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How to convert reality into Virtual Reality: Exploring colour appearance in digital models

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ABSTRACT

Today, the different actors in the design process have communication difficulties for visualizing and predicting how the not yet built environment is going to be experienced. Realistic virtual environments could make it easier for architects, users and clients to participate in the planning process. The Virtual Reality (VR) research of today has different focuses, concerning both visualization and interaction. Few studies concern colour appearance in virtual compared to real rooms. This licentiate thesis deals with the problems of translating reality into its digital counterparts, focusing on colour appearance. The main aim is to identify problems of making realistic models in VR. A following aim is to discuss chosen solutions for increased realism. Problems connected to visual appearance and interactivity in the model and technological aspects in the software are considered.

Different approaches are used: (1) a literature review including research on colour appearance, VR, and light calculation in computer graphics, (2) a comparison between existing studies on colour appearance in 2D vs 3D, (3) a comparison between a real room and different VR simulations and (4) an elaboration with an algorithm. The studies pointed out the significance of interreflections, colour variations, perceived colour of light and shadowing for the visual appearance in real rooms. The results showed various problems related to the translation and comparison of reality to VR. There were some distinct differences between the real and the virtual rooms. Some differences had to do with the arbitrary parameter settings in the software; heavily simplified chromatic information on the illumination and incorrect interreflections. Concerning interactivity, the models were experienced differently depending on the application. It therefore seems important to consider the purpose of the model when deciding which media to use when displaying it.

Current research is primarily concerned with rendered images and needs to be taken one step further. This licentiate thesis forms a base for future studies. The full development of this type of research is still a distant future goal, but it could be looked upon as a logical next step in the technological progress.

Keywords: *colour appearance, light, Virtual Reality, virtual environments, visual appearance, interaction*

PREFACE / ACKNOWLEDGEMENTS

I have carried out my licentiate project as a Ph.D-student at the Dept. of Architecture at Chalmers University of Technology. This licentiate thesis is part of the research project *To simulate the experience of colour in virtual environments: a comparison of the experience of light and colour in real and virtual rooms* which was initiated by Monica Billger at Chalmers, 2001. My studies have been financed by The Lars Erik Lundberg Foundation for Research and Education.

I would like to express my gratitude towards all the people who, in one way or the other, have been involved in this project. Especially I wish to thank my supervisor Monica Billger, who gave me the opportunity to be a PhD-student at Chalmers under her supervision and who has guided and encouraged me all the way through this project. Many thanks also to my co-supervisors Ilona Heldal at the Dept. of Technology Management and Economics and Ulf Assarsson at the Dept. of Computer Engineering, Chalmers, for their involvement and the knowledge they have shared with me.

The part of my studies concerning the test of the ACE-algorithm has been conducted in collaboration with Carlo Gatta, former Ph.D-student and Alessandro Rizzi, Professor at Dept. of Information Technology at the University of Milan. I would like to thank them for our collaboration and for letting me stay during our elaborations in Crema.

I also wish to thank Trad Wrigglesworth for revising my English; any mistakes that remain are entirely mine.

Finally, I am deeply greatful for the support, encouragement and understanding I have received during this process from my family: my boyfriend Dag and my parents Ulla and Björn.

Thank you.

Beata Stahre
Gothenburg, May 2006

PUBLICATIONS

Paper A Billger, M., Heldal, I., Stahre, B., Renström, K., *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 conference on Electronic Imaging, San José USA, 18 - 22 January, 2004

Paper B Billger, M., Stahre, B., and Heldal, I., *The Arbitrary Road from Reality to Virtual Reality,* In: Proceedings for Arquitectura 3000, Barcelona, Spain, 30 June - 3 July, 2004, *in press*

Paper C Stahre, B., Hårleman, M., and Billger, M., *Colour Emotions in Larger and Smaller Scale,* Proceedings for AIC 2004 Colour and Paints, Porto Alegre, Brazil, 2-5 November, 2004, *in press*

Paper D Stahre, B., Gatta, C., Billger, M. and Rizzi, A., *Towards Perceptual Colour for Virtual Environments*, In: Proceedings for and presented at AIC Granada, Spain, 8-13 May, 2005

DISTRIBUTION OF WORK

Paper A The experimental data from the paper is based on the project initiated and planned by Billger. Stahre and Billger accomplished the technical preparations regarding the VR-models, with assistance from Renström. Stahre carried out the interviews. Heldal initiated and designed the questionnaire regarding regarding 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 B 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 C Stahre planned and executed comparisons between Billger's and Stahre's study on colour appearance on colour chips and Hårleman's room studies, in collaboration with Billger and Hårleman. Stahre and Billger wrote the paper.

Paper D Stahre was the main author and co-ordinated the work. Stahre, Gatta and Billger planned and executed the study in collaboration. Stahre and Gatta performed the tests and analyzed the results. Stahre, Billger and Gatta all contributed in writing the paper.

ADDITIONAL PUBLICATIONS BY THE AUTHOR

Stahre, B. and Billger, M., *Physical Measurements vs Visual Perception: Comparing colour appearance in reality to Virtual Reality,* Submitted to: CGIV 2006, Leeds United Kingdom, 19-22 June, 2006

Stahre, B. and Billger, M., *Experience of Light, Colour and Space in Virtual Environments,* Poster presentation, In: Proceedings for SIGRAD 05, Lund Sweden, 23-24 November, 2005

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

Billger, M., Stahre, B., Konradsson, Y., *Colour Emotions in Sweden*; International Conference on Colour Emotion Research and Application, Bangkok, Thailand, 2002.

Popular science

Stahre, B., Hårleman, M., Billger, M., *Färg i stor och liten skala*, Färgnotiser 76., 2005

ABBREVIATIONS

2D	Two-dimensional
3D	Three-dimensional
3Ds max®	3Ds max 6, Discreet®
ACE	Automatic Color Equalization
CIE	Commission Internationale de l'Eclairage; International Commission on Illumination
CRT	Cathode Ray Tube
Dvmockup	Division Mock-Up dVise 6.0.
HDR	High Dynamic Range
HDRI	High Dynamic Range Imaging
HVS	Human Visual System
IES	Illuminating Engineering Society
IPT	Immersive Projection Technology
K	Kelvin
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
OSGExp	Open Source Exporter from 3ds max to OpenSceneGraph
SCAVE	To Simulate Colour Appearance in Virtual Environments: a Comparison of the Appearance of Light and Colour between Real Rooms and Virtual Reality Simulations
VR	Virtual Reality
VE	Virtual Environment
VUE	Visual User Environment

TABLE OF CONTENT

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

Today, the different actors in the design process have communication difficulties for visualizing and predicting how the not yet built environment is going to be experienced. Realistic virtual environments could make it easier for architects, users and clients to participate in the planning process of material choices, illumination and colouring. In this licentiate thesis I focus on the problems of converting real rooms to virtual environments. Special focus is given to the *colour appearance*[1]. I will present comparisons between real rooms and different *Virtual Reality (VR)*[2] simulations and discuss possible improvements.

Forming the base for this licentiate thesis is the project: *To simulate the experience of colour in virtual environments: a comparison of the experience of light and colour in real and virtual rooms* (SCAVE). The project is interdisciplinary and aims to develop a virtual laboratory for trustworthy simulations of colour, light and spatial experience in enclosed spaces. It was initiated and planned by Monica Billger at the Dept. of Architecture at Chalmers University of Technology in 2001. Other institutions that are involved at Chalmers are the Centre for Digital Media and Higher Education, the Dept. of Computer Engineering and the Dept. of Technology Management and Economics. External collaborator is the Dept. of Information Technology at the University of Milan.

[1] Colour appearance is in this thesis referred to as a general concept for the perceived colour of a surface.

[2] *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.

I first got involved in this project as an assistant in 2002. In 2004, we formulated my PhD project within the frame of this larger project.

The starting point and the focus of this licentiate thesis is the viewpoint of architectural research. My studies are based on the knowledge of the fields an architect, designer or colour researcher might have, as opposed to someone from a computer graphics background. Hence the structure of this thesis and the way more basic concepts are explained.

1.1. Problems and Aims

To predict the colour appearance in a room is difficult. A colour on a small sample appears differently than the same colour applied in a room, since the visual appearance will be strongly affected by the light in the room. The visual appearance also depends on our own perception, which takes in to 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 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, 1999, Derefeldt et al, 2004]. To create realistic scenes with the human visual system (HVS) as a base instead of physically correctness has been the aim for parts of the research concerning comparative studies between reality and digital simulations [Devlin, 2002, McNamara, 2005].

Today's VR-technology enables the creation of very realistic models from a geometric point of view and scenes can be created that almost cannot be distinguished from reality. However, it is often not necessary with physical correctness in a scene when it comes to the light transportation. For many applications it is enough that the scene looks 'appealing and 'believable'. The importance of reliable simulations of the lighting conditions of a building is pointed out for the fields of virtual prototyping and architecture and lighting design. [Ulbricht et al, 2005]

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. The object shown on a display is for example much smaller than the appearance in reality, as well as surrounded and limited by a frame. The display also has a smaller dynamic range than the wide range of intensity levels found in reality. Thus, 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. If different visual qualities could be correctly reproduced in the virtual environments, VR could be used as an effective design tool.

