as a design tool for predicting real world appearance, where problems of translating reality to VR are investigated. In the second phase the results from the previous phase are considered when investigating VR as a design tool for demonstrating the spatial experience in, for example, different stages of the design process. Here, the problems of visualizing reality in a way correspondent to the capacity and special character of VR are investigated.

The starting point for my studies was to investigate how colour was perceived in a real world spatial setting and make comparisons to digital counterparts, i.e. VR models. The main aim was to identify the problems of making visually realistic models in VR. The studies were conducted within the frames of the research project *Simulating Colour Appearance in Virtual Environments (SCAVE)* (see Papers B-E), and came to form my licentiate thesis (Stahre, 2006).

Since Phase One was based on a cross-disciplinary research project, it touched on different fields of research. When the project ended, it was therefore possible to choose between two different directions for the development of the thesis; one in which I could zoom in to investigate details and one in which I could zoom out to look at the spatial context.

For the direction with the focus on details, I planned to follow a technical approach in order to solve the problems previously investigated. My aim would then be to list and specify spatial light- and colour phenomena, including comparing physical data to the visual appearance of colours, in order to make them programmable. In co-operation with experts in programming and computer graphics I would then use this knowledge to create an algorithm, which could be better adjusted to the eye's perception of reality and the three dimensional vision.

For the other direction, i.e. to focus on the spatial context, I planned to follow an architectural approach in order to deal with the problems previously investigated. By taking this direction, I was able to use the information research project *The Virtual Colour Laboratory (VCL)* (see Paper F), in which I worked full time for four months after having completed my licentiate degree. The time I spent working on practical design issues concerning various aspects of visualization, got me very interested in the spatial differences of VR compared to reality. I consequently chose this direction for my continuing studies.

The starting point for the second phase was the spatial differences in VR compared to reality when visualizing, for example, colour phenomena, e.g. the results from the first phase. The research questions took shape during the work with visualizing the virtual demonstrator in VCL, where it became evident that the conditions for visualizing an object in VR did not correspond to the conditions for the same object's appearance in a real world setting. An investigation was consequently undertaken into how to convey the correct visual focus and amount of spatial information in an architectural visualization. This investigation developed into the research project *Sketching Techniques in Virtual Environments (STIVE)* (see Paper G) which focuses on how different sketching techniques can clarify and simplify the understanding of a building project during different stages of a planning process.

1.5. Choices and limitations regarding software and digital models

In this thesis I focus, above all, on the visual aspects of the virtual experience. Windows based software common among architects and designers in Sweden has been used. Mainly digital models (both in 3Ds max®/Lightscape™ and exported to VR) on a desktop PC are considered, with comparative studies of a VR simulation (Division Mock-Up dVise 6.0) in an Immersive/CAVE™ based system.

Regarding the studies on simulating spatial colour and light in VR, an important standpoint was that the real as well as the virtual rooms should be studied from within, i.e. the observer must be able to move around inside the room. Hence, established methods aimed at comparing images or comparing models through apertures were not applicable. It was important for the studies that the observers used both eyes, in order to gain full depth cues (however, in the studies with stereographic goggles a somewhat limited field of view had to be accepted). A crucial criterion for choices of software was to be able to simulate the chosen light fixtures correctly. The light fixtures were chosen on the basis that the manufacturer could provide well-made digital models. These models support photometric values and in order to use them, a radiosity based renderer was needed, e.g. as in Lightscape™ and 3Ds max®. Hence, in my studies only radiosity based solutions are investigated. Another interesting light calculation technique to apply is *photon mapping* (see p 24.), which however does not support photometric light[8] (which is used in the models) and is hence not investigated further in this thesis. Further reasons for the choice of radiosity over photon mapping include the facts that:

- Radiosity is a widely used method for calculating diffuse light spread. Though photon mapping also handles both diffuse and specular reflections, it suffers from sampling problems[9].
- In the real time applications, *rendered textures*[10] are used for the walls, which only work if the reflections are diffuse. Semi-diffuse illumination and all kinds of specular reflections require more complicated solutions than radiosity. Regarding these, there is no satisfying method for real time applications today (Assarsson, 2006).
- In the studies, only matte colours were investigated. In order to remain focused, I did not investigate the glossiness of the colours, since I aim for results that are not dependent on where in the room the observer is standing[11].

A basic condition for correct colour appearance in the digital models is that the computer is calibrated. A small displacement between the colours on different desktops is acceptable. What is important is that *the relationship* between the colours in the digital model is correct compared with reality.

Regarding the studies on the spatial experience in VR, only desktop VR were considered. The test models were designed in 3Ds max® (indoor models) and the infrastructure design software *Novapoint Virtual Map*[12] (outdoor models). Virtual Map is an add-on modeling and visualization application on the AutoCAD platform. The choice of

[8] *Photometric light* uses photometric (light energy) values, which enable a more accurate definition of lights as they would appear in the real world. In 3Ds max® lights can be created with various distribution and colour characteristics or specific photometric files available can be imported from lighting manufacturers.

[9] The photon mapping algorithm samples the illumination in a scene in such a way that a quantity of photons are traced from the source of illumination. However, not as many photons are traced as there are in reality, which can lead to an under-sampling in dark areas. Hence, it is difficult to estimate the average quantity of photons in these areas.

[10] *Rendering to texture*, or *texture baking*, is the method used for creating texture maps based on an object's appearance in a rendered scene. The textures then get "baked" back into the object and can be used to display the textured object in VR. This process is supported both by Lightscape™/3Dsmax®. In order to create virtual environments out of the room-model, texture baking for all surfaces of the room is used. In LightscapeTM rendered textures are made of separate images of each wall, the floor and other multicoloured elements in the room. In 3Dsmax® however, each object is baked separately.

[11] Regarding glossy colours, the position of the observer in relation to the light sources is crucial for the colour appearance.

[12] http://www.novapoint.se/index.asp

software has to do with the purposes of the software: in architectural contexts, 3Ds max® focuses primarily on visualizing artifacts and the built environment, while Virtual Map is developed to visualize planning of landscape and infrastructure in exterior environments. The choice of software was also connected to Virtual Map's built in function of allowing the user to switch between different texture styles in the outdoor model, without changing the actual structure of the model.

The decision to work with textures, instead of e.g. *non-photorealistic rendering (NPR)* (see p 22), was made in order to be able to elaborate with different visual expressions and combinations of expressions in the model. New NPR-techniques use given background information (e.g. from topology databases), and thus can predict the form of the final products. Contrary to this, my choice to work with textures aimed to find the necessary information (e.g. simple lines and shapes) that supports creativity in order to obtain new solutions. Here the new forms should support conceptual design thinking and not be limited by predefined structures.

1.6. Outline of the thesis

The thesis is divided into three parts: this thesis text, i.e the kappa ("the coat"), where the work is presented; a compilation of the seven appended papers which the thesis text is built upon; and one appendix, including complementary material from the studies.

Chapter 1 introduces the topic of the thesis and identifies the problem area. Here, the aims and research questions are stated; and the research approach is presented. This chapter also contains a brief overview of the development of the project, as well as choices and limitations regarding software.

Chapter 2 introduces and gives an overview of relevant concepts within the fields of VR, colour (including used colour ordering systems), light and computer graphics (including light calculation and rendering techniques), which are important for the understanding of the thesis. Since this thesis is based on cross disciplinary work, an understanding of the concepts is essential for the comprehension of the text.

Chapter 3 gives an overview of the theoretical framework. Relevant studies regarding colour and light simulation; and spatial conditions in VR (including factors affecting the spatial experience) are accounted for.

In *Chapter 4*, all the methods which I have used in my studies are described.

Chapter 5 provides an overview of the results. The findings from each conducted study are reviewed and analyzed.

Chapter 6 summarizes the thesis text with a concluding discussion, including reflections on results and methodology.

In *Chapter 7* my final conclusions and an outline of future work are presented.

Appended to this introductory part are the appendices (Appendix A-C) and the seven papers (Papers A-G). The appendices consist of A) the questionnaire used in the SCAVE-project; and B) the questionnaire used in the STIVE-project.

Appended at the back of the thesis is Appendix C, which is a CD with material from the SCAVE-; the VCL-; and the STIVE-project. The material contains 1) illustrations from the different SCAVE-studies, 2) illustrations of the demonstrator in the VCL- project and 3) a viewer file, with set-up instructions, of the interactive test model from the STIVE-project. In this model it is possible to change texture styles and to see the different styles in various settings.

2. IMPORTANT CONCEPTS IN THE THESIS

The purpose of this chapter is to give a brief introduction to the most central concepts used in the thesis. In order for the contents of the thesis to be correctly understood, it is important to define these concepts more thoroughly and explain how I use them.

2.1. Virtual Reality

Virtual Reality (VR) has no absolute definition, but in this text I refer to the technology that allows the user to feel present and interact with a computer-generated 3D-world, i.e. move around in it, move objects etc. I make a distinction between VR-models and other digital models, such as a 3Ds max®-model or a Lightscape™-model, since the latter, although computer generated, does not enable the same possibilities of presence and interaction. In this thesis I refer to a VR-model as a digital model exported from Lightscape™/3Ds max® to Dvmockup or OSGExp[13]. A virtual model can be experienced as either *stereographic* or *monographic*.

[13] The models used in the project are exported to VR with Open Scene Graph (OSG) using an open source (http://www.openscenegraph.org/projects/osg/)

Stereographic imaging refers to double depth cues which make the virtual scene look more three-dimensional. With stereographic glasses, a slight relative displacement of objects in the two monocular views of a virtual scene is caused by different image perspectives (one for each eye). This causes, for example, the perception of depth. The user is dependent on both eyes for this to work. *Monographic imaging* refers to the user only experiencing two dimensions, which requires the input from just one eye. This is the common way to display 3D-models.

Virtual Environments (VEs) is another term with no absolute definition. I consider it to be interior or exterior environments in a computer-generated 3D-world. In this thesis the digital room models are commonly referred to as VEs. In some research, VE is used as a synonymous term for VR. I use the term VR to refer to the technology, while the term VE refers to the digital spatial environment.

There are a number of visual displays used for representing virtual models. Here, I will only consider the ones relevant for the thesis. In my studies I have mainly focused on *desktop VR*, which consists of a stationary computer monitor, where the mouse and/ or the keyboard is used to interact with the VE. Today desktop displays can provide high resolution and high levels of contrast, much closer to the perceived contrast range of the human eye than was possible in the recent past. However, all interaction with the desktop VE must be done via the control device, which to a large extent prevents natural movement. Desktop VR-models can be either stereographic or monographic. In most of my studies only monographic models are considered.

In the studies focusing on colour and light simulation, the VR-models examined were also displayed in a so called *Cave Automatic Virtual Environment (CAVE™)*[14]. The CAVE™ belongs to the *immersive projection technologies (IPTs)*[15], originally described by Cruz-Neira et al (1993), and were among the first panoramic projection displays. A CAVE™ is a square box with four walls and a floor (no roof), on to which images of a visual setting are back projected (see Figure 2.1.). The CAVE™ that were used for the comparative studies at Chalmers University of Technology were 3x3x3 meters. The advantage of a CAVE™ is that the user is able to physically move around in the VE, only restricted by the physical walls of the cube. By doing so, the user can experience a sense of scale in relation to his own body. The three-dimensional experience of the virtual model in the CAVE™ is obtained with stereographic glasses in connection to a tracking device.

Other important concepts are *representations*, *models* and *simulations*.

I use the term *representation* to describe all artificial versions of "real" objects in architectural contexts, i.e. something that depicts something else. Examples of representations in this thesis are e.g. VEs showing real world settings and photographs taken in or out of the virtual models. It can furthermore be two-dimensional images of the model derived through a process called 3D-rendering (see Section 2.4).

By *models* I refer to all computer generated models which have been used in the project[16]. The term refers both to virtual models, with dynamic interaction, and to other digital models without any dynamic interaction.

A *simulation* referes, in the text, to a digital replication, or a rendering of a replication, of a real world setting, which aims for a real world appearance, i.e. an imitation of reality. In architectural modeling, I consider a simulation to be a kind of representation. A representation on the other hand does not necessarily have to be a simulation.

2.2. Colour

2.2.1. Colour appearance, perceived and inherent colour

The colour studies in this thesis are based on the colour order system *Natural Colour System (NCS)* (see Section 2.2.2). In *Forskare och praktiker om färg, ljus, rum* (*Researchers and practitioners about colour, light, space*) , the basic concepts of colour and the NCS are explained. In my thesis, this book together with Fridell Anter's and Billger's dissertations about spatial colour appearance (Fridell Anter, 2000; Billger, 1999B) will be used as main references.

[14] *CAVE* is a trademark for the University of Illinois.

[15] *Immersive Projection Technology (IPT)* refers in this thesis to the CAVE™, where you are physically surrounded by the media and react to events in the virtual world with your whole body. Immersive technology has over time become a wider concept and is today used by some for all stereographic equipment, e.g. on flat displays. *Immersion* in connection to VR (an *immersive VE*) means that the user can see a projected model in the space around his own body, and thus gains the experience that the model is surrounding him (Heldal, 2004, p.10).

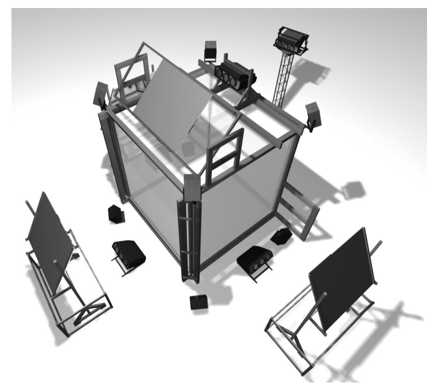


Figure 2.1.
The CAVE™ at Chalmers University of Technology that was used in the project. (Image courtesy of Karlsson, R., 2009: www.i2studios.com/)

[16] For a distinction between VR-models and other digital models, see the definition of Virtual Reality (p 14).

The word *colour* is, in the thesis, treated as a perceptual term and referred to in accordance with the NCS terminology i.e. colour is defined as the "colour one sees". The terms *colour appearance* and *perceived colour* are used as synonyms of colour in this sense. *Colour appearance* is in this text referred to as a general concept for the perceived colour of a surface. Using a strict NCS vocabulary, this is a tautology; however this is the general term used in colour science research. The term is used in order to avoid confusion.

In order to further clarify the concept of colour my studies, the distinction between *inherent colour* and *perceived colour* needs to be explained:

Inherent colour is constant and does not change due to external conditions. It can be defined as the colour a surface has when seen under standardized conditions with regard to illumination, distance, surrounding colours etc. Fridell Anter defines it as the colour an object would have if it was observed under standardized viewing conditions that are a prerequisite for the NCS colour samples to coincide with their specifications (Fridell Anter, 2000, p 24). In practice, the inherent colour can be defined through a visual comparison between standardized colour samples, which have been denoted under specified standard conditions (see Figure 2.2.).

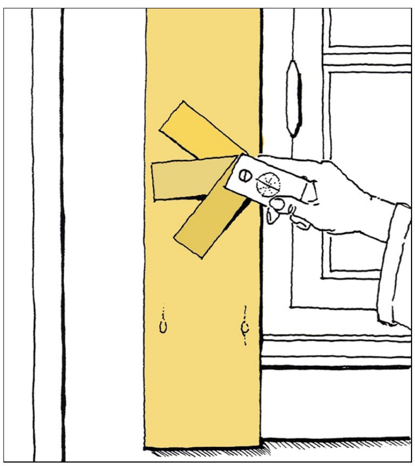


Figure 2.2.
Inherent colour is measured through direct comparison with standardized colour samples. (After Fridell Anter, 2000, see Paper F)

Perceived Colour varies with the viewing conditions. It can be perceived differently depending on illumination, surrounding colours, distance etc. It can also be affected by individual perception, knowledge and expectation. The perceived colour can be analysed on two levels: one that considers the impression of the whole and one that is more detailed. With the former we perceive *identity colours*, with the latter we perceive the *colour variations*. *Identity colour* is defined as the principal colour impression of surfaces or parts of a room that are perceived to be uniformly coloured. (Billger, 1999B, p 11) *Colour variations* are the local colour appearances of the identity colour. These differences can, for example, be influenced by light distribution, reflections from other surfaces and contrast effects. (Billger 1999B, p 11). As an example, when I stand in a room I can perceive the uniformly painted walls as having a bluegreen identity colour. Upon closer inspection, I can see many colour variations on different parts of the walls.

2.2.2. Colour systems

When working with various different digital media it is necessary to use different colour systems. I base my studies on the NCS colour ordering system, but I have also been dependent on other colour systems, due to the fact that different software and equipment is based on different systems. When working in e.g. Photoshop and other computer software, *the RGB system* has been used, while the measuring equipment used for the real and the virtual rooms is based on *the CIELAB system*. Each of those systems will be considered here.

2.2.2.1. The NCS System

The Natural Colour System (NCS) (Scandinavian Colour Institute) is a notation system that builds on our *perception* of colours, i.e. it describes the purely visual characteristics of colours, exactly as we see them. Thus it does not consider physical properties, e.g. pigments used or electromagnetic radiation. It was developed as a means for us to better be able to communicate, document and control colours. The NCS system is built on six *elementary colours* (see Figure 2.3.), which are visually perceived as "pure", i.e. they do not resemble any other colour but themselves. These six colours consist of the four chromatic elementary colours: Yellow (Y), Red (R), Blue (B) and Green (G), and the non-chromatic elementary colours White (W) and Black (S). It is possible to describe all colours through their resemblance to these colours (in terms of yellowness, redness, blueness, greenness, whiteness and blackness).

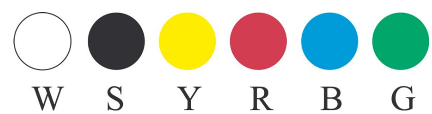


Figure 2.3.
The six elementary colours of the NCS system: White (W), Black (S), Yellow (Y), Red (R), Blue (B) and Green (G). (Image courtesy of Scandinavian Colour Institute AB, Stockholm, 2009)

The NCS notations each describe the visual characteristics of a specific colour, in terms of nuance and hue (see Figure 2.4.). *Nuance* describes the relationship between a colour's whiteness (w), blackness (s) and chromaticness (c). In the NCS colour triangle the hue can be specified by a numeric value. In the example in Figure 2.5., '2010', where '20' shows its level of blackness and '10' show its level of chromaticness. Chromaticness is the sum of the chromatic elementary attributes in a colour. *Hue* describes the relationship between two chromatic elementary attributes. In the NCS colour circle the hue is given a numeric value specifying its place, for example 'Y30R'. Y (yellow) and R (red) stand for the elementary colours that the hue shows resemblance to. '30' shows the number of steps between the hues, on a scale ranging to 100. In this example Y30R describes yellow with 30% redness and 70% yellowness.

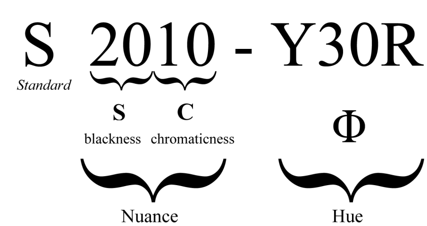
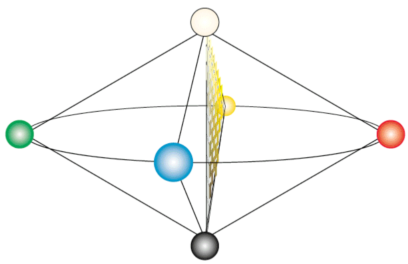
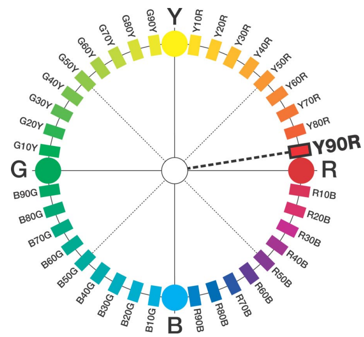


Figure 2.4.
The NCS notation. 2010 describes the nuance, while Y30R describes the hue. The letter S preceding the complete NCS notation in the example means "second edition" and is not a part of the actual colour code. It means that the NCS sample is following the NCS Quality Management system according to the Edition 2.

All imaginable surface colours can be placed and can thus be given an exact NCS notation in *the NCS Colour Space*, which is a three-dimensional model. In order to ease the understanding of the colour space, it is divided into two models: the NCS Colour Circle and the NCS Colour Triangle. Both the circle and the triangle can be used in order to graphically illustrate a colour or a colour area. (see Figures 2.5.A,B,C.).





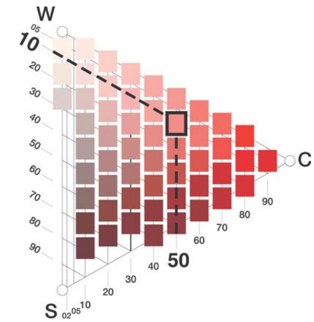


Figure 2.5.A.
The NCS Colour space.

Figure 2.5.B.
The NCS Colour Circle is a horizontal section through the middle of the colour space, seen from above. The four chromatic elementary colours are placed in the cross ends of an even cross in the circle. Between two elementary colours, each quadrant has been divided into 100 equal steps. In the colour circle every 10th step is shown. The circle describes the hue of a colour; for example it can show if a colour is a yellow or a yellowish red. Pure grey colours have no hue, and their nuance notations are thus followed by -N to describe Neutral.

Figure 2.5.C.
The NCS Colour Triangle is a vertical section through the colour space. In the triangle the nuance of the colour is shown through the visual amount of whiteness, blackness and chromaticness. The grey scale from white (W) to black (S) constitutes the base of the triangle, while the maximum chromaticness (C) constitutes the triangle's apex.
(Image courtesy of Scandinavian Colour Institute AB, Stockholm, 2009)

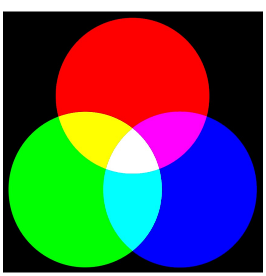


Figure 2.6.
RGB addition. The RGB system mixes the colours as light. Thus the resulting colour combinations are not the same as they would be when mixing colour pigments. If all three RGB colours are mixed as light, the result will be white light.

2.2.2.2. The RGB System

When working with computers in the studies, all colour information had to be adjusted and/or translated to *the RGB system*. For example, I used the RGB system when working in Photoshop, as it is the default colour system in this program (Photoshop CS3 Manual).

The abbreviation RGB stands for *Red Green Blue*. Red, green and blue are the primary colours in a so called additative colour mix, which means that they are added together in different ways and thus can reproduce a spectrum of different colours (Valberg, 2005, p 216-217) (see Figure 2.6.). RGB is used for the representation of images on devices such as screens in electronic systems, such as computers and televisions.

