OPTIMA

Method study about colour, light and spatial experience

Final report Karin Fridell Anter, March 2011

SYN-TES Report 1E





Preface

This study is the final report on the project Pilot studies regarding optimised energy saving, spatial experience and functionality in lighting planning (OPTIMA), which was financed by the Swedish Energy Agency in the framework of the programme Energy Effectivisation in Lighting, project number P32266-1.

The project was conducted at the Perception Studio, University College of Arts, Crafts and Design (Konstfack) during the period March 2010 – February 2011. The project group consisted of researchers from Konstfack, and of experts on light and colour from Alcro and Philips. The research was conducted integrally with the project SYN-TES: Human colour and light synthesis: Towards a coherent field of knowledge, financed by The Knowledge Foundation (ref. no. 2009/0195).

We are very grateful to all co-workers who participated hands-on in the work with OPTIMA and/or contributed with their expert knowledge and report writing. We also wish to thank all our test subjects. Special thanks are due to the Philips and Alcro companies, who within the framework of SYN-TES covered the costs of the material, the design and the craftsmanship for the full-scale rooms, as well as to the company NCS Colour, who provided material for the tests in the rooms.

Stockholm March 2011

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Partners in the OPTIMA project

I SAMARBETE MED KK·stiftelsen

NCS Natural Color System®

ALCRO

PHILIPS

OPTIMA
The Perception Studio
Konstfack – University College of Arts, Crafts and Design 2010-2011

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Contents

1 Summary

OPTIMA is a pilot project foremost aiming at developing methodology for the benefit of future research. The primary goals are to

- find and test criteria and methods for describing, evaluating and planning how light and colour may work together to produce good spatial qualities with a low energy consumption
- deepen the understanding of the complex spatial interaction between light and colour, and formulate hypotheses for continued research based on this understanding.

In earlier research on colour and light in rooms, the focus has often been on one single aspect, which was varied while all other aspects of a room were kept constant.

OPTIMA differs from previous studies in the ambition to research the interaction between several different variables: the light level, the light distribution, the colour temperature and the spectral distribution of light, the colours chosen for the room's surfaces and furnishings, and the placement and contrasts between these colours. The work was done in cooperation with the seminar group in the larger research project SYN-TES, consisting of researchers and product developers, who are all experts on different aspects of the problem complex colour – light – space

Method and evaluation of method

The methodology tested in OPTIMA builds upon the experience-based practice that is used in art and design, in interaction with scientifically executed tests. The studies were performed in full scale rooms, according to a variant of the method of successive approximation, which was tested and developed as a part of the project.

Following preliminary discussions with experts from the colour and light industry, the team of researchers formulated goals for energy consumption and spatial qualities. With these goals as a foundation, professional colour and light designers developed a design solution for light and colour. Doing this, they used their own professional experience, not the norms and standards in lighting technology or other fields. The light and colour design in the room functioned as a concrete, experience-based "hypothesis" that was scientifically tested and analysed by the research team. The results of the analysis were then discussed by the researchers and designers together, which led to new understanding and a more precise "hypothesis" in the form of a revised light and colour design.

Through a consistent iteration of this process, an accumulation of knowledge, as well as a development of new knowledge, was made possible. To reformulate the goals was another part of this knowledge process, where the important result was what we discovered during our work. Our conclusion is that the method of successive approximation is highly suitable to explore the covariance between quality of light, distribution of light, the colours chosen and their placement in rooms designed in a complex way.

The following quality criteria and functional demands were used in the work with OPTIMA:

- The energy consumption should be as low as possible
- The rooms should impart a positive experience. Two different specifications were given: the first of the alternative rooms should be experienced as dynamic and stimulating, the other as calm and harmonious.
- Reading: At the table in the test room it should be possible to read a paperback book just as well as in a comparative situation lit with daylight.
- The light should make it possible to distinguish between very similar colours. The result of a simplified Farnsworth-Munsell 100 Hue Colour Vision Test (done at the table) should be as good as in a comparative situation in a light box with a good daylight simulator.

- Colours should be rendered in a natural way. Categorizing colour samples according to chromaticness and hue should give the same results as in a light box with a good daylight simulator.

Another demand was that the lighting solution should use products and knowledge on the leading edge of today's possibilities, and simultaneously be technically and economically practicable on a larger scale.

In the pilot study four different room alternatives were tested, which each were evaluated by 12-15 individuals of differing age and gender. Some of these worked with colour and/or light in a professional capacity, others did not. The aim with this distribution was to achieve a wider spread regarding comments and the subjects' ability to perform the tests. No comparisons were made between the different categories of subjects, however.

The room was observed by one person at a time, according to a predefined procedure with an observation protocol and a manual for the test leader. The subjects answered questions about the overall impression of the room and the atmosphere they experienced in the room, and conducted tests involving reading, colour discrimination and colour categorisation. In each of the alternative rooms the illuminance and the luminance were noted for about 20 spots, along with the colour temperature, the spectral distribution and the theoretical capacity of colour rendering of the light sources, and the power of the entire lighting system expressed in W.

Results and hypotheses for future research

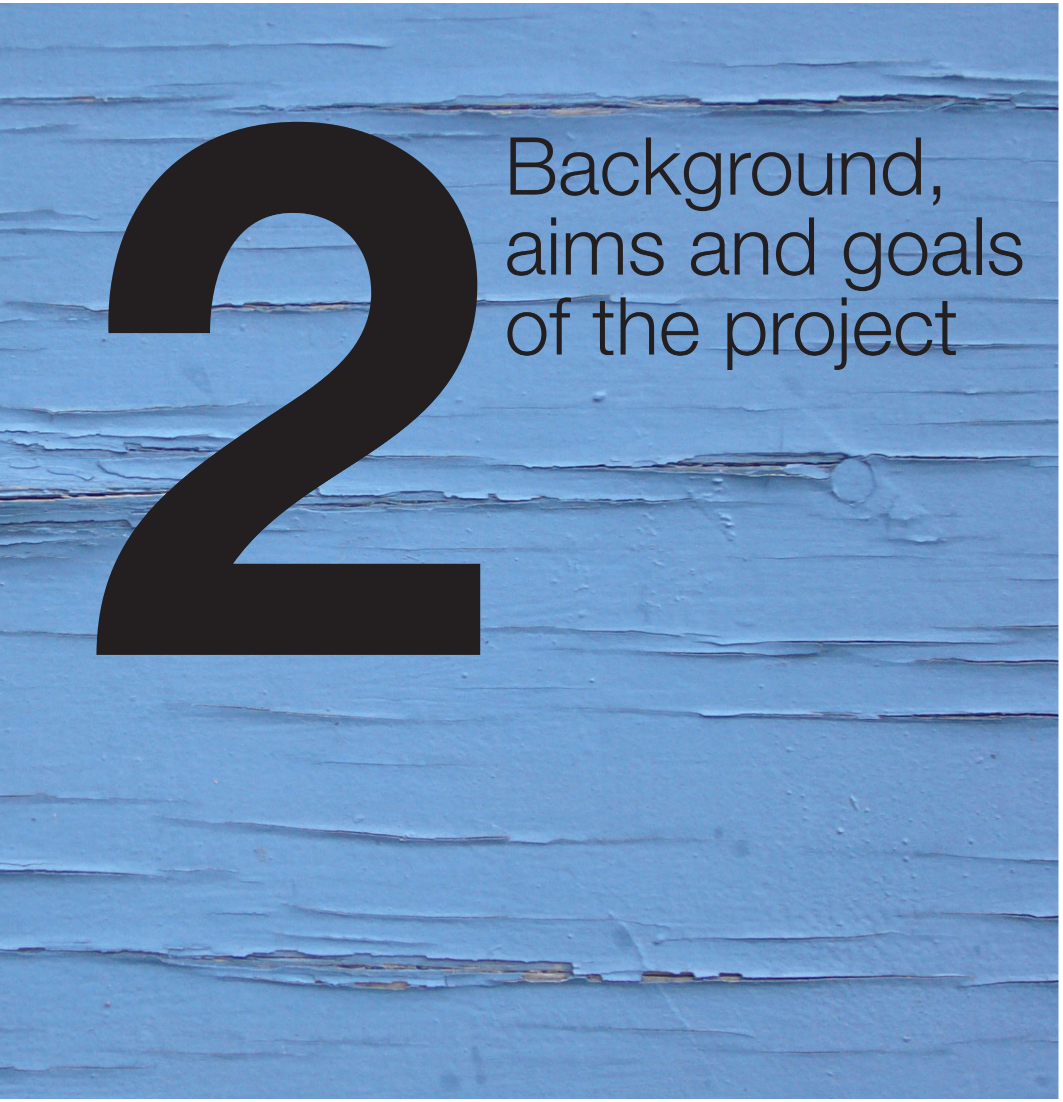
The study shows that the colour design of a room has a large importance for its perceived lightness and functionality. This not only concerns the relatively self-evident fact that lighter room surfaces result in a lighter room if the illumination is constant, but also much more complicated interdependencies between the lighting and the colour of surfaces.

On the basis of the performed tests, we posit the hypothesis that the contrast range of the colours in the room is important for the perceived brightness, meaning that a larger contrast range results in an experience of more light. Preliminarily this relates to both the contrast range in lightness, from white to black, and the contrast range between colours with different chromaticness and hue. We also posit the hypothesis that the spatial distribution of colours may interact with the real or expected distribution pattern of the light, in a way that enhances the experience of light.

Clear boundaries between different fields of colour and between surfaces with differing orientations are crucial in order to give the room a distinct form, and to counteract the merging of colours. We posit the hypothesis that such a distinctness in the room contributes to the experience of good illumination. If these hypotheses could be verified, this could lead to actively using colour design to reduce the need of illumination, while the perceived light level were kept intact.

The OPTIMA tests indicated some colour rendering effects (shift towards blue) that occured in both cool and warm LED light. This may be due to the spectral distribution of the diodes used but may also have other causes. This is a question in need of further study.

Another important experience is that the light distribution in the rooms illuminated by LED was very uneven, which impacted negatively both on how the rooms were experienced and on their functionality. This is a consequence of LED fittings being designed to be as energy efficient as possible, and thus to minimise what may be termed ”light spill”. The uneven distribution of light is, however, not a necessary corollary of the LED technology, but may be counteracted by distributing the light with, for instance, a built-in lens. This means, however, that a certain part of the energy is stopped by the lens, which results in a slightly diminished energy efficiency. To achieve a light that works well and is experienced as positive by the people that will use the lit rooms, we consider it necessary to renounce a certain part of the theoretically possible energy saving and develop fittings giving a softer distribution pattern. Such fittings could also increase the acceptance of LED illumination, and thereby contribute to an increased use of these energy efficient light sources.



2 Background, aims and goals of the project

The need for knowledge about the interaction of light and colour

The interaction of colour and light is what builds our mental, visual image of space. These experiences depend upon one another and cannot be analysed separately. The colours of the surrounding space influence the experience of light and the need for lighting, while at the same time the intensity, quality and placement of lighting is crucial for how we see and experience the colours of room. Also outdoors, and in indoor spaces lit by daylight, there is the same kind of interdependent influence between colour and light.

Today's extended demands on low energy consumption, climate considerations and a sustainable development may be met in the built environment by making colour and light interact optimally. New technical possibilities in colour and light design have a large potential for these kinds of solutions and also offer new possibilities to create experiences and emotions by using light and colour.
We are in the midst of a large-scale transition from traditional to new light sources. The new technical solutions have partly untried features regarding spatial experience, visual comfort, biological influence on humans, etc. This entails a risk that they may be used to satisfy certain specified and measurable quality requirements (for example, low energy consumption) without enough understanding of other qualities (e.g. spatial experience and biological influence on humans).

Starting points of the project

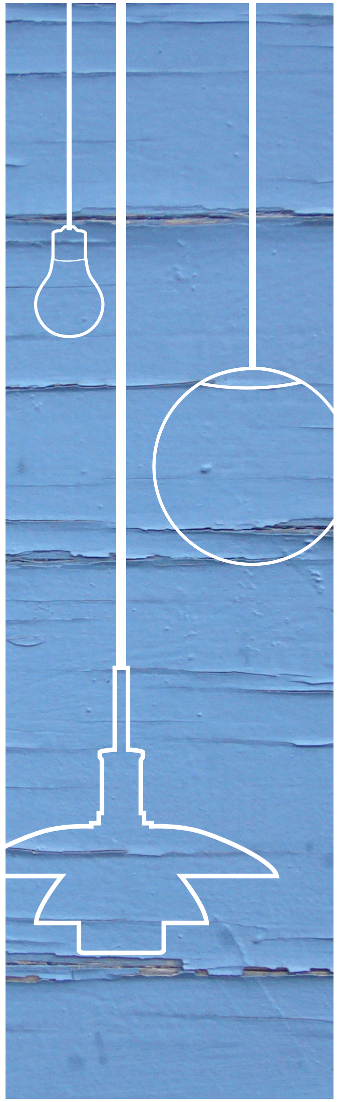
The project starts from the need to reduce the energy use for illumination purposes, as well as the transition to more energy efficient light sources. The new situation places new demands on the knowledge basis for illumination planning. Knowledge about colour, light and their spatial interaction exists in different fields of academia and in practical applications, but it is not sufficiently coordinated. The consequence of this is that already existing knowledge is not always considered, and that there is a large risk that potential energy saving possibilities are not realised. The lack of knowledge coordination may also entail that energy saving measures needlessly have negative consequences for room function and/or for the experiences of people spending time in these rooms. Thus, there is a need to investigate how different illumination solutions impact on how a room is experienced and on the functionality of rooms, with the goal of finding solutions where artificial light, daylight, as well as the design of the room and the use of colour interact optimally regarding both perceptual, functional and energy related factors.

This project is directly linked to the larger research project *SYN-TES: Human colour and light synthesis. Towards a coherent field of knowledge*. In this larger project researchers from several disciplines work together with people responsible for development and research in the industry sectors of lighting and paint, publishers of colour standards and window pane producers.

Aims and goals of the project

OPTIMA is a pilot project with the main goal of developing methods that will benefit future research. Its primary goals are to
- find and test criteria and methods for description, evaluation and planning of how light and colour may interact to produce good spatial qualities, together with a low energy consumption
- deepen the understanding of the complex spatial interaction between light and colour, and formulate hypotheses for continued research based on this understanding

A further goal is to establish some explicit examples of how different factors interact in creating good light, to document them and to present them as a part of the societal discussion and information about energy saving measures.



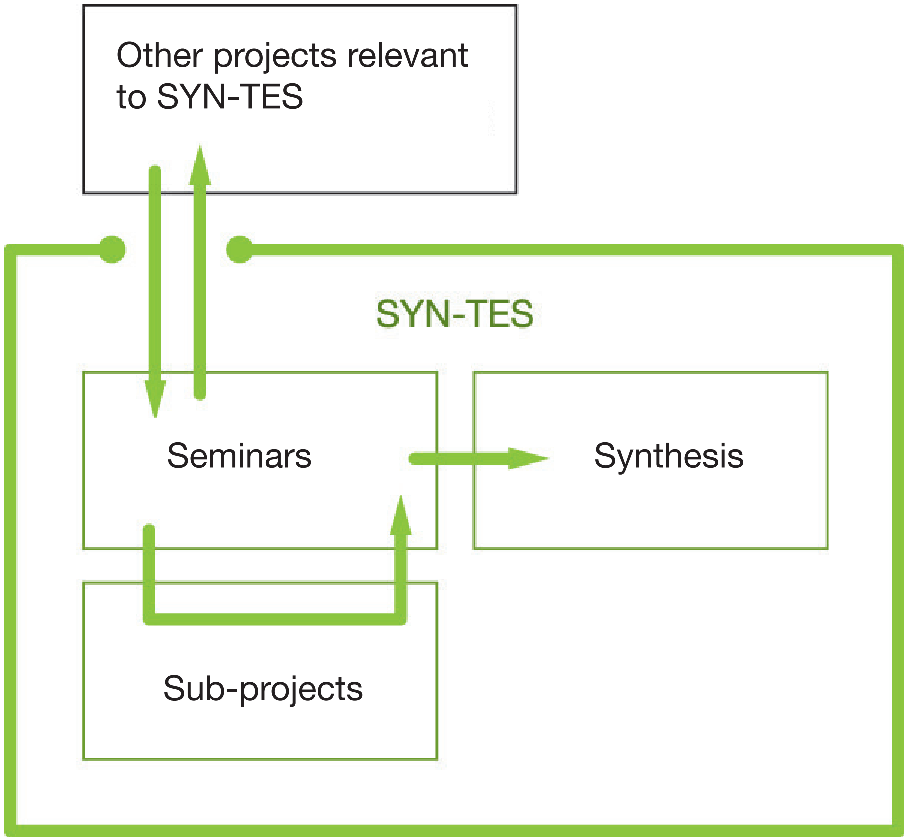
3 Previous research

A deep understanding of the spatial interaction between colour and light necessitates an interdisciplinary approach, including such as psychology, neurology and illumination technology, together with a thorough understanding of the application of colour and light in built environments. Although relevant research has been conducted for a long time in all these fields, the knowledge is fragmentised and insufficiently coordinated.[1] Internationally, the research on light is largely conducted in industrial companies. It mainly deals with technical applications, but also includes more basic research on light and its psychological and physiological importance for human beings.[2] Research on the different aspects of light is also pursued in academic institutions.[3]

The international colour research is to a large extent focused on colorimetry and colour reproduction in various media, and the relevance of this research for questions regarding spatial design is relatively small.[4] In the field of study concerned with the perception of colour, and with light and colour in spatial interaction, Swedish research has been leading internationally since several decades.[5]

1 A summary of current Swedish research can be found in Fridell Anter 2008a and 2008b.
2 One example is Vogels 2008.
3 Some examples are Matusiak 2006; Sandström et al 2002.
4 The issues are discussed in Fridell Anter & Biller 2010.
5 Summaries of research until the beginning of the 1990s are found in Hård & Svedmyr 1995a and Hård et al. 1995b. Recent research is available in the doctoral theses Billger 1999, Fridell Anter 2000 and Hårleman 2007.