The overall goal for my PhD project is to develop the knowledge of how different aspects of the virtual environment, especially light and colour, affect the spatial experience, eventually in order to develop software tools for more accurate light and colour visualization. This licentiate thesis deals with the problems of translating reality into its digital counterparts, *i.e* real rooms converted to VR-models. The main aim is to identify problems of making realistic models in VR. As a consequence of this a following aim is to discuss chosen solutions for increased realism. In order to achieve my aims, the following questions will be considered:

1. Problems connected to visual appearance[3] in the model

Will the simulated room look the same as the real one? If not, how do reality and the simulated model differ? How is the general impression of the room and the associations towards it? Is the illumination correctly reproduced from a perceived perspective? How is the perceived illumination concerning light level, light distribution, perceived colour of light? Are the colours correctly reproduced? If not, in what way do they differ? Is the relation between the colours correct?

2. Problems connected to interactivity within the model

How do we move around? How do we relate to the model, *e.g.* impression of scale and inside- or outside-perspective?

3. Problems connected to technology

Providing that the room is modelled 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 light and colour?

[3] *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 the room.

1.2. Standpoints and Limitations

This licentiate thesis deals with the problems connected to comparisons between real and virtual rooms. An important standpoint is 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 aiming at comparing *images* or comparing models through apertures are not applicable. Important for the studies has been that the observers use both eyes, in order to gain full depth cues (however, in the studies with stereographic goggles a somewhat limited field of view has to be accepted).

When it comes to the technical aspects of the study, Windows based software common among architects and designers in Sweden has been used. A crucial criterion for choice of software was to simulate the chosen light fixtures correctly.

The light fixtures were chosen on the basis of 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 this licentiate thesis only radiosity-based solutions are investigated. Another interesting light calculation technique to apply is photon mapping, which, however, does not support photometric light and is hence not investigated further in this thesis. Further reasons for the choice of radiosity over photon mapping include the facts that:

a) 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[4].

b) In the real time applications rendered textures[5] for the walls are used, which only work if the reflections are diffuse. Semi-diffuse illumination and all kinds of specular reflections demand more complicated solutions than radiosity. Regarding these, there is no satisfying method for real time applications today.

c) In the studies, only matte colours were investigated. In order to be focused, I have chosen not to study glossiness of the colours, since I aim for results that are not dependent on where in the room the observer is standing[6] [Assarsson, 2006].

[4] 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.

[5] '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™/3Ds max®. In order to create virtual environments out of the room-model, texture baking for all surfaces of the room is used. In Lightscape™ rendered textures are made of separate images of each wall, the floor and other multicoloured elements in the room. In 3Ds max® however, each object is baked separately.

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

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 *relation* between the colours in the digital model is correct compared to reality.

The main focus of my studies lies on light and colour appearance in VR compared to reality, and to a lesser extent on other aspects of the spatial experience, such as interactivity and usability. The problem of interactivity was partially studied in a specific questionnaire measuring involvement and presence. However, in order to delimit the problem area, this questionnaire is only regarded for few questions concerning interactivity.

1.3. Approach

My studies are based on the viewpoint of architectural research. When using an architectural perspective other aspects than purely technical or scientific ones need to be considered. This project is based on a qualitative approach, which has proved more important than quantitative aspects concerning 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 the colour appearance.

I investigate spatial experience in different virtual applications and focus on light and colour. The starting point for this licentiate project has been the experience of a real room, which was compared with virtual models of the same room. For my studies I have had four different approaches: (1) a literature study, (2) a comparison between existing studies, (3) an experimental study and (4) elaboration with an algorithm as a possible solution to stated problems.

1. To map out problems of making realistic models, a search through relevant studies was needed. Since this thesis describes an interdisciplinary project, the theoretical framework also touches on different research areas. The area concerning colour is closer

to my own background as an architect than the areas of VR and computer graphics. The problem for me has therefore been to find a relevant width and depth to the reference frame.

2. Concerning the problem of predicting colour appearance, many theories on colour vision are based on colour appearance in 2D. One study, aiming at creating a model for colour association, is the trans-national project *Colour Emotion* [Hansuebsai and Sato, 2002], were the experience of small colour chips are analyzed[7]. I questioned the relevance of how the experience of a small colour chip can be compared to that of spatial colour. In collaboration with Maud Hårleman [Hårleman et al, 2006] I got access to comparable results from real rooms and conducted a comparison between the results from the two studies.

3. Another approach to map out problems of making realistic models was to conduct experiments. In the experimental study, sequential comparisons between real rooms and different VR-simulations were made. How light, colour and spatiality were experienced in different light settings has been investigated through video recorded interviews with the observers. In addition, a separate questionnaire to measure some aspects of interactivity was used. The results have been analyzed, and defined problems with the simulation led to elaboration with software parameters.

4. When finding problems that could not be solved within the software, other ways of dealing with the problems had to be investigated. Tests for improving the colour appearance in the virtual rooms have been performed in collaboration with another team of researches at the Dept. of Information Technology in Milan. Their algorithm Automatic Color Equalization (ACE) was developed for the colour correction of digital images. Our joint question was if this 2D knowledge could be applied in a 3D model. We aimed at increasing balance between contrast effects and reflections.

A continuous goal has been to open up for questions concerning colour appearance in virtual rooms and to find ways of answering them. 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

[7] I conducted the Swedish part of this study and thereby had access to both the published material and the raw data.

circumstances has been necessary, and consequently questions and perspectives have been somewhat revised. The perspectives have changed in the course of learning, theoretically and through practice, and with the opportunities in terms of collaboration other researchers have provided. When, for instance, the collaboration with the Dept. of Information Technology in Milan began, no one at first realized that our approaches towards the use of their algorithm were different. The result became an exaggerated emphasis on this algorithm compared to other algorithms, but it none the less has provided me with a better understanding of what I need and a good starting point for the continued course of work.

1.4. Report Structure and Reader's Guide

Chapter 1 introduces the topic of the subject and outlines the licentiate thesis. The following chapter 2 gives a thorough overview of relevant concepts within the field of computer graphics. Emphasis is put on surveying general concepts regarding light calculation and rendering techniques in computer graphics, since these are essential for the understanding of the project. This chapter is primarily of interest for those with little or no previous knowledge of the field. Chapter 3 gives an overview of the research area within the fields of spatial colour appearance and visual appearance in VR. In chapter 4, the methods I have used in my studies are described. An overview of the results and an analysis of the simulations are given in chapter 5. In chapter 6, a concluding discussion is held and a brief outline of future work is given.

In order to separate between my own work on this licentiate thesis and the collaborative work I have done in the reference project, *To Simulate Colour Appearance in Virtual Environments: a Comparison of the Appearance of Light and Colour between Real Rooms and Virtual Reality Simulations*, I will refer to the reference project as SCAVE.

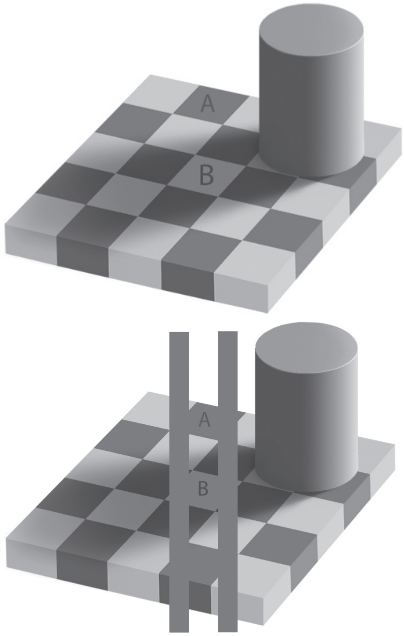


Figure 1.1.
Adelson´s “Checker-shadow illusion”. The squares A and B are exactly the same shade of grey. When the visual system interprets a scene to be 3D, a lighting vector is estimated and used in order to judge the property of the material. [http://web.mit.edu/persci/people/adelson/index.html]

1.5. Terms and Definitions

Some terms commonly referred to in the text need to be defined with short explanations.

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].

Brightness phenomena (Figure 1.1.) refer to a special sort of simultaneous contrast phenomena, which relate the perceived brightness of a region to its background. A region will become darker as the background becomes brighter and vice versa [Adelson, 2000].

Chromaticness is the sum of the cromatic elementary attributes in a colour [Fridell Anter, 2000, p 26].