In the RGB system, the three primary colours are used for reproducing other colours, by applying an intensity value to each pixel. Each colour thus has a unique value. In a colour image in, for example, Photoshop[17], these values range from 0 (black) to 255 (white), for each of red, green and blue. Pure black is obtained by the value 0 being applied to each of the three primary colours. Likewise, pure white colour is obtained when they each have the value 255. (Photoshop CS3 Manual)

[17] RGB is considered to be a device-dependent colour space, which means that a given RGB value is detected or reproduced differently depending on the application or device in which it is displayed.

2.2.2.3. The CIE System and the CIE L*a*b* colour model

In paper C, the CIE system (Hunt, 1991; Sisefsky, 1995) was used for measuring *the reflectance* (see p 21) of the paint used and *the spectral power distribution (SPD)*[18] and *luminance* (see p 44) in the test room. The CIE system was developed by the *International Commission on Illumination (CIE)*, which is responsible for international standards of photometry and colorimetry. The CIE system was developed to meet the requirement of an objective worldwide method of determining colours without the need for samples. It is independent of variations in colour vision and aims at perceptual uniformity.

The CIE System characterizes colours in a colour space, by the two colour coordinates x and y, and the luminance parameter Y. These parameters are based on the spectral power distribution (SPD) of light coming from a coloured object. CIE's chromaticity diagram represents a method of colour identification that is based on the additive mixing of light. It is based on perceptual-physiological measurements. The diagram, which is flat and tongue-shaped, contains colours occurring at mean brightness under a standard light source (Nave, 2006), (see Figure 2.7.).

*The CIE L*a*b* colour model (CIELAB)* is used as a colour reference by colour management systems, in order to transform a colour from one colour space to another. In CIELAB the original coordinates are transformed into the three new reference values of L, a and b (see Figures 2.8.). One of the colour systems in Adobe Photoshop, Lab, is derived from CIELAB. Lab was used in the SCAVE-project for translating physical measurement from reality into digital models.

Under specific standard conditions it is possible to define and "translate" NCS colour samples to CIELAB values. CIELAB is however not adequate for measuring how an observer perceives a specific colour from his or her point of view in a room. In contexts of colour technology, which for laboratory set-ups use instruments instead of observers, CIELAB is a good system, but when it comes to the human visual system other methods are required. (Billger, 1999B, p 20).

[18] *The spectral power distribution (SPD)* shows a visual profile of the colour characteristics of a light source and contains basic physical data about the light. "The SPD of light from an illuminated surface is the product of the percent reflectance of the surface and the SPD of the light which falls on the surface". (Nave, 2006).

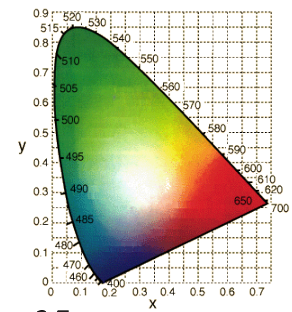
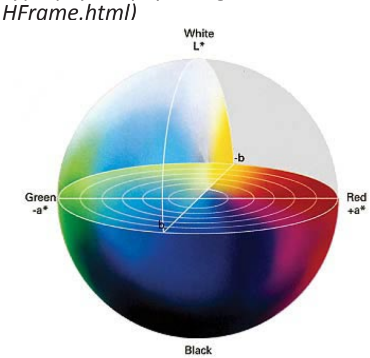


Figure 2.7.
CIE's chromaticity diagram.
(Image courtesy of Nave, C.R., 2009: http://hyperphysics.phy-astr.gsu.edu/hbase/HFrame.html)



Figures 2.8.
The CIELAB colour space is organized in a cube form. The L axis runs from top to bottom, where the lightness parameter (L) in the Lab Colour mode ranges from 0 (bottom) to 100 (top). 100 represents a perfect white, and 0 represents a perfect black. The a* and b* axes can be either positive (+) or negative (-) but have no specific numerical limits. Positive a* is red while negative a* is green. Positive b* is yellow, while negative b* is blue. The CIE-LAB hue is thus determined in terms of hue angle ranging from 0 to 360 degrees. Lab is considered to be a device-independent colour model.*
(Image courtesy of Newspapers & Technology; Ifra and CIELAB, 2009)

2.3. Light

Concepts concerning light can be divided into the visual and the physical. The central light concepts in this thesis are used in order to describe the light character in the test rooms (Liljefors and Ejhed 1990; Billger 1999B, p 15-17; Liljefors, 1995).

2.3.1. Visual qualities

The level of lightness is used in the thesis for describing how bright or dark it is in a room. Physical factors that affect the level of lightness are principally the reflectance of the surfaces in the room, illumination, luminance distribution and the colour temperature of light.

The perceived light spread in a room is referred to as the *spatial distribution of light* (or *light distribution*). For example, where in the room is it brighter and where is it darker? Major factors influencing the spatial distribution of light are the placement and design of the light sources, the reflectance of the surfaces in the room and luminance distribution.

(Perceived) colour of light means the perceived colour character that the room illumination has. It is expressed as warm or cold, or as a hue. The colour of light in a room is affected mainly by the colour temperature of the light, the level of lightness, the spatial distribution of light, glare and colour on surfaces and furnishings in the room.

Shadows are here referred to as areas which, due to obstruction by an object, are shielded from direct light from a light source. Physical factors that have an impact on shadows are the illuminated area and distance of the light source in relation to the shadowing object, the spectral distribution of the light and factors connected to the level of lightness.

2.3.1. Physical qualities

Illuminance refers to the amount of light falling on an illuminated surface. It is measured in Lux (lx). The light intensity of 1 lux describes a light flow of 1 lumen being evenly distributed over a surface of 1 meter.

Luminance L is the light that reaches the eye, measured in candela per square meter (cd/m^2). It is often used to characterize the lightness of a surface or a light source from the perspective of the eye. In the studies, the luminance in the real and in the virtual room models is measured for comparison and for documentation.

Reflectance (or *reflectance factor*) of a surface is the ratio of a ray of light reflected under certain conditions from that surface to the same light reflected from a perfectly diffusing surface (Kuehni, 1997, p. 167).

Colour temperature is a characteristic of visible light that is measured in Kelvin (K). A yellow–reddish, i.e. warmer light is obtained at lower colour (Kelvin) temperatures (2700–3000 K). Conversely, a greenish blue, i.e cooler light is obtained at higher Kelvin temperatures (5000 K or more) (see Figure 2.9.). In the room studies both warm and cold light were studied.

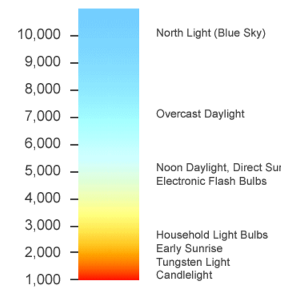


Figure 2.9.
Colour Temperatures in the Kelvin scale.
(Image courtesy of www.mediacollege.com)

2.4. Computer graphics

Different software has been used in the studies on colour and light simulation, which has lead into the area of computer graphics. I approach this field from the architect's viewpoint, and base my investigation on the questions and perspectives for the thesis. The field of computer graphics is undergoing constant development and it is thus important to point out that I include concepts here that were relevant when the studies were performed. Relevant software development that has been done after my studies on colour and light simulation finished in 2006 will be accounted for in the discussion. The purpose of the following sections is to give a brief introduction to the issues of light calculation and rendering in computer graphics. Due to the complexity of the interaction between light and objects in a scene, simulating light in an accurate way is extremely difficult (Slater et al. 2002, p 74) and there are a number of techniques used for calculating light in 3D-programmes. As a main reference I have used the book *Computer Graphics and Virtual Environments* by Slater et al, which deals with the basics of computer graphics.

2.4.1. Light calculation, rendering and rendering techniques

The radiance equation[19], developed by Kajiya (1986), is one of the most central problems to solve in computer graphics. Attempts to solve this equation are made through all 3D-display methods in computer graphics and there are various ways to do it. The essence of the equation is:

Radiance = emitted radiance + total reflected radiance

[19] *The radiance equation* is usually referred to as the 'rendering' equation (Assarsson, 2006). However, since the equation deals with radiance, in this thesis for the purpose of explanation I have chosen to refer to it as 'the radiance equation'.

Radiance is dependent on the three factors of where, i.e. at which point, the ray hits the surface; the sum of all incoming directions of radiance; and the sum of the outgoing radiance (Slater et al., 2002, p 82). What makes the radiance equation so interesting in computer graphic applications is that it includes the totality of all 2D views of a scene. Different approaches to solving the radiance equation have been developed. Since the equation embodies all possible 2D views of the scene it represents, the problem becomes how to extract such an image.

Rendering in computer graphics is the name of the process of extracting 2D images from the radiance equation (Slater et al. 2002, p 83); or rather it creates a 2D image or animation based on a 3D-scene. When rendering an image the scene's geometry becomes shaded by use of the light settings, the materials applied and environment settings, such as background and atmosphere. The view-independent and the view-dependent solutions are two approaches to rendering. The view-dependent solution means that the radiance equation embodies only the set of rays that are needed for one image. If the viewing conditions were to change, the process of computing the radiance would have to be carried out again. The view-independent solution pre-computes *the reflectance*[20] in a scene across all surfaces and directions.

The local and *the global* solutions are two more ways of classifying the radiance equation. The local solution means that only the interaction between a light source and a single surface is considered, i.e. reflections between surfaces are not taken into account. Usually the light source is a single point, so that the incoming radiance at a surface is represented by just one ray. The advantage with local illumination is that shadows are easily calculated and give acceptable results in simple scenes. It is also fast enough for 3D-animation and -interaction in real time. The global solution takes into account, to a greater or lesser extent, the ways in which light is transferred between surfaces, i.e. all surfaces affect each other. In the thesis only global solutions are considered.

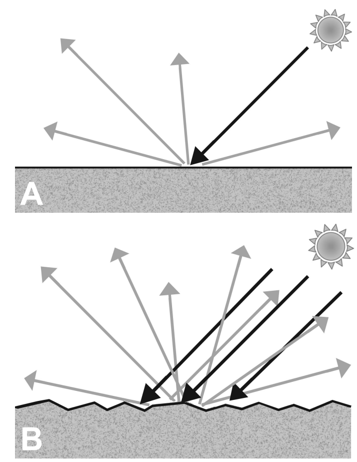
[20] *Reflectance* (or *reflectance factor*) of a surface is the ratio of a ray of light reflected under certain conditions from that surface to the same light reflected from a perfectly diffusing surface (Kuehni, 1997).

2.4.1.1. Non-photorealistic rendering

Within computer graphics, the traditional representational style is photorealistic rendering. The aim with photorealistic rendering is to create images of spatial 3D-models that have a "real world appearance". *Non-photorealistic rendering (NPR)* can thus be explained as any technique which, in a style other than realism, produces images of simulated spatial 3D-models. The focus for this area of computer graphics is the enabling of a variety of expressive styles in 3D-rendering. Often NPR-styles focuses on traditional artistic styles and can be reminiscent of e.g. drawing, sketching and painting.

2.4.2. Radiosity

Radiosity is the realistic, real-time rendering technique most relevant to my aims. The 'real-time' aspect means that the images are displayed at interactive rates, i.e. more than 10 images per second, which is of the utmost importance as a lesser pace will make the application useless in many cases. The radiosity solution assumes that all surfaces are *diffuse*[21] reflectors only. Since the inter-reflections between the diffuse surfaces are taken into account, radiosity is a global solution. Radiosity as a rendering technique was a good choice in our studies because: 1) the solution is view independent, meaning that it will look the same from every viewpoint (only its projection changes), 2) due to the previous point, the solution can be pre-computed and then displayed in real-time, which is one major reason to use it in this project, 3) it handles diffuse-diffuse inter-reflections and 4) it is supported by many programs, including 3Ds max® and Lightscape™. However, there are also some disadvantages. Radiosity cannot handle specular reflections i.e. reflections from mirror-like surfaces, as opposed to diffuse reflections, gloss and shadows in 3D (Wann Jensen, 2001, pp 5-6).



Figures 2.10.A,B.
A. *Specular surface.*
B. *Diffuse surface.*

[21] According to their ability to reflect light, surfaces can be either *diffuse* or *specular* (see Figures 2.10.A,B). A *specular* surface only reflects a narrow ray at a certain angle depending on the angle which the light hit the surface. A *diffuse* surface spreads light equally at all angles (Slater et al., 2002, pp. 133-134).

2.4.3. Ray tracing

Ray tracing is another method that can be used for global illumination. The original algorithm by Whitted (1980), often referred to as *Whitted Ray Tracing*, models specular-specular inter-reflections (Slater et al. 2002, p 154). It is a relatively realistic model of how light travels in an environment where all surfaces are specular reflectors. Reflections are treated on a global scale, and/or as diffuse reflectors with diffuse local illumination. This algorithm can be extended by *Monte Carlo Ray Tracing*[22] or *Path Tracing*[23] to handle global illumination by tracing several sample rays in the possible reflection directions.

Included in the calculation is the fact that a single ray, hitting a surface, illuminates that spot on the surface and further generates two new rays: one reflected and one refracted. These rays then contribute to the illumination of other surfaces in the same way as rays from other surfaces contribute to the illumination of the surface mentioned. Solutions are found only for the specific set of rays entering the eye.

[22] *Monte Carlo ray tracing* algorithms generate random walks through a scene, where reflection rays and refractions rays are created. By averaging a number of sample estimates, the pixel radiance is computed. It is normally a very time consuming method (Wann Jensen, 2001, pp 33-50).

[23] *Path Tracing* by Kajiya (1986) is also a form of ray tracing. Each ray is traced along a path recursively; until it reaches a light-emitting source where the light contribution along the path is calculated. Through this recursive tracing the lighting equation can be solved more accurately than by conventional ray tracing.

Ray tracing is thus considered view dependent, and its relevance for me is therefore small.

In my studies of relevant research I came across the ray tracing based light calculation program *Radiance* (Larson and Shakespear, 1998; Radiance Manual, 2003) which “takes as input a three-dimensional geometric model of the physical environment, and produces a map of spectral radiance values in a colour image” (Radiance Manual, 2003). Studies show that this software gives good results (McNamara, 2005). However, Radiance is image-generating only, and does not therefore correspond to my aims regarding analyzing 3D-environments.

2.4.4. Photon mapping

As an alternative approach to rendering realistic images, *photon mapping* (Wann Jensen, 2001, pp 51-54) could be a method for evaluating the appearance of colours in VR (Assarsson, 2006). This is a full global illumination algorithm, meaning that it takes into account all kinds of light interactions including, for example, specular effects. Photon mapping has great potential for creating more realistic images, but it is currently too slow to be used in interactive applications (Assarsson, 2008). Due to its view dependent nature, the entire solution cannot easily be pre-computed into textures, unlike the radiosity solution.

3. THEORETICAL FRAMEWORK AND RELEVANT STUDIES

The object of this chapter is to describe the state of the art knowledge connected to the aims of the thesis. Since the projects that form a base for this thesis are interdisciplinary; the theoretical framework also touches on different research areas. The central areas that are referred to include *spatial colour and light appearance* within the field of colour research (including everything from colour research within psychology and science to architecture and interior design), *colour and light rendering* within the field of computer graphics; *spatial experience in VR* within the field of human machine interaction (including aspects of usability and cognition), and *visual representation in VR*, connected to both photorealism and non-photorealism.

3.1. Spatial colour and light appearance

Spatial colour appearance is one of the cornerstones of this thesis. Light is closely connected to colour i.e. when you study colour you consequently study light. The illumination in a room is one of the factors that have an impact on its colour appearance. Colour and light are therefore difficult to separate. The focus of the thesis will however mainly concern colour.

In order to discuss the translation of colour appearance from reality to VR, one first needs to consider the background of real world spatial colour appearance. Colour is an important factor in the spatial experience. It facilitates spatial orientation and our perception of the surrounding environment. Colour is also important for attracting attention and mediating information.

To predict the colour appearance in a room is difficult. A colour on a small sample has a different appearance from the same colour applied in a room, since its visual appearance will be strongly affected by the light in the room. The perceived colour in rooms or on buildings is difficult to identify, since there are no instruments to measure what we see. The visual appearance depends on our own perception, taking into account how the brain handles information perceived through the eyes, and the state of adaptation (Zeki, 1993). Research on colour vision has developed theories on how humans perceive and experience colours. These are however mainly based on studies of colour patches and images, and in fewer cases on simple three-dimensional settings (Fridell Anter, 2000, pp 40-48), (Gegenfurtner and Sharpe, eds, 2001, pp 303-416; Derefeldt et al, 2003). Knowing what factors affect the colour appearance can help designers and architects predict the final colour experience more accurately.

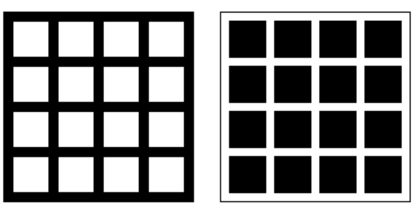


Figure 3.1.
The Hermann Grid Illusion. Viewing two colours at the same time influences the appearance of both. When looking at the left matrix gray patches are visible in the intersections of the black crosses formed by the white squares, and vice versa for the right matrix. (Redrawn after http://www.michaelbach.de/ot/lum_herGrid/index.html)

One example of factors known to have an impact on the colour appearance is simultaneous contrast phenomena (see Figure 3.1.), which are constructed in the human visual system. These phenomena refer to visual effects in which the appearance of a light patch is affected by other light patches that are close in space. The fields change their appearance in the opposite direction from the colour of the other field. For example, a turquoise field on a green background looks bluish, while on a blue background it looks greenish.

Brightness phenomena (see Figure 3.2.) is another example of factors having an impact on the colour appearance. This refers to a special sort of simultaneous contrast phenomena, which relate the perceived brightness[24] of a region to its background. A region will become darker as the background becomes brighter and vice versa (Adelson, 2000).

[24] *Brightness*, or *perceived luminance*, is defined as the perceived intensity of light coming from an image itself, rather than from any property of the scene it depicts (Adelson, 2000).

As far as I understand, there has been a vast amount of research published covering colour appearance in 2D. Spatial colour phenomena in three-dimensional environments have not been investigated to the same extent, and comparatively few studies have been published on the subject. The ones that exist show the impact of colour combination and lighting conditions e.g. the room's compass orientation and room illumination, for the perceived colour appearance in indoor settings (Billger 1999B; Hårleman, 2007A; Pungrassamee, 2005). The way that the reflections in a room enhance both the colour and the colour experience has been demonstrated (Billger, 1999A; Hårleman, 2007A), as has the way in which size affects the colour appearance (Xiao, 2005). In outdoor settings, the perceived colour on facades depends on light, viewing distance and surrounding colours (Fridell Anter, 2000). Both in indoor and outdoor colouring, these factors often cause different results from the expected outcome of a design.

As far as I have been able to determine, when it comes to the software technology used among architects for visualizing their projects, the results from this perception based research are not included in the parameter settings concerning colour and light.

When it comes to research on the knowledge on illumination, I have learned that most studies are based on a quantitative approach and that the spatial experience and light distribution are less researched. The importance of light distribution for the spatial experience has been pointed out by Wänström Lindh (2006). In her studies, she shows how the luminary placement, which affects where in the room it is darker and where it is brighter; and the light patterns, which affect the perception of the size and shape of the room, have an impact on how the room is perceived.

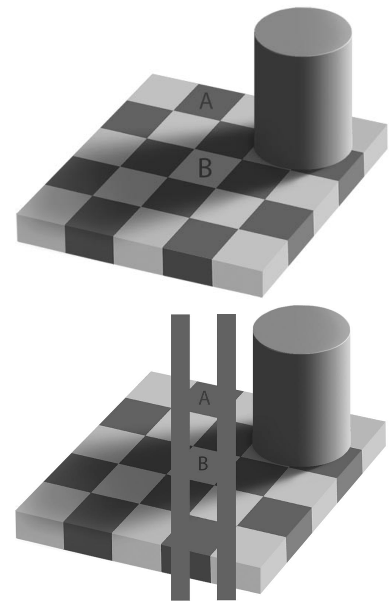


Figure 3.2.
Adelson´s "Checker-shadow illusion". The squares A and B are exactly the same shade of grey. When the visual system interprets a scene to be 3D, a lighting vector is estimated and used in order to judge the property of the material. (Image courtesy of Adelson, E.H., 2009: http://web.mit.edu/persci/people/adelson/checkershadow_downloads.html)

3.2. Simulation of colour and light in Virtual Reality

Through my investigation I found that the simulation of colour and light in VR is a relatively small research field. The focus of this overview will thus mainly concern the results from different studies, in order to identify what has already been done and what is lacking in connection to the problem area for this thesis. I will consider the state of the art that was important when my studies were carried out. Thus, for the area of colour and light simulation, my framework does not include studies conducted later than 2006, i.e. when my studies were finished.

3.2.1. Visual appearance

Today's VR-technology enables the creation of very realistic models from a geometric point of view and scenes can be created that are almost impossible to distinguish from reality. The importance of reliable simulations of lighting conditions for the fields of virtual prototyping and architecture and lighting design is pointed out. Virtual prototyping is used in many appearance-sensitive branches of industry, where costs can be reduced by using virtual prototypes compared to real ones. In architecture and lighting design the interest lies in reliable simulations of indoor lighting conditions. The accuracy of the output of the design process will be dependent on the accuracy of the simulation. (Ulbricht, et al, 2005)

One research project which focuses on the experience of VR compared to reality is the project Simulating *Colour Appearance in Virtual Environments* (in this thesis referred to as SCAVE). In this project the spatial experience of a room is studied from an "inside-perspective". Since a large part of my thesis project is carried out within the frames of this project, most of it is accounted for in the thesis text and the appended papers. However, a few of the SCAVE-publications are not accounted for and merit consideration here. A pilot study for the SCAVE-project was carried out by Billger and d'Élia (Billger and d'Elia, 2001), focusing on different problems associated with the comparisons of reality to VR in a CAVE™. How colours in rooms are perceived was one of the problems discussed, along with technical problems connected to the creation of realistic images at a satisfying rate. The study showed that the colour appearance in the CAVE™ was affected by difficulties in creating enough light and correctly simulating the light situation in the real room. The poor rendering of the simulation affected the spatial experience. As part of the SCAVE-project, Billger and Heldal (Billger and Heldal, 2003) studied the potential of VEs to become a usable design tool with regard to colour and light. They referred to the same test room and simulations as are described in this thesis (see Paper B), and highlight in their analysis the relation between the factors influencing the spatial experience. Benefits and disadvantages of the models were discussed. The study showed that better rendering quality led to higher task performance and had a positive effect on the spatial experience. That the digital models in their present state do not show rich enough colour and light variations is consistent with the conclusions drawn in the previous study.