Project process for SYN-TES



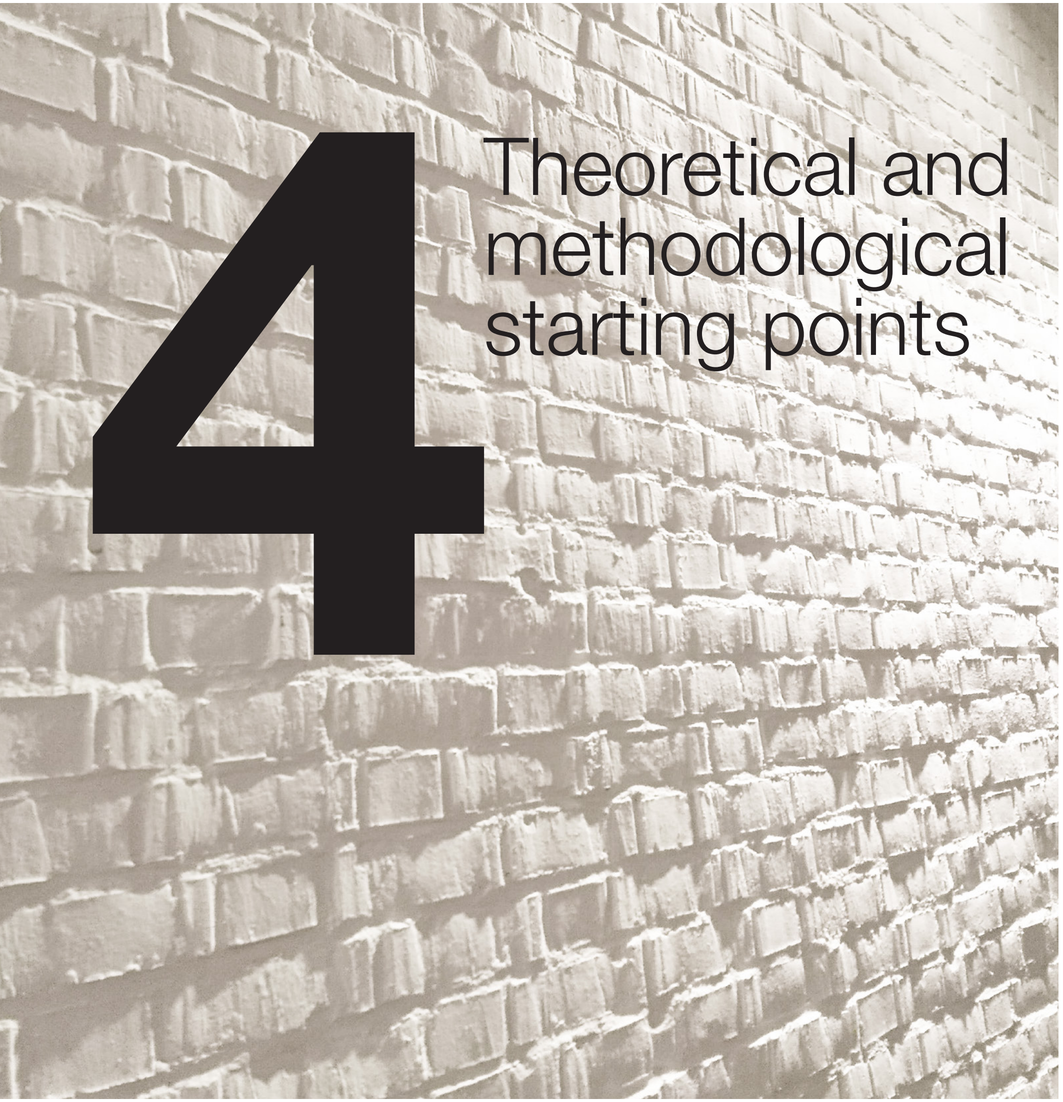
Project process for the interdisciplinary project *SYN-TES. Human colour and light. Synthesis for a coherent knowledge field.*

As research on colour and light is split between different institutions and organisations, different research traditions and cultures of knowledge have developed, meaning that researchers often have difficulties in understanding and relating to each other's methods and results, despite working with similar questions. An important aspect of this is the absence of shared and generally accepted concepts.[6]

The research project SYN-TES

During the years 2010 and 2011 the interdisciplinary project *SYN-TES: Human Colour and light synthesis: Towards a coherent field of knowledge*, was conducted at Konstfack – University College of Arts, Crafts and Design. In this project about fifteen colour and light specialists from different companies and academic institutions participated. All participants were also active in other research and/or in development work regarding light and/or colour issues. In the SYN-TES work, the group met regularly in seminars, with the aim of bringing the different knowledge traditions nearer to each other, and to formulate together the basis for a coherent field of knowledge, comprising both colour and light. In combination with this, several subprojects, focussing on more limited questions, were conducted. OPTIMA is one of these subprojects.

6 The conceptual problems are discussed regarding colour in Green-Armytage 2006 and regarding light in Liljefors 2006.



4 Theoretical and methodological starting points

The methodology tested in OPTIMA builds upon the experience-based practice used in art and design, in interaction with scientifically conducted tests. Piet Hein – the Danish mathematician, philosopher, designer, poet and more – holds that art, in its meaning of creativity, is to solve problems that cannot be clearly formulated before they are solved.[7] He also says that, doing creative work, one cannot clearly distinguish the problem from the solution. To formulate a problem is to solve it.[8]

Based on this, Hein formulates a scientific method, which differs from what the science philosopher Thomas Kuhn calls "normal science".[9] Traditional research method may be described as problem formulation/hypothesis –survey/experiment - conclusion/evidence. No formal opposition can be made against this, but, according to Piet Hein, this does not promote creativity or new thought.

Really new approaches appear when someone, sketchily and intuitively "starts with the conclusion", formulates "the answer" first, and then questions the formulation, revises and reformulates, again and again; making the formulation more and more correct . Hein calls such a method "successive approximation" – we gradually approach an acceptable result – and names it the production process of science itself. He also describes the process in a grook, Hein's own characteristic form of expression.

The road to wisdom

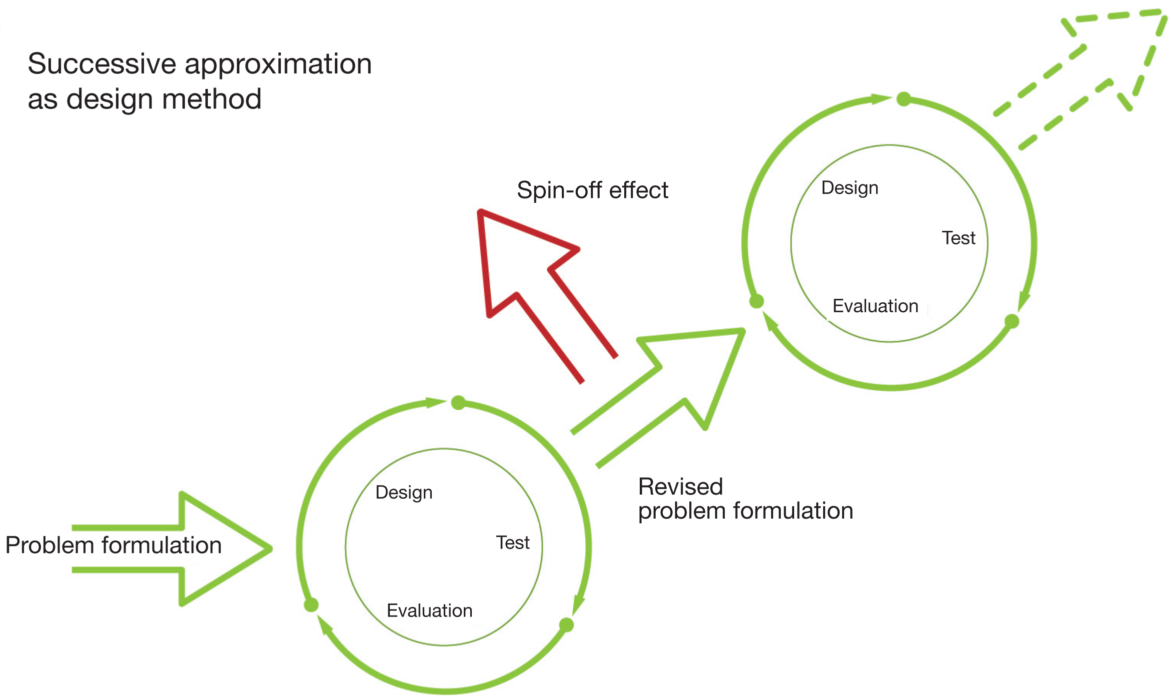
The road to wisdom?
Well it´s plain
and simple to express:

Err
and err
and err again
but less
and less
and less.

Piet Hein (1905-1996)

Successive approximation is an important element in the artistic process, just as important as when we continuously formulate – and reformulate – our world view in our normal lives. Piet Hein also shows how advanced and innovative researchers in the natural sciences have used this method.

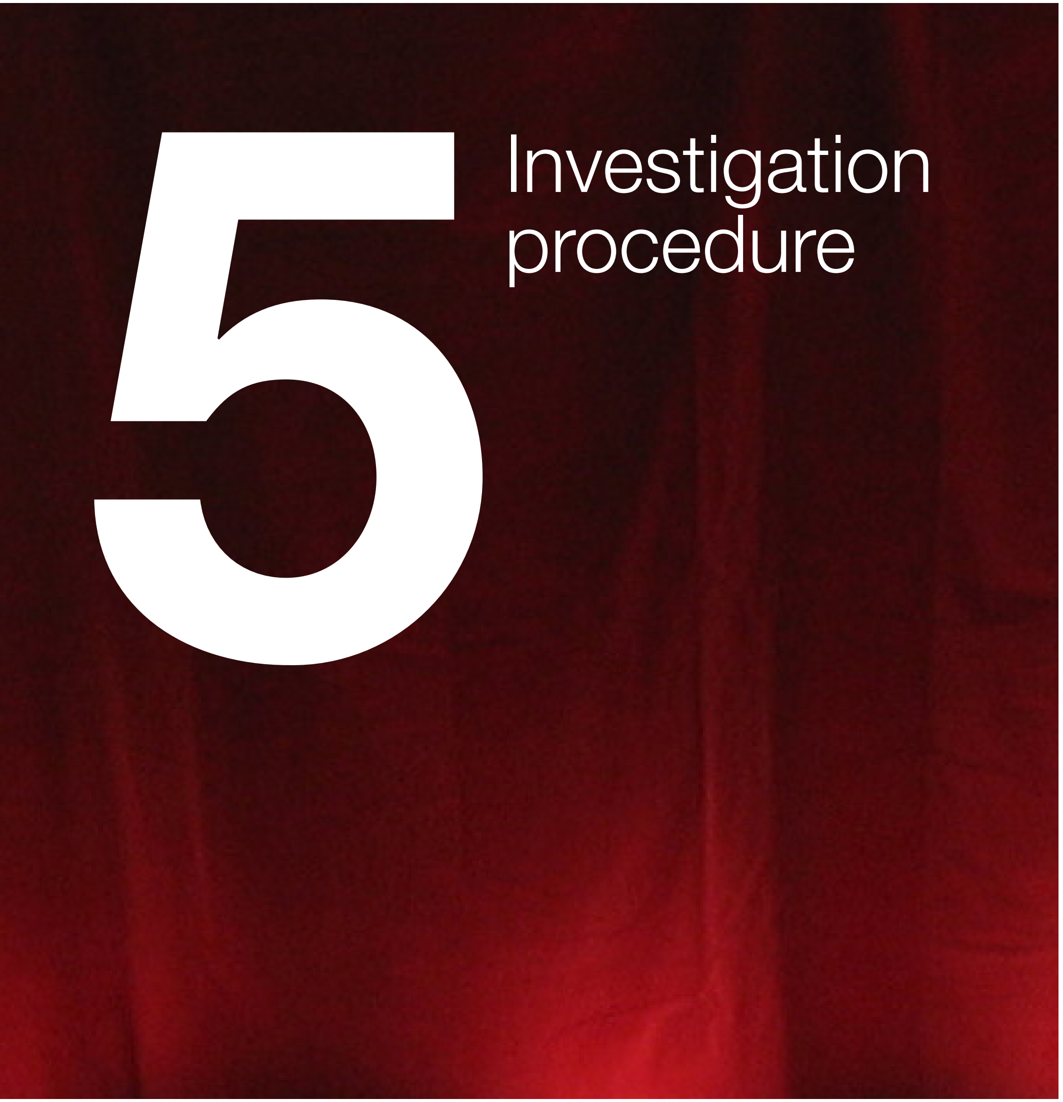
The philosopher of science Karl Popper (1902-1994) understands the formulation of new hypotheses as a creative pursuit, which has no need to follow any logical rules and the direct results of which are intuitive, comprehensive formulations based on experience. The testing of the hypotheses, on the contrary, is performed according to rational, logical criteria.[10] Without a "wild" initial stage of the scientific work, science cannot develop, and turns inward into its own already accepted theories, whence it risks positioning itself defensively versus new and different ways of thinking. Without the wild hypotheses, science is thus preserving itself against paradigm shifts.



Intuitive formulations may of course be put forward on different levels. Their quality or degree of complexity depends upon the totality of the individual researcher's experience and knowledge. The researcher may allow him-/herself to make a holistic formulation without knowing for sure, and immediately thereafter start the revision, in the same way as when an artist makes a sketch that is subsequently reworked repeated times, until he/she perceives that it is right – at least for the time being.

The tests within OPTIMA have been performed in full scale rooms according to a variant of the method of successive approximation, which has been tested and developed as a part of the project. The research team formulated goals for energy consumption and for the quality of colour and light after preparatory discussions with experts in the colour and light industry. Based on these goals, professional colour and light designers created a solution for the colour and light design. The colour and light design of the room became a concrete, experience based "hypothesis" that was scientifically tested and analysed by the research team. The results of the analysis were discussed by researches and designers together, which lead to a new understanding and a more precise "hypothesis" in the form of a revised light and colour design. Continuous repetition of this procedure resulted in accumulation of knowledge and development of new knowledge. Also to reformulate the goals was part of this knowledge process, where the important results are the discoveries made during the ongoing work.

7 The text in the report's section 4 is partly taken from Klarén 1997.
8 Hein 1985
9 Mårtensson 1980
10 Ibid



5 Investigation procedure

Quality criteria and research methods, formulated by an interdisciplinary seminar group

OPTIMA differs from previous research on colour and light in rooms through the ambition to study the interaction between several different variables: light level, light distribution, the colour temperature and spectral distribution of light, the colours chosen for the room's surfaces and furnishings, as well as the placing and contrasts between these colours. The possibilities and the difficulties of a multi-dimensional approach were discussed by the seminar group of the SYN-TES project, consisting of researches and product developers, all with their own expertise in different areas of the field colour - light - spatial perception. See page 4 for a presentation of the seminar group.
Starting from their own research and experience, and with a knowledge of the international frontier of research, the seminar group discussed how requirements of a "good light environment" may be formulated, without postulating technical specifications or measurement values needed to reach this quality. The discussions resulted in several quality criteria and functional requirements to be used as a basis for tests in full scale rooms. What is "good light environment" of course varies with the situation and the function of the room, and the criteria we chose were not meant to express any general requirements. The purpose instead was to test the degree to which one can reach desirable qualities without starting from technical specifications, and to discover potential interaction effects and/or conflicts between different qualities.