CIEL*a*b (CIELAB) is a system for assessing colour experience, developed by the CIE. It assumes that two hues cannot be either equally green and red at the same time nor equally blue and yellow. It is therefore possible to determine single values of a hue for its red/green and yellow/blue properties. The coordinates *a* and *b* represent nuance and hue and can be either positive (+) or negative (-). The a* and b* axes form one plane. The lightness L^* axis is orthogonal to this plane [Westland and Ripamonti, 2004, p. 9]

‘Colour’ The word ‘colour’ is in this licentiate thesis treated as a perceptual term and referred to in accordance with the NCS terminology [www.ncscolour.com], *i.e*. colour is defined as the “colour one sees”. The terms *colour appearance* and *percieved colour* are used as synonyms of colour in this sence.

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.

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 ‘Y10B’. Y (yellow) and B (blue) stand for the elementary colours that the hue shows resemblance to. '10' shows the number of steps between the hues, on a scale ranging to 100 [Fridell Anter, 2000, p 26].

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

Inherent colour is constant and does not change due to external conditions. However, it can be operationally determined under specified standard conditions. Fridell Anter defines it as the colour an object would have, if it was observed under standardised viewing conditions that are a prerequisite for the NCS colour samples to coincide with their specifications [Fridell Anter, 2000, p 24].

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].

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].

Nuance describes the relationship between a colour's whiteness, blackness and chromaticness, *i.e.* in the NCS-system to the elementary colours W (white), S (black) and C (pure chromatic colour). In the NCS colour triangle the hue can be specified by a numeric value, for example '1020', where '10' shows its level of blackness and '20' show its level of chromaticness [Fridell Anter, 2000, p 26].

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. The lighting I refer to in the digital room models is photometric light downloaded from AB Fagerhult as IES files. This choice enabled a simulation of the lighting originally used in the real room.

Simultaneous contrast phenomena (Figure 1.2.) are constructed in the HVS. This refers to visual effects in which the appearance of a light patch is affected by other light patches that are close in space. The fieleds change their appearance in the opposite

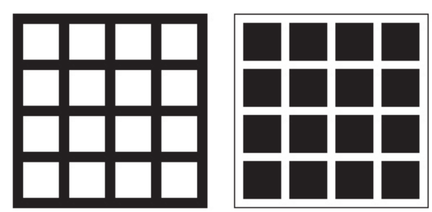


Figure 1.2.
Hermann Grid Illusion. Viewing two colours at the same time influences both their appearance. When looking at the left matrix gray patches are visible in the intersections of the black crosses formed by the white squares, and vice versa for the right matrix.

direction from the colour of the other field [Kuehni, 1997, p. 163]. For example, a turquoise field on a green background looks bluish, while on a blue background it looks greenish.

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]

Virtual environments (VEs) Interior or exterior environments in a computer-generated 3D-world. In this licentiate thesis all digital room models are commonly referred to as VEs.

Virtual Reality (VR) has no absolute definition, but in this text 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. 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 compuer generated, does not enable the same possibilities of presence and interaction. In this licentiate thesis I refer to a VR-model as a digital model exported from Lightscape™ /3Ds max® to Dvmockup or OSGExp.

2. OVERVIEW: LIGHT CALCULATIONS AND COLOUR RENDERING

This thesis describes a project based upon the tools of an architect. In the course of analyzing the appearance of the simulated rooms, different software has been used, which unavoidably leads one into the field of computer graphics. However, I have approached this research area from the architect's viewpoint and perform the studies based on my perspective as an architect. For my own understanding, the concepts have had to be learnt from the beginning.

The purpose of this chapter 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 a correct way is very difficult [Slater et al, 2002, p.74]. There are a number of techniques used for calculating light in 3D programmes.

Computer Graphics and Virtual Environments by Slater et al deals with the basics of computer graphics. In this chapter I use this book as a main reference.

2.1. Rendering and Rendering Techniques

The radiance equation[1], 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

Radiance is depending 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 solve 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 has to be carried out again. The view-independent solution pre-computes the reflectance in a scene across all surfaces and directions.

The local and global solutions are yet 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

[1] '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'.

solution takes to a greater or lesser extent into account the ways in which light is transferred between surfaces, *i.e.* all surfaces affect each other. In this thesis only global sollutions are considered.

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

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. In the studies, the scanline default renderer is used, because of its radiosity calculation, supporting the photometric lights used.

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 the light settings used, *i.e.* photometric light.

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.

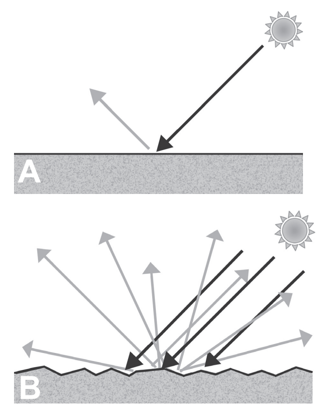


Figure 3.1.A,B.
A. Diffuse surface.
B. Specular surface.

2.2. Radiosity

Radiosity is a realistic, real-time rendering technique most relevant to my aims (see section 1.2.). The 'real-time' aspect means that the images are displayed at interactive rates, *i.e.* more than 10 images per second, which is of utter importance as a lesser pace will make the application useless in many cases. The radiosity solution assumes that all surfaces are *diffuse*[2] reflectors only. Since the inter-reflections between the diffuse surfaces are taken into account, radiosity is a global solution.

[2] According to their ability to reflect light, surfaces can be either diffuse or specular (Figure 3.1.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 in all angles [Slater et al, 2002, pp. 133-134].

Radiosity as a rendering technique was a good choice of method for the project because of: 1) the solution is view independent, meaning that it will look the same from every view point (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, 4) and 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].

2.3. 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 diffuse reflectors with diffuse local illumination. This algorithm can be extended by Monte Carlo Ray Tracing[3] or Path Tracing[4] 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 mentioned surface. Solutions are found only for the specific set of rays entering the eye. Ray tracing is therefore considered view dependent, and its relevance for us is hereby small.

In my studies of relevant research I came across the ray traced based light calculation programme Radiance [Ward Larson and Shakespeare et al, 1998] 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" [manual at www.radiance-online.org]. Studies show that this software gives good results [McNamara et al, 2005].

[3] 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, 1996].

[4] 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 conventional ray tracing.

However, Radiance is *image*-generating only, and does not therefore correspond to my aims regarding analyzing 3D-environments.

2.4. Photon mapping

As an alternative approach to rendering realistic images, photon mapping [Wann Jensen, 2001] could be a method for evaluating the appearance of colours in VR [Akenine-Möller and Haines, 2002]. 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 [Akenine-Möller and Haines, 2002] such as ours in the SCAVE-project. Due to its view dependent nature, the entire solution cannot easily be pre-computed into textures as could the radiosity solution. The main reason not to have used photon mapping in the SCAVE-project, is due to the use of photometric lights in the models, which currently, to the best of our knowledge, no available implementation of photon mapping supports [see 1.2.]. However, with alternative lighting, photon mapping is an interesting alternative for future studies.

2.5. Different ways to improve Colour Appearance in Images

The concepts in this section are the ones that I have been recommended to consider from computer graphics experts at conferences.

HDRI

The range between the darkest and the brightest part of an image is known as the 'dynamic range'. Conventional images, considered as low dynamic range (LDR), consist of 8 bits per channel, with pixel values ranging from 0 to 255. When an image has a greater dynamic range than can be shown on a device it is known as a High Dynamic Range Image (HDRI) [gl.ict.usc.edu/HDR/Shop]. For generating HDRI the typical way, multiple images of the same scene taken with different intensity levels are combined. The light quantities HDR pixels are capable of representing ranges from one to beyond a million through using floating point numbers.

Tone mapping

The purpose of tone mapping is to reproduce the appearance of HDR scenes in a media which have a limited dynamic range, such as 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 details in an image. [Ledda et al, 2005]

ACE – A tone mapping operator

The Automatic Color Equalization (ACE) [Rizzi et al, 2003], algorithm is 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 (HVS) and simultaneously tries to solve the tone mapping problem of compressing the dynamic range and to recover colour appearance [Gatta, 2005, p 87]. Like the HVS, 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 this licentiate thesis.

3. OVERVIEW:
VISUAL APPEARANCE IN REAL AND VIRTUAL ENVIRONMENTS

The objective of this chapter is to describe the state of the art knowledge. Since this licentiate thesis describes an interdisciplinary project, the theoretical framework also touches on different research areas. I will focus mainly on the results of the studies, in order to encircle what has already been done and what is lacking from my point of view. Emphasis will be put on studies concerning colour appearance in rooms and in VR, since this is central in the project. It is also relevant to mention something about usability in VR.

My studies of the state of the art are based on my questions and perspectives, and compared to the SCAVE-project (see chapter 1).

3.1. Studies on Spatial Colour Appearance

Colour is an important factor for the spatial experience as well as important when it comes to attract attention and mediate information. It is an efficient aid for finding and interpreting information as well as arousing emotions. Colour also facilitates our perception of the surrounding environment and spatial orientation [Derefeldt and Berglund 1994]. For example, the importance of colour for flight simulators was tested, using a real-time simulation of an air-to-air mission with test pilots as subjects. The results proved that a display showing colours has many advantages over a monochromatic one, in terms of increased situation awareness, significantly lower reaction time and higher preference ratings. Thus colour might improve tactical situation awareness in combat aircraft. [Derefeldt et al, 2004].