A method for comparing real environments with digital images was introduced by Meyer et al (1986). This method was built upon measurements of radiant energy flux densities in a simplified physical environment; i.e. a box with some blocks, compared to a simulation where radiosity was used. The simulation was then converted to a digital television image, which was compared with the physical environment. In order for the comparison to be as accurate as possible, both the image and the box were viewed simultaneously through a view camera. The results showed many similarities between the image and the physical model, and the matching between the simulation and reality turned out to be quite good. The observers found, for example, that colours matched slightly better than good and the shadows slightly less than good.

Another study where simulations were compared to a real scene was carried out by McNamara et al (2005). The study aimed to determine how much computation is enough in order to create a trustworthy image, based on the human visual system rather than on physical correctness. For this the ray tracing based software *Radiance* was used. Objects were viewed in a real scene, i.e. a lighting booth, and compared to rendered images. A difference from my aims is that McNamara et al aimed at studying lightness[25], without chromatic qualities. The observers' impressions of the objects' lightness formed the basis of the study, where levels of grey were matched. An important difference from my studies is the fact that scenes were viewed monocularly in order to eliminate depth cues. In contrast, my studies demand that the room is studied from within and that the observers use both their eyes.

Studies comparing digital simulations to real world scenes have different aims and approaches (Meyer, et al. 1986; Hornyánszky Dalholm and Rydberg Mitchell, 1999; Mania, et al, 2003; McNamara, 2005). In most research on digital visualization issues, colour has not been the main topic, but rather one aspect in the study of something else. One place where colour is considered is in a pilot study performed by Hornyánszky Dalholm and Rydberg Mitchell (1999). In this study, models in different digital media (both desktop-VR and a CAVE™) were compared to a full-scale model. However, the aims and focus of this study differ from mine; while the colour appearance is central in my studies, it was used here as a tool to affect the spatial appearance.

Mania et al (2003) aim for photo-realistic simulations and made great efforts to control colour and lights, using objects painted in the same shade of blue. In their study, the focus lay on mnemonic recall of individual objects in a room. Colour appearance was not visually assessed or discussed, though the study involved the translation of

[25] *Lightness* is defined as the perceived reflectance of a surface. It describes the light intensity of a colour, i.e. its degree of lightness. With these values a hue can be classified as either light or dark (Adelson, 2000). Lightness cannot be expressed in NCS terms. It's a comparative quality, while NCS terms are descriptive.

colours from reality to VR in different viewing conditions. In order to achieve a more 'naturalistic' awareness state, the realism in the simulations was sometimes forgone. Mania et al. considered questions concerning cognition, through demonstrating the difference between using task performance based metrics and human evaluation of cognitive awareness states. I find this study relevant because of its translation of colour from reality to VR. However, their approach and focus differ from mine since they come from another field and have different goals.

3.2.2. Different ways to improve colour appearance in images

With today's technology, it is possible to calculate highly realistic scenes where the colourimetric data for each pixel is physically correct. It is however difficult to apply this data such that the colour appearance corresponds accurately to reality. For example, objects shown on a display appear much smaller than they do in reality, as well as being surrounded by the frame. The display has a smaller *dynamic range* than reality's wide range of intensity levels (the 'dynamic range' referring to the span between the darkest and the brightest parts of an image). Therefore, even though colourmetric data can be computed to a high degree of accuracy and with a large dynamic range, it needs to be downsampled to fit the limitations of the display. When it comes to improving colour appearance in two dimensional images, there are different methods to consider.

One of these methods is known as *High Dynamic Range Imaging (HDRI).* HDRI aims at accurately represent the wide range of intensity levels of a real world setting, ranging from shadows to direct sunlight. Conventional images, considered as *low dynamic range (LDR)*, consist of 8 bits per channel. When an image has a greater dynamic range it is known as a HDRI. Thus, in order to use HDRI, a monitor is needed which can display more than 8 bits per channel. Such monitors are currently rare and fairly expensive. HDRI is thus of interest as a future concept, but until such screens are more common, it is currently of little use for the general user.

Another method to consider is *tone mapping*. The purpose of tone mapping is to reproduce the appearance of HDR-scenes in media which have a limited dynamic range, such as common CRT/LCD displays and projectors. It deals with the problem of reducing strong contrasts from the values in a scene, i.e. radiance, to a range that is displayable and still preserves the original colour appearance and level of detail in an image. (Ledda et al, 2005)

One example of a tone mapping operator is the *Automatic Color Equalization (ACE)* (Rizzi, et al. 2003) algorithm, which was developed for unsupervised enhancement with simultaneous global and local effects for digital images. It is based on a computational model of the human visual system and simultaneously tries to solve the tone mapping problem of compressing the dynamic range and recovering colour appearance (Gatta, 2005, p 87). Like the human visual system, ACE can adapt to varying lighting conditions and extract visual information from the environment. ACE aims to perform a 'partial' adjustment to the context, considering the spatial distribution of colours in an image, which is why ACE seemed to be an interesting approach to the problems discussed in the thesis.

3.3. Spatial conditions in Virtual Reality

In the previous section I discussed the state of the art on problems connected to the simulation of spatial colour and light. Here, I will connect to other spatial factors which differ in reality compared to VR and thus affect the simulation. The objective of this chapter is to describe the state of the art knowledge connected to the second aim of this thesis; i.e. to identify spatial conditions in VR for conveying believable experiences. When it comes to architecture and building design, there are different focuses in the VR-studies. On the one hand there are studies from the user perspective on functional issues, such as ergonomics, disability and workspaces. On the other hand there is a focus on the visualization of spatial models, with regard to issues such as size and spaciousness in VR. The latter will be considered here.

3.3.1. Spatial experience in Virtual Reality

The research field dealing with spatial experience in VR is vast, and includes many aspects such as e.g. distance perception, size, scale and speed of movement in VR. In my investigation into the state of the art, I have found that many studies refer to immersive VR, with observers using head mounted displays or goggles, while fewer studies seem to deal with spaciousness in desktop VR. However, it is important to point out that even if the representations are intended to give the same experience, people often experience models of the same artefact differently depending on which VR technology they are using (Heldal et al. 2008).

In architecture and building design, the use of VR in the planning of e.g. building environments in smaller and larger contexts as well as infrastructure e.g. roads and tunnels has proved very useful. Due to different conditions in VR compared to reality, the visualization of a real setting in VR is however difficult, even when the real world appearance is known. The different experience of space in VR simulations compared with reality is affected by e.g. the perception of *distance*. There are numerous studies focusing on distance perception in immersive VR compared to the real world (Witmer and Sadowski, 1998; Sinai et al, 1999; Willemsen and Gooch, 2002; Plumert et al, 2004; Thompson et al, 2004; Willemsen et al, 2004; Messing and Durgin, 2005). Many results show that distances are perceived as significantly compressed in VR (Willemsen and Gooch, 2002; Willemsen et al, 2004; Frenz et al, 2007; Armbrüster et al, 2008). Factors having an impact on the perception of distance are, for example, the quality and fidelity of the visual graphics, restrictions in the field of view and the lack of near-space scaling information (Campos et al, 2007). Interrante et al (2006) suggest that the experience of distance compression in VR is not necessarily caused by the technology, but may instead have its basis in cognitive issues relating to the interpretation of the visuals presented (Interrante et al, 2006). Different studies show that, among other factors, rich texture information (Sinai et al, 1999) and accurate perception of eye-height (Ooi et al, 2001) are important when simulating VEs. The results dealing with distance perception on different types of displays, i.e. desktop vs. head mounted displays, are divided. The type of display, i.e. desktop or head mounted display, is reported to have both lower (Waller, 1999) and higher (Heineken and Schulte, 2001) influence on the perception of distance.

The perception of distance has an impact on the perception of, for example, size and scale. Studies show that size and distances diminish as the field of view narrows and thus appear to be smaller when seen through a truncated field of view, for example when using goggles or a head mounted display (Henry and Furness, 1993; Neale, 1996). Consequently, the perception of size can also differ between a VE and reality (Kenyon et al, 2008), which is important to consider when visualizing space in VR. Some studies have investigated size perception in VEs compared to reality. In a study performed by Heldal et al (2008), size estimation of objects in different VEs was investigated. They concluded that large-scale systems, such as the CAVE™, provide better size estimation. Hornyánszky Dalholm and Rydberg Mitchell (1999) performed a pilot study where different VEs (desktop-VR and a CAVE™) were compared to reality. Their results showed that colour and texture had an impact on size perception in the desktop-model but not in the CAVE™ and that they facilitated navigation in the desktop-model but impeded it in the CAVE™.

Another perceptual difference between reality and virtual settings is the experience of visual speed, which has however been subject to considerably less investigation (Banton et al, 2005; Durgin et al, 2005; Mohler et al, 2007). Studies investigating this aspect show that visual motion rendered to correspond to the actual speed of walking appeared too slow in the VEs (Banton et al, 2005; Durgin et al, 2005).

Today it is a well known fact that, when it comes to particular spatial properties, perceptual judgments differ in VR compared to the real world; this can be referred to as perceptual error. (Campos et al, 2007; Heldal et al, 2008). Makany et al (2006) argue that spatial cognition and behaviour might be essentially different in reality compared to equivalent desktop VEs. They have shown in their research that our exploration and navigation behaviours differ between reality and desktop VEs. In the real world setting their observers moved around in patterns which showed a distinct strategy, leading to efficient navigation. In comparison, the observers' exploration of the desktop VEs lacked strategic patterns, and consequently resulted in relatively inefficient navigation. The reason for this might, according to Makany et al, be that people are more confident and experienced in exploring various spatial strategies in physical settings than they are in VEs.

Balakrishnan et al (2007) observe that physical objects rather than the spatial experience are emphasized in common digital tools for design visualization. In current rendering technologies great achievements are made in representational similarity through increased photorealism. Accordingly the challenge lies in the experimental concordance with a corresponding real space. Balakrishnan et al. state that more work needs to be done exploring current tools of digital representation, in order to improve aspects related to the experience of a simulation (Balakrishnan et al, 2007). Although exploratory usability-oriented studies involving VR-programs have been carried out e.g. (Petridis et al, 2006), very few studies have been reported on the role that VR plays, and could play, in ongoing environmental planning contexts e.g. (Heldal et al, 2005).

3.3.2. Different ways to visualize spatial experiences in Virtual Reality

Three main uses for architectural drawing can be distinguished, according to Unwin (2007): as a medium for communication (with clients, builders etc), as a medium for *design* (private 'play') and as a medium for *analysis* (to acquire knowledge and understanding). Among architects VR as a tool for visualization is used, above all, to communicate ideas (Setareh et al, 2005).

When VR is used in architectural design, the traditional style of expression for which most visualizations aim has (as far as I understand) been photorealism. Today it is possible to obtain a high level of visual realism. The traditional assumption has been that by making interactive models look as visually realistic as possible, more believable virtual experiences have been created (Drettakis et al, 2007). Even with today's progressive technology it is however still difficult to design and implement a visually trustworthy VE. Visual realism is hard to obtain, mainly due to the complexity and richness of the real world. Interactive models for planning and design mostly lack, due to still looking too artificial, the necessary believability to be accepted as reliable tools for evaluating the proposed urban or architectural space (Neto, 2003).

For the design, communication and criticism of architecture, architects depend on representations (Bermudez, 1995). Two dimensional sketches and drawings can sometimes be hard for laymen to interpret, and might therefore not be optimal for architects as a means of communication. With sketches it is, for example, difficult to provide a correct impression of scale and perspectives of every space from every angle; something that VR-visualizations instead facilitate (Savioja et al, 2003). Communication to non-specialists seems thus to be made clearer and easier through the use of computer visualizations, i.e. both interactive representations and renderings (Neto, 2003) However, the value of sketches in the development of a design project lies in their capacity to show a concept rather than the real world as it is. Using photorealism as a standard representational style in architectural visualizations raises issues concerning the visual expression. When it comes to the early phases of a design process, visualizations which aim to look as finished and realistic as possible may inhibit creative thinking, since the flexibility for the final representation is reduced too early (Oh et al, 2006). Kwee (2007) notes that the area of digital architectural presentations focuses on the technology's provision for speed and ease of information retrieval. In the meantime, the quantity and presentation of information in these visualizations is assumed, without proof, to be currently adequate for mediating correct understanding. He states that there still needs to be much rethinking and improvement in order to understand the potential of digital visualization for architectural presentations. (Kwee, 2007)

In relation to the technical development of visual rendering, there are new techniques that support *non photorealistic rendering (NPR)*, which aim to create alternative visual expressions to photorealism, often artistic and sketchlike. Examples of NPR include e.g. generating textures with boundary effects (Ritter et al, 2006) and creating 3D-shapes from 2D-contour sketches (Karpenko and Hughes, 2006). In this work, the background information is obtained from e.g. topology databases, where the naturalism of certain features (e.g. boundaries, volumes – provided by the databases) is important. Thus the form of final products can be predicted.

One aim for a large part of this research is to depict an unfinished appearance and thus recreate imperfection, incompleteness and vagueness. Nienhaus and Döllner (2004) have developed an algorithm that sketches 3D-scene geometry by generating visually important edges and surface colours. Another purpose with non-photorealistic rendering, which has been subject to significantly less investigation, is improving the usability of 3D-interaction (Igarashi et al, 1998; Cohen et al, 2000; Döllner et al, 2007). Hagedorn and Döllner (2008) present for example a sketch-based navigation technique for VEs, with the aim of giving users extra facility when they are navigating and interacting with the 3D-world. This technique, however, requires a touch sensitive screen, since the user navigates by drawing an intended path directly on the screen, which the camera in the animated VE then follows.

3.4. Summary

With regard to the research on colour and light simulation, the relevant research fields I have looked at include spatial colour appearance, VR-research and light calculation and colour rendering in computer graphics.

A survey of the research within the field of spatial colour appearance has shown that few studies exist on spatial 3D colour phenomena compared to 2D. The ones that exist show that size, illumination and surroundings are important factors for how we experience colour.

The investigation of the studies on VR shows that this research has different focuses, concerning both visualization and interaction. The studies I have read show that a correct reproduction of scenes in VR, both physically and on the basis of the human visual system, is a highly important and current topic. However, few studies deal with colour appearance in virtual compared to real rooms, and I have not found any that applies the results of spatial colour appearance mentioned earlier (see Section 3.1.). In most VR-studies, colour has not been the main topic and has therefore not been closely studied in itself.

Except for the SCAVE-studies, none of the comparative studies I have read seem to consider the impact spatial factors have when looking at a room from within, i.e. standing inside it. Instead, in the research I have found, the room is looked at from a distance, or rendered as an image. There are many studies comparing reality to virtual simulations. However, most of the research that I encountered focused on simulated rooms through an outside- or a 2D-perspective. Thus, from what I have found, there appears to be a gap in existing research that needs to be filled. Current research, which is primarily concerned with rendered images, needs to be taken one step further in order to study visually correct 3D-environments, if it is to be of use in simulating colour experience that resembles reality as closely as possible.

Concerning the research on additional aspects affecting spaciousness in VR, the relevant research fields I have looked at include various different aspects of the spatial experience, such as perception of distance, size and scale. In my studies, I consider spaciousness from an architectural perspective, which means that the general impression of a spatial setting is important. Different aspects of the spatial setting are combined to form this entirety. However, I did not find any research studying the spatial whole of a VR setting in a similar way.

To conclude, I can bring with me some useful knowledge from this previous research in my own investigation, but no one of the studies I have found covers my aims completely.

4. METHODS

The applied methods were divided into the two main groups of 1) Literature reviews and 2) Empirical studies. I had different approaches to the empirical studies: (I) to learn more about spatial colour experience, I made a comparison between two existing studies, (II) to encircle the problems of translating colour from reality to VR, an experimental study (SCAVE) was carried out, (III) to test a possible solution to the problems of making visually realistic models in VR, elaborations with an algorithm were made, (IV) to investigate the spatial differences in VR compared to reality, reflections in action on a virtual demonstrator for colour phenomena (VCL) were conducted and (V) to investigate a possible solution to spatial problems in VR, non-photorealistic texture styles were developed and evaluated in a usability study with professional VR users (STIVE).

Important to point out is that most of the studies involve several of the techniques for collecting data and exploring phenomena. Each study answers more than one of the stated research questions, i.e. a study does not solely focus on one single issue. The studies thus interact and complement each other. The literature study has already been presented in Chapter 3; the empirical methods will be presented in this chapter.

4.1. A comparison between existing studies

Figure 4.1.
One of Hårleman's full scale experimental rooms.

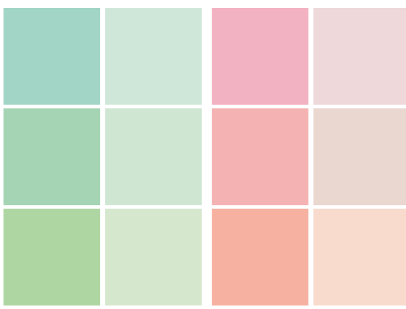


Figure 4.2.
The inherent colours in which the rooms were painted in Hårleman's study.

Figure 4.3.
Room study
Colour Emotion

In order to learn more about spatial colour experience, a comparison between two existing relevant studies on colour appearance was made: (1) Hårleman's room study (Hårleman et al., 2007B) and (2) the Swedish part of the *Colour Emotion*-study (Hansuebsai and Sato, 2002), in which I participated. This comparison is accounted for in Paper A.

It is extremely difficult to predict the way the colour of a small sample will appear when applied on the walls of a room, since the light in the room and its size considerably affect the visual appearance. A comparison was made between results from two existing relevant studies on colour appearance, with the aim of explaining differences in colour appearance in various contexts. The appearance of isolated colour patches in a viewing cabinet was compared to the complexity of colours in rooms.

In her study, Hårleman conducted experiments in two full-scale rooms with similar colour schemes; one room facing north and the other one south (see Figure 4.1.). The aim was to investigate if and how the character of the rooms changes through the differences in colour the light creates. Six hues in two nuances (see Figure 4.2.) were used for painting the rooms. Semantic differential scales, graded from one to six, were used to describe the character of the rooms, complemented with oral interviews.

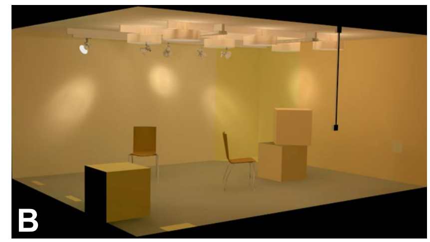
The trans-national project *Colour Emotion* aimed to investigate how people from different countries and cultures make associations with colours, in order to create a model for colour association. In each participating country, observers studied small textile colour chips, in 10-12 nuances of 10 hues, along with 6 achromatic samples. A semantic 2-point method was used for the assessment i.e. the observer chose which word in a word-pair corresponded most with the colour.

In the comparison between the two studies, a translation of the adjectives used was made to reasonably correlate with the other study. Thus a picture was gained of how the colours were perceived in the different situations. When gathering the descriptive adjectives from each study, a collection of impressions was formed which together constituted a good basis for comparison.

The two studies are based upon two different colour order systems. In the room-study the NCS-system was used, and the Colour Emotion-study used a system adjusted to textile samples. To make the comparison between the two studies correct, a translation of the textile chips into the NCS-system was made (see Figure 4.3.).

4.2. The experimental study

In order to map out problems in creating realistic VR-models, sequential comparisons between a real room and simulations of the same room were made. As a base for this investigation, the studies in the project *Simulating Colour Appearance in Virtual Environments* (SCAVE) were used. All or parts of the methods used in the SCAVE project are accounted for in Papers B-E. How light, colour and spaciousness were perceived and experienced in different light settings was investigated through video recorded interviews with the observers. In addition, a separate questionnaire to measure some aspects of involvement and interactivity was used. The results were analyzed, and defined problems with the simulation led to elaboration with software parameters. The real room was always the reference against which the other models have been measured. An important standpoint was that the real as well as the virtual rooms should be studied from *within*, i.e. the observer must be able to move around inside the room. Thus, established methods aiming at comparing images or comparing models through apertures were not applicable. Important for the studies was that the observers should use both their eyes, in order to gain full depth cues (however, in the studies with stereographic goggles, a somewhat limited field of view had to be accepted).



Figures 4.4.A,B.
View of the VR-model (incandescent light). The colours used in the room were NCS S0510-G90Y, NCS S0510- Y10R, 1030-G90Y, 1030-Y10R, 2040-G10Y and 2045-Y80R. The points of special interest in the room were the colour appearance of the sides of the upper cube, the two different red walls and the two different light walls. These parts formed the basis for my studies on different colour phenomena.

4.2.1. From a real room to virtual rooms

The starting point was the experience of a 25 m^2 multi-coloured real room, which was compared with virtual models (see Figures 4.4.A.B.).The room was designed to show clear examples of how simultaneous contrast phenomena and reflections cause different appearances. The room was painted in six different colours, and studied in three different light situations. The illuminations were incandescent light, fluorescent 2700K and fluorescent 3000K. Digital models of the room were made in Lightscape™ and in 3Ds max®[26]. The 3Ds max®-model was exported to VR. In the VR-models, the two illuminations, incandescent and fluorescent 3000K were used, whereas in Lightscape™ and 3Ds max® all three illuminations were used. The lighting I refer to in the digital room models is photometric light downloaded from AB Fagerhult as IES[27] files. This choice enabled a simulation of the lighting originally used in the real room. In the studies, the default scanline renderer[28] in 3Ds max® were used, because of its radiosity calculation, supporting the photometric lights. For technical data on the set-up for the virtual models see Paper B.

[26] The reason for this was that halfway through the project, Lightscape was incorporated into 3Ds max® and ceased to exist as a free-standing product, without any future development. The light calculation functions of Lightscape™ were incorporated into 3Ds max®, which led to the use of this program for the continued studies.

[27] *IES* stands for *Illuminating Engineering Society* and is the standard file format for photometric data (www.iesna.org).

[28] In 3Ds max® there are three renderers provided (3Ds max®6 helpfile , under 'rendering'):

1) *The default scanline renderer* is active by default. The scene gets rendered in a series of horizontal lines. For this renderer, the global illumination options of light tracing and radiosity are available. This type of renderer can also render materials to texture, which is necessary when exporting a model to VR.

2) *The mental ray renderer* renders the scene in a series of square buckets. It uses its own method of global illumination and can generate caustic lighting effects. A number of effects can be reached through the mental ray shaders, which only the mental ray renderer can display. Mental ray was not applied in the elaborations, because it does not support photometric light.