The following quality criteria and functional requirements were used in the OPTIMA work:
- Energy consumption should be as low as possible
- The room should impart a positive experience. Two different specifications were given: The first room version should be experienced as dynamic and stimulating, the second as calm and harmonious.
- Reading: At the table in the test room it should be possible to read a paperback just as well as in a comparative situation in daylight.
- The light should make it possible to differentiate between very similar colours. The result of a simplified Farnsworth-Munsell 100 Hue Colour Vision Test (done at the table) should be as good as in a comparative situation in a light box with a good daylight simulator.

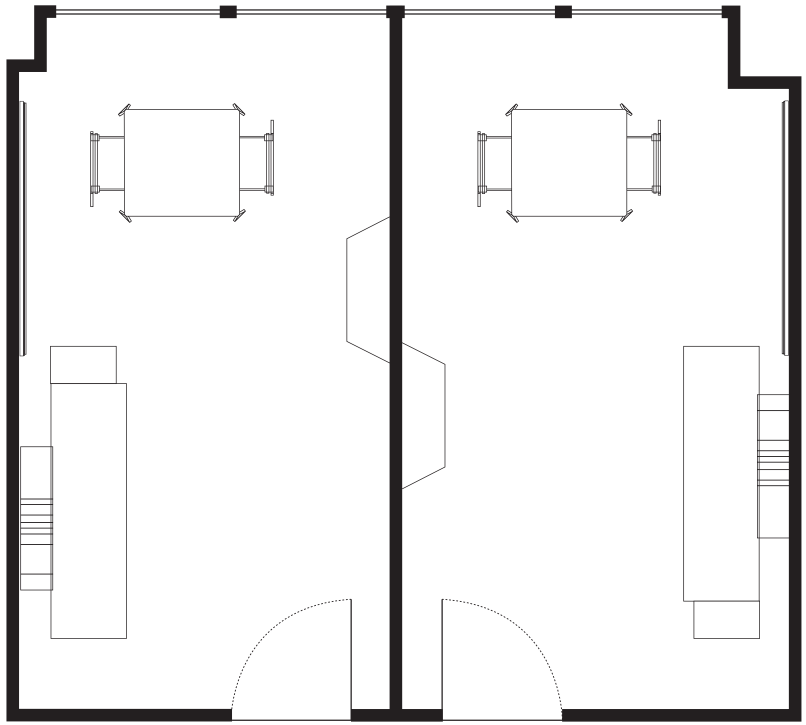
- Colours should be rendered in a natural way. Categorisation of colour samples according to chromaticness and hue should give the same results as in a light box with a good daylight simulator.

Further, it was required that the light solution should make use of products and knowledge on the cutting edge of today's possibilities, but also be technically and economically possible to implement in a larger scale.
The seminar group also developed methods to study to what degree implemented colour and light solutions satisfied the different requirements. This included:
- questions put to test subjects regarding room experience, visual comfort, etc.
- tests, where the subjects performed different colour evaluations tasks
- measuring lux values and the luminance values calculated from these
- spectrophotometrical measurement of the spectral distribution of direct light from the light sources and of reflected light from different room surfaces.
- calculations of energy consumption were made from the producer's specified performance of light sources and fittings, including losses due to driver devices.

A thorough report on the investigation methods and their results can be found in Section 7 of this report.

Full scale test rooms

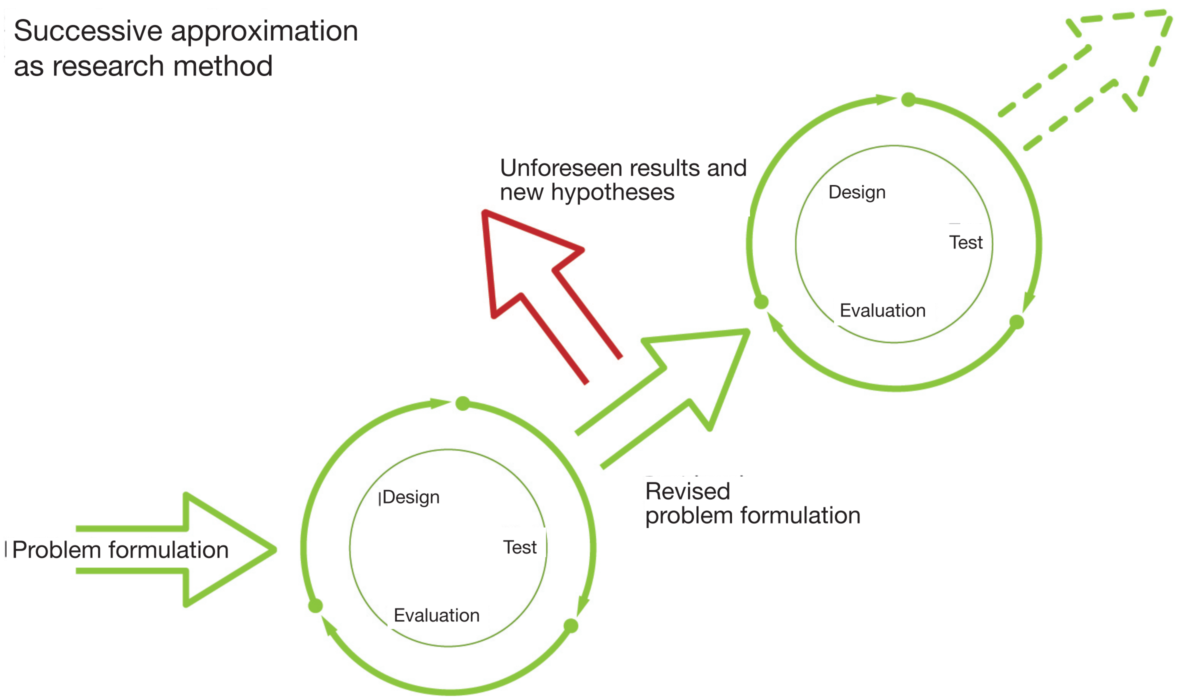
For the purposes of this study two test rooms were furnished. One was the test room proper, while the other was used as a reference in certain parts of the study.
The test room measured approximatively 18 square meters, with a ceiling height of 2.60. It had a window opening onto (simulated) night darkness and was furnished with specially built furniture, making it possible to sit on chairs at a table (height like a dining table) and to sit/lounge on a sofa. The furnishings were designed to create a spatiality that did not tell anything about time and style periods, and that did not signal any specific function for the entirety of the room.
The reference room had the same area and furnishings as the test room, but a much higher ceiling. It had large windows and fluorescent lamps placed high up.



Plan drawing on daylight rooms/reference rooms and test rooms

Successive approximation – description and evaluation of the method

The investigations were conducted in full scale rooms according to a variant of the method *successive approximation*, which was tested and developed as a part of the project. The method is a way to create interaction between theoretical understanding and experience-based knowledge, and to create new understanding and knowledge by critical evaluation and successive change of preliminary solutions to specific problems.



Concretely, the work was performed in the following manner:

- Formulation of requirements: The quality criteria and functional requirements formulated above did not specify the means to be used in reaching the goals.
- Room design: Experienced designers in the fields of colour and light (Yvonne Karlsson, Svante Peterson and Ida Järlsjö), based on their experience, together performed the task of creating the colour and light design of the test room to meet the requirements. They chose to do this as they preferred, and they painted, mounted the light fittings, etc. according to their intentions.
- Test: The research group investigated, with the help of test subjects, the degree to which the room met the stated requirements (method in this respect, see below).
- Evaluation: The researchers and the designers responsible for the colour and light design met in the room and went through the test results. We noted in which ways the room had been successful or unsuccessful in meeting the stated requirements, discussed possible causes for the test results obtained, and together created concrete suggestions for changes in the room's colour and/or light design, to better meet the stated requirements.
- Modification of room design: The light and colour design of the room was changed according to the decisions of the evaluation meeting.
- Test: A new round of tests were performed with new subjects.
- Evaluation: During a new evaluation meeting, new conclusions were drawn.

The entire process was performed two times during the period from August 2010 to January 2011. The first time, the room was meant to be experienced as dynamic and stimulating, and the second time as calm and harmonious. The other requirements were the same at both times. After the first evaluation meeting the test protocol/procedure was revised and was after this kept constant.
The notes from the evaluation meetings led to conclusions that would not have been possible to draw without the project group's collective expertise. This pertains both to concrete observations on the interaction of colour and light in the room, and the interpretation of the test results, seen against the background of specific knowledge.

In previous research concerning colour and light in rooms, focus often was on one aspect, which was varied while all other features of the room were kept constant.[11]
The work with OPTIMA shows that the method of successive approximation is very suitable for investigating the covariance between light quality, light distribution, colours chosen and their placing in rooms of complex design.

Through the successive approximation, we were gradually able to define those aspects in the total design of the rooms that were important to the subjects' evaluations and test results. In a longer test series, were time permits several rounds of evaluation and modification based on an unchanged specification of requirements, this method may lead to more specific conclusions than were possible in this pilot study. With some modification, the method may also be used in the way that at first only a few factors are varied and the totality is thoroughly evaluated by experts. In a room that is optimised in this way, a larger group of subjects may then be used to investigate its qualities with more traditional methods.

Farnsworth-Munsell colour discrimination test

11 Billger 1999; Hårleman 2007;Vogel 2008; Matusiak 2006

6 The different test rooms

The test rooms

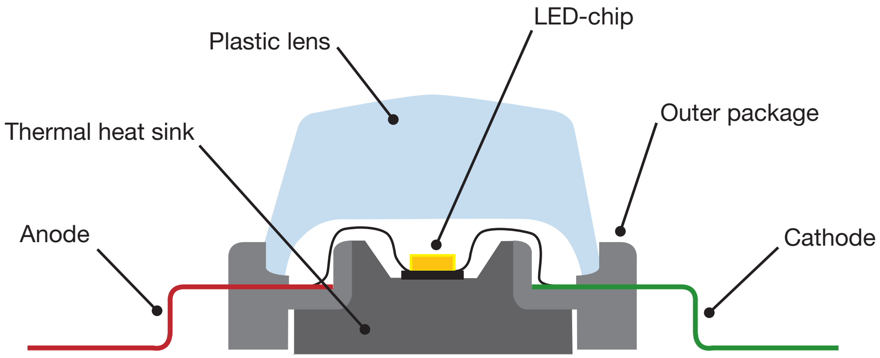
Most of the tests were conducted in one and the same room, which was modified several times and thus is treated as four different rooms. The first room version was designed to be experienced as dynamic and stimulating. It had grey and white walls and strongly coloured details, mainly in red and yellow. Initially the room was tested with four different light designs, which each were evaluated by only a few subjects (room 1:1). After evaluation of these tests, the room was changed, for example by removing the red curtain. A cool LED illumination was mounted in the room, in the form of a ”string” following the walls and a few spotlights (room 1:2).

Test room variant 1: 1

The next version of the test room was designed to be experienced as calm and harmonious. The walls were warm grey and white, and the furnishing details had muted colours in a brown-green colour scale. The illumination consisted of spotlights with warm LED:s (room 2:1). After evaluation of the tests in this room, the colour design was changed to become somewhat richer in contrasts, and some more warm LED light sources were added to the illumination (room 2:2).

The four room versions are presented in more detail on the following pages.

Schematic diagram of a LED (Light Emitting Diod)



The technology used to produce LED lights differs significantly from the traditional techniques for producing incandescent and discharge light.
LED light is produced by directing DC through a semiconductor in an LED chip which is then stimulated to emit light. The light produced is monochrome and has different colour depending on the type of semiconductor. White LED light is often based on a blue LED covered by a phosphor compound that converts part of the light radiation from the diode to more wavelengths.

Reference room with daylight and light box

In some parts of the tests the neighbouring room, lit with daylight, was used as a reference. Its furnishing and colour design were similar to the test room version 1:1, but without a curtain and with a much higher ceiling. The daylight entered through four large windows and varied significantly between the different test situations. In a few instances the daylight was too weak to perform the tasks, and in these cases the room was also lit with fluorescent lamps.[12]. In the daylight room, there was a light box[13] with a good daylight simulator, which was used as a reference in some of the tests. The lux value in the middle of the light box was 2560.

Daylight room / reference room

12 Spectral curve for fluorescent lamps in the daylight room is shown in Appendix 3.
13 Ortospectra. Inside gray 2000-N. Dimensions 50x50x70 cm.

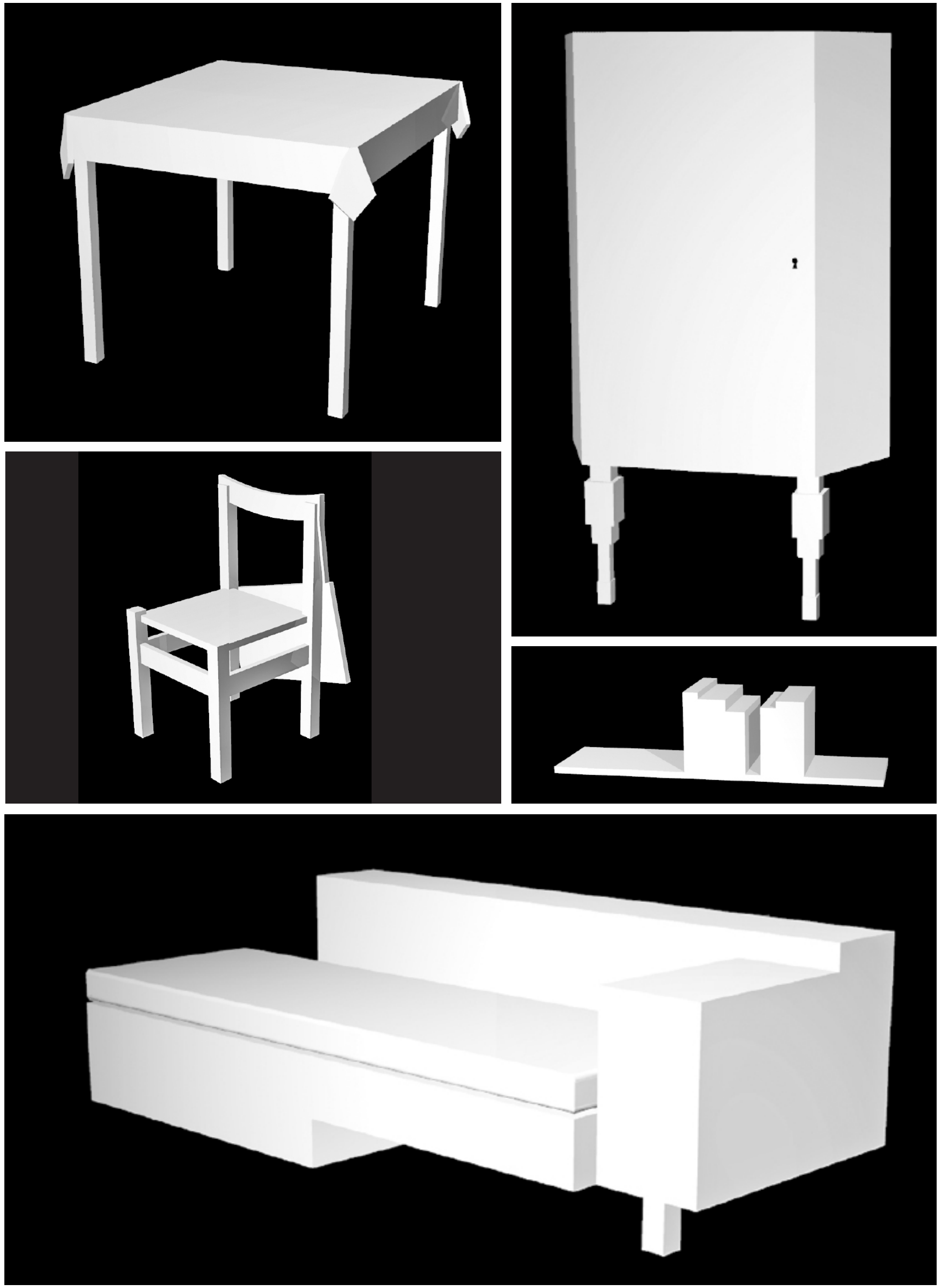
Sketch of reference room/daylight room

The test room and the daylight room initially had the same furnishings, which were designed and produced by two Master's degree students at Konstfack, based on discussions with the project group. Their work comprised neither light nor colour design.

Concept

By seeing "the room" as a monochrome body and not separating surfaces touching each other, we stylised the objects to be a "tableness", a "chairness" etc. This aimed at creating a "roomness" that does not tell anything about time periods or highlights "design". (Marcel Granfeld Saavedra & Peter Svensson)

Illustration of the daylight room. Marcel Granfelt Saavedra & Peter Svensson, Master's students at Konstfack 2010



Lighting plans

The lighting of the test room was planned to create, together with the colours, a positive atmosphere that should be either dynamic and stimulating (blue markings on the plans) or calm and harmonious (red markings). Simultaneously, the ambition was to use as little energy as possible to achieve a functional environment.