As far as I can 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 equally investigated, and in comparison few studies have been published on the subject.

Concerning colour appearance in architecture, several research projects have been carried out over the last decade. The perceived colour in rooms or on buildings is problematic to identify, since there are no instruments to measure what we see. Karin Fridell Anter has in her thesis *What colour is the red house? Perceived colour of painted facades* [Fridell Anter, 2000] presented methods of analyzing the perceived colour on facades through different interview techniques with observers. In her studies, a mixture of skilled and untrained observers performed several tests where a selection of facades where viewed and compared to NCS colour samples. In doing so, Fridell Anter could discover tendencies in the perception of the different colours, where light, viewing distance and surrounding colours had their impact on the façade colour.

Billger [1999] and Hårleman [2001] have shown how the reflections in the room enhance both the colour and the colour experience. In her thesis *Colour in Enclosed Space* Billger deals with the problems of how to identify and compare colour appearances in rooms and how interior colours appear differently due to lighting condition and colour combination. She has developed different methods and concepts for colour analysis in enclosed spaces.

Hårleman [2001, 2006] has in her studies investigated how the colour appearance indoors differs depending on the room's compass orientation. As with exterior colouring, this is a problem often causing different results from the expected outcome of a design. The studies showed that the colour appearance in rooms became darker and more colourful compared to a colour chip. Knowing what factors affects the colour appearance can help designers and architects predict the final colour experience more correctly.

Xiao et al [2005] describe in their paper a method for predicting how the same colour will appear in varying sizes. Their aim is to construct a colour appearance model based on colour vision, which could be integrated into the already existing CIE colour appearance model [Publication CIE, 2004] and meet the strong industrial demands for predicting colours correctly. In order to achieve this, experiments of assessing colours of different sizes have been performed and size effect has been modelled on the basis of these experiments. In the methods applied, this study is close to the ones that I have used in the SCAVE-project. However, Xiao et al only study one wall while the overall colour appearance is the focus of my aims. From my viewpoint the way in which Xiao present their results, is difficult to apply. Still their results seem to agree with mine with regard to the chromaticness increasing with size.

Another approach to spatial colour appearance is provided by Pungrassamee et al [2005], who investigate adaptation through colour appearance. Their research focuses on the impact of room illumination, compared to retinal chromatic adaptation, on the colour appearance of a test patch placed in a room. However, they do not include the entire room in their study, but restrict the spatiality to what is visible through a frame varying in size. They discovered that the colour appearance was not affected by colours surrounding it, but determined by the room's illumination.

3.2. Simulation of Colour Appearance in Virtual Environments (SCAVE)

The SCAVE-project is the basis for my studies and the starting point from which I have formulated my questions. In this licentiate thesis I refer to the SCAVE-project for comparison with the state of the art. A more thorough account of the studies included in this project is therefore necessary.

A pilot study to the SCAVE-project was carried out by Billger and d'Élia [2001], where different problems associated with the comparisons of reality to VR (a cave), were discussed. How colours in rooms are perceived was one of the discussed problems, as well as technical problems connected with the creation of realistic images at a satisfying rate of time. The conclusions of this study revealed that the colour appearance in the cave was affected by problems of creating enough light and correctly simulating the light situation in the real room. The poor rendering of the simulation affected the spatial experience.

Billger [2003A], as part of the SCAVE-project, carried out a comparison of colour appearance in two different light situations conducted in the same room. The paper discusses the three applied methods of verbal description, magnitude estimation and colour matching using a colour reference box. The results showed that the colour appearance differed between the two light situations. Also, there was a difference in the descriptions regarding both magnitude and precision. The colour matching technique revealed a distinctly higher precision than the other two methods, though some deviations occurred due to the adaptation effect. Clear differences in the colour appearance were expressed in the verbal descriptions that the magnitude estimation did not show. The verbal descriptions however agreed well with the colour matching data.

As part of the SCAVE-project Billger and Heldal [2003B] wrote a paper discussing the potential of VEs to become a usable design tool concerning light and colour. They referred to the same test room and simulations as is described in this thesis and highlight in their analysis the relation between the factors influencing the spatial experience. Benefits and disadvantages of the models used are discussed. The conclusions drawn were 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 light and colour variations is consistant with the conclusions drawn in the previous paper.

3.3. Studies on Visual Appearance in Virtual Reality

According to Ulbricht [2005] there are different focuses for VR-research when it comes to using it as a tool for increased realism in appearance: 1) virtual prototyping and 2) architecture and lighting design. Virtual prototyping is used in many appearance-sensitive branches of industry, where costs can be reduced by using virtual prototypes, compared to real ones, for example such as in the case of a car. 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]

In Sweden, according to Nilsson [2000], there are different focuses in the VR-studies when it comes to architecture and building design. 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 visualization of architectural models, which regards issues such as the visualization of spatiality and size in VR. Nilsson emphasizes the importance of interdisciplinary VR-research.

In the design process, VR can be used as a tool that can more correctly reproduce the planned reality than traditional design tools are able to. Due to their abstract nature, traditional plans, perspectives and sections are usually difficult for laymen to interpret and understand correctly [Dorta and Lanlande, 1998, Hornyánsky Dahlholm, 1998]. 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]. While considerable work is being done on usability issues concerning technical interaction in VEs [Bowman et al, 2001, Tromp, 2001 and Heldal, 2003], there are few studies concerning how people experience different VEs in comparison with reality.

Meyer et al [1986] introduced a method for comparing real environments with digital images. 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 revealed many similarities between the image and the physical model. Observers had difficulties in telling them apart. The matching between the simulation and reality turned out to be quite good. The observers found for example colours to match slightly better than good and the shadows slightly less than good. An important difference between Meyer's project and the SCAVE-project is that in SCAVE, measured values were not used initially for describing the room as in Meyer's study, but instead applied as a retrospective reference and documentation. Furthermore, the test rooms in the SCAVE-project were analyzed from within and not, as in the Meyer project, through a frame, *i.e.* as an image.

Another study were simulations are compared to a real scene has been carried out by McNamara et al. [2005]. The study aims at investigating how much computation is enough in order to create a trustworthy image, based on the HVS[1] rather than on physical correctness. For this the ray tracing based software Radiance is used. Objects are 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 aim at studying lightness, not colour. The observers' impressions of the objects' lightness have formed the basis of the study, where levels of grey are matched. An important difference is the fact that scenes were viewed monocularly in order to eliminate depth cues, in contrast to the SCAVE-project where observers had to use both their eyes (see section 1.2) and were required to move inside the models. The similarity with the SCAVE-project is that McNamara et al base their study on the Radiance-manual in a similar manner as the 3Ds max-manual was used in the SCAVE project.

Hornyánszky Dalholm and Rydberg Mitchell [1999] have performed a pilot study where different VEs are compared to reality, which reports on the impact of colours and textures on size perception. The similarity with the SCAVE-project is that both studies compare models in different digital media (here desktop-

[1] To create realistic scenes with the HVS as a basis instead of physically correctness has been the aim for parts of the research concerning comparative studies between reality and digital simulations. Devlin et al [2002] point out that new psychophysical research is needed. Changes of contrast and colour perception need to be considered in order to produce perceptually accurate images on a display. There are new psychophysically based visual models that aim to create solutions for these problems. However, the focus tends to lie on singular aspects for single purposes. The knowledge of HVS is still, according to Devlin, limited and needs developing. [Devlin et al, 2002]

VR and a cave) to a full-scale model, and that colour is included in the research. However, the aims and focus of the studies differ; while in the SCAVE-project the colour appearance itself is in focus, colour in the Hornyánszky Dalholm/Rydberg Mitchell-study is used as a tool to affect the spatial appearance, and focus is held on the observer's experience of the room. Their results showed that colour and texture had an impact on size perception in the desktop-model but not in the cave and that it facilitated navigation in the desktop-model but impeded it in the cave.

Mania et. al [2002] aim at photo-realistic simulations and have made great efforts to control light and colours, using objects painted the same shade of blue. In their study, they did not visually assess or discuss colour appearance. Instead their focus lied on memory recalling of objects in a room. Their study has considered questions concerning cognition, through demonstrating the difference between using task performance based metrics and human evaluation of cognitive awareness states. Mania et al are relevant because they face some of the same problems in their study as my licentiate thesis does. The similarity with the studies performed in the SCAVE-project is the translation of colours from reality to VR in different viewing conditions. The methods applied sometimes show similar features. However, their approach and focus differs from mine since they come from another field and have different goals. Their focus on individual objects differs from the SCAVE-project, which studies the combined colour appearance of the whole room. Mania et al sometimes forgoes the realism in the simulations in order to achieve a more 'naturalistic' awareness state, while in the SCAVE-project achieving a higher sense of realism is the focus.

3.4. Summary

The concerned research fields I have looked at include spatial colour appearance, VR-research as well as light calculation and colour rendering in computer graphics.