3) *The VUE file renderer* generates a so called ASCII text description of the scene and is used for only special purposes. Multiple frames, specifications of transforms, lighting and changes can be included in a view file. This rendering technique has not been used in the studies.

Additional renderers such as *Brazil* are available as plug-in components to 3Ds max®. Brazil was applied in the tests, however the improvements compared to the default scanline renderer were not found to correspond with the issues focused on.

The experimental study was conducted in two phases (see Table 4.1.). Phase I comprised studies in the real room, in a CAVE™ and in Lightscape™. To compare the Lightscape™-model and the real room, the results of the visual assessments were analyzed. Results from Phase I lead to adjustments of the digital model that were used in Phase II. Phase II comprised studies in Lightscape™ and in VR (monographic and a stereographic).

In order to compare colours with their digital counterparts, a process was developed to translate real colours to digital values (see Figure 4.5.). This process is described in Paper B. Since the translation was complex, it was important to find an acceptable level of correctness. The relations between differently coloured surfaces had to be as correct as possible. On the other hand, small translocations of the colour scale could be accepted, since they were results from the adaptation to the surrounding light and the light from the computer.

For documentation and reference, physical measurements of the spectral composition were conducted for the room surfaces both in the real room and in VR.

4.2.2. Study procedure

The tests started by allowing the observer 10-15 minutes for introduction and adaptation to the illumination and the application. After that, the observer spent 30 to 60 minutes in each model assessing space, colour and light, while being interviewed. After the interview, he/she completed a questionnaire about the experience of interacting with the room model and the sense of presence and involvement. Straight after the study, the participant also made a match from memory between the model just studied and the other models in the current study.

Equally important to the observer's evaluation of the current experimental room was the correspondence between the evaluations made in the different models.

The participants walked/moved around inside the room model and assessed colour, light and space. Data was collected from video-recorded interviews and questionnaires. In total 56 observers participated (see Table 4.1. for details). The observers were students from Chalmers University of Technology with ages varying from 20-35. Half were male and half female. All observers had normal colour vision.

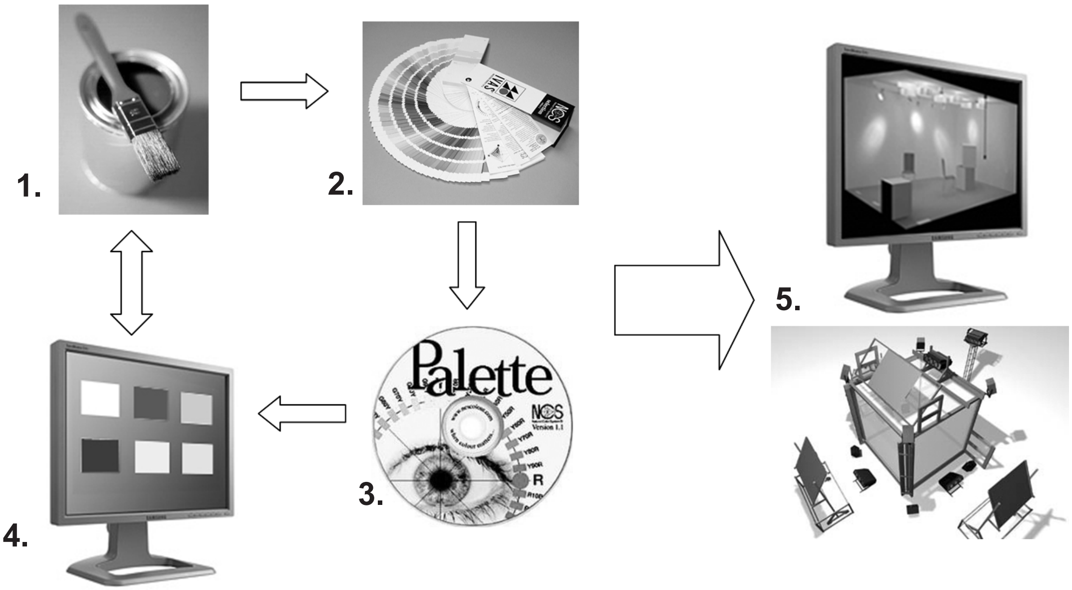


Figure 4.5.
1) The real paints are translated to the NCS-system by 2) physical measurements, conducted with a NCS Index and a spectrophotometer, then by 3) digital transformation in the NCS Palette program. 4) The digital colours are then adjusted with the original paints. 5) The colours are finally inserted in the digital model.

Note that in the project CRT displays were used, not LCD as shown in the figure.

4.2.3. Evaluation techniques

A combination of both quantitative and qualitative techniques was used in order to assess various aspects of perceiving and experiencing the virtual room models and the real room (see Table 4.1.). Techniques A and B deal with evaluating light, colour appearance and space. Technique C is a comparison of the models, which allows the observer to explore both spatial and interactive aspects. Technique D deals with involvement and interactivity with the models. How the observers related to the model was analyzed also by studying the video recorder interviews.

Phase I	Real room	VR: Cave	VR-desktop/ Lightscape		
Illumination	**F3000K/Incand.**	**F3000K**	**F3000K**		
Technique A+B No of observers	23 / 19	29	10		
Technique A+C No of observers	16				
Technique D No of observers	9	26	10		
Phase II			**VR-desktop/ Lightscape**	**VR-desktop: stereo**	**VR-desktop: mono**
Illumination			**F3000K/Incand**	**F3000K/Incand.**	**F3000K/Incand.**
Technique A+B+D No of observers				6 / 19	4 / 16
Technique C No of observers			10 / 35	4 / 16	6 / 16

Table 4.1. *A = Space, B = Colour and Light, C = Memory Matching, D = Involvement and Interaction*

A. Space

1. ***Description of the room***
   The task was to give an immediate response to the room as a whole. The observers talked about their associations, impressions and attitudes towards the room. The experience of the specific model, such as realism, distinctiveness and spaciousness were discussed.

2. ***Motivated semantic differential scaling***
   The participants were asked to mark 12 qualities on an open 7-grade scale and to motivate the markings. It is rather the verbal motivations than the quantitative data that is accounted for.

3. ***Size estimation***
   The observers were asked to estimate the size of the room in square meters as well as length and width.

B. Colour and Light

Note that B 1 and 2 were used with all of the observers. B 3 and 4 were applied with only a few, especially trained for the methods.

1. ***Visual evaluation of light*** (Billger, 1999B, pp 14-18), methods developed by Liljefors and Ejhed (1990). The observer described various aspects of the light, such as light distribution in the room, light level, shadows, perceived colour of light.

2. ***Semantic descriptions of the colours***
   The observers described and compared coloured surfaces, using everyday language and the terminology in NCS (Hård et al, 1996).

3. ***Magnitude estimation***
   The hue of the colour was estimated according to its resemblance to the four chromatic elementary colours, and the nuance was estimated according to its degree of whiteness, blackness and chromaticness. The technique was modified from (Hård and Sivik, 1979) by the addition of a colour reference sample used for calibration of nuance. Only a few observers were chosen to use this technique. They received specific training in estimating colour attributes, according to the NCS system. This method is time consuming; thus it was not possible to include the majority of observers.

4. ***Colour matching with the colour reference box method*** (Billger, 2000B)
   A colour matching method (see Figure 4.6.) is more precise than magnitude estimation and requires fewer observers (Billger, 2000A). The observer's state of adaptation had to be taken into consideration. In the studies using this technique the same illumination was used in the box and in the room. In addition, the fluorescent light 2700K was used in the box in all room illuminations.

Figure 4.6.
The colour reference box.

C. Compared Impressions

Memory matching
Besides comparing the visual assessment results, the participants were asked to compare their impressions of the different room models. In applicable cases, they were asked to describe differences and similarities between one situation assessed directly after the other.

D. Involvement and Interaction

1. ***Description of involvement and interactivity***
   Spontaneous reactions on interactivity were verbally expressed during the interview. The observers' video recorder movements were analyzed.

2. ***Questionnaire***
   A questionnaire provided and analyzed by Ilona Heldal was used to a limited extent (see Paper E). The questionnaire included both questions requiring answers with free descriptions and answers on a 7-graded scale.

4.2.4. Exploring software parameters

In order to define the discrepancies, a direct comparison between the display and colour samples was made. The colour samples, picked out by the observers to match the surfaces in the real room, were placed and analyzed in the colour reference box (Billger, 2000B). With this analysis as a starting point, the parameters describing colour bleeding, reflectance and colour temperature (i.e. the colour of the light source) (see Figure 4.7.) were manipulated to make the model resemble the real room as closely as possible. On the basis of these manipulations the changes that were needed in the parameter settings could be noted.

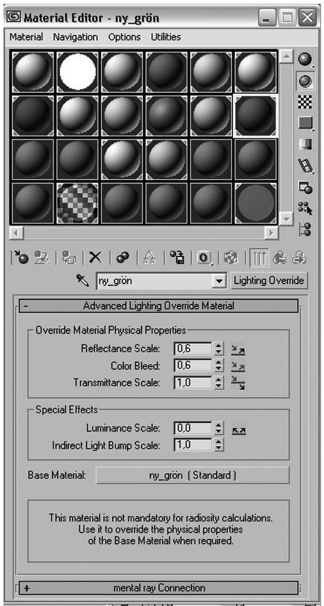


Figure 4.7.
The parameters in 3Ds max® describing colour bleeding and reflectance.

4.2.5. Visual assessments compared to physical measurements

In the SCAVE-project, measurements of reflectance with a BYK-Gardner Colour Guide spectrophotometer[29] were made for the seven used paints in the room. However, measured values with a Photo Research PR-650 spectroradiometer[30] were not used initially for describing the room, but instead applied as a retrospective reference and documentation. Measurements of luminance[31] and spectral composition were made. 40 local points of the real room and 27 corresponding points in the VR-models were measured.

These measurements were above all conducted as documentation and in order to make the studies reproducible. However, the measurements also provided a possibility to evaluate our visual assessment techniques and our process of making comparisons between different media. Thus, in a pilot study, comparisons were made between the visual assessment data and physical measurements. In order to get comparable measurement values between the reference room and the display we had to re-calculate them to corresponding colours under the same illuminant[32]. Only four surfaces that matched well between reality and VR were analyzed thoroughly.

Since this study involves methods which are not within my field of expertise, it is important to point out that it was conducted in collaboration with other researchers, who had a deeper knowledge of the applied methods. The calculations and analysis of the measurement data were done with the assistance of Dr Rejean Barbier at the National Research Council in Canada. Professor Ronnier Luo at the University of Leeds provided useful reflections and comments on the study.

[29] A *spectrophotometer* is an instrument that measures the spectral reflectance or transmittance of an illuminated object or a surface, as well as the light source's spectral-energy distribution (Hurwich, 1981, p.284).

[30] A *spectroradiometer* is an instrument that measures the amount of radiation from a source at each wavelength throughout a pre-defined portion of the spectrum (Hunt, 1991, pp 110-111).

[31] *Luminance* (L) is the amount of visible light that reaches the eye from a surface. It is measured in candelas per square meter (www.schorsch.com/kbase/glossary).

[32] The white reference values for the reference room and the digital models were different. *The Bradford transform* (Berns et al., 2000, p. 213) was used to bring the L,x,y-values to a connection space (D65).

Area:	Reference room: A	B	C	Visual assessments: D	E	F	VR-room: G	H
1	**1030- G90Y**	L* a* b*	L= x= y=	**NCS=1030-G70Y:** L= x= y=	2030- G60Y		L= a= b=	L= x= y=
2	**1030- G90Y**	L* a* b*	L= x= y=	**NCS 2010-Y10R:** L= x= y=	1020- Y10R		L= a= b=	L= x= y=
3	**1030- Y10R**	L* a* b*	L= x= y=	**NCS 2020-Y10R:** L= x= y=	2040- Y20R		L= a= b=	L= x= y=
4	**1030- Y10R**	L* a* b*	L= x= y=	**NCS 1520-Y:** L= x= y=	1218- Y13R		L= a= b=	L= x= y=

Table 4.2.
The table shows the matrix for the collected data from physical measurements and visual assessments in the room under 3000K illuminants. A=Matching NCS-code, B=Reflectance (spectrophotometer measurements), C=Spectral composition (spectroradiometer measurements: the average values of L (Luminance), x and y (CIE 1931, 2O) D=Light box 3000K (measurements of matching NCS-sample), E=Magnitude estimation (assessed in NCS), F=Verbal description, G= Display Lab values, as defined in Photoshop, H= Display spectral composition. Note that D to F is visual assessments results using 3 different techniques.

4.3. Test with an applied algorithm

In order to test solutions for solving problems discovered in the comparative studies, tests with an algorithm, developed for colour correction of digital images, were performed. In collaboration with the PhD-student Carlo Gatta and Dr. Alessandro Rizzi at the Dept. of Information Technology at the University of Milan, the *Automatic Color Equalization (ACE)* (Rizzi, et al, 2003) algorithm was applied to the models (see Paper D) The aim was to see if any improvement in the model's colour appearance could be reached (Figure 4.8.). Together, we wanted to investigate the possibility that this algorithm, developed for colour corrections in 2D images, could also be applied in a 3D-model. We aimed for increased balance between contrast effects and reflections (see Figure 4.8.). The analyzed differences in colour perception between reality and VR in previous studies formed the basis for the ACE studies. The discrepancies were defined by comparisons of the original video clips and images from the real room with the observers' results. On the basis of these results, images showing what the results should look like were produced in Photoshop (see Figures 4.9. A,B). The ACE algorithm was then applied on video clips of the real room and renderings of the digital models. In order to identify any improvement in the colour rendering, the images with the "correct" appearance were compared to the filtered images with ACE. The comparisons and evaluations were made by us in the research team.

To see the effects of ACE on an interactive model, rendered textures of walls and floor in the 3Ds max®-model were filtered with the ACE and combined with a VR-model. This was then compared with the results from reality.

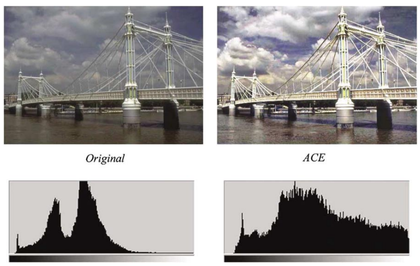
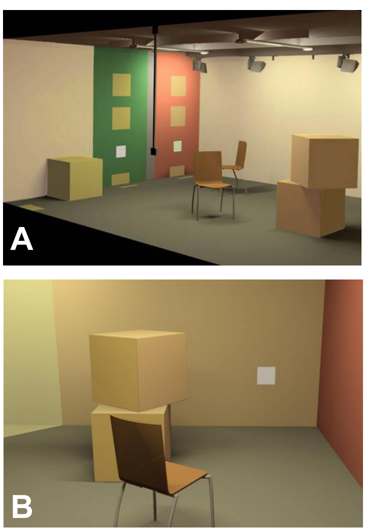


Figure 4.8.
The ACE-algorithm is developed for colour correction in images and aims to increase the dynamic range.



Figures 4.9.A,B.
Example made in Photoshop showing what the results should look like.

4.4. Reflections in action on a demonstrator for colour phenomena

In order to investigate the spatial conditions of VR compared to real world settings, reflections in action were made in the design of a demonstration model for spatial colour phenomena (see Paper F). The reflections were conducted with the approach of practice based research (Frayling et al, 1997; Rust et al, 2007; Biggs, 2004), i.e. in this case the design I was developing.

The reflections in action were performed within the frames of the information project *The Virtual Colour Laboratory* (VCL), which resulted in a demonstrator for existing research results on spatial colour phenomena. The elaborations concerned the design and development of this demonstrator. In its final shape, the demonstrator was going to be an application which the user could open and use without having access to other 3D-visualization software other than that included in the VCL package. Users of the application would then be guided through a virtual world, and there would interactively explore indoor and outdoor colour phenomena as well as receive adjoining written information (see Figures 4.10.A,B,C,D and Appendix C). Different approaches were applied for the reflective work:

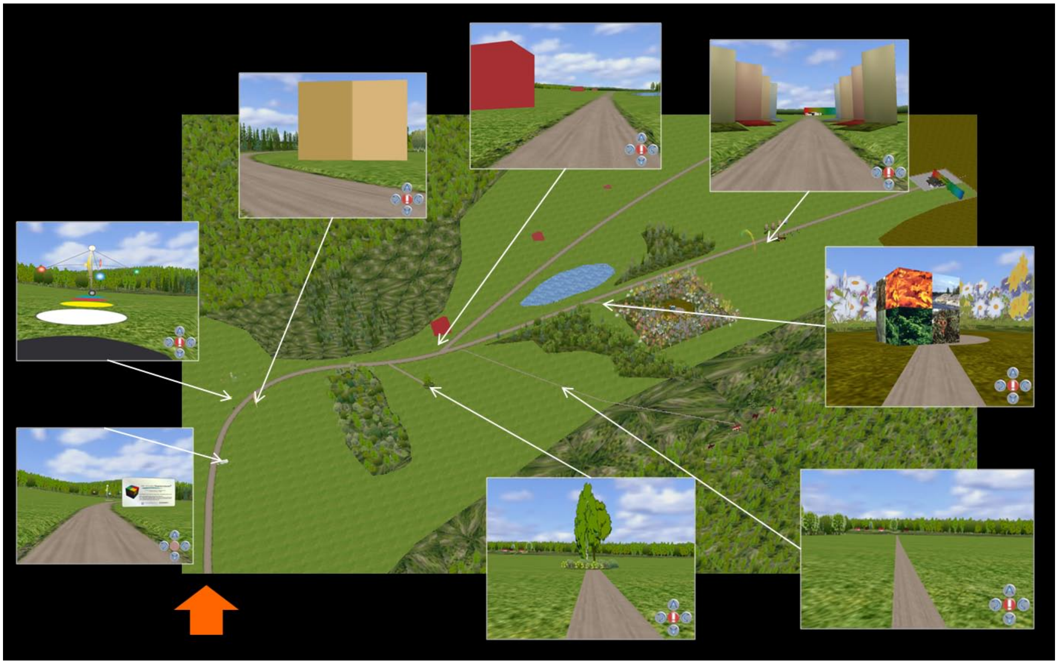
1. ***Elaborations with the models in 3Ds max® and in Virtual Map***
   In the export to VR, the models lost much of their graphical information as well as gaining visually different proportions. Elaborations with size, scale and visual expression were conducted in the 3Ds max®- and Virtual Map-models, in order for them to be experienced correctly in VR.

2. ***Documentations in a logbook***
   The results for each elaboration were documented in a diary, together with other findings on the design work, and personal thoughts and comments on the development of the project.

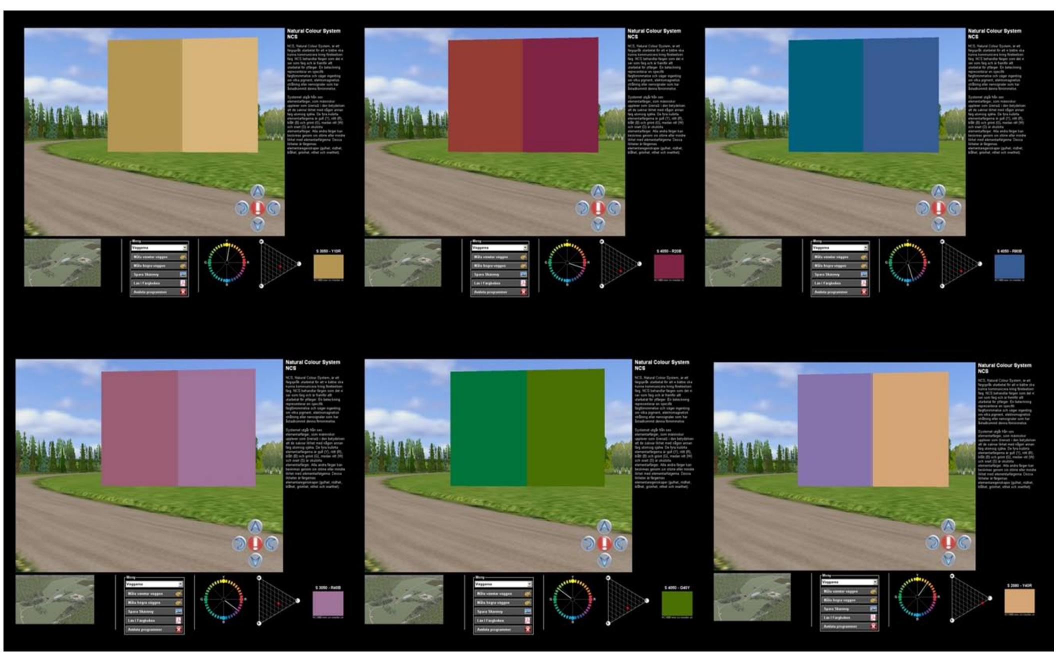
3. ***Discussions and note-takings from meetings in the research team***
   The research group evaluated the results from the elaborations in the models together, and took decisions on the development of the project.

The approach consists of constantly changing perspective, i.e. to switch between reflections on the work (both my own, through writing and reading, and the group discussions with the research team), to practical elaborations in the design of the models. It was necessary to go back and forth between these approaches in order to carry the design onward. I refer to this research approach as *abductive* (Reichertz, 2004), in regard to that I constantly move between theory and empery and let the understanding of the project successively grow.

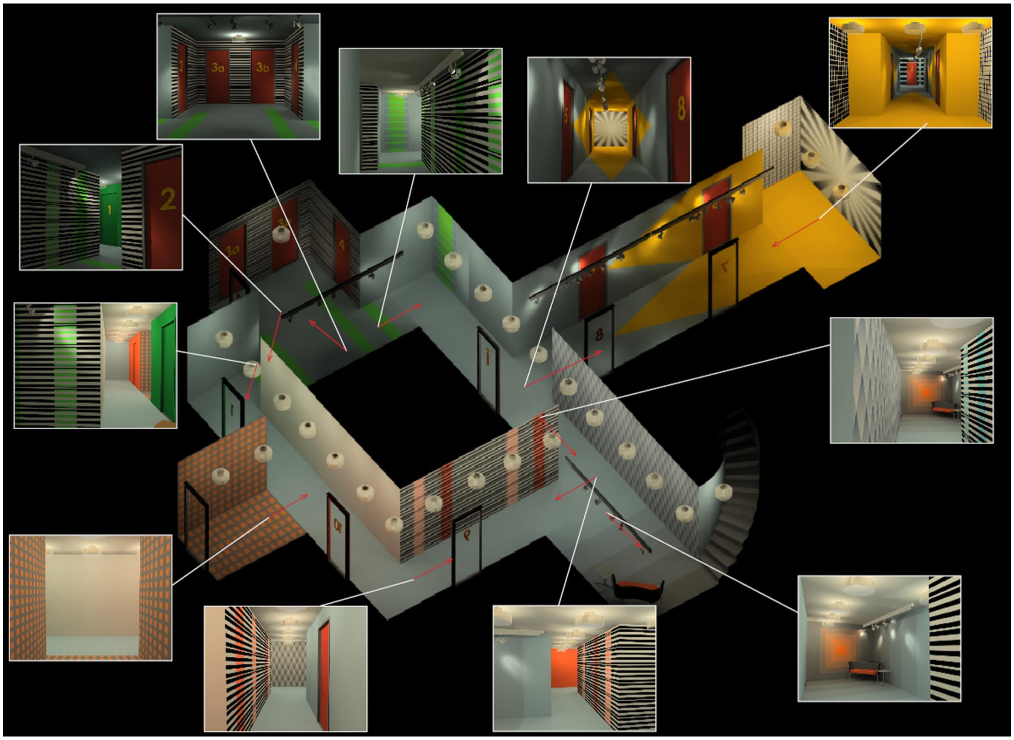
Figures 4.10. A,B,C, D.