All the lighting was mounted at the same time, which made it possible to test different combinations. As a reference a light bulb of 60 W was also mounted (yellow marking). The test results and the discussions after each test round led to the lighting being changed, as fittings were added, changed or reoriented. This process may be followed in the successively changed drawing. On the following pages, the light sources used for each room version are noted.

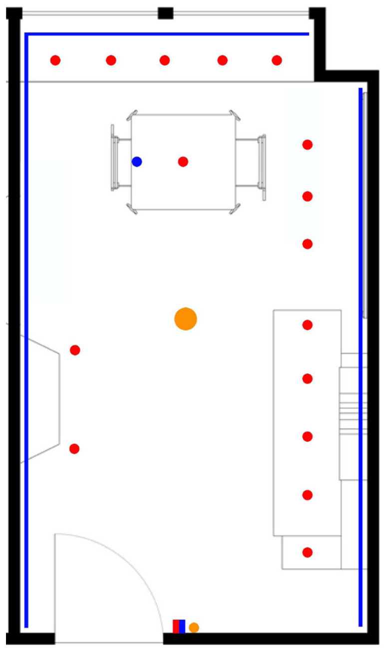


Figure 1

Lighing plan (Svante Pettersson - Philips AB, Lighting)

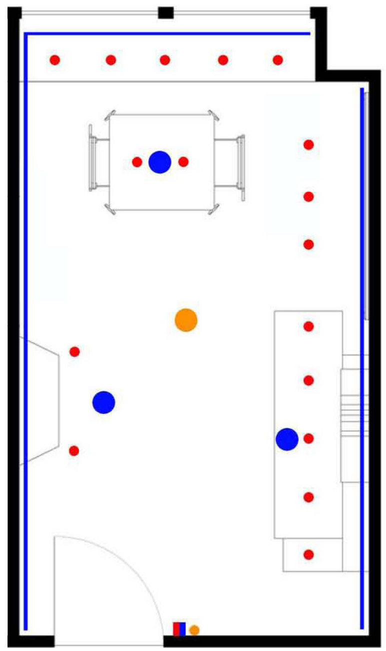


Figure 2

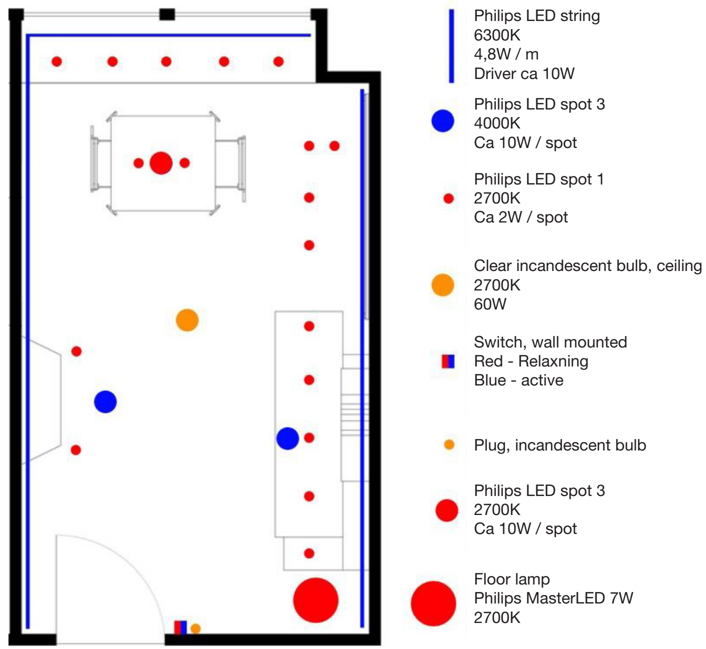


Figure 3

Room 1:1 ”Dynamic and stimulating”

The walls were grey, except for the wall with the window, which was white. The table and the chairs were white, other furniture was painted in strong red, green and yellow. The window was blocked with black plastic, simulating night-time, and the ”view” was hidden by greyish white blinds. In the room, there were decoration details and textiles in red, orange, yellow and grey.

The room was tested with different types of LED :s, combined in three different ways, and with incandescent light. Each illumination was used for only three or four subjects, and the tests should be seen as a way to adjust the methodology and make a first assessment of the rooms' light and colour design. They formed the base for clarifying discussions in the project group and led to changes, both in the room's design and in the test procedure. The result of these discussions is presented in the next paragraph, as well as under the heading ”A light or a dark room” in Section 8 of this report.

Figure 4: Colour scheme of the room in alternative 1: 1 ”dynamic and stimulating” (Yvonne Karlsson)

The numbers below represent NCS-codes and gloss values, respectively.

Longitudinal walls and back wall:	Grey (2000-N), photometric light reflectance appr. 59%. Matte (5)
Wall with window:	White (0500-N), photometric light reflectance appr. 95%. Matte (5)
Floor:	Light linoleum in mixed shades of beige (appr. 2010-Y20R), with a strong red carpet (appr. 1085-Y95R) in the middle.
Ceiling:	White. Fully matte (2)
Chairs and table:	White (0500-N). Matte (10)
Cupboard:	Yellow (0560-Y). Glossy (80)
Sofa:	Grey (3500-N) Matte (10)
Shelf:	Green (3050-G70Y). Matte (10)
Board:	Red (1580-R). Matte (10)
Frame of board:	Grey (2000-N). Matte (5)

The room was tested from August 8th to September 16th 2010 in four different light situations, see lighting plans p. 21. The light sources were:

A) The one initially planned to make the room ”dynamic and stimulating”. (The blue alternative in Figure 1).

B) The above in combination with the one initially planned to make the room ”calm and harmonious” . (The blue and red alternatives in Figure 1).

C) A clear light bulb of 60 W, in the middle of the ceiling. (The yellow alternative in Figure 1)

D) An reinforced version of the light design planned to make the room ”dynamic and stimulating” . (The blue alternative in Figure 2).

Except for situation C (3,3 W/square meter) the lighting energy consumption has not been calculated for these situations.

Also, lux values or spectral distributions have not been measured

Alternative 1: 1 ”Dynamic and stimulating”

Room 1:2 ”Dynamic and stimulating”

After an evaluation meeting on September 21:th the following changes of colour design and furnishings were implemented, relative alternative 1:1

- The blinds were pulled up to make the window black, and the subjects were explicitly informed to think of the situation as being night-time.
- The curtain was removed and replaced by two small monochrome “paintings” with black frames.
- Black details were added to augment the contrast range.
- The boundaries between white and grey wall parts were moved in order to make the contrasts between them more apparent.
- Some of the light sources were redirected.

Figure 5: Colour scheme of the room in alternative 1: 2 ”dynamic and stimulating” after half-time conversion (Yvonne Karlsson)

The numbers below represent NCS-codes and gloss values, respectively.

Longitudinal walls and back wall:	Grey (2000-N), photometric light reflectance appr. 59%. Matte (5)
Wall with window:	White (0500-N), photometric light reflectance appr. 95%. Matte (5)
Floor:	Light linoleum in mixed shades of beige (appr. 2010-Y20R), with a strong red carpet (appr. 1085-Y95R) in the middle.
Ceiling:	White. Fully matte (2)
Chairs and table:	White (0500-N). Matte (10)
Cupboard:	Yellow (0560-Y). Glossy (80)
Sofa:	Grey (3500-N) Matte (10)
Shelf:	Green (3050-G70Y). Matte (10)
Board:	Red (1580-R). Matte (10)
Frame of board:	Grey (2000-N) + black (9000-N). Semi glossy (35)

The room was tested from September 28:th to October 6:th 2010. The light sources were:

- A LED string invisibly mounted along three walls, in the angle between wall and ceiling, with raking light oriented downwards along the wall, colour temperature 6300.
- Three LED spotlights on the ceiling above the table, the sofa and the floor in front of the cupboard, respectively, colour temperature 4000 K (See illumination plan, the blue alternative in Figure 2 p. 21)

The distribution and colour of light varied between different parts of the room. There was much more light high up on the walls than further down, and there were some strong spotlightings on furniture and floor. The strong colours of the cupboard and carpet made visible reflections onto the grey of the walls.

The energy consumption in this room was approximatively 5 W/m2.

The illuminance and the luminance in different locations are reported on p. 65

Alternative 1: 2 ”Dynamic and stimulating”

Room 2:1 ”Calm and harmonious”

The longitudinal walls were a warm grey and the transverse walls were white. The table and chairs were white, other furniture was painted in beige, brown and greyish green.
The window was blocked with black plastic, meant to suggest night-time.
In the room there were decoration details and textiles in brown, beige, black and white.

The numbers below represent NCS-codes and gloss values, respectively.

Longitudinal walls:	Grey (2005-Y20R, photometric light reflectance appr. 59%. Matte (5)
Transverse walls:	White (0500-N), photometric light reflectance appr. 95%. Matte (5)
Floor:	Light linoleum in mixed shades of beige (appr. 2010-Y20R), with a darker beige carpet (appr. 3010-Y20R) in the middle.
Ceiling:	White. Fully matte (2)
Chairs and table:	White (0500-N). Matte (10)
Cupboard:	Greyish green (3010-G60Y). Glossy (80)
Sofa:	Brown (7020-Y50R). Matte (10)
Shelves:	Beige (4010-Y10R). Matte (10)
Board:	White (0502-Y) Matte (5)
Frame of board:	Beige (4010-Y10R). Semi glossy (35)

The room was tested from October 25:th to November 3:rd 2010. The light sources were:

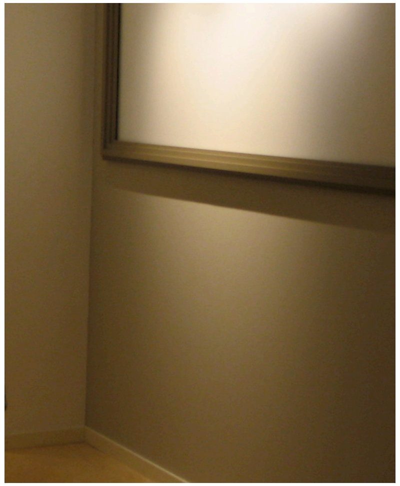
- 17 LED spotlights in the ceiling above the table and the sofa, above the floor in front of the cupboard and the board, and above the window sill. Colour temperature 2700 K. (See illumination plan, the red alternative in Figure 2 p. 21)

The light distribution varied strongly between different parts of the room, with high light levels in small areas lit by spotlights, and much darker zones between these.

The energy consumption in this room was approximatively 2 W/m2.

The illuminance and the luminance in different locations are reported on p. 65

Figure 6: Colour scheme of the room in alternative 2:1 ”calm and harmonious” (Yvonne Karlsson)



Alternative 2: 1 "Calm and harmonious"

Room 2:2 ”Calm and harmonious”

After an evaluation meeting on November 9:th 2010 the following changes of colour design and furnishings were implemented, relative alternative 2:1.

- The cupboard was repainted in a darker and stronger green nuance to increase the contrast range
- Additional ceramic vases in beige, white and dark turquoise were placed on the windowsill and the shelf as ”targets” for the existing spotlights.
- Additional brown and beige patterned textiles were placed in the sofa.
- One more light source was added, a large spotlight that increased and evened out the lighting over the table, as well as with light sources in two of the corners to make the boundary between different wall colours more distinct.
- Some of the light sources were redirected.

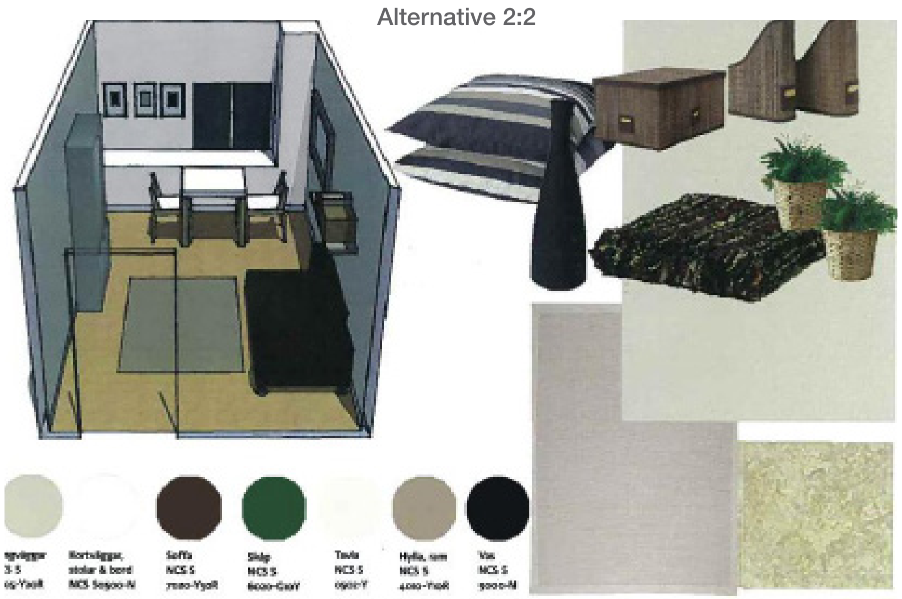


Figure 7: Colour scheme the roon in alternative 2: 2 ”calm and harmonious” after half-time conversion. (Yvonne Karlsson)

The numbers below represent NCS-codes and gloss values, respectively.

Longitudinal walls:	Grey (2005-Y20R, photometric light reflectance appr. 59%. Matte (5)
Transverse walls:	White (0500-N), photometric light reflectance appr. 95%. Matte (5)
Floor:	Light linoleum in mixed shades of beige (appr. 2020-Y20R), with a darker beige carpet (appr. 3010-Y20R) in the middle
Ceiling:	White. Fully matte (2)
Chairs and table:	White (0500-N). Matte (10)
Cupboard:	Green (6020-G10Y). Glossy (80)
Sofa:	Brown (7020-Y50R). Matte (10)
Shelf:	Beige (4010-Y10R). Matte (10)
Board:	White (0502-Y) Matte (5)
Frame of board:	Beige (4010-Y10R). Semi glossy (35))

The room was tested from November 11:th 2010 to January 17:th 2011.
The light sources were:

- 17 small LED spotlights in the ceiling above the table and the sofa, above the floor in front of the cupboard and the board, and above the windowsill.
- Colour temperature 2700 K, Ra-index 80
- A small spotlight of the same type and with the same temperature (2700 K, CRI 80) as the others was directed at the inner right corner. It was placed in alignment with the farthest of the three spotlights illuminating the picture, and between this and the painting/ wall (added after adjustment from 2:1)
- A larger LED spotlight over the table (2700 K, CRI 80) (added after adjustment from 2:1)
- A floor lamp with LED:s (2700 K, CRI 80) was placed in the right corner near the door (added after adjustment from 2:1). (See lighting plan, the red alternative, Figure 3 p. 21)

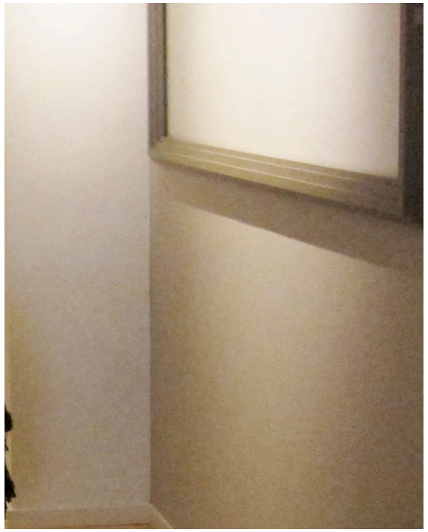
The light distribution varied strongly between different parts of the room. Near the window and in some light cones directed at furniture, objects and at the floor, the light was much stronger than further into the room and between the light cones.

The energy consumption in this room was approximatively 3 W/m2.

The illuminance and the luminance in different locations are reported on p. 65.







Alternative 2: 2 ”Calm and harmonious”

7 Test specification

The composition of the test groups

In each of the four rounds, the room was observed by 12-15 individuals of different age and gender (see Table 1). Some of these worked with colour and/or light in a professional capacity, others did not. The aim with this distribution was to achieve a wider spread of comments and in the test subjects' ability to perform the tests. No comparisons were made between the different categories of test subjects, however.

Prior to each test the subject was questioned about any known defect in colour vision, and one subject stated that she was "somewhat colour blind". The colour vision was also tested indirectly through the Farnsworth-Munsell 100 Hue Colour Vision Test being part of the test, and the answers from the two subjects with a low capability of distinguishing colours were not considered in the colour rendering part of the test.[14] Also, the subjects were asked about other visual disorders. There were no serious disorders, but many used glasses, which were used in the normal way at the tests.[15] None of the glasses were tinted. Six of the subjects mentioned dyslexia, which was considered in the reading part of the test.

Structure of the tests and questions

The room was observed by one person at a time, according to a predefined procedure with an observation protocol and a manual for the test leader. Each observation was planned to last about an hour, including 10 minutes of initial adaptation time and reference observations in the neighbouring daylit room. The procedure and the questions used in the first test round (room 1:1) were evaluated at the first evaluation meeting, and thereafter revised. In the following three test rounds one and the same procedure was used. Below follows a summarising presentation and a method discussion. The final questions, as well as an evaluation of the questions in the first test round can be found on pp. 35-37. There, the colour samples used in the tests are also listed.