A difficulty for me has been to find relevant references. Many of the studies presented in this chapter have not been found until late, depending on my use of keywords (virtual reality, virtual environments, colour, light, spatiality, experience) in search for references. Some of them I have been recommended from reviewers. Sometimes it has been frustrating to find so little material published concerning specific topics, e.g. spatial colour appearance in reality and in VR. Colour has in most VR-studies not been the main topic and therefore not closely studied in itself. Except for earlier SCAVE-studies, none of the studies put the colour itself in focus. In the field of computer graphics, my difficulty has been to find 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.

A survey of the concerned research within the field of 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 VR-research of today 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 HVS, is a highly important and current topic. There are many studies comparing reality to virtual simulations. However, few studies deal with colour appearance in virtual compared to real rooms, and I have not found any that applies the above-mentioned results of spatial colour appearance. 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 to an image.

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. The full development of this type of research is still a distant future goal, but I believe it to be a logical next step in the technological progress.

4. METHODS

As mentioned in the introduction, I had four different approaches in my studies: (1) in order to gain knowledge about the relevant fields of research I conducted a literature study, (2) to learn more about spatial colour experience, I made a comparison between two existing studies, (3) to encircle the problems with translating colour from reality to VR, an experimental study (SCAVE) was carried out and (4) to test possible solutions to the stated problems, I made elaborations with algorithms. The literature study has already been presented in chapter 2; the other methods will be presented in this chapter.

Since the experimental study is based on the SCAVE-project, the methods described in this licentiate thesis are inherited from this project. I have used the ones that are relevant for my study. However, I have had no influence over the choice of methods applied in the SCAVE-project and have therefore had to accept both their advantages as well as their disadvantages.

4.1. A Comparison between Existing Studies

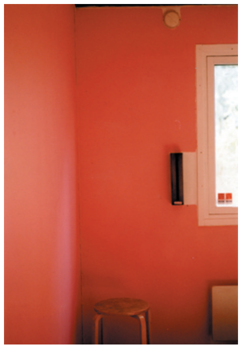


Figure 4.1. One of Hårleman's full scale experimental rooms.

As part of the four different approaches I have used in my studies, a comparison between two existing relevant studies on colour appearance was made; (1) Hårleman's room study and (2) the Swedish part of the Colour Emotion-study, where I participated [Paper C].

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 affects the visual appearance. The aim with this comparison was to understand differences in colour appearance in various contexts. The appearance of isolated colour patches in a viewing cabinet compared to the complexity of colours in rooms was investigated.

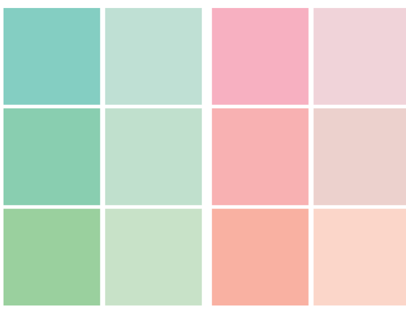


Figure 4.2. The inherent colours in which the rooms were painted.

In her study, Hårleman conducted experiments in two full-scale rooms with similar colour schemes, one room facing north and the other one south (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 (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 Colour Emotion-study aimed to investigate how people from different countries and cultures associate towards colours. 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.

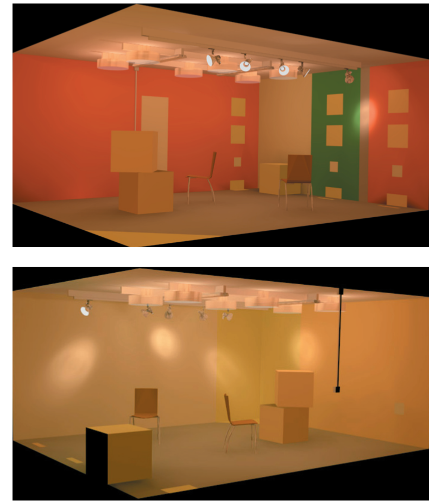
Figure 4.3.
Room study
Colour Emotion

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 base for comparison.

The two studies are based upon two different colour order systems. In the room-study the NCS-system was used and the CE-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 (Figure 4.3.).

4.2. The Experimental Study

The first aim of this licentiate thesis has been to map out problems of making realistic VR-models. In order to do this, a comparison between a real room and simulations of the same room was necessary. As a base for this investigation, the studies in the SCAVE-project were used. The real room has always been the reference against which the other models have been measured.



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 (Figure 4.4.A,B), which was compared with virtual models. The room was designed to get clear examples of how simultaneous contrast phenomena and reflections cause different appearances of the 6 different paints used. Three different light situations were used: incandescent light, fluorescent 2700K and fluorescent 3000K.

Digital models, both in Lightscape™ and in 3Ds max®, of the room were made[1]. The 3dsmax-model was exported to VR. In the VR-models two illuminations were used: incandescent and fluorescent 3000K, whereas in Lightscape™ and 3Ds max® all three illuminations were used.

Comparisons were made between (1) a real full-scale room-model, a Lightscape-model and a cave-based model, (2) a monographic and a stereographic VR-model on desktop, and (3) a monographic and a stereographic VR-model and a Lightscape-model. For technical data on the set-up for the virtual models see paper A.

In order to compare colours with their digital counterparts, a process was developed to translate real colours to digital values (Figure 4.5.). This process is described in paper A. 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.

Figure 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 base for my studies on different colour phenomena.

[1] 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 programme for the continued research.

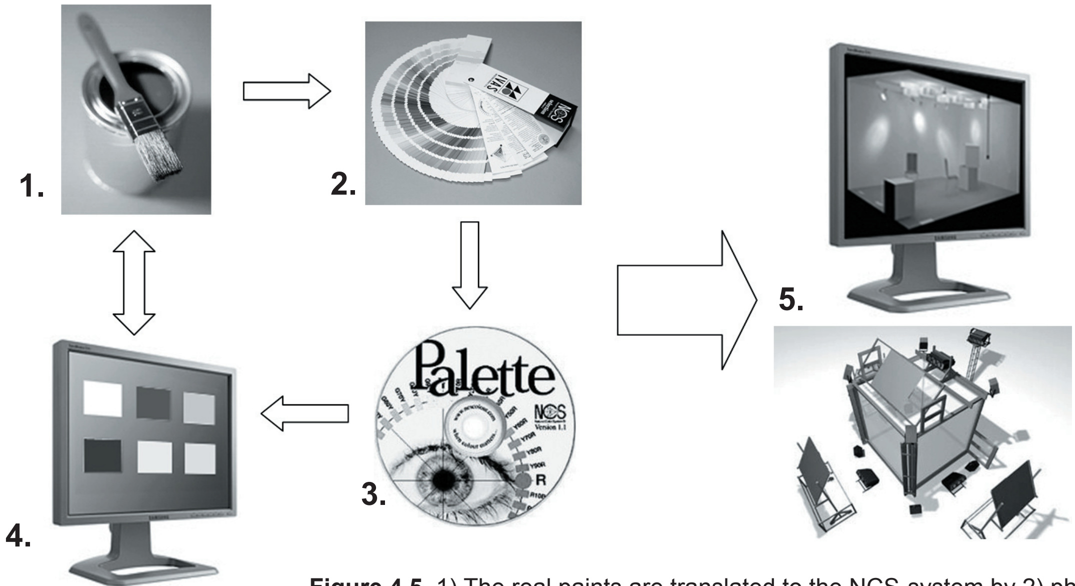


Figure 4.5. 1) The real paints are translated to the NCS-system by 2) physical measurements, then by 3) digital transformation in the NCS Palette program. 4) The digital colours are then adjusted with the original paints. 5) The colours are finally inserted in the digital model.
Note that in the project CRT displays were used, not LCD as shown in the figure.

4.2.2. Study Procedure

The tests started with 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, light and colour, 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 focus in the project lay on the visual appearance in the simulated rooms and on the interactivity and the usability of the different applications tested. The participants walked/moved around inside the room model and assessed colour, light and space. Data was collected from video-recorded interviews and questionnaires.

4.2.3. Evaluation Techniques

A combination of both quantitative and qualitative techniques was used in order to encircle various aspects of experiencing the virtual room models and the real room. 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 interactivity with the models.

The interviews were video-recorded. 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 of them were male and half female. All of them had normal colour vision.

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 = Light and Colour, C = Memory Matching, D = 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. **Size Estimation**
   The observers were asked to estimate the size of the room in square metres as well as length and width.

B. Light and Colour

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

1. ***Visual evaluation of light*** [Billger, 1999, pp. 14-18]
   The observer described various aspects of the light, such as light distribution in the room, light level, shadows, perceived colour of light, dimness and clarity.

2. ***Semantic descriptions of the colours***
   The observers described and compared coloured surfaces, using everyday language and the terminology in Natural Colour System (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 requires a long time; thus it was not possible to include the majority of observers.

Figure 4.6.
The colour reference box.