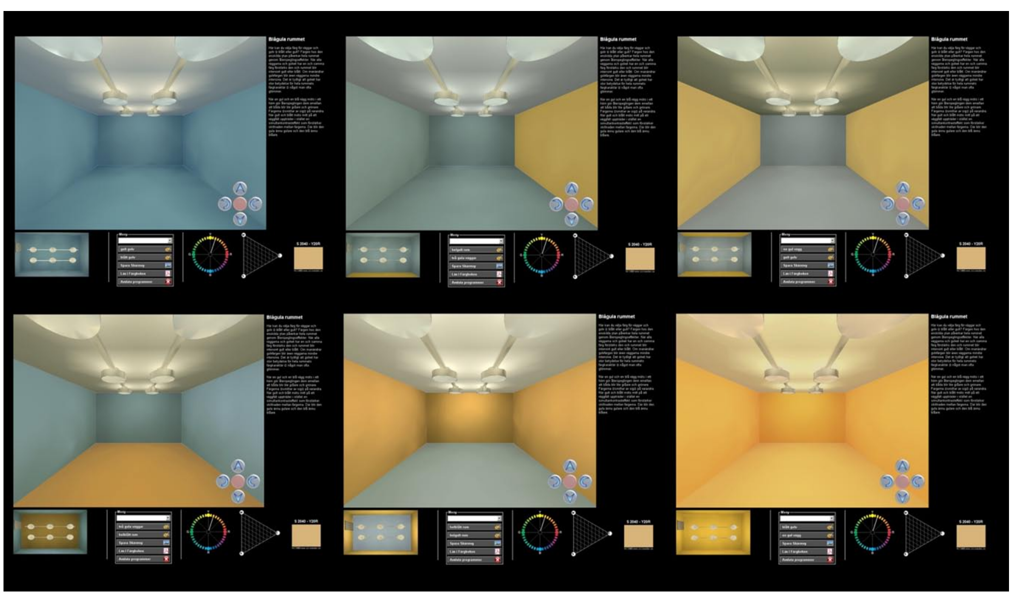
A. *The virtual landscape offers opportunities to demonstrate different characteristic aspects of colour in nature, such as the impact of distance on the perceived colours and their interaction with the surrounding landscape.*



B. *Example of one of the stations in the exterior part of virtual model. Here it is possible to change and combine colours on a wall, in order to experience the influence of adjacent colours on the colour appearance.*



C.*Overview of the corridor-system inside the colour laboratory, which demonstrates two-dimensional colour phenomena.*

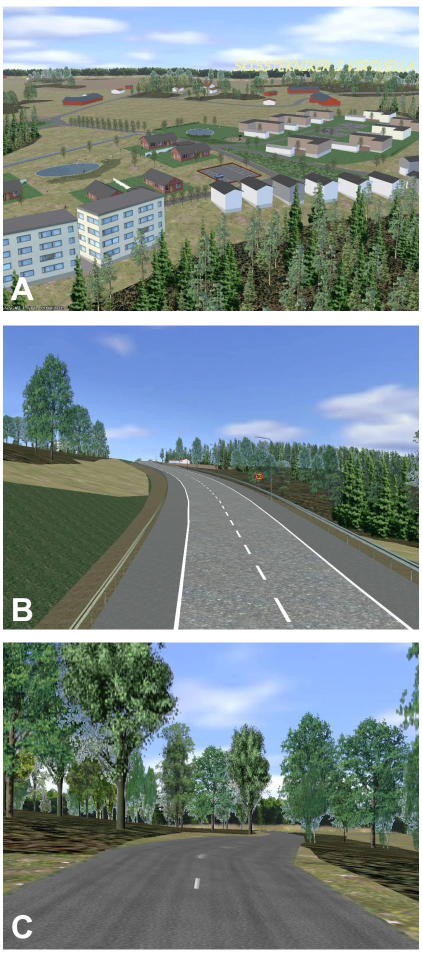


D. *Inside the building there are different rooms showing effects of different choices of colour, light, pattern and material The information in the graphical user interface (GUI) allows the user to make interactive choices, for example to choose between different colour alternatives at certain spots in the model.*

4.5. Evaluation of a demonstration model for texture styles

In order to investigate visual expressions in a spatial VR model better adjusted to the spatial prerequisites for VR and to different design phases, a usability study and elaborations with textures in a VE were performed (see Paper G). In collaboration with software developer Vianova Systems Sweden a selection of textures was applied in a demonstration model, designed to present the different styles in varying environmental contexts. The model was shown to professional VR users. Their evaluation of the different texture styles as well as their general experience of VR was investigated through a questionnaire[33].

[33] *The questionnaire was developed after (Ejlertsson, 2005).*



Figures 4.11.A,B,C.
A.*View of the housing estate in the model.*
B. *View of the main road in the model.*
C. *Example of countryside in the model.*

4.5.1. The demonstration model

Reflections in action were made in the design of different artistic texture styles which were developed and applied in a test model (see Figures 4.13.A-F; 4.14.A,B and Appendix C). The elaborations consisted of practical design work on different expressions for the textures and evaluations made by myself and van Raalte at Vianova Systems Sweden on choices and development of different styles (for approach see Section 4.4). The model's default photorealistic textures were the starting point for the new styles. It was important in the design of the new textures that they should work in different stages of a planning process. Thus, variations in detail, expression and abstraction were considered. I assumed for example that textures containing few details would work better in the beginning of the design process, where the concept rather than the details is most important, while the textures containing more details should be suitable for later stages.

The virtual setting that the model displayed consisted of different environmental contexts (e.g. built environment, infrastructure and landscape) in a typically Swedish summer landscape. Since the context was to be usable for both landscape architects, architects and planners, the virtual setting included parts relevant for each profession. One part of the model thus showed a housing estate, consisting of both single houses and blocks of flats of different sizes, detail and expression (see Figure 4.11.A). Another part described different types of roads (see Figure 4.11.B), while the third part described countryside displaying various trees, bushes, flowers and ground materials (see Figure 4.11.C). In order to simplify the task for the participants, a selection of different viewpoints, showing what was relevant in the model, had been preset. One important criterion was that the model should contain common types of objects in a spatial outdoor VR-visualization (see Figures

4.12. A-E), including *billboards* (i.e. trees, bushes, people); *buildings* (i.e. facades of different building types); *ground material* (i.e. gardens, meadows, fields, farmland, woodland etc); *roads* (i.e. paving, slopes, ditches) and *fences* (i.e. the edge of a forest, wood fences etc).

The model was designed in the infrastructure design software Novapoint Virtual Map. For details regarding the choice of software see Paper G. The participants assessed the task on desktop PCs. As part of the set-up, they were required to download the model from the Vianova ftp site and install the accompanying Style-library, which contained the seven different texture styles. When evaluating the model the participants were asked to go through different viewpoints in each texture style, before answering the questions in the accompanying questionnaire. In the study, 20 participants took part, both architects and civil engineers, all of them professional users of VR in environmental and architectural contexts.

Figures 4.12.A,B,C,D,E.
Examples of the different texture types common in a spatial outdoor VR-model:

A. *Billboard.*

B. *Building.*

C. *Ground material.*

D. *Road.*

E. *Fence.*

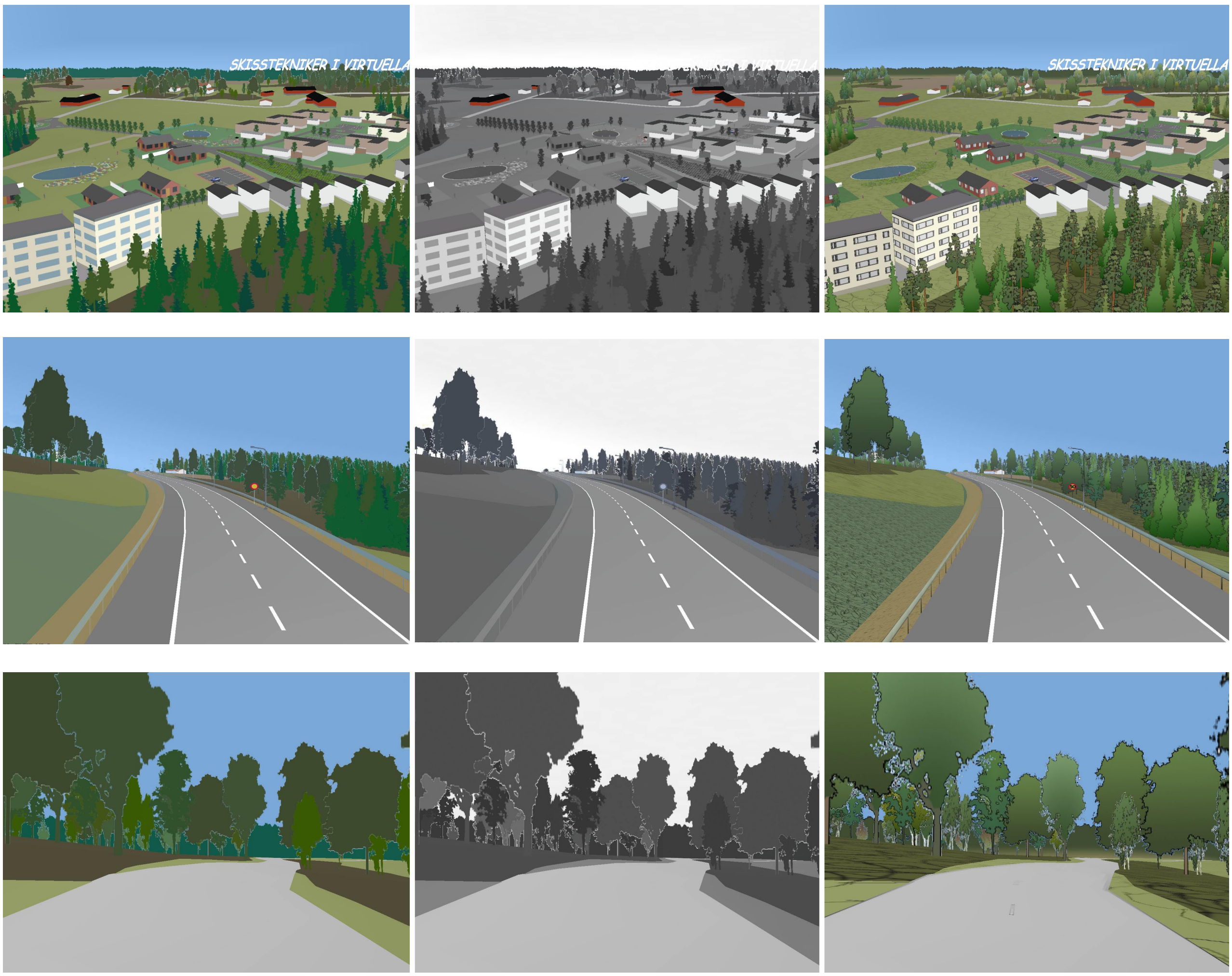
4.5.2. Evaluation technique

A questionnaire

The questionnaire was divided into four sections. The first section concerned the professional profile of the participants, while the second focused on their use and experience of working with computers in general. The third section concerned their experience of VR-visualizations. In section 2-3 free descriptions were used to a large extent, sometimes as a supplement to encircled answers of a *yes/no/don't know*-character. The fourth and biggest section of the questionnaire concerned the evaluation of the experience of textures in the accompanying test-model. In this section a few more evaluation techniques were added:

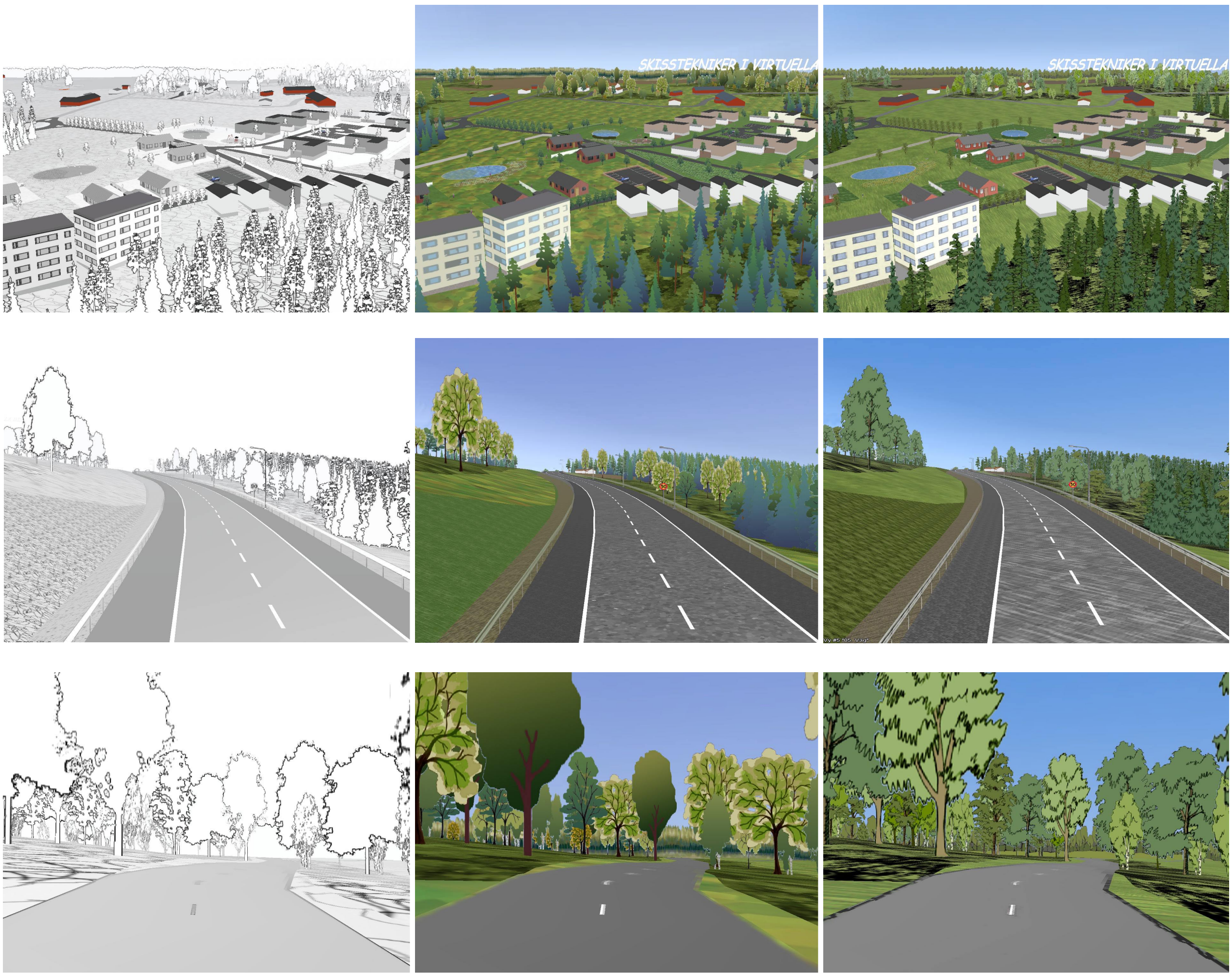
1. ***Free description of each style.***
   The participants were asked to describe, in one or two words, the experience of each texture style.
2. ***Motivated semantic differential scaling.***
   The participants were asked to mark the importance of different characteristics (colour appearance, detailing and aesthetics) for the textures on an open 7-grade scale and to motivate the markings.
3. ***Visual evaluation of the model.***
   The participants were asked to encircle the texture style best suited for each component in the model (ground, billboards, buildings, road, and side-scenes).

The questionnaire was composed of both qualitative and quantitative questions, which were important complements to each other.



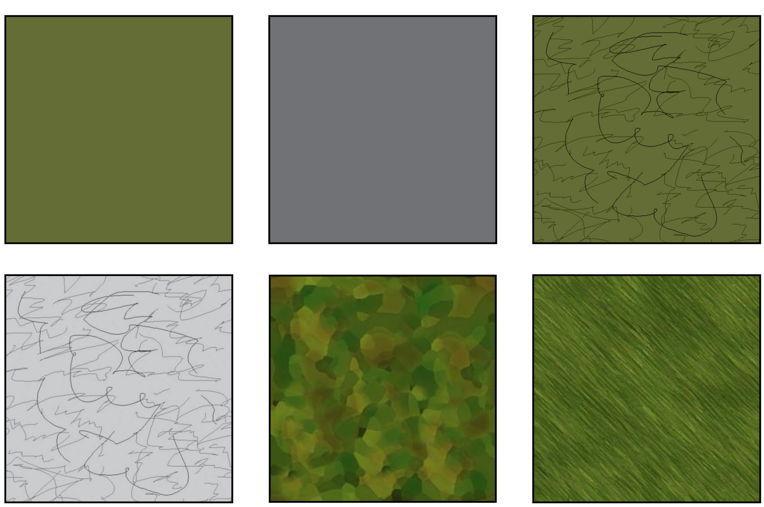
A. *Colour* ***B.*** *Greyscale* ***C.*** *Contour (Colour)*

Figures 4.13.A,B,C,D,E,F.
The texture styles in the different settings (road; housing estate; countryside) of the model.



D. *Contour (Monochrome)* ***E.*** *Graphical* ***F.*** *Sketch*

Figures 4.14.A.
The styles on billboards.
From top left: Colour; Greyscale; Contour (Colour); Contour (Monochrome); Graphical and Sketch. These styles included different expressions, ranging from less to more detailing, from realistic to more abstract and artistic, and from monochromatic to polychromatic.



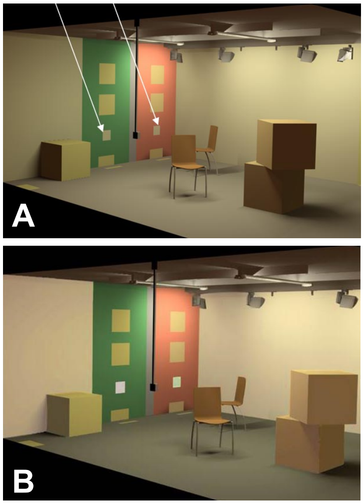
Figures 4.14.B.
The styles on ground textures.
From top left: Colour; Greyscale; Contour (Colour); Contour (Monochrome); Graphical and Sketch.

5. OBSERVATIONS AND ANALYSIS

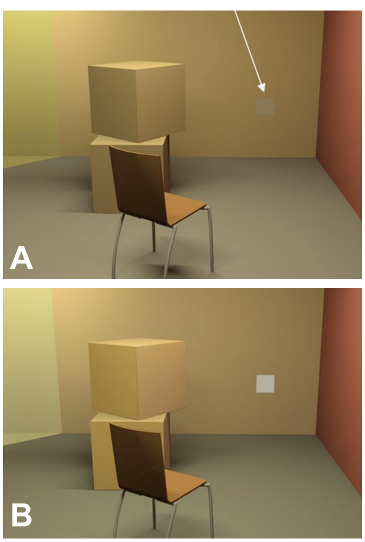
In this chapter the findings from the conducted studies will be reviewed. In order to facilitate understanding, the results are divided according to the stated research aims. I have furthermore chosen to divide them into groups correlating to the area they concern, rather than showing them in the chronological order in which they were conducted.

5.1. Problems of simulating spatial colour and light in Virtual Reality

For most surfaces in the room, the colour appearance in reality and in VR proved to be visually similar. Most room surfaces were well reproduced throughout the SCAVE project; in phase II of the project even more so than in Phase I. The section below will however primarily concern the encountered problems. The results of the visual assessment techniques (verbal description, magnitude estimation and colour matching with the colour reference box) were analyzed. With this analysis as a starting point, the parameters describing colour bleeding, reflectance and colour temperature (i.e. the colour of the light source) were manipulated to make the model resemble the real room as closely as possible. Results from Phase I lead to adjustments of the digital models which were used in Phase II. Phase II comprised studies of the Lightscape™ model and the VR-desktop models (mono and stereo). Papers B, C and D discuss the problems of simulating spatial colour and light in VR. The problems are considered in connection to visual appearance (colour and light) and software technology (manipulation of software parameters).



Figures 5.1.A,B.
A. *The 3Ds max®-model.*
B. *Manipulations made in Photoshop in order to demonstrate the appearance in reality.*



Figures 5.2.A,B.
A. *The 3Ds max®-model.*
B. *Manipulations made in Photoshop in order to demonstrate the appearance in reality.*

5.1.1. Colour appearance

Paper A showed that the experience of a room-colour makes it stronger in colourfulness and blackness compared to the same NCS colour on a small sample. The room-colour will hence correspond to a significantly stronger nuance on a sample. Papers A and B showed that in the real room differently painted surfaces perpendicular to or opposite each other became more similar by reflections. These caused large colour variations on equally painted surfaces that did not show in the virtual rooms. In the real room, the surfaces painted in either of the two yellow nuances, one reddish and one greenish, appeared to have more nuance compared to the digital models. In the digital models there were problems simulating the areas with the whitest nuances. These areas became too greyish. In the real room, the white fluorescent (3000K) illumination made the long light wall almost white, and the short wall light beige. The small squares were white with a tint of pink and green. This was not seen at all in the digital rooms. The colour quality in the CAVE™-based system was low and the colours appeared greyish and weak. The room was more transparent; the screen walls shone through and were always present. In stereographic and monographic desktop-VR, the room-model appeared more realistic regarding colour, light and the way the room was defined.

In the real room, each uniformly painted area showed different colour variations, and contrast effects were evident between differently painted surfaces on the same level. For example, the greenish light yellow square (NCS 0510-G90Y) on the green background (2040-G10Y) appeared pinkish, and the reddish light yellow square (0510-Y10R) on the red background (2045-Y80R) appeared greenish. This did not show in any of the simulations (see Figures 5.1.A,B).