14 The Farnsworth-Munsell 100 Hue Test Guide (page 4) indicates that 16% of the population receive more than 100 error points the first time they perform tests with 85 colour samples under standard light conditions, and classify this as low discrimination ability, though not necessarily coincident with defect colour vision. In our tests, we used 20 of these 85 colour samples, and a recalculation then indicates that low colour discrimination ability would be characterized by 24 error points or more. Two subjects, one of whom indicated colour blindness and received 24 error points in the light box, were not included in the analysis of colour rendering.
15 Two of the subjects had forgotten to bring their special reading glasses. This was taken into account in the part of the test that was about reading. One had a cataract on his left eye, but in his tests his answers shows no specific deviation from the others.

The subjects were given questions regarding the look of the room. In the revised questionnaire the answers were given by choosing a maximum of four out of twelve presented words, where the subjects' choice of words gave information about what qualities of colour and light were observed and how these were evaluated. Open questions about how the room looked were also posed. These methods turned out to be suitable for capturing what the person found important and did not direct the attention onto such things that were not spontaneously experienced.

The subjects also answered questions about how they experienced the mood in the room. For this, they again chose a maximum of four out of twelve given words, and they also answered other questions regarding the mood of the room. The different ways of asking about the mood gave unanimous answers between them, which supports the reliability of the answers.

The room's functionality for reading was tested by letting the subjects read a few pages in a paperback in two different lighting situations and answering questions about this. It turned out that all subjects, except one or two individuals, could read the book in both lighting situations. Thus, the value of this test is primarily found in the comments of the subjects, as they compared the different situations.

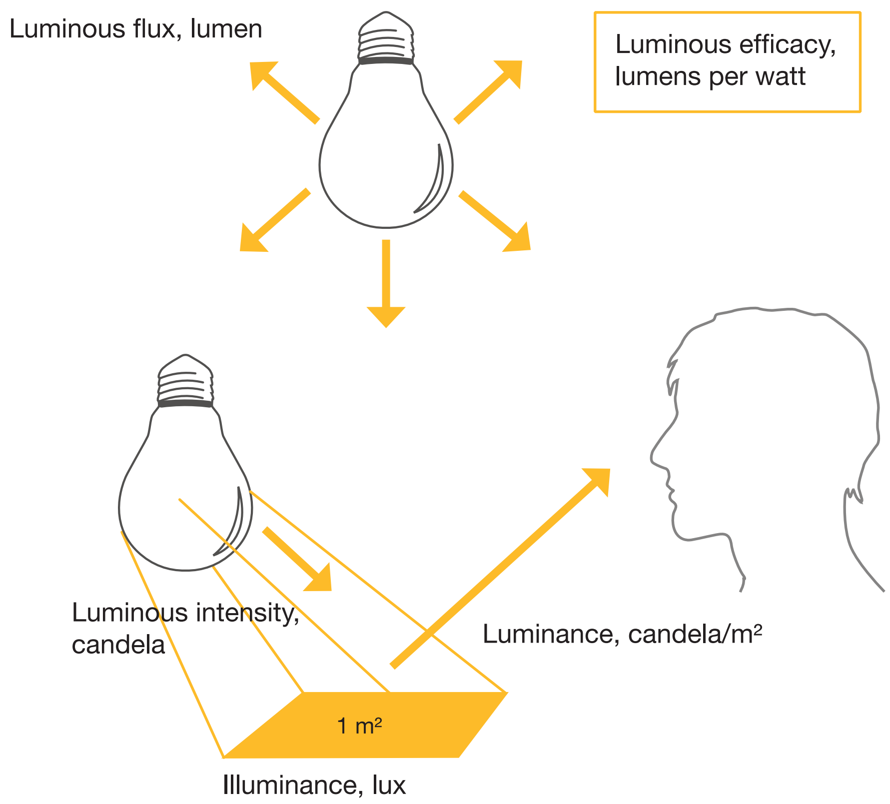
The possibility to discriminate between very similar colours was tested with a selection of samples from the Farnsworth-Munsell 100 Hue Colour Vision Test. The complete test contains 85 samples and is designed to track and diagnose possible defects in colour vision. In that case, it should be used in daylight or under a good daylight simulator. Here, we instead used it to compare the performance of one and the same person in two lighting situations. 20 selected samples were sorted, once in the test room and once in a light box with simulated daylight, placed in the daylit room. For each individual, we compared the results in the two situations. The analysis of the results of all the subjects showed to what extent the situation in the test room differed from the one in the daylight box regarding the possibility of discriminating colours, and if this was different for different hue areas.16 The method was shown to give results that could be interpreted.

The light's colour rendering ability was tested through a simple colour categorisation test. The subject was asked to answer simplified questions about the hue and nuance of twelve colour samples, which were shown in random order both in the test room and in a light box with a good daylight simulator, placed in the reference room. The intention was to investigate if the situation in the test room resulted in a systematic shift of the hue (e.g. a tinge of green in yellow colours) and/or certain hue areas were weakened or enhanced (e.g. green colours becoming more greyish or red colours becoming stronger). Each subject's evaluation was only compared with their own evaluation in the other situation, which eliminated the effect of the different individuals being more or less used to and skilled in categorising colours.

Room nr	Number of subjects	Year of birth	Median age	Students	Staff	Others	Men	Women
1:1	15	1946-88	28 years	7	7	1	6	9
1:2	15	1943-87	45 years	4	5	6	6	9
2:1	12	1964-89	28 years	8	1	3	8	4
2:2	15	1962-88	37 years	5	3	7	7	8
Total	57	1943-89	37 years	24	16	17	27	30

Table 1. The composition of the test group with students and staff from Konstfack and others.

16 Two individuals who showed weak results in both situations were excluded from the analysed material.



Room	Total power	Power per square meter
1:2	98 W	5,4 W
2:1	34 W	1,9 W
2:2	52 W	2,9 W

Table 3. The light installations' effect calculated by Svante Pettersson

Technical measurements and specifications

In each room version technical data were noted according to the below. They have only partly been analysed and used as a basis for conclusions, but all data are available for the benefit of those who wish to gain more information.t.

Illuminance

In room version 1:2 as well as in 2:1 and 2:2 the lux value was measured in appr. 20 locations, comprising
- walls, at different heights (60, 12 and 180 cm) and different distances from the windows
- the lightest and darkest parts of the table's surface
- dark and light portions in the middle of the floor
- other locations deemed to be of interest

The lux values are reported on page 65.

Luminance

For several locations in each room version the luminance was calculated. For each surface colour (grey wall, white wall, floor, etc.) we chose those locations that had the highest and the lowest measured lux value, respectively, and for these the luminance was calculated (cd/m2) according to the formula Luminance = Reflection value of the surface x Measured lux value / π.

The calculations were only made for surfaces painted with a matte paint or coated with linoleum or fabric. The value for light reflectance differs, however, in different sources, and we especially noted that the photometric light reflectance factor (Y1) given in the NCS atlas is higher than the values usually applied in illumination calculations. Table 2 on p. 34 shows light reflectance factors obtained from three different sources. In our calculations we have used the values given by Matusiak. The luminance values are reported in an appendix on p. 65.

The light sources' theoretical colour rendering ability, expressed in CRI , was obtained from the producer's product specification.

The colour temperature of the light sources, expressed in K, was obtained from the producer's product specification.

Colour discrimination test and colour categorization test.

The lighting system's power expressed in W

The energy consumption for each room version was calculated based on the producer's stated performance for light sources and fittings, including losses due to driver devices. See Table 3.

Spectral distribution graphs for the light sources and for the light reflected from certain surfaces were created with the use of a spectrometer. 17 Figure 8 shows the graph for the large spotlight above the table in room 2:2, measured with the meter placed on the table surface, and the graph for reflected light from the grey wall near this spotlight, behind the subject. For other graphs, see p. 68.

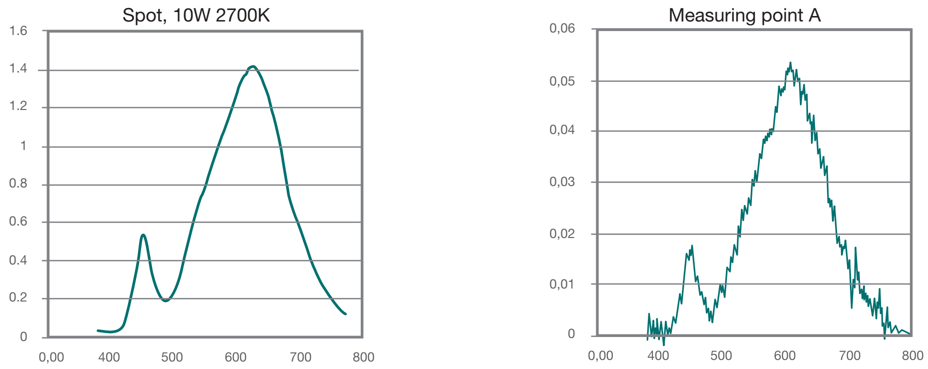


Figure 8: Spectral distribution curves for the spot above the table and the reflected light from the gray wall.

Colour name / location in test room	NCS number	Light reflectance according to NCS atlas	Light reflectance according to Starby 155[18]	Light reflectance according to Matusiak[19]	Annotation
White as on window wall and table	0500-N	95%		88%	
White enamel paint			85%		Not specified in detail
White paper			80%		Not specified in detail
Grey as wall in room 1	2000-N	59%		57%	
Light grey enamel paint			60%		Not specified in detail
	3500-N	40%		39%	
Dark grey enamel paint			15%		Not specified in detail
	6500-N	16%		14%	
Red picture in room 1	1580-R	8%		6%	Refers to 8000-N which according to NCS atlas has the same lightness as 1580-R
	9000-N	4%		1%	

Table 2. Light reflectance of different colours according to different sources

17 AvaSpec-2048 Fiber Optic Spectrometer from Avantes. The measurements were carried out 10/2 2011 by Thorbjörn Laike and Johanna Enger
18 Lars Starby: En bok om belysning (A book on lighting) is a standard of lighting technology
19 Measurements of NCS samples conducted by Barbara Matusiak, NTNU, 28/5 2010

Different questions in the test protocol

Experienced light and colour

Choice between words describing a room

The subject was given the task to mark which ones, among twelve given words, best described the look of the room. At least one word, and at a maximum four words, must be marked. The words were placed in two random orders, and half of the subjects were given one order, the other half the other order. The subject's choice of words informs about which colour and light qualities were noted, and how these were evaluated.

The words were chosen in the following manner:

Four words (light, dark, colourful, low-coloured described the colour and light situation

Four words (varying, cohesive, monotonous, sprawling) described variation and the amount of contrast, with a positive and negative undertext, respectively.

Four words (cool, warm, pale, powerful) evaluated the totality regarding colour and light

Experienced mood

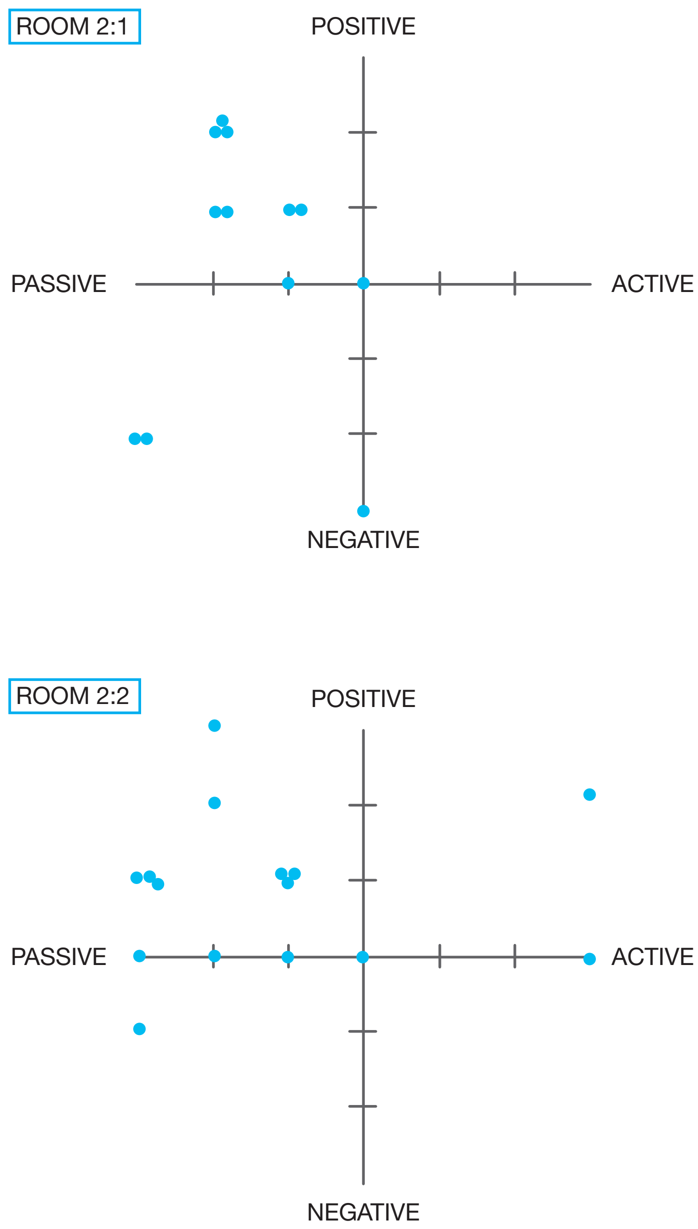
Markings on semantic scales of differentiation

The subject was given the question: How do you experience the mood in the room? The answer was marked on two separate scales; one from "positive" to "negative" and one from "active" to "passive". During processing the two scales were put together in the form of a cross. If the mood was experienced according to the intentions of "dynamic and stimulating", the subjects' markings would fall into the upper right field (positive – active), and if it was experienced according to the intentions of "calm and harmonious", the markings would be in the upper left field (positive – passive).

Choice of words describing the mood

The subject was given the task to mark which, out of twelve given words, best described the mood in the room. At least one word, and at a maximum four words, must be marked. The words were placed in two random orders, and half of the subjects were given one order, the other half the other order. The subject's choice of words informed about to which degree the mood was experienced according to the intentions.

Experienced mood in room 2:1 and room 2:2



The words were chosen in the following manner:
Four words (pleasant, inviting, unpleasant, rejecting) were expected to be of use for both room versions, as a positive or a negative evaluation.
Four words (stimulating, dynamic, restless, divisive) were expected to be of use for the ”dynamic” room version, as a positive or a negative evaluation.
Four words (calm, harmonious, boring, soporific) were expected to be of use for the ”calm” room version, as a positive or a negative evaluation.

Questions with open answers
”What is positive in this room? ” – ”What is negative in this room?” - ”Is there something disturbing in this room, and if so, what is it?”
”Which function – except as an experiment room – could this room have? Explain your answer!”
The open questions gave answers we might not have got with more controlled questions, and they also gave us a possibility to see what aspects of the room were deemed important by the subjects.

Functionality - reading
The subjects were given the task of reading two pages in a fiction paperback with small print. When the book was closed, the subject answered a simple factual question about the text (to check that they really had read it) and made the following evaluations in the form of markings on semantic differential scales:
- How hard did you think it was to read the text (could not read it – read it without any difficulty)
- Was your reading experience impacted by the light situation (negatively – not at all - positively)
- How does the thought of reading an entire paperback, which you choose for yourself, in this light situation make you feel? (Definitively not – no problems at all)

The subjects were also asked to give their own comments on the situation.
The experiment was repeated twice (at the table in the test room and at the table in the daylight room). Two text sections from the same book were used. Different subjects received these in different order. After reading in the reference situation, the subjects were asked to compare the two situations.

In the analysis the situation in the test room was compared to the reference situation regarding:
- understanding the text
- the subjects’ assessment of the situation

Functionality – colour discrimination
This test may result in knowledge about to which degree the situation in the test room makes it more difficult to discriminate between colour objects with very similar colours, and to see if this also differs between different hue areas.
We used parts of ”The Farnsworth-Munsell 100-hue test for the examination of Color Discrimination”. The test is designed to examine a person’s colour vision in daylight or in an illumination situation resembling daylight. We instead used it to investigate the difference in the capability to discriminate between colours in the test room and in a light box with a good daylight simulator. Thus, for each person we compared the results from these two situations. As each person was only compared with themselves, we minimised the effect due to different subjects being more or less good at performing the task.

We chose 20 out of the 85 colour samples of the test, with a distribution of five greens (no. 35-39, distributed around NCS appr. 3030-G), five yellows (no. 15-19, around 2030-Y), five reds (no. 84-85 and 1-3, around Y90R) and five reddish blues (60-64, around 3030-R75B). The subject received all the samples mixed up randomly and was first asked to group them according to main hue, and then to sort them according to hue inside of each group. The result was noted and evaluated according to the test manual.