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

C. Compared Experiences

Memory matching
Besides comparing the visual assessment results, the participants were asked to compare their experiences 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. Interaction

1. ***Description of interactivity***
   Spontaneous reactions on interactivity were verbally expressed during the interview.

2. ***Questionnaire***
   A questionnaire provided and analyzed by Ilona Heldal was used to a limited extent [paper B]. In this licentiate thesis, I focus on interactivity rather than presence. The questionnaire included both questions requiering 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, 2000A]. With this analysis as a starting point, the parameters describing colour bleeding, reflectance and colour temperature (*i.e.* the colour of the light source) (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.

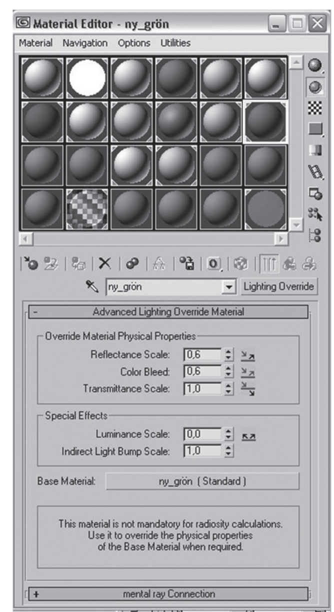


Figure 4.7.
The parameters in 3Ds max® describing colour bleeding and reflectance.

4.2.5. Physical Measurements

In our study measured values were not used initially for describing the room, but instead applied as a retrospective reference and documentation. Measurements of reflectance, luminance and spectral composition were made. 40 local points of the real room and 27 corresponding points in the VR-models were measured.

Table 5.1. (page 39) gives examples of the collected data for four areas in the room, as well as the NCS-codes for the paints and results from magnitude estimation and verbal description. These areas are examples of surfaces that matched well and their matching values.

The reflectance of each painted area was measured with a BYK-Gardner Colour Guide spectrophotometer. The L*a*b-values are shown in column B. The display Lab-values, as defined in Photoshop, for the digital colours are shown in column G.

The spectral composition of the differently painted areas was measured with a Photo Research PR-650 spectroradiometer at different locations around the reference room and in the VR-room. The average values of L (Luminance), x and y (CI E 1931, 2 $^{\circ}$) in the real room are presented in column C. The values for the VR-room are presented in column H. The L, x and y-values were measured for the closest matching colour patch placed in the light box (column D).

4.3. Tests with Applied Algorithms

The focus of my research lies on simulating light and colour phenomena more correctly. A step in this process is to focus on problems concerning the realistic reproduction of contrast effects in rooms. The final approach I had in my studies was to test solutions for solving problems discovered in the comparative studies. Tests with an algorithm, developed for colour correction of digital images, were performed.

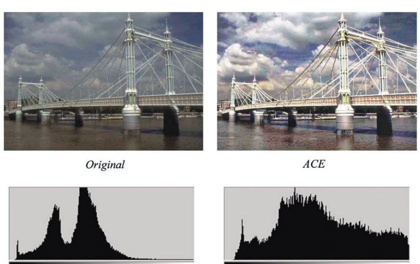


Figure 4.8. The ACE-algorithm is developed for colour correction in images and aims to increase the dynamic range.

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 [Paper D] The aim was to see if any improvement in the model's colour appearance could be reached (Figure 4.8.).

The analysed 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 observer's results. 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 were then compared to the observer's interviews in the real room.

To see the effects of ACE on an interactive model rendered textures of walls and floor in the 3dsmax-model were filtered with the ACE and combined to a VR model. It was then compared with the results from reality.

5. OBSERVATIONS AND ANALYSIS

In this chapter I will review the findings from the conducted studies. In order to facilitate the understanding of the results I have choosen to divide them into groups correlating to the area they concern, rather than aiming at showing them in the chronological order in which they were conducted.

5.1. Light

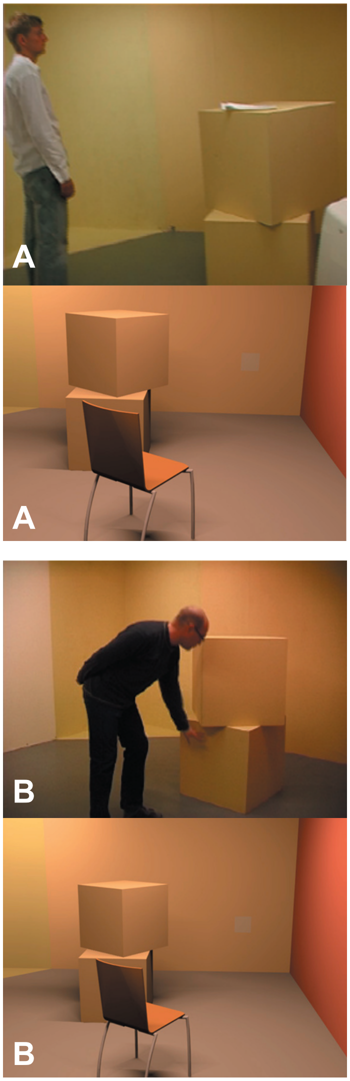


Figure 5.1.A, B.
A. 2700K in the reference room and in 3Ds max®.
B. 3000K in the reference room and in 3Ds max®.

In paper A, 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 (Figure 5.1.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.

Shadows: 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. 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.

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.

Light colour: 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 to simulate light distribution and light colour. None of the software's settings for incandescent light was red enough.

5.2. Colour

Paper C 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.

Paper A 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 (Figure 5.2.A,B).

In the reference 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 (Figure 5.3.A,B).

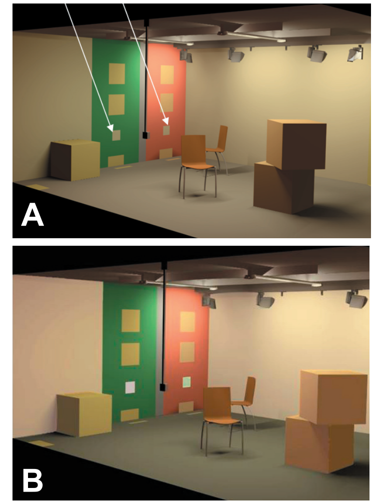


Figure 5.2.A, B.
A. The 3Ds max® model.
B. Manipulations made in Photoshop in order to demonstrate the appearance in reality.

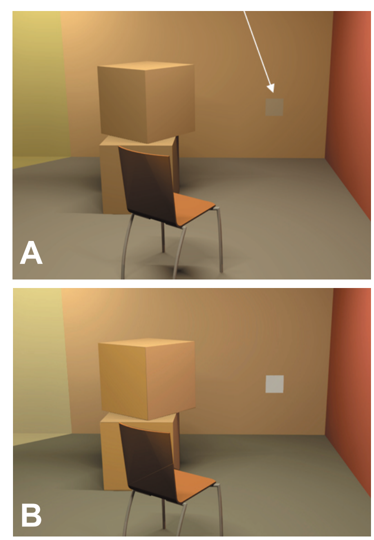


Figure 5.3.A, B.
A. The 3Ds max® model.
B. Manipulations made in Photoshop in order to demonstrate the appearance in reality.

5.3. Manipulations of Parameters

General elaborations with the software parameters in Lightscape™ and 3Ds max® are shown in paper A. 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 (Figure 5.4.A,B,C).

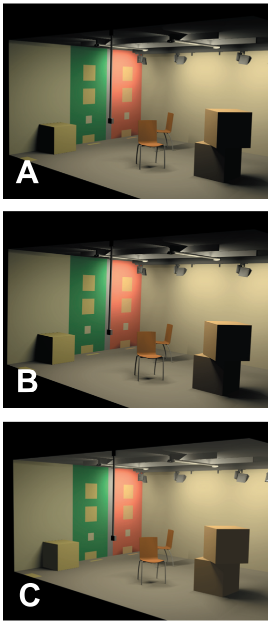


Figure 5.4.A,B,C.
Reflectance - Fluorescent light, 3Ds max®
A = 0,5 colour bleed, 0,5 reflectance
B = 1,0 colour bleed, 0,5 reflectance
C = 1,0 colour bleed, 1,0 reflectance

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 (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 programme.

It has showed that in order to make true and realistic visualizations in virtual environments, the colour appearance of the objects in reality must be known. However, even if the properties of the real objects are known, to obtain a correct simulation is not always possible. For example, high reflectance in the digital models turned out to brighten up the areas around the long red wall too much (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 conducted experiment a fairly good match was obtained between the real and the virtual room.

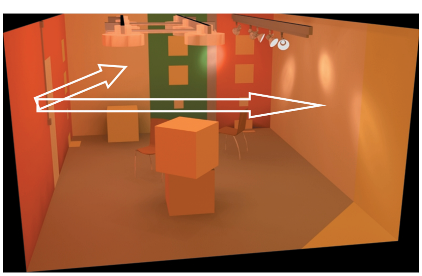


Figure 5.5. Problems regarding the simulation of reflection between surfaces.