In the real room a brightness phenomenon appeared, i.e. the light square (0510-Y10R) on the yellow wall (1030-Y10R) in the darkest corner was perceived as whitest and lightest of all surfaces, although five other areas in the room were painted in the same nuance (0510-G90Y, 0510-Y10R). This phenomenon did not appear either in any of the digital models (see Figures 5.2.A,B).

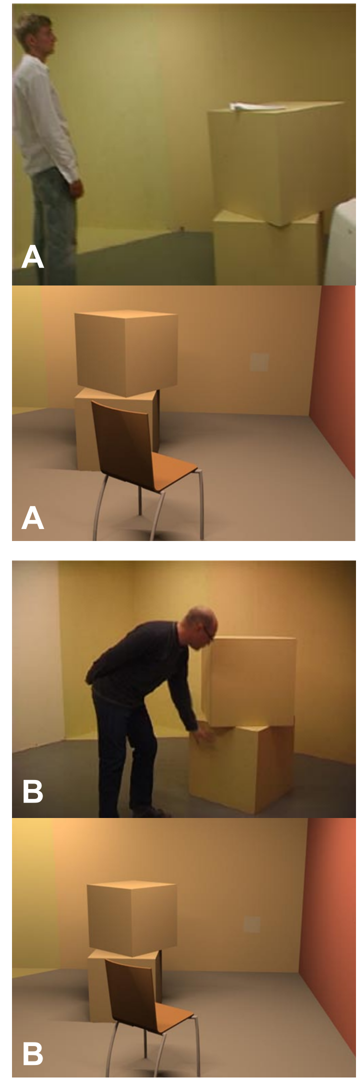
5.1.2. Perceived light

In Papers B and C, results concerning the appearance of light are presented. Due to the fact that the fluorescent lights 3000K and 2700K appeared identical in the virtual models (see Figures 5.3.A,B), the decision was made to mainly focus the analysis on 3000K and incandescent light. In general, the perceived light in the desktop-models with the simulated white fluorescent illumination (3000K) agreed fairly well with the real room in all aspects but the shadows. In the CAVE™, the perceived light turned out to be difficult to simulate.

Light distribution and shadows: The light from the spotlights were not spread enough in the room simulations. In the CAVE™, the observers found the light distribution unacceptable. The light was not perceived to come from the light fixtures and the shadows looked unnatural and misplaced. In the desktop-models, the shadows were found to be too achromatic, however natural in their placement. The observers described them as greyish and thin, as if they were placed on a separate layer on top of the coloured surfaces.

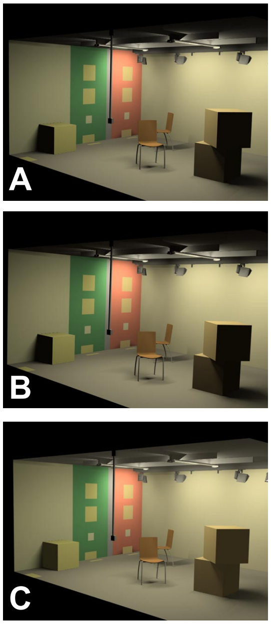
Light level: The desktop-models were perceived as somewhat lighter than the real room. In the CAVE™, the level of light was perceived as much lower. The estimation was more difficult in this situation and the model was sometimes interpreted as a simulation of a light room, although it was dark in the CAVE™-model.

Perceived colour of light: In both reality and in the desktop-models, the white fluorescent illumination was by most observers found to be cold or neutral. This light was in reality and on the desktop experienced as having basically no colour, though in reality some observers found it to be slightly yellowish. In the CAVE™ it was perceived as being grey, and most observers found the perceived colour of light to be warmer than in the other models. The light colour did not turn out the same in Lightscape™ and 3Ds max®. In the desktop-model with simulated incandescent illumination the parameter analysis revealed problems in simulating light distribution and light colour. None of the software's settings for incandescent light was red enough.



Figures 5.3.A,B.
A. *2700K in the real room and in 3Ds max®.*
B. *3000K in the real room and in 3Ds max®.*

5.1.3. Manipulation of parameters



Figures 5.4.A,B,C.
Reflectance - Fluorescent light, 3Ds max®
***A** = 0,5 colour bleed, 0,5 reflectance*
***B** = 1,0 colour bleed, 0,5 reflectance*
***C** = 1,0 colour bleed, 1,0 reflectance*

General elaborations with the software parameters in Lightscape™ and 3Ds max® are shown in Paper B. The default values for the simulations did not correspond well with the colours of the real room regarding bleeding, reflectance and colour temperature (i.e. the colour of the light source). In order for the digital models to resemble reality as much as possible, the parameters in both Lightscape™ and 3Ds max® concerning colour bleed, reflectance and colour temperature were manipulated (see Figures 5.4.A,B,C). The manipulations were analyzed and used for improving the VR models which were used in Phase II.

Through the elaborations, problems with the radiosity calculations were pointed out. Both the manual for Lightscape™ and 3Ds max® recommend 100% colour bleed for physically correct results during radiosity calculation. However, the manual for 3Ds max® indicates that adjustments of the settings might be necessary in order for excessive effects to decrease, due to, for example, a large area of colour. In both programmes, the recommended setting resulted however in fewer colour variations compared to reality (see Figure 5.5.). The recommendation from the manufacturer of the light fixtures, suggesting 4-15% colour bleeding for the matte surfaces in the room, was used initially. It turned out that this setting was too low. At least 40% is needed, and different colours require different levels of the parameter setting, depending on the program.

It has been shown that in order to make true and realistic visualizations in VEs, the colour appearance of the objects in reality must be known. However, even if the properties of the real objects are known, it is not always possible to obtain a correct simulation. For example, high reflectance in the digital models turned out to brighten up the areas around the long red wall too much (see Figure 5.5.). Low reflectance on the dark areas gave a better result, in combination with increased colour bleeding. For the light long wall high reflectance was needed for the light areas to get enough brightness. High reflectance for this wall resulted in its lightness being mirrored on the opposite red wall, which then became too light. In order to compensate for this, the luminance level needed to be decreased significantly. As with the colour bleed in both programmes, different colours need different levels of the parameter setting. Through the experiment conducted, a fairly good match was obtained between the real and the virtual room.

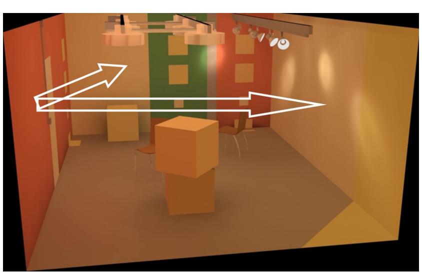


Figure 5.5.
Problems regarding the simulation of reflection between surfaces.

5.1.4. How to convert reality to Virtual Reality

Papers B and C deal with methodological issues concerning how to compare visual results between different media and how to convert real room settings into digital counterparts. This includes problems with mixed adaptation when using the colour reference box and when studying a display in a room; and problems with arbitrary parameter settings in the software. In order to study the rooms from within and adapted to the illumination, sequential comparisons are necessary.

While Paper B only considers results from Phase I of the SCAVE project, Paper C accounts for results from the whole project (Phase I and Phase II). From what we can see, the visual assessment techniques (verbal description, magnitude estimation and colour matching with the colour reference box) provide us with a well-functioning method. However, sequential comparisons are problematic; every step creates a possible “slide” in judgment. Measurements of reflectance, luminance and spectral composition were therefore made.

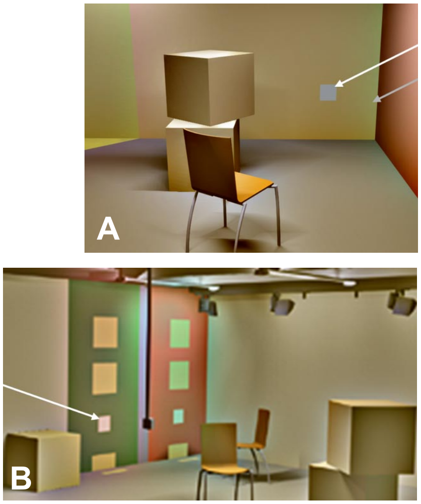
Paper C also includes a pilot study, which compared data acquired through different assessment techniques. These data concerned surface areas where the colour appearance in reality and in VR proved to be visually similar. An analysis was performed where spectral composition values measured in the different models were transformed, in order for them to be compared in the same illumination (D65).

The comparison showed that the surfaces between the real and the simulated room agreed fairly well. More detailed results are accounted for in Paper C. Overall, the methods used here provide a reasonable level of accuracy for describing the colour appearance of the room. However, when brought to the connection space, there was a small difference between the measured values. To a certain degree this could be the result of either measurement errors, since different measuring instruments have been used; or problems with the formula used for bringing the values to the connection space, e.g. the normalization of the white point, or the methodology used. The translation method used is a complicated procedure, where the *NCS Digital Palette* and the colour reference box are used in the process of reproducing the paint correctly.

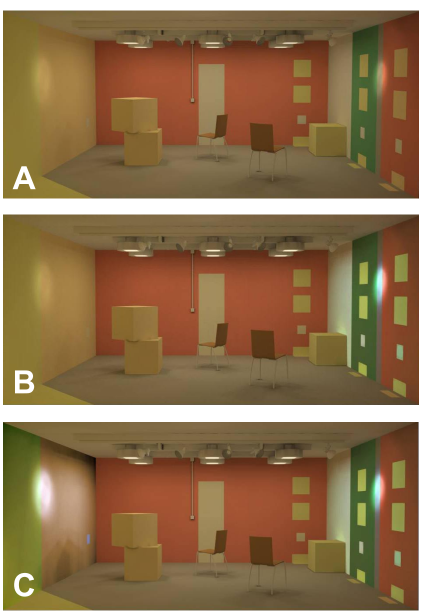
An alternative solution could be to use reflectance data (L*a*b*) for the paints, and apply these data as digital Lab values in, for example, Photoshop. However, the analysis showed that this did not work: L*a*b*-values measured in reality could not be directly applied as digital Lab-values (see Paper C: Table 1, Column B and G). They needed to be slightly adjusted. Corresponding Lab-values on the display were too brownish for the four different yellow paints. The strong red and green needed to be adjusted in the opposite way. Otherwise the simulation became too brilliant and whitish.

5.2. Tested solution to stated problems of simulating colour and light in Virtual Reality

Paper D discusses an attempt to try one solution to the above mentioned problem of too few colour variations and incorrectly reproduced contrast effects in the simulations.



Figures 5.6.A,B.
Model in 3Ds max® filtered with the ACE.



Figures 5.7.A,B,C.
***A.** The original model in Lightscape™.*
***B.** The right wall filtered with the ACE.*
***C.** The left and right wall filtered with the ACE.*

5.2.1. Elaborations with rendered textures

The ACE algorithm was applied to the digital models. In the first elaborations, rendered images of the room in 3Ds max® were filtered with the ACE. The tests showed interesting results. After having filtered them with the ACE, the light areas in the model improved in colour appearance. The small square in the darkest corner of the room became distinctly whiter and closer to its real appearance (see Figures 5.6.A). The other two white squares regained the greenish and pinkish appearance they had in reality (see Figures 5.6.B).

However, the ACE also showed contrast phenomena between all differently coloured parts of the room, regardless of where in the room they were located. This led to unrealistic contrast effects between walls and between walls and floor (see Figures 5.6.A,B).

In the following elaborations, the ACE was applied in the process of preparing a model to be exported from Lightscape™ to VR. The ACE was used for filtering rendered textures of multicoloured flat surfaces (i.e. walls, floor etc) in the model, which were then combined into a complete model (see Figures 5.7.A,B,C). Through these elaborations, the best result so far concerning the colour appearance was obtained. This concerned the red and green wall, where all colours turned out to be well simulated and in accordance with their real appearance; even the contrast phenomena became visible! However, when filtering the opposite wall, the colours turned out to be extremely exaggerated and incorrectly reproduced.

The conclusion drawn from the elaborations is that since the ACE does not consider the amount of information in an image, it thus treats all surfaces equally, disregarding if the image is detailed or not.

5.3. Problems of conveying believable experiences in Virtual Reality

Papers E, F and G discuss the problems of the spatial conditions in VR for conveying believable experiences. The problems are considered in connection to the spatial experience of different models, colour reproduction and the spatial experience in a desktop virtual setting.

5.3.1. Spatial experience of different models

Paper E shows how the observers moved around, and experienced spaciousness differently in the real room, in the CAVE™-based model and in the desktop model.

The real room: The observer could in reality walk around; taking close looks at different locations and still keep general conceptions of the room as a whole, in a way not possible when interacting with VEs (see Figure 5.8.A). Additional senses, i.e. hearing and touching, helped to increase the sense of presence.

The CAVE™-based model: The studies showed that the observer felt surrounded by the room in the CAVE™ and was physically able to walk around and examine it, though the level of detail, the light quality and the physical sensations of direct contact with objects were absent. The way of moving was different from reality and the best illusion was perceived when standing still, letting the room move around (see Figure 5.8.B).

Desktop VRs (monographic and stereographic versions): The observers found it very difficult to relate the body to the desktop models. A difference compared to the other room models was that it was hard to be able to get an overview of a larger part of the model. For example, one had to lean forward in order to see the floor. A jaggedness in the stereographic model reduced the sense of presence. In addition, double silhouettes in the glasses disturbed the 3D-experience. Despite these factors, most observers still found the highest sense of presence in the stereographic model, due to the 3D-effect (see Figure 5.8.C).

Desktop Lightscape™: The Lightscape™-model was perceived, in comparison with the VR desktop models, to be more artificial. The observers expressed frustration over the difficulty in getting close

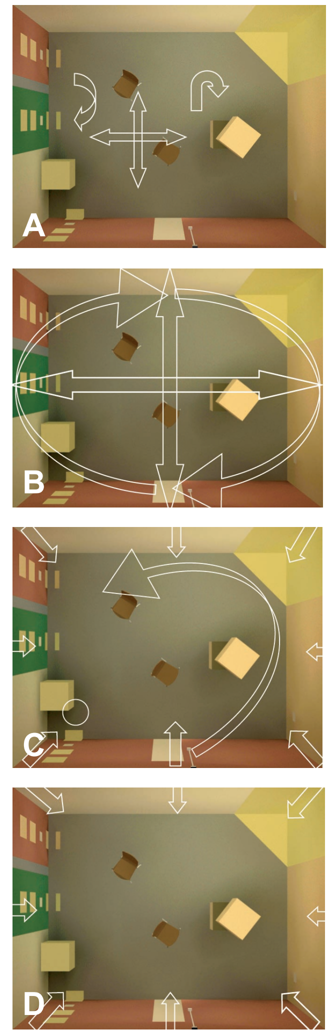


Figure 5.8.A,B,C,D.
How observers moved around in:
A. *The real rom*
B. *The CAVE™-based model*
C. *The desktop VRs (mono and stereo)*
D. *The desktop Lightscape™-model*

inside the model. At closer distances, the overview was lost and the objects became abstract. It was also more difficult to relate the body to the Lightscape-model, which was observed from the outside rather than from within (see Figure 5.8.D). The *graphic user interface* (GUI) of the Lightscape™-software, confounded by screen menus and controls, emphasized the sense of a computer model. By contrast, the VR-models filled out the screen, and therefore did not split the attention.

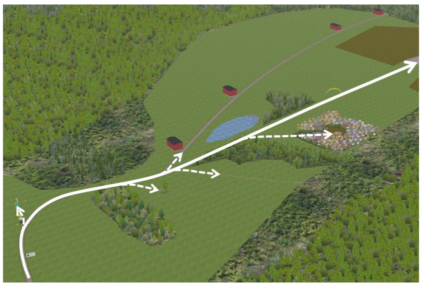


Figure 5.8.E.
How observers moved around in the VCL demonstrator.

The *Virtual Colour Laboratory*-desktop model: When analyzing the interactivity in the demonstrator, I regard my own and the research group's impressions. Those in the group who were used to playing computer games on a desktop perceived it as easy moving around, while the others in the group found it more difficult. A camera path was added to the model, which improved the non-gamers' movements, but was perceived by the gamers as inhibiting their ability to move around (see Figure 5.8.E.). Group members commented on feeling larger than in reality inside the VE. Compared to Lightscape™, the GUI of VCL had a lesser impact on the experience of moving in a virtual world instead of in a model.

5.3.2. Spatial experience in a virtual desktop environment

Paper F discusses several problems connected to the spatial experience in a virtual desktop setting. However well made, a VE can never offer the sense of real presence in a virtual desktop context. We do not move around in the same way in a virtual model as we do in reality and our attention is not drawn by the same means. A virtual setting consists mainly of sight impressions and the active investigation is strongly restricted. To make a user observe a specific detail of colour or a certain phenomenon is therefore difficult. In the VCL project this was most obvious in the outdoor model, where a constant problem was that the landscape, meant to look as natural as possible, did not look natural enough. This problem was visible in the model's final appearance: although it looked sufficiently natural in Virtual Map, a significant loss of light and details became visible in the export via 3Ds max® to the interactive demonstrator. The interior model, with its straight lines, was less affected than the outdoor model, with its rounded shapes. As a result, much of what in reality is experienced as harmonic became dull and uninteresting in the virtual VCL model. Consequently, there is a need for strengthening effects in the model in order to create an interest and attract attention to parts of it that are of special interest.

In the demonstrator it was difficult to focus on relevant aspects of what was visualized, since the different parts of the model contained equal information, with no protruding elements. This problem is also connected to the different experience of scale in VR compared to reality. The objects in the model were perceived by the research team as smaller than in reality and further away (see Figure 5.9.). This was clearly shown with the exterior façade in the VCL outdoor model. The changing colour of a façade according to distance was one central phenomenon to be demonstrated in the model (see Figure 5.10. and Appendix C). In reality, our attention is drawn to that which contrasts to the background. Thus a solitary building by the edge of a forest would be observed, even if its part in our field of vision is very small. However, in the VCL outdoor model buildings were hardly noticed at a distance, even less their colours. Even after having largely increased the size of the front façade of the virtual laboratory, to 50 m x 20 m, at 600 meters distance the façade was only a few pixels wide, and only at 150-100 meters distance was it large enough to be able to show any changes in colour appearance.

Since colour realism could not be accurately reproduced for technical reasons, the problem of visualizing colour phenomena correctly in the model became a problem of correctly compensating for the different conditions in VR compared to reality. In VCL it was enough to “feign” accuracy, since the colour appearance of reality was known. For compensating and thus producing a correct colour appearance, Photoshop was used. In order for this to work, the colour appearance of reality must known, since the digital simulations could not be trusted. This required comparisons between real environments and the digital models.

Figure 5.9.
The objects in the model were perceived as smaller than in reality and further away. This is an early version of the colour laboratory.

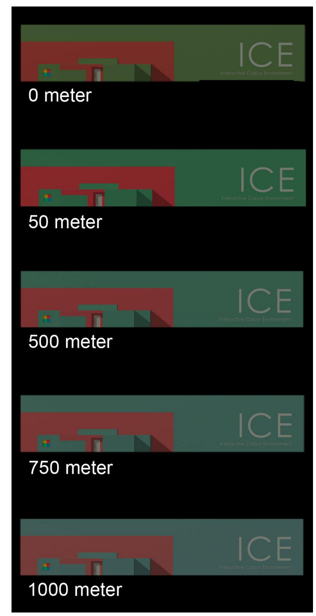


Figure 5.10.
The changing colour of a facade according to distance was a central phenomenon to be shown in VCL (formely named ICE).

5.4. Tested solution for conveying believable experiences in Virtual Reality

Paper G discusses one solution to the above mentioned problem of conveying believable experiences in VR.

5.4.1. Evaluation of VR as a visualization technique

The use of VR as a visualization technique among professional users is discussed in Paper G .

The 20 participants in the study were all occupied with work concerning planning and design of architecture and infrastructure. 10 of the participants were architects and 10 were civil engineers. The participants confirmed what earlier studies have already acknowledged as advantages of using VR, such as an increased understanding of a project. Above all, the results point out the potential to mediate ideas to clients / the public. Other benefits of using VR were allowing dynamic content of the visualizations, understanding volumes, and better support for orientation. Regarding the problems of using VR, important results for this study include the representation of realism, which many participants considered a problem; above all the level of realism in the visualizations. The participants also considered it to be difficult to find good basic data (maps, orthophotos, terrain data etc) for the visualizations. A large part of what was considered problematic in using VR was related to technological issues, above all time-consumption and the overly large size of the visualizations. Usability issues and work effort were also pointed out as problems, i.e. difficulties in learning new software and visualizations being too complicated to make.

5.4.2. Evaluation of the texture styles in the demonstration model

The study proved that more attention needs to be given to considering appropriate texturing styles in VR visualizations. We assumed that the less complex styles would suit the early stages of the design process, while the more artistic and detailed ones would best suit the later stages. The results showed that participants disliked certain styles, especially if they were not used to these in their everyday work. For example, the low ratings for the simplest styles (*Colour* and *Greyscale*) proved that we misjudged these styles as fitting the early phases of the design process.

The gradient, providing a more varied colour range, and the black borders, were probably the reason for the otherwise similar *Contour (Colour)´s* much higher rating. (see Figures 5.12. A,B,C,D.) The study also showed that the characteristics colour, aesthetic values and detailing all have an impact for the interpretation of visualizations.

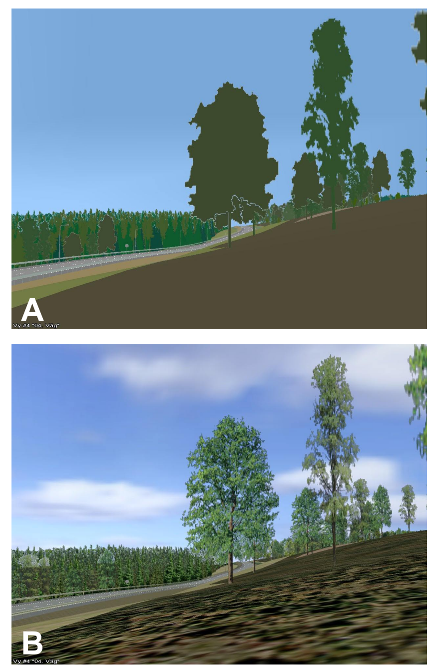
Colour appearance: The high mean and modal values (see Table 5.1.), and an overall disregard for the monochromatic texture styles among the participants, show the importance of colour in VR visualizations. From the qualitative answers it generally appeared to be of lesser significance that the colour appearance was correct, than that the overall impression of the total and combined colour appearance was satisfying and harmonious.