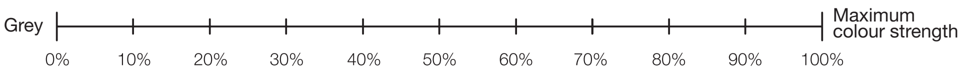
Functionality – colour categorisation

The aim of this test was to investigate if the situation in the test room created systematic hue shifts (e.g. a tinge of green in yellow colours) and/or if it weakened or enhanced certain hue areas (e.g. green colours becoming more greyish or red colours becoming stronger). This was done through the subjects' assessments in the test room and in a light box with a good daylight simulator, after which the results of the two assessments were compared for each person.
The observation material was twelve NCS samples (A6) mounted on white cardboard (A4).
The samples were selected to cover different nuance areas, and at the same time be easy to name with the colour names of yellow, red, blue or green. The samples were:

Yellow: 0510-G90Y, 0580-Y, 1040-Y10R
Red: 1085-Y90R, 3050-R, 2020-R10B
Blue: 2065-R90B, 1010-B, 6030-B10G
Green: 6020-B90G, 3010-G, 2070-G10Y

The task was initiated with a short presentation of the variables to be used. The subject then filled in a training form, so that the test leader knew that the subject had understood the basic question and the method. The questions were based on the categories that form the base of the colour system NCS, but no previous or deeper knowledge about NCS was needed to answer the questions.
For each colour sample a question was asked according to the following model (the example concerns a yellow sample).

1. How strong is the colour relative to the yellowest yellow you can imagine?



2. Do the colour tend towards green, towards red or neither? (Highlight one option)

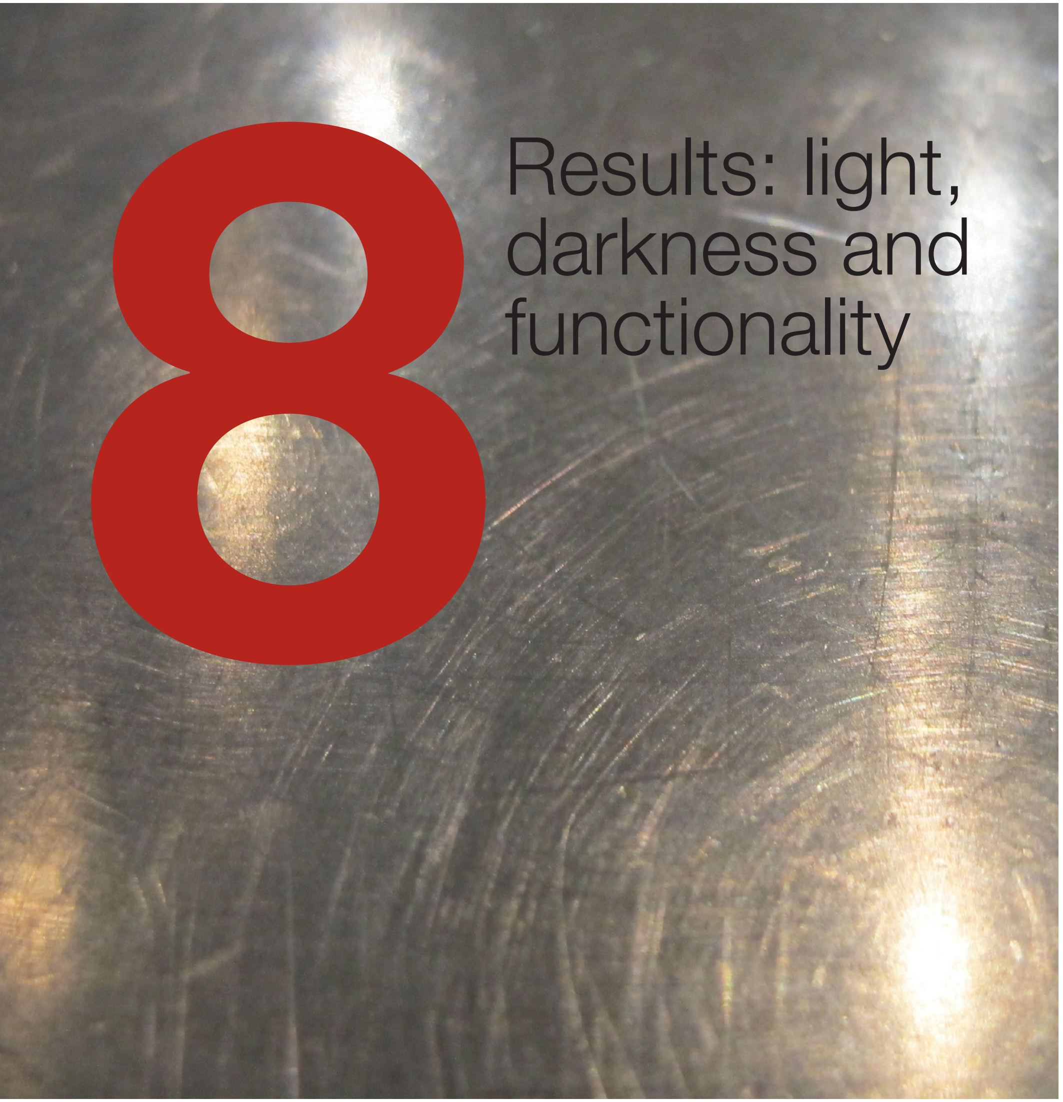
The samples were shown in random order, in two different series that were used for every second subject. The same samples, in another order, were later shown together with some further samples, during the reference test the light box in the daylight room, without the subject being informed about the series comprising the same samples.
The assessments of each subject were compared to this same individual's assessments in the other situation, and we noted in which situation the colour was deemed to be stronger (question 1) and compared the assessment of the hue. As the subjects were not compared with one another, the large differences in previous knowledge and assessment capability between the subjects could be ignored.

Comments regarding the questions of the first test round

The first questionnaire contained the question of whether the room was light or dark. This question turned out to give disparate answers that were not possible to interpret. One reason may be that expectations regarding experienced light level are very different in rooms with different functions. Thus, it is not appropriate to explicitly pose these questions in this context. In the following test round, we instead chose to let questions about light and dark be included among other words, which may be chosen to note or not.

The first questionnaire also had direct questions about light distribution and colour contrasts, but these were interpreted completely differently by different subjects. We concluded that such questions require having learned to decompose a holistic experience into separate and definable aspects. Thus, they can be understood by experts in the field, but hardly by lay persons, and are not suitable in a test that wants to capture the holistic experience. The question about experiencing glare tends to be leading*. If you get the explicit question if there is an anything with a glare, you will always find something. It is better not to mention glare, but instead to ask an open question about anything being disturbing.

* According to our experience, also from PERCIFAL, another sub-project in SYN-TES



8 Results: light, darkness and functionality

The following section is based on the answers of the test subjects. Since the test groups were small and did not have a controlled composition, there is no possibility of meaningful statistical processing and no certain conclusions can be drawn from the answers. Instead, we use the answers as the starting point for a discussion, in which we also draw upon the experiences and knowledge of the project group. The discussion leads on to possible interrelations, which then are used as a foundation for the hypotheses presented in section 13.

A light room or a dark room?

The subjects were asked to evaluate the appearance of the room by marking maximally four out of twelve words, comprising ”light” and ”dark”. They were also asked to comment upon the illumination situation in connection with reading at the table, where the illuminance was larger than in the rest of the room.

Regarding room 1:2, only four out of fifteen subjects chose any words describing the level of light in the room, and they were not in agreement about whether it was light or dark. When reading at the table (illuminance 605 lux in the strongest part of the light cone), they made some comments about the light, but these were about the light quality and not about the question ”light or dark”.

For room 2:1 six out of twelve subjects stated that the room was dark, and no one considered it light. When reading at the table (illuminance 1040 lux in the strongest part of the light cone), they made some comments about the light, but these were not about it being light or dark.

For room 2:2 six out of fifteen subjects stated that the room was dark, while one stated it was light. Here, the light cone over the table gave a total of 1600 lux on the table's surface, but in this case also the reading did not result in comments about light or dark.

How well do these answers fit with what can be expected from measured luminance values?

In room 1:2 the luminance of the walls varied between 6 and 27 cd/m2, in room 2:1 it varied between 2 and 11 cd/m2 and in room 2:2 between 5 and 28 cd/m2. Room 2:1 being experienced as the darkest is thus what may be expected considering the luminance. But why was room 2:2 experienced as darker than room 1:2, even though the luminance was roughly the same in both cases?

One possibility has to do with what is called contrast range. This term is often used to describe the relationship between the lightness of the darkest and the lightest colours in a picture, or in the field of vision. But it also relates to the fact that a stronger illumination makes it possible to perceive many more steps/gradients in chromaticness between the grey scale and the most strongly chromatic (intense) colour. In a stronger light we experience contrasts in lightness and/or chromaticness between colour fields that would look the same in a dimmer light.

The reverse is also true. If we perceive a larger contrast range between the colours of surfaces (from really light = white, to really dark = black) our experience is that there is more light in the room. If the contrast range is small, this may be interpreted as the result of ”weak light” – even if it is due to there being no really light or really dark objects/surfaces in the room. The same is valid for the contrasts between greyish colours and strongly chromatic colours. If we do not perceive any such contrasts, we may experience the light as ”dim” (”like dusk”) and if we see clear differences between different colours, we may perceive the light as stronger and clearer.

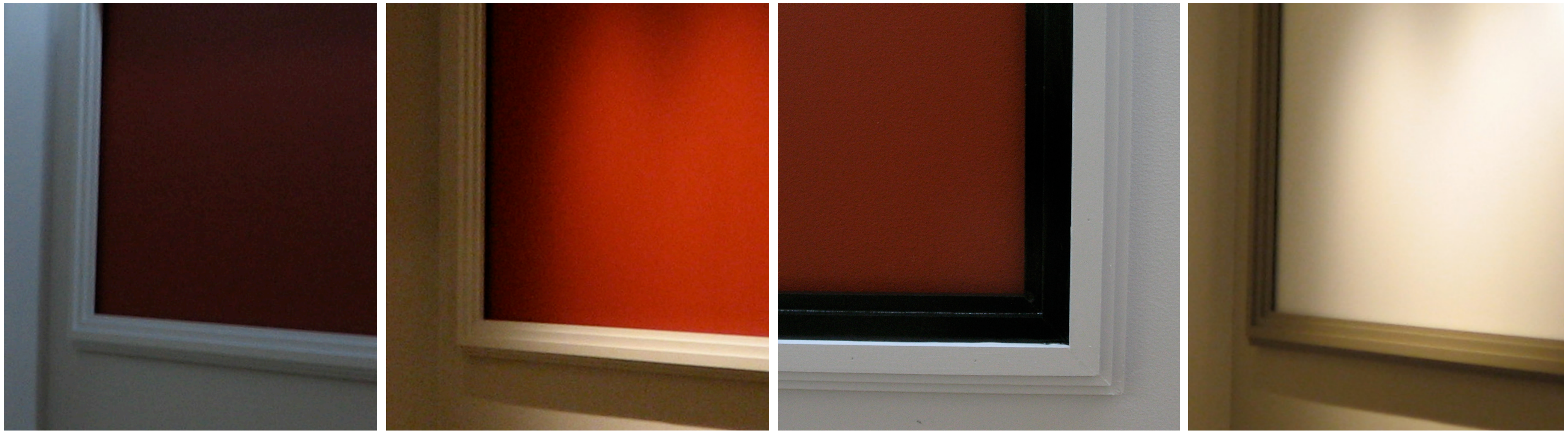
In the corner between the long wall and the window wall different locations of the boundary between white and grey were tested.

Room 1:2 had a large contrast range between achromatic and strongly chromatic colours, as well as between white and black. In room 2:2 there was the same contrast range between white and black, but not between distinctly different chromatic colours. In other words: the strong colours of the yellow cupboard and the red carpet may have contributed to the room being experienced as lighter, compared with when these objects had more muted and congenial colours.

We experienced another example of the significance of contrasts at the evaluation meeting for room 1:1, which is not treated in detail in this report. In this room version the boundaries between the white window wall and the grey side walls were difficult to discern (hid by the curtain or in the angle of the window niche). This meant that it was not clear that the grey sidewalls were actually painted grey.The could instead be perceived as being white and very weakly lit, which could produce a general sense of darkness. To avoid this, we removed the curtain in room 1:2, so that more could be seen of the white window wall. In the inner left corner it thus became evident that the window wall was white, and the longitudinal wall was grey. Similarly, the inner right corner was changed by painting the pillar white to create a clear boundary between grey and white.

Further, we placed a black vase in the room and added a black line on the frame of the red board. This increased the contrast range and gave a black reference to which the grey walls could be compared.

In the test rooms in question, mainly diodes with very narrow angled light beams and with a quite concentrated light distribution were used. This gives us another possible, but seemingly paradoxical, explanation of why room 2:2 was experienced as dark. The strongly lit parts of this room were lighter than in all other alternatives, at the same time as there were very sharp boundaries between these light cones and the larger and darker parts of the room. Thus, the contrast with the defined, light parts made the



The contrast range in the room was changed by adding completely black details, such as a black list on the board frame in room 1: 2.

main part of the room be experienced as dark. Furthermore, the edge lines of the room and the furniture became much clearer in the strongly lit areas, and the relative unclearness in the darker parts may have contributed to them being experienced as even darker.

The light distribution may also have influenced the total comprehension of the room in a negative way. When a room is lit by daylight or by fittings with a good light distribution, the light level changes gradually between the different parts of the room, and the change that can be observed is experienced as logical in relation to the light sources and the shape of the room. The light has a direction, which helps us to understand the colours, shapes and size of the room. A light distribution that is difficult to comprehend makes for a room that is difficult to comprehend, and this may easily lead to the experience that the reason for this difficulty is darkness.

What is needed of good reading light?

The subjects read a paperback at the table in the test room and at the table in the daylit room. For both scenarios, they were asked the same questions about the situation as such, and after reading in both places they were also asked in which reading situation it was most difficult or most easy, respectively, to read the text. The answer to the comparative question was well in line with what could be observed in the subjects' assessment of the separate situations.

In room 1:2 the absolute majority (11 of 15 subjects) stated that it was easier to read in the daylight room than in the test room. This was not due to more light on the book in the daylight room – on the contrary, the illuminance was in most cases less in the daylight room than in the test room. The lux value on the table surface in the test room was 580 lux in the middle of the light beam and 370 lux at the farthest edge, but most subjects preferred to read in the daylight room although its table surface was lit by down to 215 lux.

The test room table illuminated with a LED spot with colour temperature 4000K, and two LED spotlights with colour temperature 2700 K

In room 2:1 as well, the absolute majority (7 of 11) stated that it was easier to read in the daylight room than in the test room. The lux value on the table surface in the daylight room for these subjects varied between 290 and 5 lux, while the table in the test room was lit by two light cones, each giving a patch of light with 1040 lux and 40 lux at the edge of the table. Two individuals stated that it was easier to read in the test room, and for those the lux value on the table surface in the daylight room was 410 and 210 lux, respectively. Thus, it was not the light level in the daylight room that defined what was preferred, and most individuals preferred the daylight room despite the illuminance there being much weaker than in the test room.

In rom 2:2 the illuminance on the table was as large as 1600 lux in the middle of the light cone and 115 at the edge of the table. The lux value on the table in the daylight room varied between 283 and 84 for the different individuals. The assessment of which situation was best varied between the subjects and showed no connection to the lux value in the daylight room. Thus, it was not the light level in the daylight room that defined what a person preferred. We may conclude that the reading situation in this test room was evaluated as equal to the situation with a relatively weak daylight.

Thus it is absolutely clear that ”good reading light” is not the same as ”a lot of light”. With the help of the subjects’ comments, we may instead find other indications of what is needed from a good reading light. Several subjects commented positively on the light in the daylight room being precisely daylight (”to follow the day”) and on having a view of the outside world (”lessens the claustrophobic feeling”). That people prefer daylight to most types of artificial light and accept a lower light level in daylit rooms has been shown in several previous studies.[20] To increase the understanding of how artificial light should be constituted, we here take one step further by analysing which properties of daylight were experienced as positive in the reading situation, and what in the test room light was experienced as negative.

The glossy painted surfaces in combination with narrow-beam light sources made even minor changes in the direction of light result in great effects to the overall impression of the room.