5.4. Elaborations with Rendered Textures

Paper D discuss an attempt to try one solution to the above mentioned problem of too few colour variations and incorrectly reproduced contrast effects in the simulations. 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 with the ACE algorithm 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 (Figure 5.6A). The other two white squares regained the greenish and pinkish appearance they had in reality (Figure 5.6B).

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 (Figure 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 to a complete model (Figure 5.7.A,B,C). Through these elaborations, the best result so far concerning the colour appearance was obtained. This regarded the red and green wall were all colours turned out to be well simulated and in accordance with their real appearance; even the contrast phenomena (see chapter 5.2) became visible! However, when filtering the opposite wall, the colours turned out to be extremely exaggerated and incorrectly reprocuced.

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

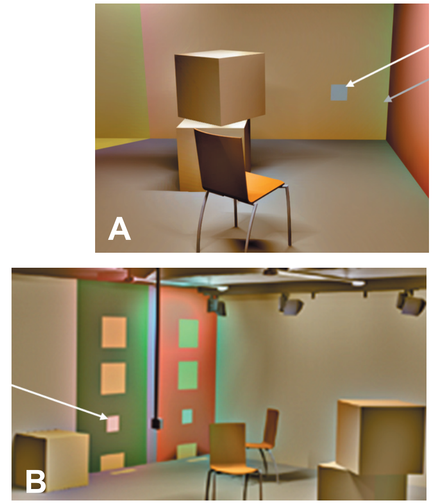


Figure 5.6.A,B.
Model in 3Ds max® filtered with the ACE.

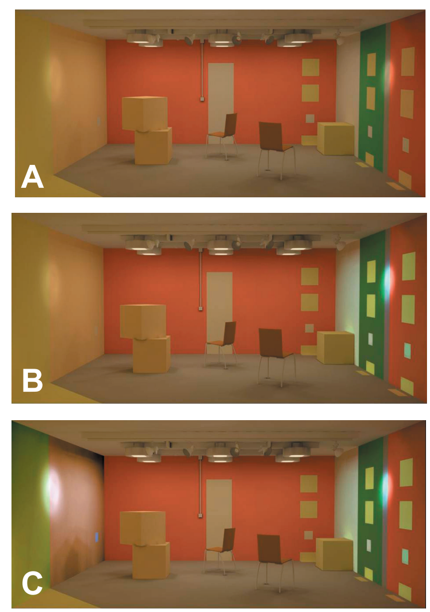


Figure 5.7.A,B,C.
A. The original model in Lightscape™.
B. The right wall filtered with the ACE.
C. The left and right wall filtered with the ACE.

5.5. Measurements

5.5.1. Data Analysis and Preliminary Results

These results are not accounted for in my appended papers. However, after having made the measurements, I found them to be an interesting addition for the thesis. They will be further analyzed in future studies.

L*a*b*-values measured in reality could not be directly applied as digital Lab-values (Table 5.1, column B and G). They needed to be slightly adjusted. Corresponding Lab-values on the display were too brownish for our 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.

The luminance was naturally very different between the reference room and VR. However, the light level in the VR-room was assessed almost the same and the colours agreed fairly well (Table 5.1, column C, D, E and F). The lightest areas were not simulated well; they became too grey.

Spectral composition of the areas in the reference room and the matching colour patches in the light box were close. However, the corresponding areas in the VR-room had distinctly different L, x and y values (Table 5.1, column C and H).

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 (Table 5.2). The white reference values for the reference room and the digital models were different. When bringing the L,x,y-values to a connection space (D65), using the Bradford transform [Berns et. Al, 2000] it showed that they were fairly close.

Area:	Reference room:			Visual assessments:			VR-room:	
	A	B	C	D	E	F	G	H
1	**1030-G90Y**	L* 84,24 a* -2,97 b* 34,36	L=96,8 x=0,491 y=0,450	**NCS=1030-G70Y:** L=452 x=0,492 y=0,450	2030-G60Y	Greenish yellow	L=92 a= -12 b= 39	L=18,8 x=0,422 y=0,430
2	**1030-G90Y**	L* 84,24 a* -2,97 b* 34,36	L=92,0 x=0,490 y=0,443	**NCS 2010-Y10R:** L=359 x=0,490 y=0,443	1020-Y10R	Clear, light yellow	L=92 a= -12 b= 39	L=15,5 x=0,415 y=0,421
3	**1030-Y10R**	L* 81,04 a* 5,02 b* 32,15	L=95,8 x=0.498 y=0,439	**NCS 2020-Y10R:** L=357 x=0,496 y=0,440	2040-Y20R	Reddish yellow	L=89 a= 2 b= 35	L=11,5 x=0,434 y=0,406
4	**1030-Y10R**	L* 81,04 a* 5,02 b* 32,15	L=85,9 x=0,498 y=0,437	**NCS 1520-Y:** L=481 x=0,495 y=0,442	1218-Y13R	Light yellow. As 2, but greyer and weaker	L=89 a= 2 b= 35	L=16,9 x=0,425 y=0,404

Table 5.1. Examples of room surfaces with a good match between reference room and VR-room. The table show examples of collected data from physical measurements and visual assessments from the room under 3000K illuminants. A=Matching NCS-code, B=Reflectance (spectrophotometer measurements), C=Spectral composition (Spectroradiometer measurements) 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.

Area:	Difference between Reference room and VR-room:		Difference between Reference room and VR-room:	
	Original data (table I)		Connection space	
	x	y	x	y
1	-0.0690	-0.0200	0.0198	0.0098
2	-0.0750	-0.0220	0.0195	0.0179
3	-0.0640	-0.0330	0.0287	0.0018
4	-0.0730	-0.0330	0.0208	0.0037

Table 5.2. X and y differences in the original data compared to the connection space.

5.6. Interaction with the Model

The observers moved around differently in the real room, in the cave-based model and in the desktop-model [paper B] .

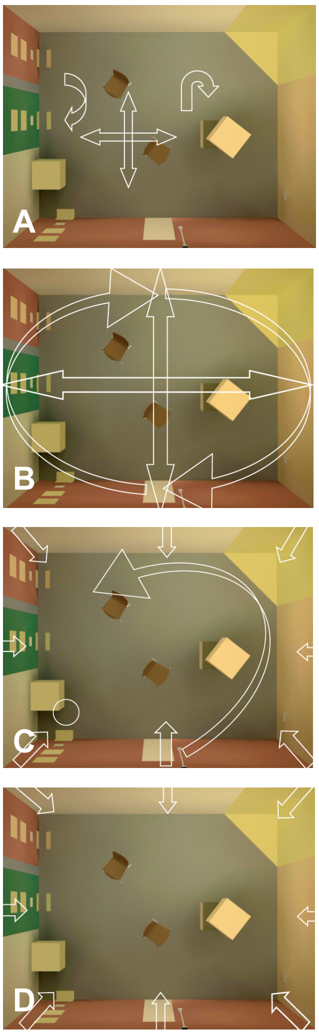


Figure 5.8.A,B,C,D.
Example of how observers moved around in:
A. The real rom
B. The cave-based model
C. Desktop VRs (mono and stereo)
D. Desktop Lightscape

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 (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 (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 in 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 (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 to get close inside the model. At closer distance, 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 (Figure 5.8.D). The graphic user interface 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.

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

- Claude Monet

6. CONCLUDING DISCUSSION AND FUTURE WORK

In this chapter I will discuss my stated research questions in order to see if they have been answered in this thesis. A short discussion regarding each stated question will be presented, together with the results from the studies.

This study deals with various problems related to the translation and comparison of reality to VR. As a basis for the project the following questions was formulated (see Chapter 1.1.):

1. Problems connected to visual appearance in the model

How is the general impression of the room and the associations towards it? Will the simulated room look the same as the real one? If not, how do reality and the simulated model differ? Is the illumination correctly reproduced from a perceived perspective? How is the perceived illumination concerning light level, light distribution, perceived colour of light? Are the colours correctly reproduced? If not, in what way do they differ? Is the relation between the colours correct?

2. Problems connected to interactivity within the model
How do we move around? How do we relate to the model, *e.g*. impression of scale and inside- or outside-perspective?

3. Problems connected to technology
Providing that the room is modelled 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 light and colour?

6.1. Reflections on Results

1. Problems connected to visual appearance in the model
In order to understand what is a trustworthy visual appearance, I found it fruitful to investigate earlier research and conduct my studies of my own. These studies pointed out the significance of interreflections, colour variations, perceived colour of light and shadowing in real rooms. From what I found out was that there were 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 surfaces were too small and incorrectly reproduced, the colour variations were too few, the chromatic information on light sources were too simple and the shadows too achromatic. Also the whitest areas were too greyish. Some of these differences had to do with arbitrary parameter settings in the software and heavily simplified chromatic information on the illumination. Other problems, such as incorrect interreflections and that the whitest surfaces came out too dark and greyish, were not possible to correct.

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 reference room.