Detailing: The slightly lower mean value (see Table 5.1.) and more scattered modal value for detailing indicate that this was not considered to be as important as colour. However, the texture styles with fewest details, i.e. *Colour, Greyscale* and *Contour (Monochrome)* (see Figure 5.11.A and Appendix C), were generally the least popular (except a slightly higher rating for *Colour* as a work tool). This is interesting, since the lack of details in those textures was an attempt to fit them to the initial stages of a design.

Aesthetics: Both qualitative and quantitative results proved the importance of aesthetics for a visualization. Comments pointed out the value of non-realistic representations when using VR for presenting project proposals. To produce sketchy, unfinished expressions was considered relevant. Also, there was a call for combinations of different styles.

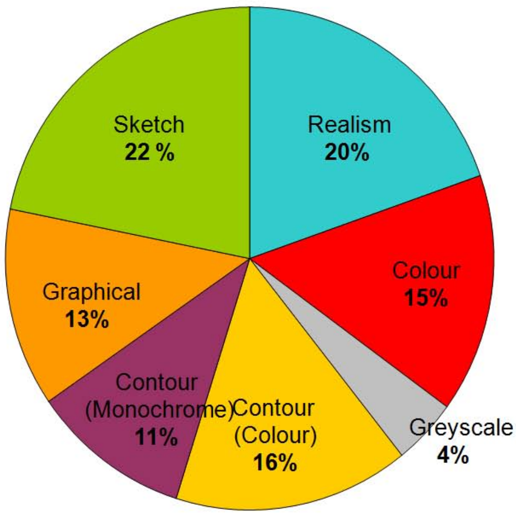
	Colour appearance	Detailing	Aesthetics
Sum	36	19	34
Mean value	2	1,1	1,9
Modal value	2	2	2
Non-response	2	3	2

Table 5.1.
The importance of colour appearance, aesthetics and detailing for the visual expression of a VR-visualization.

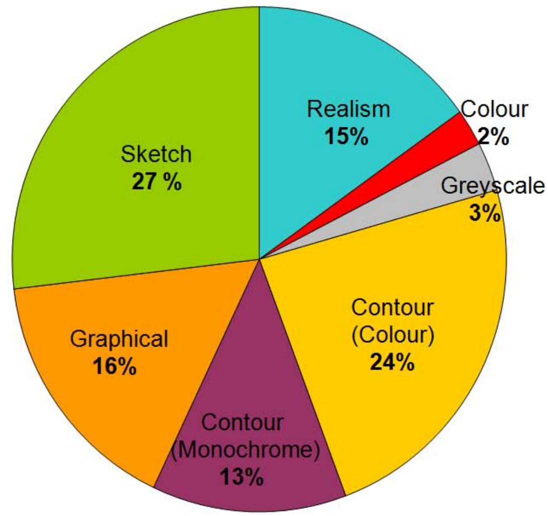


Figures 5.11. A,B.
***A.** The Colour-style: Low level of detailing.*
***B.** The Realism-style: High level of detailing.*

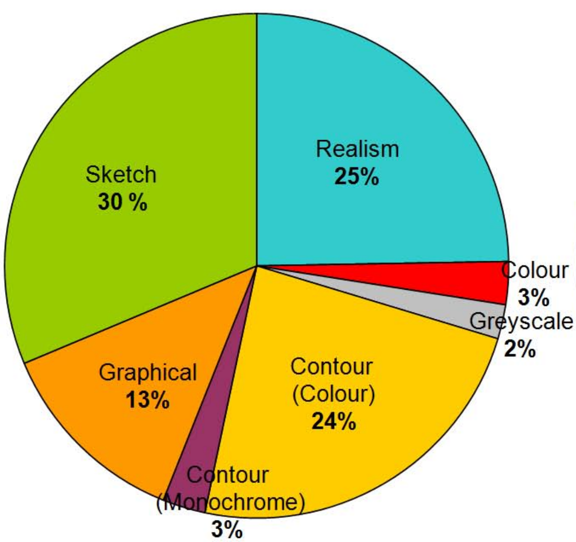
Figures 5.12. A,B,C,D.



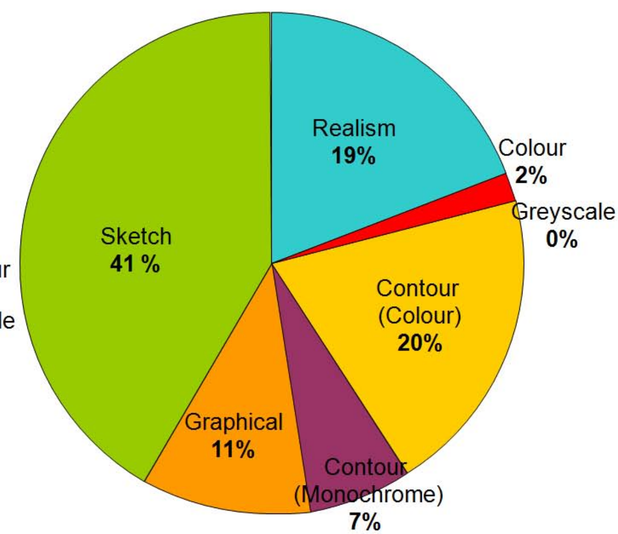
***A.** The texture style best suited as a tool for sketches and projections.*



***B.** The texture style best suited as a tool for presentation.*



***C.** The best working texture style for each object type in the model.*



***D.** The most popular style in the model.*

It's on the strength of observation and reflection that one finds a way.
So we must dig and delve unceasingly.

- Claude Monet

6. REFLECTIONS ON RESULTS AND METHODOLOGY

In this chapter a short discussion about the stated research questions will be presented, which summarizes and reflects on the results from the studies, in relation to the applied methodology. The following questions were considered:

Questions concerning visual appearance: Will a simulated room look the same as the real one? If not, how do reality and the simulation differ? Are the colours correctly reproduced? If not, in what way do they differ? Is the relationship between the colours correct? How is the illumination perceived with regard to light level, light distribution, perceived colour of light? How can we compare different spatial settings with regard to visual appearance, when we can only be in one setting at a time?

Questions concerning software technology: Providing that a room is modeled with the information on physical conditions available before it is built, how well does the software meet the demands? What are the limitations of the parameters of the software concerning colour and light? How can we convert real paints to digital colours and how can we evaluate the reliability of appearance?

Questions concerning spatial experience: How does the spatial experience differ in VR compared with reality? How do we relate to the model, e.g. movements and impression of size and scale? How can different visual expressions in architectural VR-models contribute to a better understanding of a visualization? How can we compare different spatial settings with regard to spatial experience, when we only can be in one setting at a time?

6.1. Conveying visual reliability in Virtual Reality

6.1.1. Visual appearance

In order to understand what a trustworthy visual appearance is, I found it fruitful to investigate earlier research and conduct studies of my own. These studies pointed out the significance of interreflections, colour variations, perceived colour of light and shadowing in real rooms. In the real room in the SCAVE-studies, contrast effects appeared between coloured areas on flat surfaces, while surfaces in angles affected each other by reflections. Visual assessments showed that even small differences in colour appearance can be important for the experience. The colours showed very different appearance in the different light situations. This was, for example, obvious with regard to the four different yellow colours in the room. The colour category of yellow only covers a small colour area, and it does not take much for the colour to be experienced as beige, white or green.

Concerning the similarities found between the real room and the simulations, the colour appearance in reality and in VR proved to be visually similar for some colours and surfaces. However, from what I found, there were also some distinct differences between the real and the virtual rooms, concerning the colour appearance; the relation between the colours; and the reproduction of illumination. In the simulations, the contrast effects between coloured areas on flat surfaces were too small and incorrectly reproduced; the interreflections between angled surfaces were not big enough; the colour variations were too few; the whitest surfaces came out too dark and greyish; and the shadows were too achromatic.

Differences between illuminations are often felt to have especially great impact on light colours or when the colour category changes. The experimental room was designed to show significant effects of illumination and contrasts. The colour category of yellow only covers a small colour area and it does not take much for the colour to be experienced as beige, white or green. This was obvious in the study accounted for in Paper C, which involved four different yellow colours, all of which showed very different appearances in the different light situations.

Concerning the appearance of light, the fluorescent lights 3000K and 2700K appeared identical in the virtual models. There were however fewer problems concerning light distribution in the simulation of fluorescent illumination, while more problems appeared in the simulations of incandescent illumination, especially for light distribution and perceived colour of light. The perceived colour of light did not turn out the same in Lightscape™ and 3Ds max® and none of the software's settings for incandescent light was red enough. It made me wonder how the predefined settings of illuminants in the software were obtained. The reproduction of illumination and the appearance of light were found to be unacceptable in the CAVE™, and it is therefore not relevant to discuss them here.

Colour and light is important for the visual appearance and impression of the rooms. For example it showed that when the reproduction was poor (e.g. in the CAVE™) the spatial experience differed between the model and the real room.

6.1.2. Software technology

A basic prerequisite for correct colour appearance in the digital models was that the computer was calibrated. Most important was that the relationship between the colours in the digital model was correct, compared to reality. If so, small displacements between the colours on different displays were acceptable. The studies of converting real rooms to virtual counterparts revealed various problems related to the translation and comparison of reality to VR. Even when the real world appearance was known, it turned out to still be difficult to simulate a reliable appearance in VR. Thus, for a correct colour appearance, adjustments in Photoshop proved to be necessary. These difficulties had to do with e.g. arbitrary parameter settings in the applied software. Some problems concerned the parameters defining the illumination. These parameters define temperature as well as offering a choice between different default settings. This is however only a choice of coloured filters, which together with arbitrary parameter settings in the software lead to heavily simplified chromatic information on light sources. Other problems, such as incorrect interreflections and that the whitest surfaces came out too dark and greyish, were impossible to correct.

In order to get correct colour rendering in a scene, there is a need to program various spectral energy distributions in the software. However, the spectral composition for the light sources cannot be specified. To fully simulate the interaction between light and objects in an interactive scene would require more advanced real time technology than is available today (Assarsson, 2006). This was a basic problem in the studies of 3Ds max®. In software like e.g. 3Ds max® different illuminations are simulated by different filters simply added in front of the light source. Instead, in order to be able to reproduce the colours correctly, the spectral composition must be defined and programmed into the software. Another problem is that in the tested software, the amount of colour which is reflected from one surface to another in the room is not correctly defined.

In the tests, Lightscape™ proved to be of more use than 3Ds max®. One major limitation with 3Ds max®, compared to Lightscape™, is that it is a complicated procedure to produce rendered interactive models. The main purpose of 3Ds max® is to produce rendered images. While Lightscape™ instantly provides a fairly accurate view of the illuminated room; 3Ds max® gives an approximation of the model and requires rendered images in order for the result of the light calculations to be visible.

Radiosity is a widely used method for calculating diffuse light spread. However, as regards the radiosity calculations in the software used, some problems were pointed out. It can, for instance, be very time consuming to use in the experimental colour design process. This implies that it is not enough to use only information on physical conditions of the not yet built environment (materials, illumination, colours). Knowing the colour appearance of the real objects (rooms, buildings, etc) proved to be essential for the creation of true and realistic colour visualizations in VEs. In order to solve the problems of incorrectly reproduced contrast effects, it would have been necessary to change the settings of the program (3Ds max®) and especially the radiosity equation, something we were not able to do. However, an alternative to this was tested, i.e. elaborations were made with an algorithm which filtered rendered images produced in the program.

The ACE-algorithm was applied in an attempt to correct the lack of contrast phenomena visible in reality but lost in the simulations of the room. However, the ACE, developed for colour correction in images, filtered only one flat surface at a time, and did not consider the impact of adjacent surfaces. The elaborations showed that ACE treats the surfaces reproduced in an image as one unit, therefore creating contrast effects between all surfaces in the image, disregarding their location. The conclusion will therefore have to be that such an algorithm can be used, but only in a very restricted context and not as a solitary method for filtering images of a complete room. I regard these elaborations as a starting point in the process of creating a new algorithm. Through them, my understanding of the problems regarding differences between 2D and 3D has deepened.

Interesting software development has been undertaken in recent years (Ritschel, et al 2009; Tonn and Donath, 2006; Donath and Tonn, 2004A; Donath and Tonn, 2004B; Maxwell Renderer™, 2007; V-Ray, 2008). It is now possible to obtain real time radiosity. Developers like Geometrics (2008) and Lightsprint (2006) use it in order to get diffuse bounces in e.g. games. However, it has no physical correctness, and is, as yet, of poor quality (Harrysson, 2008), and is therefore not of relevance for my aims.

The most interesting new rendering engine that I have found is Maxwell Render™ (2007). It was developed in 2006, and is a physically correct renderer; which means that all lighting calculations are performed using spectral information and high dynamic range data. However, in this development it is important to evaluate the fidelity of the parameter settings. The experience gained through the SCAVE-studies is that even if correct data for light and surface colours are applied, software such as 3Ds max® cannot correctly simulate interreflections between coloured surfaces, as is shown in Papers B and C. Further systematic research is required in order to solve this complex problem, concerning parameters of colour and light in both reality and in the applied software, in connection with elaborations in VR. Full manipulation of parameters in the software is desirable. Psychological phenomena and the way the human visual system works need to be included in the research as a complement to today's mathematical modeling of physical conditions.

6.2. Conveying believable experiences in Virtual Reality

6.2.1. Spatial experience

In order to understand the differences between the spatial experiences of VR and reality, I conducted a literature study on existing research as well as performed my own investigations. The research that I looked into pointed out differences in the spatial experience in VR connected to aspects such as the perception of distance, size and scale. This is in concordance with my own findings in my studies. The VCL-study showed, for example, how our attention was not drawn by the same means in the desktop VR setting as in reality, since the active investigation was strongly restricted.

Comments from observers participating in the SCAVE-studies show that we experience the same model in different applications differently, not only with regard to colour and light, but also in regard to how we move around in it, from which perspective we look at it, the scale we perceive it to have and the general associations we make with it. From what the studies showed, most observers experienced the CAVE™-based model and the monographic and stereographic desktop models to be simulations of full scale rooms which they could move around inside, while the Lightscape™-model in comparison was experienced as a model with indeterminable scale, and was most easily looked at from an outside-perspective. The frame and surrounding of the desktop screen provided visual limitations to the spatial experience.

I can draw the conclusion that the experience of a model regarding spaciousness concerns aspects such as speed, opportunities to get close to objects and to stay inside the model, graphical interface in the software (or lack thereof) and use of mouse versus, for example, game pad. It therefore seems important to consider the purpose of the model when deciding which media to use when displaying it.

Through the reflections in actions with the VCL-demonstrator, I learned that it is difficult to obtain a believable visual appearance in VR, even if the appearance of reality is known. Some of these differences had to do with the software. A significant loss of details became visible in the export via 3Ds max® to VR, which consequently meant that the landscape, intended to look as natural as possible, did not look natural enough. Also, objects in the model were perceived as smaller than in reality and further away. The problem of spatial orientation (Bakker, 2001) became obvious when designing the VCL-demonstrator.

Since the virtual setting consisted mainly of sight impressions, it became important to strengthen visual effects in the model in order to attract attention to parts of special interest. This is a problem of how to correctly *compensate* for the different conditions in VR compared to reality. In doing so, more traditional architectural visualization methods are of interest, above all the architectural sketch. In a sketch, the architect chooses not to show reality as it is. What is important is instead to mediate the focus of the idea, i.e. to illustrate the different levels of relevance in accordance with the concept. I refer to these levels as the *hierarchy of relevance*. In order to create a focus in the visualization, the most important layers of information to mediate need to be identified. For VR to be a useful visualization tool when communicating projects which are under development, this needs to be considered.

Photorealism might not always be the best style for conveying what the visualization is intended to show. Thus, if a visualization was better adjusted to what it is intended to show and not only based on photorealism, i.e if the appropriate hierarchy of relevance was found, it would be easier to convey a believable experience. The texturing styles in the STIVE-project were developed in an attempt to compensate for spatial differences in VR compared to reality. The aim was to clarify and simplify the understanding of a building project during different phases of the design through believable visualizations, where the level of the visual expression would be in concordance with the level of information intended to be shown.

Through my literature studies, I found that most current research aiming at visual expressions in VR other than photorealism, works with non photorealistic *rendering*. Contrary to this I wanted to focus on *textures*, in order to obtain more varied expressions in the visualizations. One important feature for the choice of textures above NPR, was to enable users to combine different styles for a more individual expression in each visualization. However, this could not be carried out at this point. A selection of texture styles was developed and applied in a demonstration model. When developing the styles, we worked with a hierarchy of relevance in that the styles would go from less to more detailing, and from grayscale to colour; thus assumed to fit early sketch phases vs later phases when the project design was to be more settled. The surprising results indicated however that the participants did not agree on this assumption, and seemed to generally prefer the styles with more detailing and colours. The monochromatic styles were constantly considered to be the least useable, which indicates the importance of colour and distinctiveness for the spatial experience in virtual settings. Possibly it became too abstract and difficult to grasp the full spatial context in the monochromatic styles. The assumption that less detailing should support conceptual design thinking was not correct, indicating the importance of detailing also for earlier phases of a design in VR. It is interesting to note the generally high ratings for the most sketch-like style (*Sketch*). Comments from the participants indicated that they liked the sketch like expression while it reminded them of architectural sketches, thus possibly providing a more familiar expression in the visualization (“the architect will recognize himself” one comment read).

In the evaluation with the user group, some of the styles were highly rated, and can be considered as a step on the way towards the creation VR-visualizations with varied expressions which better support conceptual design thinking.

The evaluation showed that there is a need among professional users for possibilities to affect the expression of the visualizations according to purpose, as well as dissatisfaction among many users with the level of photorealism in the visualizations that is possible to obtain today. The STIVE-project is a pilot study, which shows interesting tendencies among the participants, but needs to be further developed before any real conclusions can be drawn.

6.3. Reflections on methodology

As an architect I study the whole complex spatial situation, and have to consider a large number of different factors influencing the visual appearance as well as the spatial experience. One of the most important contributions of this study therefore concerns the methodology. A variety of different approaches for investigating, developing and adjusting have been applied for both visual appearance and spatial experience. By combining many different methods, it has been possible for me to identify the issues investigated in connection to both the appearance of colour and light and the spatial experience in the digital settings. The thesis project can thus be looked upon as a trial of different sorts of approaches, where the methodology itself is an important result.

The difficulty when researching spatial issues from this perspective is the large framework and complexity of the studies. Consequently, it has proven necessary to include and to study many different research areas, and it has sometimes been difficult to know how many and to which extent various aspects should be considered. The different approaches adopted for my studies have however proved useful in many ways and overall I think that the methods applied in the studies complemented each other well. The results accounted for in the thesis are the product of several years of work. Many of them need to be analyzed further and some aspects of the recorded interviews still need to be investigated.

The theoretical framework concerned different approaches to the stated problems, i.e. issues connected to both visual appearance and spatial experience. Since this thesis describes an interdisciplinary project, the theoretical framework has also touched on different research areas. The area concerning colour is closer to my own background as an architect than the areas of e.g. computer graphics. In the field of computer graphics, my difficulty has been in finding the right level of relevance and where to draw the boundaries of information, since to someone from outside this field much needs to be explained. I have not always been familiar with the technical language used in connection to specific research areas, or which specific part of a research area to investigate, which might have affected the outcome of the literature search.

In the experimental room study, the questionnaire provided rough quantitative guidance as well as measurable results and a good base for analysis. The interviews provided more nuanced answers and more thorough explanations. Recording the interviews turned out to be very helpful; listening to them again while focusing on different questions enabled more objective reflections, compared to notes and memory. The qualities measured with the semantic differential scaling were not defined by us (e.g. “heavy”, “soft”, “open”). Instead the participants made their own definition of each concept. Thus, their explanations turned out to be of more use than the quantitative data. In retrospect, it would have been sufficient to only use selected concepts for the participants to reflect upon.

The visual assessment techniques (verbal description, magnitude estimation and colour matching with the colour reference box) provided a well-functioning method when evaluating the colour appearance. The use of magnitude estimation gained further precision in the descriptions of surfaces in the real room. The colour reference box enabled a good match between the chosen samples from the real room and the display. It was necessary to compare the models sequentially, because of the importance of studying the room from within and adapted to the illumination. Sequential comparisons are however problematic since every step creates a possible “slide” in judgement. Overall though, the methods used here provided a good level of accuracy, and when combined they provided a good base for describing the colour appearance of the room.

The physical measurements in the real room and the simulations is an interesting and difficult research problem and an issue to further investigate in future. Since this is an area outside my expertise, I do not grasp the full meaning of the results at this stage; for example what does count as a significant difference between visual assessments and physical data.

Considering the knowledge gained in the experimental study, elaborating with algorithms such as ACE was a way to find solutions to the stated problems in recreating a visually correct colour appearance. ACE is however based on theories of 2D-colour phenomena. The studies showed that it cannot be applied for rendering a complete 3D-model. Nonetheless, elaborating with it provided a good basis for the understanding of the more technical aspects of the problems.

Regarding the knowledge gained from the elaborations with textures in the VCL- and the STIVE-projects, it is relevant to note that design-based research is not a linear process; instead it was necessary to change perspective and go back and forth between theory and practice. It was time consuming to determine what was needed and how to approach the task. The many hours of elaborations can be used to create better design and, but above, all to increase the understanding of VR's possibilities, and answer questions on when and how we can use this relatively new media and what the implications of it are for participants with different expertise.

When evaluating different visual expressions in a VR-model, the questionnaire provided a good base for analysis. Above all the qualitative answers, and written comments from the observers, were very valuable. Through their combination, the qualitative and quantitative answers complemented each other well. Furthermore, the variety of questions enabled me to identify tendencies for participants fitting the profile in their approach and experience of VR-visualizations, which is also a useful basis for further studies. However, a few questions turned out to give less informative answers than others, or to be a bit too obvious; something that I was not aware of until I analyzed the answers. This seemed to be the only problem with sending the participants the questionnaire to complete by themselves, instead of doing face to face interviews. I take this learnt lesson with me in the design of future questionnaires. Regarding the software used in the study (Novapoint Virtual Map), the set up and installation of the texture library and the viewer file was difficult for some participants. However, the overall impression is that it worked well.

Finally, concerning my approach to the overall thesis work; my perspectives have changed in the course of learning, theoretically and through practice, and with the opportunities in terms of collaboration which other researchers have provided. When for instance the collaboration with the Dept. of Information Technology in Milan began, no one realized at first that our approaches towards the use of their algorithm were different. The result was an exaggerated emphasis on this algorithm compared to other algorithms, but it none the less provided me with a better understanding of what I need. The collaborations with other researchers have had a great impact on this thesis work, since they have sometimes affected my perspectives and research direction, but above all provided me with new influences, insights and openings.