20 Kronqvist 2010

A recurring comment concerned the light distribution. The daylight was experienced as even and thus as positive, while the reading light in the test room produced strong, disturbing shadows, the feeling that the page of the book had a glaring effect, that the light field was too narrow and that there were too large contrasts in the visual field. These comments pertained to all test rooms. It is thus clear that it is easier and more pleasant to read if the contrast between the reading light and the ambient light is not so large. This is consistent with earlier research and recommendations. For those illuminance levels that were used on the tables in the test rooms (appr. 600 – 1600 lux on the lightest spot) Starby[21] recommends that the nearest environment of the work surface should be lit with 300-500 lux, in order to eliminate disturbing and unpleasant contrasts. In our tests the ambient illumination was much less, in the extreme case only 40 lux the table's edge while the illumination on of the work surface's centre was 1040 lux (room 2:1). Since the light was oriented directly from above, sharp shadows and risk of glare was also generated. We may thus draw the conclusion that the chosen placement of the illumination (spotlights mounted in the ceiling) did not give a good light for reading.

Other comments concerned more elusive properties of the illumination situation. In room 1:2 (with LED:s 4000-6300 K) words like ”cold”, ”boring”, ”static”, ”annoying” and ”strenuous” were used. In room 2:1 and 2:2 (with LED:s 2700 K) there were comments both on the light being ”prickly” and it being soft and having a pleasant colour temperature. In both these rooms five out of a total of 27 subjects expressed that they had inexplicable difficulties when reading: ”difficult to focus”, ”my eyes were jumping across the text, as when I am tired”, ”felt like I had dim sight”.

The reason why the light was experienced as annoying cannot be ascertained within the framework of this project, but some possible hypotheses may be made. One possibility is that the spectral distribution of the diodes caused chromatic aberration, which means that different wave lengths are refracted to different positions in front of, on and behind the retina. The visual sense in this case has to deal with several different retinal images, which requires extra effort even if we do not consciously experience "double sight". As can be seen in Appendix 4, all the diodes used hade a sharp emission peak around 440 nm, a dip around 490 nm and another peak at around 590 nm. This could mean that the visual sense had to work with two retinal images in a way that does not happen when the emission distribution is more even.

Another possible disturbance of the vision may be due to the LED fittings used giving sharply delimited light cones, without a diffusion of light between them. On spots that were lit by several diodes the result was several simultaneous shadows, and at the edges of each light cone a significant re-adaptation was needed in order to see between lit and dark parts. Multiple shadows are also generated on a smaller scale, due to every LED fitting being constructed from several small, bright points.

The LED fittings used in room 2:1 and 2:2 had a nominal homogenous colour temperature of 2700 K, but looking closely it was seen that the light colour varied slightly. One and the same diode also seems to have had a different colour of light depending on the viewing angle. It is also possible that a small frequency flicker was observed at the periphery of the light cone. In addition, there are the already discussed difficulties to create a clear spatial experience when the light distribution deviates strongly from the expected.

All these possible sources of disturbance may have contributed to the visual sense needing to work harder than usual to create a clear visual image of the room, and of the text the subjects had to read. This kind of effort can result in visual fatigue, even though we may still see a clear image. The price of adaptation is paid in effort

21 Starby 2006 pp 269.

9 Results: Colour rendering

To investigate how the light situation impacts on the perception of colours we have used two different methods. One was constituted by sorting samples with very small differences in hue (colour discrimination test) and the other was constituted by noting the perceived hue and chromaticness of paper samples against a white background (colour categorisation test). In both cases the subjects' results in the test room were compared to their own results in a light box with simulated daylight. See Table 4 for illumination data.

Colour discrimination

The result of the colour discrimination test is shown in Table 5. Since the different series comprised different persons, which possibly had differences in their ability to perform the test, no direct comparisons may be made between results in the different rooms. The columns stating the difference between the test room and the light box may be compared, however, since they are based on the difference between each subject's results in the two situations. An inversion between two samples corresponds to 4 error points. Differences of less than 0,4 error points thus correspond to every tenth person placing one sample differently in the test room as compared with the light box. These were considered marginal and are not considered in the analysis below.

Table 5 shows no large differences between the results in the light box and in the respective test room, but there is still a pervading tendency of the subjects making more

	Backdrop colour	Light source	Illuminance
Test room 1:2	White	LED 4000 K	610 lux
Test room 2:1	White	LED 2700 K	1040 lux
Test room 2:2	White	LED 2700 K	1600 lux
Light box	White	Flourescent D65	2560 lux

Tabel 4. Summary of the light conditions at the workplace, during colour discrimination and colour categorization tests.

mistakes in the test rooms. This could be due to the illumination in the light box being stronger than in any of the test situations. This explanation is not likely, however, since the greatest difference between test room and light box applies to room 2:2, which had the highest lux value on the work surface.

Sorting the samples into colour areas, the following could be seen:
Yellowish samples could be separated less well in the test rooms than in the light box, regardless of which LED illumination was used.
Reddish samples could be separated just as well in cool LED light as in the light box, but significantly less well in warm LED light.
Blueish samples could be separated just as well in the test rooms as in the light box, regardless of which LED illumination was used.
Greenish samples could be separated approximately as well in room 1:2 and 2:1 as in the lightbox, but distinctly less well in room 2:2.
The difference as compared to the light box thus was most significant in room 2:2, with warm LED light, and least significant in room 1:2, with a cooler LED light.

Colour categorisation

In the colour categorisation test the subjects were asked to, in a simplified way, state the hue and nuance of twelve samples that were shown in the test room and in the light box. When processing the results, the answers of each person were compared, and we noted how the answers in the test room differed from those in the standardised light of the light box. Only the direction of the difference (more or less chromatic, a shift towards one hue or the other) was noted, not its size.

The colour categorisation test gave the following results:
Hues around Y: Clear tendency to diminished chromaticness and hue shift from red towards green in all three rooms.
Hues around R: No shift tendencies in cool LED light (room 1:2), while warm LED light in both 2:1 and 2:2 resulted in a tendency to hue shift from blue towards yellow, and in room 2:1 to lessened chromaticness.
Hues around B: A tendency to increased chromaticness, which was larger in warm LED light (both 2:1 and 2:2) than in cool LED light. No tendency regarding hue in cool LED light, some tendency to shift towards green in warm LED light (both 2:1 and 2:2).
Hues around G: A tendency to lessened chromaticness in cool LED light, a clear tendency to increased chromaticness in warm LED light (both for 2:1 and 2:2). A distinct tendency to hue shift from yellow towards blue in cool LED light, no hue shifting in warm LED light (both for 2:1 and 2:2).

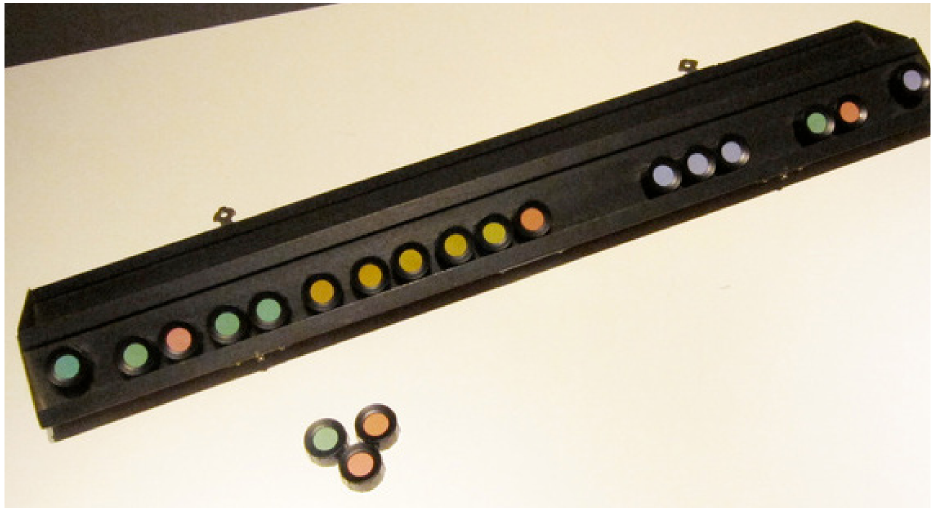
		Test room (T)				Light box (L)				Difference T-L				
Sequence	n=	G	Y	B	R	G	Y	B	R	G	Y	B	R	Tot.
1:2	13	2,5	0,9	1,8	1,5	1,8	0	1,2	1,8	0,7	0,9	0,6	-0,3	1,8
2:1	12	1,0	0,7	1,3	1,7	0,7	0	1,3	0,3	0,3	0,7	0	1,4	2,3
2:2	15	1,9	1,6	1,1	1,3	0,3	0,3	0,8	0,3	1,6	1,3	0,3	1,0	4,3
Total	40	1,8	1,1	1,4	1,5	0,9	0,1	1,1	0,8	0,9	1,0	0,3	0,5	2,9

Table 5. Average error points / person in colour discrimination test per colour area and test series. A reversal between two samples corresponds to 4 error points. G, Y, B, R indicate colour zones according to NCS.

The results in the two rooms with warm LED light were totally coherent with one another, except for the possible reduction of chromaticness in reddish samples. On the other hand, there were certain differences between the results in warm and cool LED light, respectively. Unsurprisingly reddish samples shifted from blue towards yellow in warm LED light, while greenish samples shifted from yellow towards blue in cool LED light. More surprising – at least for the project leader – was that the warm LED light led to an increased greenness both in greenish and blueish colours, and that the chromaticness of the blueish colours was increased to a larger extent in warm LED light than in cool.

Comparison between the results of the two colour tests

The results of the two colour tests point largely in the same direction:
In comparison with the standardised light in the light box, both the cool and the warm LED light resulted in a reduced chromaticness for yellowish colours and made them harder to discriminate.



Material for Farnsworth-Munsell colour discrimination test colour.

Reddish colours were categorised and discriminated just as well in cool LED light as in the light box, while the warm LED light gave worse results in both aspects.
Blueish colours got a increased chromaticness in both warm and cool LED light, which reasonably should strengthen the possibility to discriminate different hues. [22]
For greenish colours, however, the results cannot be interpreted in any clear way.
It may be considered logical that the cool LED light enhances blueness and diminishes yellowness, but it is harder to understand that these tendencies also appear with warm LED light. My (project leader) spontaneous assumption was instead that warm light would enhance warm colours and cool light would enhance cold colours.
How could this surprising result be explained? Below, three alternative explanations are discussed:
1) The difference in perceived colours was caused by the different composition of the test groups in the different alternatives – that would mean that the results from the three situations cannot be compared.
2) The difference in perceived colours was caused by the intensity of the light that illuminated the work surface in the different situations.
3) The difference in perceived colours was caused by the spectral distribution of the light that illuminated the work surface in the different situations.

Discussion of the result based on the composition of the test groups

All test groups had a fairly even distribution of women and men, but age distribution was varied as test group 1:2 comprised four persons that were significantly older than the others. However, of these four two were not considered in the analysis of the colour tests[23] and the answers from the others did not differ significantly from the rest of the group. There was also a difference in the composition of the groups regarding the professional relation to design, but this did not result in any systematic differences regarding the colour assessment questions. The differences between the results of the different test situations thus cannot be explained by the test groups being different. See Table 1.

22 When asking what colour the walls were , this also pointed to the same direction: The nominal neutral grey walls were perceived more blueish in room 1: 2 (cool LED) than in the daylight room. In room 2:1 and 2:2 with warm LED light, the walls were re-painted in a nominal warm grey colour, which made it impossible to compare with the unchanged daylight room.
23 One subject did not do the test, another was excluded due to generally poor colour discrimination ability.

Discussion of the result based on the light intensity

It is well known that differing light intensity may change the perceived hue of an unchanged physical object. Framed in different words, this means that one and the same spectral distribution of the light energy gives different perceived hues, depending on the intensity. The Bezold-Brücke effect is well known in the literature on light and colour, and means that a higher radiation intensity enhances the hue's blueness or yellowness (depending on the wave length), while a lower intensity enhances the redness or the greenness. For pure blue, green and yellow there is no change.[24] This effect has been shown for radiation with only one single wave length, and it is uncertain to which degree it applies to physical objects seen in complex illumination situations. If we assume this to be the case, yellowish green colours would be perceived as less yellowish, and blueish greens as less blueish, when light intensity was lowered. Table 7 shows how the hue of three green colour samples was assessed in the three test situations, compared with when they were seen in the light box, which was the situation with the highest illuminance.

The most significant reduction of light intensity was between the light box and room 1:2. There, the nominally yellowish sample was on average perceived as less yellowish in the lower intensity, while at the same time the nominally blueish sample was perceived as bluer. In the rooms 2:1 and 2:2 the nominally blueish sample was instead perceived as less blue than in the light box, while the yellowish sample was assessed as approximately the same in both cases. Thus, the result does not indicate that the shown hue shifts can be explained with the Bezold-Brücke effect.

Hue shifts in more complex illumination situations have been studied by Hunt, who has shown that when the light intensity increases, the perceived hue of light colour samples is changed towards blue, while darker samples become more yellowish.[25] In Table 8 and 9 it is shown how the hue of the light colour samples and the dark colour samples in the study, respectively, were assessed in the different light situations, in comparison with the light box. The answers imply that the darker colours got less blueness/ more yellowness when the light intensity was reduced, which is the opposite of the effect documented by Hunt.
The results shown in Tables 8 and 9 must be interpreted with a large amount of caution, since the underlying material was too small for a reliable statistical treatment and the colour samples varied both in hue and nuance. We have not found anything that suggests that the hue shift between the different light situations is caused by the intensity of the light radiation. To clarify this we suggest, however, further tests, specifically designed to highlight this issue.

		Yellowish samples				Reddish samples				Bluish samples				Greenish samples			
Series	Number	Towards C	Away from C	Towards R	Towards G	Towards C	Away from C	Towards Y	Towards B	Towards C	Away from C	Towards R	Towards G	Towards C	Away from C	Towards Y	Towards B
1:2	36	6	**16**	2	**8**	12	10	5	7	**12**	9	4	5	8	**12**	4	**13**
2:1	36	5	**15**	5	**9**	10	**14**	**8**	3	**15**	5	3	**7**	**17**	7	7	7
2:2	45	7	**15**	7	**12**	13	14	**9**	6	**17**	9	1	**4**	**18**	13	6	7

Colour categorization. The column 'number' indicates the total number of nuances and hues in each colour category. For each colour category, the number of assessments is given where the sample was assessed differently in test rooms and lightboxes. Other assessments gave the same answer in both situations. Colour markings indicate clear trends, as explained in the text

Nuance difference (first two columns in each colour category):
Towards C = the sample was estimated to be more chromatic in the test room.
Away from C = the sample was estimated to be less chromatic in the test room

Hue difference (the two following columns in each colour category):
Towards R = the sample was judged redder or less green in the test room.
Towards R = The sample was judged redder or less green in the test room.
Towards G = The sample was judged greener or less red in the test room.
Towards Y = The sample was judged yellow or less blue in the test room. or less yellow in the test room
Towards B = the test was judged blueer or less yellow in the test room

24 Lillo et al. 2004; Derefelt & Berggrund 1994 page 22
25Fridell Anter 2000 note 12 page 232

Discussion of the result based on the spectral distribution

Could it be the case,that the difference in perceived colours was due to the spectral distribution of the light that illuminated the work surface in the different situations? Light with short wave lengths may dominate even in diodes giving a warm light colour (see Appendix 4), and according to the experience of the project group it is entirely possible that this could lead to an enhanced blueness and a reduced yellowness of surfaces and objects in the room. The problem is well known to the light industry, which continuously improves their products to achieve a better colour rendering.

The spectral graphs for the diodes that were used in the test all show a peak for wave lengths around 440 nm, but it was significantly more dominant in the diodes with a cool light colour (6300 K), compared to those with a warm light colour (see Appendix 4). This means that we cannot find an explanation for the warm diodes giving just as large a shift towards blue as the cool ones. This should be further investigated in tests specifically designed to shed light on this question.

Old generation LED

New generation LED

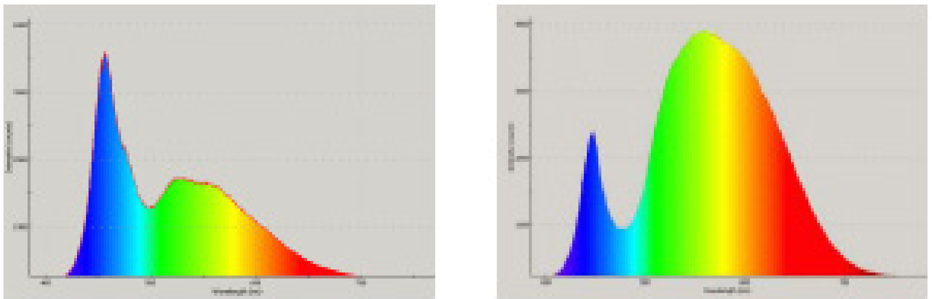


Figure 9. Schematic illustration of spectral distribution of different generations of LEDs. Image from Philips AB

Comments on colour rendering

We can draw the conclusion that the colour of the light tells us very little about how colours will be perceived, and that warm light actually can result in colours with a tinge of blue. This is a problem that has appeared in connection with discarding light sources with a continuous spectrum, which is what our visual sense has been evolved for. The new, more energy efficient light sources put up entirely new demands for specification of both colour of light and colour rendering, in order to allow understanding of how they will influence our experience of a room and its colours.