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. It proved to be able to reproduce the contrast effects visible in the reference room. However, the ACE, developed for colour correction in *images*, filtered only one flat surface at a time, *i.e.* each wall separately 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. In the reference room, contrast effects appeared between coloured areas on flat surfaces, while surfaces in angles affected each other by reflections. The exaggeration of the contrast effects shown through the elaborations can probably be corrected through adjustments of the ACE's parameter settings.

The conclusion will therefore have to be that the ACE can be used, but in a very restricted context and not as a solitary method for filtering images of a complete room. I regard the ACE as a starting point in the process of creating a new algorithm. Through the elaborations with the ACE, my understanding of the problems regarding differences between 2D and 3D has deepened. As reflections do not exist in 2D but are evident in 3D, theories on colour perception in 2D cannot atomically be applied in interactive 3D simulations.

Concerning the physical measurements where focus was pointed at 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. The relation between the measurements and the physical data is an interesting and difficult research problem and a future issue to further investigate. At this stage, I do not grasp the full meaning of the results, for example what counts as a significant difference between visual and physical data and between physical data. When it comes to the visual data, we can see that small differences in colour appearance can be significant for the experience. It is desirable to obtain estimations of at least 5 NCS-steps. 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 our study, which involved four different yellow colours. These colours showed very different appearance in the different light situations.

2. Problems connected to interactivity within the model

The studies concerning these aspects of the simulations revealed that we experience the same model in different applications differently, not only with regards 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 experience it to have and general associations towards 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 easiest looked at from an outside-perspective. It showed that the colour appearance and light reproduction was of little importance for the way in which the model was experienced. The conclusions I can draw is that the experience of a model regarding interactivity instead concerns aspects such as speed, possibilities to get close to objects and to stay inside the model, graphical interface in the software (or lack of) 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.

3. Problems connected to technology

The studies revealed various problems related to the translation and comparison of reality to VR. One problem in the applied software concerns the parameters defining the illumination. These parameters define temperature as well as offer a choice between different default settings. This is however only a choice of coloured *filters*. 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 rather correct view of the illuminated room, 3dsmax™ gives an approximation of the model and requires rendered images in order for the result of the light calculations to be visible.

Concerning the radiosity calculations in the used software, some problems were pointed out. This implies that it is not enough to use only information on physical conditions of the not yet built environment (materials, illumination, paints). To know the colour appearance of the real objects (rooms, buildings, etc) proved to be essential for the making of true and realistic colour visualisations in virtual environments.

Further systematic research is required to solve this complex task, in connection with elaborations in VEs. Psychological phenomena and the way the HVS works need to be included in the research as a complement to today's mathematical modelling of physical conditions. The objects appearance in reality must be known in order to be able to create more accurate simulations regarding light and colour appearance. Still, even should the real appearance be known, today's technologies will need further development. Full manipulation of parameters is desirable. The parameters regarding light and colour in both reality and in the applied software will need further exploration.

The results accounted for in this 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.

6.2. Reflections on Methodology

The different approaches adopted for my studies proved useful in many ways. The methods applied in the study complemented each other. In the experimental room study, the questionnaire provided a rough quantitative guidance as well as measurable results and a good base for analysis. The interviews provided more nuanced answers and more thorough explanations. To record the interviews turned out to be very helpful; to listen to them again while focusing on different questions enabled more objective reflections, compared to notes and memory. To perform the comparisons of the models sequentially was necessary, because it is important to study the rooms from within and adapted to the illumination.

Further precision in the descriptions of surfaces in the reference room was gained through the use of magnitude estimation. The colour reference box enabled a match between the chosen samples from the reference room and the display. From what we can see, this provides us with a well-functioning method.

Overall, when combining the methods in the experimental room study they provided a good base for describing the colour appearance of the room.

Considering the knowledge gained in the experimental study, to elaborate with algorithms such as ACE was a way to find solutions to stated problems of 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. None to less to elaborate with it constituted a good basis for the understanding of the more technical aspects of the problems.

6.3. Final Conclusions and Future Work

I will here give a short account of how I see that this thesis, and the project it is based upon, has contributed to new knowledge within the research fields they concern.

Both my thesis and the SCAVE project have aimed at opening up for questions concerning the simulation of colour appearance in 3D; a research that so far merely has been focused on *images* of 3D environments. From what I have gathered during my studies, much of the research within this project is unique in the sense that no one (as far as I understand) investigates the exact same issues.

To explore the research fields which this study is based upon has provided me with an idea about what the research of today is focused on, and consequently helped me form my niche. It has also provided an understanding for the complexity of the task.

Knowledge about the research questions and related aspects to the problems they concern has been provided, which in turn has given an understanding of the stated research problem. It can be argued whether problem 2, regarding interactivity, was necessary to involve in this thesis. The problems of visual appearance and technology could be enough. However, to include the aspect of interactivity has given me a better understanding for the spatial experience within the models. I consider this knowledge an important base for the future study and development of correct reproduction of colour appearance in 3D-environments. To better relate aspects of visual appearance to usability aspects of VEs needs to be further investigated and is a possible research question for future studies.

Knowledge has also been gained about the methods applied in the studies, especially about the qualitative methods regarding the experimental study. 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.

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. A colleague has remarked that this project is 10-20 years before its time, and though it might seem like the goal is far fetched, I do believe that my aims will become of interest to research within the field of computer graphics in the future.

Since this project is cross-disciplinary it touches on different fields of research. For the future development of my work, it is therefore possible to choose between different directions. A strategy for future work which I find of interest is 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 hope to use this knowledge to create an algorithm, which will be more adjusted to the eye's perception of reality and the three dimensional vision. The focus will 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 need to be investigated through elaborations with the room models. The software Radiance also needs to be further explored.

From what I have learnt through this licentiate project a development of better algorithms is needed, preferably one that can take into accounts 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 problems I faced. 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 my 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. However, I hope that this project will form some of the initial groundwork which might be applicable as VR-technology continues to advance.

Gothenburg, Sweden
May, 2006

Summary of Appended Papers

Paper A

Virtual Reality has great potential to become a usable design tool for the planning of light and colour in buildings. The technical development has provided us with better computer graphics and faster rendering techniques. However, the reliability and usability are 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.

We present a comparison between a real room and a digital model evaluated on a desktop PC and in an IPT type system, *i.e.* a cave. Data were collected from video recorded interviews and questionnaires. The participants assessed the appearance of light, colour 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 ITP system. The comparison of real and virtual rooms revealed unsatisfying differences in shadowing and colour appearance. We defined the magnitude of perceived colour reflections in the real room, and elaborated with some of the parameters in Lightscape™/3Ds max®.

Paper B

Our research project deals with questions concerning realistic light and colour appearance in Virtual Reality (VR), with the aim of developing VR as a design tool. In a larger study a real room has been translated and compared to digital counterparts. This paper presents one part of the study which focuses on how observers interact with the models. Comparisons between three desktop-applications have been made. The applications included two VR-models; one stereographic and one monographic, and a Lightscape-model.

We give a preliminary overview of the experience of the different applications, such as the use of technical devices, possibilities to explore 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. We also found the differences between the stereographic and the monographic model to be very small.

Paper C

It is well known that the appearance of a colour can differ between a small colour chip and the same colour applied to a real room. The impression of the colour changes with these circumstances; e.g. on the chip it can be subdued, while it is perceived as striking in the room. In this paper, we compare the Swedish results of an international colour chip study, Colour Emotion, to a full-scale room study 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 corresponded 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 results from the two studies showed a distinct difference between words associated to colours of the same nuance and colour category. A clear pattern could be seen. In the room, the colours were perceived as more distinct, stronger and they arouse much stronger emotions. Generally, a colour chip had to be much more colourful to give comparable associations.

Paper D

For most areas applying computer graphics today, it is enough that the visualizations look realistic, rather than that they are psychophysically correct simulations of reality. However, if Virtual Reality (VR) shall be used as a colour design tool, light and colour must appear in the VR-environment as in reality. In this project, the aim is to simulate perceptual light and colour phenomena more correctly. This paper describes one part of the project, were we focus on the lack of contrast phenomena in the digital models. To propose a solution to these problems, digital renderings are filtered with the Automatic Color Equalization (ACE) algorithm.

The results showed that by filtering rendered textures of each multicoloured wall, the Virtual Reality model improved in colour appearance. However, it created some unwanted contrast effects. In this paper, the benefits and the disadvantages of ACE are discussed.

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Edward H. Adelson homepage	http://web.mit.edu/persci/people/adelson/index.html
IES	http://www.iesna.org
Lighting Design Glossary	http://www.schorsch.com/kbase/glossary
NCS	http://www.ncscolour.com

Computer Graphics:

HDR Shop	http://gl.ict.usc.edu/HDRShop/
OSGExp	http://osgexp.vr-c.dk
Radiance	http://radsite.lbl.gov/radiance/refer/index.html

Dictionaries and Encyclopedias:

Graphic Design Dictionary	http://www.graphicdesigndictionary.com/h.html
National Encyklopedien	http://www.ne.se