7. FINAL CONCLUSIONS AND FUTURE WORK

7.1. Final conclusions

The overall goal for my PhD project has been to develop knowledge of how different aspects of the VE, especially light and colour, affect the spatial experience. Much of the research conducted within this work is unique in that no one (as far as I have discovered) investigates the exact same issues with the perspective of the spatial whole. This thesis therefore contributes to new knowledge within the field of spatial VR visualization, and thus the knowledge development on how VR can be used as an architectural visualization tool.

- ***Concerning visual appearance:*** This thesis provides an insight into the problems of simulating visually realistic spatial colour and light in VR. The SCAVE studies showed that it is not possible today to obtain trustworthy simulations of colour and light in VR. The research on simulation of colour appearance in 3D has so far merely been focused on images of 3D environments. Through elaborations I have shown that theories on colour perception in 2D cannot automatically be applied in 3D, due to the fact that reflections do not exist in 2D, but are evident in 3D. Instead, the radiosity calculation in the software needs to be changed, i.e. the visual perception needs to be included.

- ***Concerning spatial experience:*** This thesis contributes to a better understanding of the prerequisites for visualizing believable spatial VR models. Elaborations in the VCL project showed that it is difficult to directly translate a visually believable spatial experience of reality to VR, even if the experience of reality is known. In order for VR to be applied as a useful design tool, visual compensations in the visualizations are needed. Depending on the purpose for which the visualizations are used, it is important to develop both reliability in appearance, and more conceptual visual expressions. In order to highlight the focus of the visualization, it is important to consider visual *hierarchies of relevance*.
- ***Concerning the methodology:*** One of my most important contributions concerns the methodology. It is a complex task to study visual appearance and spatial experience from an architectural perspective, since the whole of the spatial setting needs to be considered. By combining many different methods, it has been possible to identify the issues investigated in connection with both the appearance of colour and light and the spatial experience. Above all the qualitative results, i.e. written and verbal comments from the observers in the studies, were very valuable. When it comes to the studies performed on visual appearance, I assume that the applied methods can be used as tools for future meaningful investigations, although they may not be able to provide predictions for every coloured material in all situations. Instead they should be looked upon as means to deepen the awareness and understanding of how spatial and lighting factors affect coloured material.

7.2. Future work

This project is part of a process with continuous findings and revelations in interaction with adaptation to the circumstances and sometimes changes in approach. It has not ended with this thesis, but can instead be looked upon as a starting point for further research. For the future development of the work, different directions are mapped out below.

In order to continue with the aim of simulating colour and light for a visually reliable appearance, a more technical approach is of interest. An interesting strategy would be to follow the direction already planned as an alternative when the licentiate project finished, i.e. to list and specify spatial light- and colour phenomena, including comparing physical data to the visual appearance of colours, in order to make them programmable. In co-operation with experts in programming and computer graphics, this knowledge would then be used to create an algorithm, which will be more adjusted to the eye's perception of reality and the three dimensional vision. The focus would be placed on:

- Better balance between contrast effects and reflections
- Better represented spectral composition for the light sources
- Increased colour variations

HDRI and tone mapping would need to be investigated through elaborations with the room models. The software *Radiance* would also need to be further explored. Regarding photon mapping, the main reason not to have used it in the SCAVE-project, was due to the use of photometric lights in the room models, which currently, to the best of my knowledge, no available implementation of photon mapping supports. However, with alternative lighting, photon mapping is an interesting alternative for future studies.

From what I have learnt through this thesis project is that a development of better algorithms is needed, preferably one that can take into account the amount of information given in different parts of an image. ACE proved to be a good starting point for learning and understanding some of the faced problems. However, it leads the project in the direction of imaging, which was not the original intention. Hence, it will probably not be further applied in the studies. Today's technology is not yet ready to fully reproduce colour appearance in 3D-environments from a 3D-perspective. To a great extent I believe that this has led to most of the relevant research focusing 2D-images of 3D-environments. A colleague once remarked that this project is 10 - 20 years before its time, and though it might seem like the goal is farfetched, I do believe that these aims will become of interest to research within the field of computer graphics in the future.

In order to continue with the aim of visualizing spaciousness in VR for a believable experience, there are many improvements and strategies to consider. With the results from the evaluation in the VCL- and the STIVE-projects, I now have a base for further elaborations. The results from the conducted usability study confirm that further research on technological and usability aspects of VR-visualization is needed, e.g. avoiding time-consuming loading times and non-intuitive menus.

The concept of hierarchy of relevance is important to consider in the development of either the texture styles or of some sort of rendering machine for NPR. In the development of the texture styles, a greater variety of expressions and textures needs to be created and more different levels of information, concerning e.g. details, colour and aesthetics need to be included in each style. Most important would be to enable different styles to be freely combined. Concerning rendering instead of textures, it would be very interesting to, in collaboration with experts in programming and computer graphics, develop a rendering machine for NPR with a built in function considering different hierarchies of relevance. I would for example like to develop and investigate how different levels of information for e.g. foreground (coloured surfaces and more detailing) and background (monochromatic surfaces and less detailing) could be applied and adjusted to the constantly changing location of a user in a VR setting.

Concerning the users, it would be very interesting to further investigate the differences and similarities in the approach towards visualizations between professional users with different backgrounds and/or different professional roles. In the STIVE-project, architects and civil engineers were included, and tendencies were found that would be interesting to investigate further with a larger number of participants. Since VR-visualizations are commonly used by city planners to communicate projects and proposals to the public, it would also be of great interest to include the general public as a new target group. To fully adjust and adapt the project to different design phases, a future aim is to incorporate it into a real design process, i.e. to follow a real planning project.

To conclude with, I hope that my thesis and the projects it is based upon, will form some of the initial groundwork concerning architectural and spatial visualization, which can be applicable as the VR-technology continues to advance.

Göteborg, Sweden
January, 2009

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Appendix A

Simulating Colour Appearance in Virtual Environments:

Interview questions used in the study

Study: A1, A2 and B.0

(Translated from Swedish)

Time: 30 min/light situation, including time for adaptation

Study ……A and B0…………….. **Illumination:…………….**

Subject nr ……

Name …………………………………………………….
Tel:……………………………………………...................
E-mail:…………………………………………………
Profession/Student: ....
Colour vision:...

+ Background questions

A. Experience of the room:

1. First impression of the room. Describe with your own words what you see/ where you are, how large the room looks.
2. Semantic differential scales (open scales;” Not at all - Completely”). Free associations over the concepts in the scales.

B. Assessment of colours and light:

0. Questions

+ Presence questionnaire

A. Experience of the room:

- Describe with your own words your impression of the room.
- How large is the room?

How well does the word (the claim) correspond with your experience of the room?
Mark with a cross on the 7-graded scale:

Beautiful
(Vackert)

1 2 3 4 5 6 7
Not at all Completely

Pleasant
(Trevligt)

1 2 3 4 5 6 7
Not at all Completely

Consistent
(Enhetligt)

1 2 3 4 5 6 7
Not at all Completely

Clear
(Tydligt)

1 2 3 4 5 6 7
Not at all Completely

Heavy
(Tungt)

1 2 3 4 5 6 7
Not at all Completely

Bright
(Ljust)

1 2 3 4 5 6 7
Not at all Completely

Warm
(Varmt)

1 2 3 4 5 6 7
Not at all Completely

Soft
(Mjukt)

1 2 3 4 5 6 7
Not at all Completely

Happy
(Glatt)

1 2 3 4 5 6 7
Not at all Completely

Harmonious
(Harmoniskt)

1 2 3 4 5 6 7
Not at all Completely

Powerful
(Kraftfullt)

1 2 3 4 5 6 7
Not at all Completely

Open
(Öppet)

1 2 3 4 5 6 7
Not at all Completely

Calm
(Lugnt)

1 2 3 4 5 6 7
Not at all Completely

Stable
(Stabilt)

1 2 3 4 5 6 7
Not at all Completely

Surrounding
(Omslutande)

1 2 3 4 5 6 7
Not at all Completely

B. **Assessment of colours and light:**

How is the *light distribution* in the room (on a scale from 1-10, where 1 is almost dark and 10 is the brightest imaginable in a room)? Can you, for example, read in the room?

Describe the *light distribution* in the room. Where is it dark? Where is it light?

Describe the *shadows*. Are they hard; soft; clear; diffuse?

Describe the *colour of light*. Is it a warm or a cold light? Does the light in the air/room have any colour?

Has the light any other character? (clear – diffuse; hard – soft…)

Compare the two light walls in the room (nr 9 and 10): How do they differ in colour?

Compare the two red walls in the room: How do they differ in colour?

Look at the short wall that does not have any pattern of squares:
Compare the colour in the corner with the larger area on the wall, and with the cubes on the floor.

Look at the short wall with the patterns of squares:
Compare the colour of the three columns of squares (the larger squares) with each other and with the cubes on the floor.

Look around the room:
Which of the yellow- or greenish yellow coloured surfaces are most alike?

***On a scale of 1-7:* How present do you feel in this environment with the tasks you have performed?**

1 2 3 4 5 6 7

Appendix B

Sketching Techniques in Virtual Environments:

Questionnaire used in the study

(Translated from Swedish)

Questionnaire for the project
Sketching Techniques in Virtual Environments

This questionnaire is divided into 4 sections. Sections 1-3 are common questions which you can answer without studying the included model. For section 4 however you will need to study the model. You don't need to answer the questions at the same time or in chronological order. If you run out of space, please continue on the back!

1. Personal information

Name: ……………………………………………………………………………………………

Telephone, work: ….…………………………………………………………………………

E-mail, work: ………………………………………………………………………………..

Age: ……………………………………………………………………………………......

Company/ Organization:………………………………………………………………….

Profession: ………………………………………………………………………….....

*With a **3D-visualization,** we consider in the following questions a computer generated architectural 3D-model which can be used both as a base for rendered images, for animations or for an interactive visualization.*

2. Computer usage

1. How many years' experience of working with computers do you have (roughly)?

…………………………………………………………………………………………………

2. How many hours per week do you work with a computer? Circle your answer.

0-10 10-20 20-30 30-40 40 or more

3. Which programs do you have most experience of? ………………………………………

……………………………………………………………………………………………………

……………………………………………………………………………………………………

4 a. Who creates the visualizations that your company/ organization uses?

Your company ☐ Consultants ☐ Others …………………..☐

4 b. In which programs are these 3D-visualizations made? ……………………………

…………………………………………………………………………………………………..

5. Describe your work experience of 3D-visualization programs! Do you work with 3D
Frequently (experienced user) ☐ Sometimes ☐ Rarely ☐

Comments ……………………………………………………………………………………………..
……
……
……

6. Which of Novapoints' modules do you use? ………………..………………….…….
……

*With a **VR-visualization***, in the following questions, we consider an *<u>interactive 3D-model in which it is possible to move around in realtime.</u>*

3. Visualization technique

7. What do you consider to be the biggest *<u>advantages</u>* of using VR-visualizations?
……..
……..
……..

8. Can you give an example (with reasons!) of a *<u>good</u>* VR-visualization, *i.e*. a VR-visualization which, in your experience, has corresponded well to expectations (either in your own project or another's)?
……
……..
……..
……..

9. What do you consider to be the biggest *<u>problems</u>* of using VR-visualizations?
……..
……..
……..

10. Can you give an example (with reasons!) of a *poor* VR-visualization, i.e. a VR-visualization which, in your experience, has *not* corresponded to expectations (either in your own project or another's)?

……………………………………………………………………………………………………

……………………………………………………………………………………………………

……………………………………………………………………………………………………

11. How well do you think the VR-visualizations that your company/ organization works with convey what they are intended to show?

Very well… ☐
Quite well… ☐
Not so well… ☐
Poorly… ☐

Comments ……………………………………………………………………………………

……………………………………………………………………………………………………

……………………………………………………………………………………………………

12. Does your experience suggest that the VR-visualizations can be improved?

Yes ☐ No ☐ Don't know ☐

If the answer is yes, in what way? If no, why not? ……………………………………………

……………………………………………………………………………………………………

……………………………………………………………………………………………………

……………………………………………………………………………………………………

……………………………………………………………………………………………………

13 How well do you think your clients / customers find that your visualizations meet their expectations?

Very well… ☐
Quite well… ☐
Not so well… ☐
Poorly… ☐

Comments ……………………………………………………………………………………

……………………………………………………………………………………………………

14. Is there anything you think your clients / customers lack in your VR-visualizations?

Yes ☐ No ☐ Don't know ☐

If the answer is yes, what would that be?………………………………………………………

……………………………………………………………………………………………………

……………………………………………………………………………………………………

15. Which sectors are your clients / customers active in? ……..…..…………………….

…………………………………………………………………………………………….....

…………………………………………………………………………………………….

The questions 16-24 (Section 4) require you to have opened the included model.
<u>Follow the attached instructions!</u> Take a few minutes to familiarize yourself with the model. Position yourself at the different viewpoints and compare the experience of the setting in the different styles one after the other. Then answer the following questions!

4. Evaluation of the sketch styles

16. Describe with one or a few keywords the feeling that each of the different styles gives the model!

a. *Realism*…...…………………………………………………………….……………

b. *Colour*…………..………………………………………………….………………

c. *Greyscale*..……..……………...………………………...……………………………………

c. *Contour; colour*..……………..……………………...…………………………………………

d. *Contour; greyscale* ……………………………………………….…………………...

e. *Graphical*…………………………………………………………………………..

f. *Sketch*………... ……………………………………………………………………..

17 a. Which style do you prefer? ……………………………………………….............

17 b. Explain! ……….................................……………………….…………………………

…………………………………………………………………………………………….

……………………………………………………………………………………………..

18 a. How significant do you think that *<u>the colour experience</u>* is for the experience of the VR-visualizations with which you work?

	☐	☐	☐	☐	☐	☐	☐	
Not at all	-3	-2	-1	0	1	2	3	Highly

18 b. Which style do you think gives the best colour experience in this model?

Style: ..……………………………………………………………...…………………….

Explain! …..…………………………………………………………..…………………......

………………………………………………………………………………………………..

18 c. Which part of the planning process (sketch to final presentation) do you think this style would fit in? …………………………………………………………………………...

……………………………………………………………………………………………….

19 a. How significant do you think *the aesthetic* is for the experience of the VR-visualizations with which you work?

	☐	☐	☐	☐	☐	☐	☐	
Not at all	-3	-2	-1	0	1	2	3	Highly

19 b. Which style do you consider to be the most aesthetically pleasing in the model?

Style……………………………………………………………………..……………………….

Explain! ……………………………………………………..……………..…………………….

……………………………………………………………………………………………….

19 c. Which part of the planning process (sketch to final presentation) do you think this style would fit in? ……………………………………………………………………………….

……………………………………………………………………………………………….

20 a. How significant do you think *the detailing level of the textures* is for the experience of the VR-visualizations with which you work?

	☐	☐	☐	☐	☐	☐	☐	
Not at all	-3	-2	-1	0	1	2	3	Highly

20 b. Which style do you think has the most useable level of texture detail in the model?.................……………………….…………………………….………..……………….

Explain: ………………………………………………………………………..………………....

………………………………………………………………………………………………...

20 c. Which part of the planning process (sketch to final presentation) do you think this style would fit in? ……………………………………………………………………………….

……………………………………………………………………………………………….

21. Which style do you think works best on the respective objects in the model? Put <u>one</u> cross in each column of the table!

	ground	trees, bushes, people	buildings	road	edge of forest
Realism					
Colour					
Greyscale					
Contour; colour					
Contour; monochr.					
Graphical					
Sketch					

22 a. *The styles as a <u>work tool:</u>*
Can you see the benefit of using any of these styles as a work tool in different phases of the planning process, in your line of work?

Yes ………… ☐
No …..………… ☐
Don't know …☐

Explain! ..………………………………………………………………………………………

…………………………………………………………………………………………………

If the answer is yes, which style(s)?..………………………………………………..………………

22 b. *The styles as a <u>tool for communication</u>:*
Can you see the benefit of using any of these styles as a tool for presentation, in your line of work?

Yes ………… ☐
No ………… ☐
Don't know… ☐

Explain! ………………………………………………………………………………………

…………………………………………………………………………………………………

If the answer is yes, which style(s)?..……………………………………..…………………….....

23. Does your experience suggest there is a general need for showing shadows in 3D models?

	☐	☐	☐	☐	☐	☐	☐	
Not at all	-3	-2	-1	0	1	2	3	Completely

24. Other comments (please continue on the other side of the page if necessary!):

…………………………………………………………………………………………………..

…………………………………………………………………………………………………..

Appendix C

CD containing material from the conducted studies:

- **The SCAVE-project:** Illustrations from the different SCAVE-studies
- **The VCL-project:** Illustrations of the VCL-demonstrator
- **The STIVE-project:** Viewer file of the STIVE-demonstration model, and Set-up instructions

CD appended at the back of the thesis

SUMMARY OF APPENDED PAPERS

Paper A

This paper provides a background to my studies, in focusing on the complexity of spatial colour appearance. It is well known that a colour's appearance can differ between a small colour chip and the same colour applied in a full scale room. The impression of a colour changes with these circumstances; e.g. while it can be perceived as subdued on a chip, it can be striking in the room. In this paper, results from an international project on the experience of small colour chips, the *Colour Emotion*-study, are compared to those of a study on spatial colour experience in full scale rooms, made by Hårleman. In the first study, textile chips were viewed against a grey background in a viewing cabinet. In the other study, two rooms were painted in 12 hues in two different nuances: NCS 1010 and NCS 1030. They correspond well to the hue areas and to two of the nuance categories used in the chip study. Semantic scaling was used in both studies. The two studies show a distinct difference between words associated with colours of the same nuance and colour category. A clear pattern could be seen. In the room, the colours were perceived as more distinct and stronger, and they aroused much stronger emotions. Generally, a colour chip had to be much more colourful to give comparable associations.

Paper B

This paper presents comparisons between real rooms and different VR simulations, conducted in order to map out problems of simulating realistic colour and light appearance in VR. VR has great potential to become a usable design tool for the planning of colour and light in buildings. The technical development has provided us with better computer graphics and faster rendering techniques. However, the reliability and usability is delimited by lack of knowledge about how humans perceive spatial colour phenomena. The setting up of parameters for material properties in light calculation software is done arbitrarily. This paper presents the first phase of the project *Simulating Colour Appearance in Virtual Environments (SCAVE)*, where comparisons were made between a real room and digital models evaluated on a desktop PC and in a CAVE™. Data were collected from video recorded interviews and questionnaires. The participants assessed the appearance of light, colours and space. They also evaluated their involvement in solving this task, and their presence in each environment. The results highlight the benefits and disadvantages of the real and virtual models. The participants had difficulties in estimating the size of both the desktop room and the room in the CAVE™. The comparison of real and virtual rooms revealed unsatisfying differences in shadowing and colour appearance. The magnitude of perceived colour reflections in the real room was defined, and elaborations were made with some of the parameters in the programmes used.

Paper C

This paper presents the second part of the SCAVE-project (see Paper B) which deals with methodological issues concerning how to compare visual results between different media, mixed adaptation and arbitrary parameter settings in the software. In the SCAVE-project measured values were not used initially for describing the room, but were instead applied as a retrospective reference and documentation. Measurements of reflectance, luminance and spectral composition were made, which are accounted for in this paper. The paper discusses the problems of translating reality to its digital counterparts. The comparison between a 25 m^2 real room and different VR-simulations showed various problems related to the translation and comparison of reality to VR. Data were collected from video recorded interviews with 56 observers. Colour appearance was assessed with semantic descriptions, magnitude estimation and colour matching.

Paper D

This paper presents one part of the SCAVE-project, where elaborations with an algorithm were conducted as a possible solution to the stated problems of making visually realistic models in VR (accounted for in Papers B and C). The same digital desktop models were used as in the previous studies. In the digital models, some contrast phenomena did not show. To propose a solution to these problems, i.e. to improve the colour appearance in the virtual rooms, digital renderings were filtered with *the Automatic Color Equalization (ACE)*-algorithm, originally developed for colour correction of digital images. By filtering rendered textures of each multicoloured wall, different results were obtained. The parts of the VR model containing enough visual information improved in colour appearance. However, when the visual information was not enough, i.e. when there were not enough visual details, the contrasts in the filtered renderings became exaggerated.

Paper E

This paper focuses on how participants moved around in and experienced size and scale in digital models. The study which the paper is based upon, is one part of the larger SCAVE-project (see Papers B, C and D), where a real room has been translated and compared to digital counterparts. In this paper, comparisons between three desktop-applications were made. The applications included two VR-models; one stereographic and one monographic, and a Lightscape™-model. A preliminary overview is given of the experience of the different applications, such as the use of technical devices, possibilities for exploring space, ways to move around and the sense of involvement and presence. The results showed interesting differences, especially concerning size and scale, between the desktop VR-models and the Lightscape™-model. The differences between the stereographic and the monographic model were also found to be very small.

Paper F

This paper presents an investigation of spatial differences in VR compared to reality, where reflections in action on a virtual demonstrator for colour phenomena were conducted. Problems related to visualizing colour appearance in an interactive real-time VE are discussed from the viewpoint of practice based architectural research. The discussion is based upon the research information project *The Virtual Colour Laboratory (VCL)*, the aim of which is to visually present and demonstrate existing research results on spatial colour phenomena for educational purposes, in the shape of a software application. During the work on this project, various problems connected to the visualization of colour appearance emerged which are discussed in relation to current research on spatial experience and visual appearance in VEs. A design based research approach was applied, where elaborations with the model's visual expression were alternated with inter-reflections and group discussions. The aim of the paper is to focus on the importance of colour appearance in digital modelling as well as to highlight the problems of visualizing colour appearance interactively.

Paper G

This paper presents a study where a possible solution to the difficulties of conveying believable experiences in VR is investigated. In the project *Sketching Techniques in Virtual Environments (STIVE)*, non-photorealistic texture styles were developed and evaluated in a usability study with professional VR-users. Results are presented from a comparison between different sketching styles and photorealism in the texturing of an urban planning model. The aim is to show how sketch-like expressions in the texturing of a model can clarify and simplify the understanding of a building project. Data was collected from questionnaires answered by 20 participants, all of them professional users of VR. They assessed the experience of the texturing styles in the test model on desktop-PCs. The results revealed important differences and similarities in the perception of the sketching styles vs. the photorealistic style. The evaluation showed a desire for more sketch-like expressions supporting conceptual design thinking. Even so, models should provide a high level of detail and good spatial experience. Aesthetic factors were considered important. The results contribute to a better understanding of technical and aesthetic limitations of photo-realism in VR.