The example also points out how important it is do distinguish between the technical/physical properties of light and its perceptive properties. Short wave radiation with wave lengths abound 440 nm are often called ”blue light”, but such a denomination becomes only confusing when it is realised that light from a LED with a radiation peak in this area does not need to be bluish at all, but may on the contrary be warm, both regarding experience and correlated colour temperature (K).

In addition to the light's colour rendering properties, we also observed how furniture and other objects in the room influenced the perceived colour on other room surfaces. Most evident was that the nominally neutral grey walls both in the daylight room and in room 1:2 got a red tone through reflection from the red carpet. Such reflection effects are very important in spatial contexts and have been researched in more detail by Monica Billger.[26]

Another observation was made in room 2:2, where the illumination directed at the grey walls was much stronger in the front part of the room than in the back part, while all the light sources had the same colour temperature (2700 K) and their spectral distribution was very similar (large spotlight, small spotlight and floor lamp in Appendix 4). We noted that the nominally warm grey wall colour was perceived as colder/almost bluish where it was strongly illuminated and more greenish where the light was weaker. To investigate the causes of this has not been possible within the framework of this pilot study, but the effect was very pronounced and should be studied in more detail to increase the understanding of how LED lighting influences what we see in a room.

26 Billger 1999; Billger 2006

Hue shifts in green samples

Room no./lux	Number of judgments	Nominal yellowish green sample 2070-G10Y: Less yellow than in the light box	Nominal yellowish green sample 2070-G10Y: More yellow than in the light box	Sample with nominal elementary green hue 3010-G: More blue than in the light box	Sample with nominal elementary green hue 3010-G: More yellow than in the light box	Nominal bluish green sample 6020-B90G: More blue than in the light box	Nominal bluish green sample 6020-B90G: Less blue than in the light box
1:2 / 610	12	5	0	3	2	5	2
2:1 / 1040	12	3	1	3	1	1	5
2:2 / 1600	15	3	2	3	1	1	3
Summa	39	6	3	9	4	7	10

Table 7. Perceived hue shift in green samples. The numbers indicate how many subjects indicated a different hue in the test room than in a 2560 lux lightbox. Those who indicated the same hue in both cases are not listed. Lux notation refers to lighting on the work surface.

Hue shift in light samples

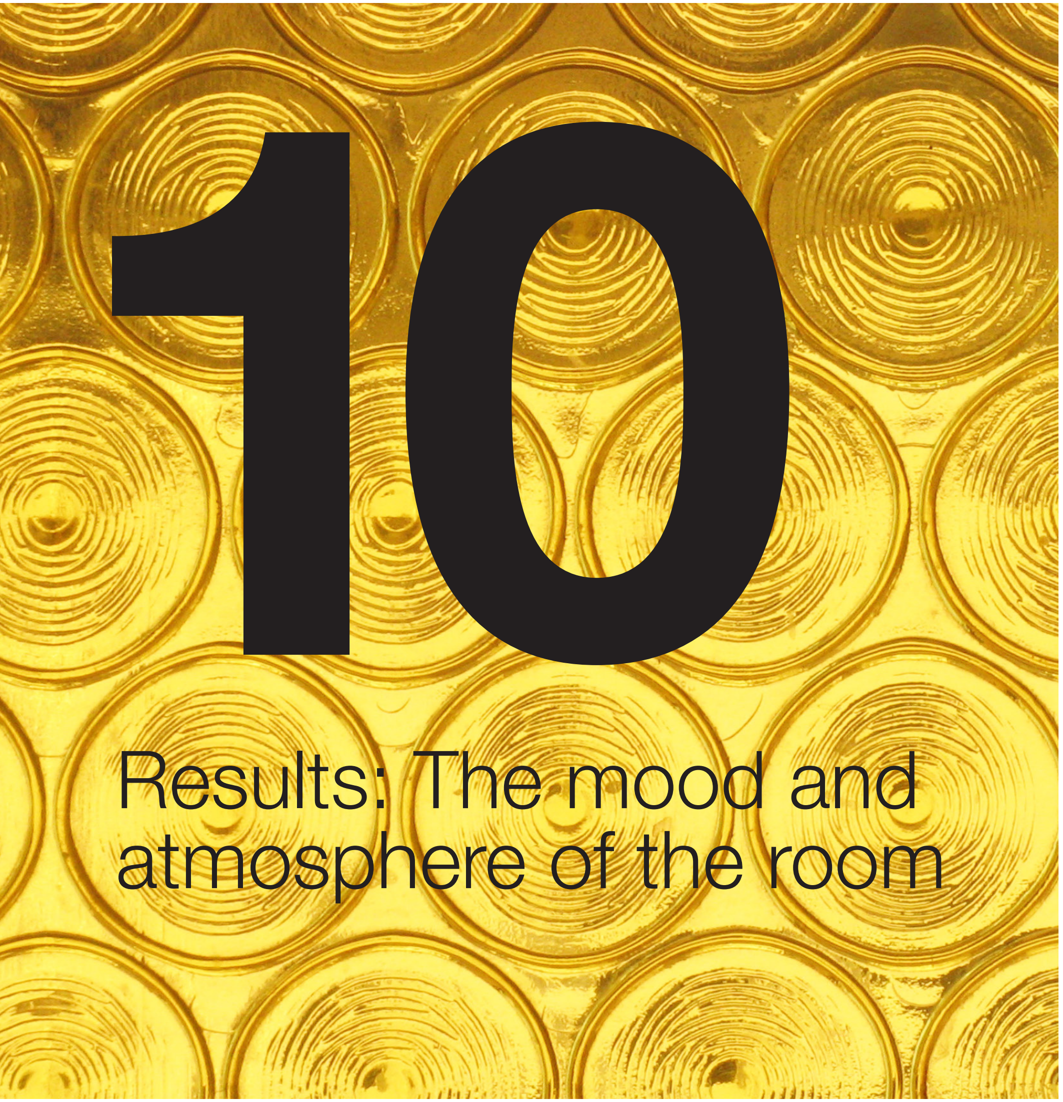
Room no./lux		Number of judgements	Less yellow/ more blue than in the light box	Less blue/ more yellow than in the light box
1:2 / 610	Lightest red sample 2020-R10B, Y_1 = 46%	12	0	1
	Lightest green sample 3010-G, Y_1 = 41%	12	3	2
2:1 / 1040	Lightest red sample 2020-R10B, Y_1 =46%	12	1	0
	Lightest green sample 3010-G, Y_1= 41%	12	3	1
2:2 / 1600	Lightest red sample 2020-R10B, Y_1=46%	15	2	2
	Lightest green sample 3010-G, Y1 = 41%	15	3	1
Total	Light samples	78	12	7

Table 8. Perceived hue shift in light samples. The numbers indicate how many subjects indicated a different hue in the test room than in a 2560 lux lightbox. Those who indicated the same hue in both cases are not listed. Lux notation refers to lighting on the work surface. Y1= photometric light reflectance according to NCS atlas.

Hue shift in dark samples

Room no./lux		Number of judgements	Less yellow/ more blue than in the light box	Less blue/ more yellow than in the light box
1:2 / 610	Darkest red sample 1085-Y90R, Y_1 = 13%	12	1	2
	Darkest green sample 6020-B90G, Y_1 = 11%	12	5	2
2:1 / 1040	Darkest red sample 1085-Y90R, Y_1= 13%	12	0	7
	Darkest green sample 6020-B90G Y_1= 11%	12	1	5
2:2 / 1600	Darkest red sample 1085-Y90R, Y_1= 11%	15	1	7
	Darkest green sample 6020-B90G, Y1= 11%	15	1	3
Total	Dark samples	78	9	26

Table 9. Perceived hue shift in dark samples. The numbers indicate how many subjects indicated a different hue in the test room than in a 2560 lux lightbox. Those who indicated the same hue in both cases are not listed. Lux notation refers to lighting on the work surface. Y1= photometric light reflectance according to NCS atlas.



10

Results: The mood and atmosphere of the room

One of the demands on the light and colour design of the rooms was that they should be experienced in a positive way, with the specification of dynamic and stimulating for room 1, and calm and harmonious for room 2. This proved very hard to achieve, and only version 2:2 complied in some respects with the stated requirements. The goal of the investigation was not, however, to achieve rooms with a perfect light and colour design. The goal of the successively changed colour and light designs was rather to explore how colour and light may cooperate in giving a room its properties, amongst them its mood and atmosphere. Regarding the actual evaluation of the rooms, there were, unsurprisingly, very different opinions, but a good deal of conclusions may be drawn from the more descriptive comments.

Summary of the comments about room 1:2

This room version had a colour and light design with the goal of giving av positive, dynamic and stimulating impression. It was evaluated by 15 individuals. Most did not experience the room as especially light or especially dark. Direct comments on the colours were made by half of the subjects, but they disagreed on the room being colourful or low-coloured, which means they either focussed on the walls or on the furniture. More than half (eight individuals) used the word ”cold” as a description of the room, but two individuals deemed the room to be warm instead.

In the choice between words describing the mood, the most common choices were ”calm” and ”soporific”, while only one person stated that the room was stimulating.
The (positive and negative) words denoting passive moods were chosen much more frequently than the words denoting active moods.
The negatively charged words were chosen somewhat more frequently than the positively charged ones.

When the subjects were asked to describe the room in their own words, they repeatedly used words like ”anonymous”, ”impersonal”, etc. Most of them suggested the room be used for quiet, passive functions (resting room, waiting room). However, they did this for different reasons: some stated that the room did not contain anything distracting, while others pointed out that there were interesting things catching the attention. Regarding the light, the lack of daylight was clear-cut negative for those subjects who commented on it. Otherwise, there was a great difference of opinion about what was positive and negative, respectively. The colour was commented upon by almost everyone. The colour of the walls was experienced as negatively cold by several, and the colours of the furniture caused many individuals to react either positively or negatively, without any consensus at all. Thus it would seem that the positive or negative experience of light and colour varies a lot between human beings, even when they can agree on a description more void of subjective opinions.

Summing up, the answers point in unison to the room being perceived as calm, but there were different opinions on if this was positive or negative. Obviously, we had not managed to make the room stimulating and dynamic in accordance with our goal.

Summary of the comments about room 2:1

This room version had a colour and light design with the goal of giving a positive, calm and harmonious impression. It was evaluated by 13 individuals.

When the subjects were asked to choose between words describing the room, there was a great consensus regarding the room being experienced as dark, low-coloured and cohesive. Half of them commented directly on the light level, and they all agreed on it being dark. The evaluation of the light was however not unanimous, on some occasion not even the same for one and the same person (who himself noted these contradictions). The most usual comment was that there was too large – and sometimes annoying – a contrast between strongly and weakly lit surfaces and parts of the rooms. In comparison with room study 1:2, it is remarkable that nobody mentioned the lack of daylight.

About half the subjects commented directly on the colours, and they all agreed on colours being weak. But also here evaluations differed. The room could be considered to have a pleasant and harmonious colour design, or a colour design making all things flow into each other to a mushy mix: ”No resonance in the room”.

Further comments pointed out that the room had a kind of double character – on the one hand it was cosy, on the other a bit weird. ”A bit like looking through a fog, a little like an opium den, a tipsy, drowsy feeling”.Our interpretation of this is, that the room's colour and light design was perceived as a little odd because it was so coherent and at the same time included such significant contrasts. Many subjects made this type of comment, but they did not agree on if this was something positive or negative.

Most of the subjects suggested that the room could be used for quiet, passive functions (resting room, meditation room). Those who disliked the room could not think of any use for it. Summing up, the answers unaninmously pointed to the room as calm, but at the same time some individuals experienced a conflict between calm and disturbing, either over time or depending on where in the room they were. It is clear that we were successful in making the room calm, but not as good at making it harmonious.

Summary of the comments about room 2:2

This room version was created by changing room 2:1 after going through the test results. Like room 2:1, it had a colour and light design with the goal of giving a positive, calm and harmonious impression. It was evaluated by 15 individuals.

There was a consensus about the room being perceived as cohesive, low-coloured and dark. The light was commented upon by most subjects, but the opinions differed, and the same person could be positive about one aspect of the light and negative about another. Most often the negative comments had to do with the light being unevenly distributed (”I want to have more general light in order to feel comfortable”) and specifically mentioned that this was irritating at the table. The uneven illumination, however, also resulted in most of the positive comments, as interesting objects in the room were illuminated by spotlights. Just as in version 2:1, no one mentioned the lack of daylight.

More than half of the subjects made explicit mention of the colours. Also here, there was an even distribution between positive and negative comments, sometimes from the same individual. However, only one person mentioned something colour-related as directly annoying ("that the furniture blends in with the walls"). The comments, both positive and negative, were mainly focussed on the coherence. Some thought this caused harmony, while others wanted more contrasts.

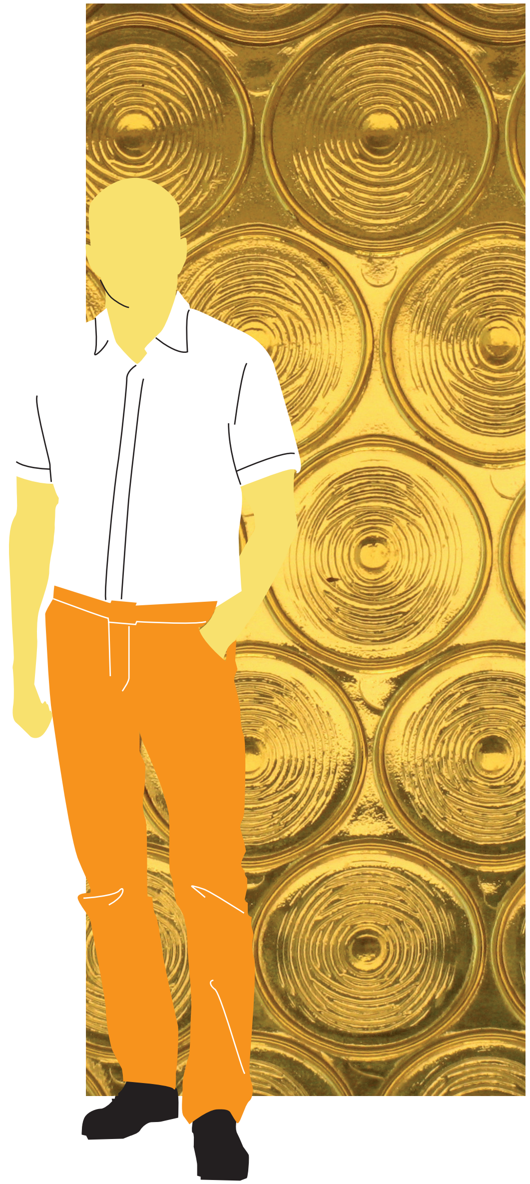
It was obvious that the light was perceived as varied and the colouring as uniform, but the evaluation of this differed. A negative judgement summing up aspects of both colour and light was "the feeling of bad eye-sight". Several individuals stated that the room was calm, cosy, harmoniously restful, while others had the opinion that it was cool, boring, impersonal, artificial. These large differences surely had to do with the evaluation of coherent colours in combination with varied light.

Most individuals suggested the room for calm functions (resting room, waiting room, therapy room). The motivations for this were largely positive. Summing up, the answers point in unison to the room being perceived as calm, in accordance with the goal. Some subjects perceived the calm as boring and negative, however, rather than as harmonious. Even one and the same person often expressed a kind of double assessment of positive and negative, a contradiction that was also mentioned explicitly by some subjects.

Comments on the test situation itself

Several of the comments from the subjects were not about light or colour, but rather about the test situation itself and the room's design and furniture. Acoustics and the air quality were mentioned by many, sometimes in a positive sense (calm and quiet), but more frequently as irritating. The furniture in the room also generated many comments, both positive (playful details) and negative (abstract, weird trompe l'oeil-chairs).

Our intention with the room design was to create a room that would not tell anything about epoch or style, nor signal any specific function of the room as a totality. The Master's degree students who designed and produced the furniture followed our intentions and created a "roomness" with "furniturenesses". However, the subjects did not get the intended experience of universality and started instead to wonder why the furniture looked as it did, and how they, as subjects, should relate to this.



In the early room versions, and especially in the first version, some individuals were irritated by the perfect order. In later versions we tried to compensate for this by placing more objects – ceramic bowls, textiles, etc. – in the room. This led to positive comments, but many individuals still perceived the rooms as strange and impersonal. That the room was experienced as impersonal is, however, a natural consequence of it being, and being perceived as, a test room.

"It is not possible to look out of the window, and so one starts instead to associate the room with a person. Why does it look like this? Why are there flowers here? You seek associations all the time, and as nothing looks as usual, you must decide whether it looks good or not. This becomes a distraction." (Comment from a test subject)

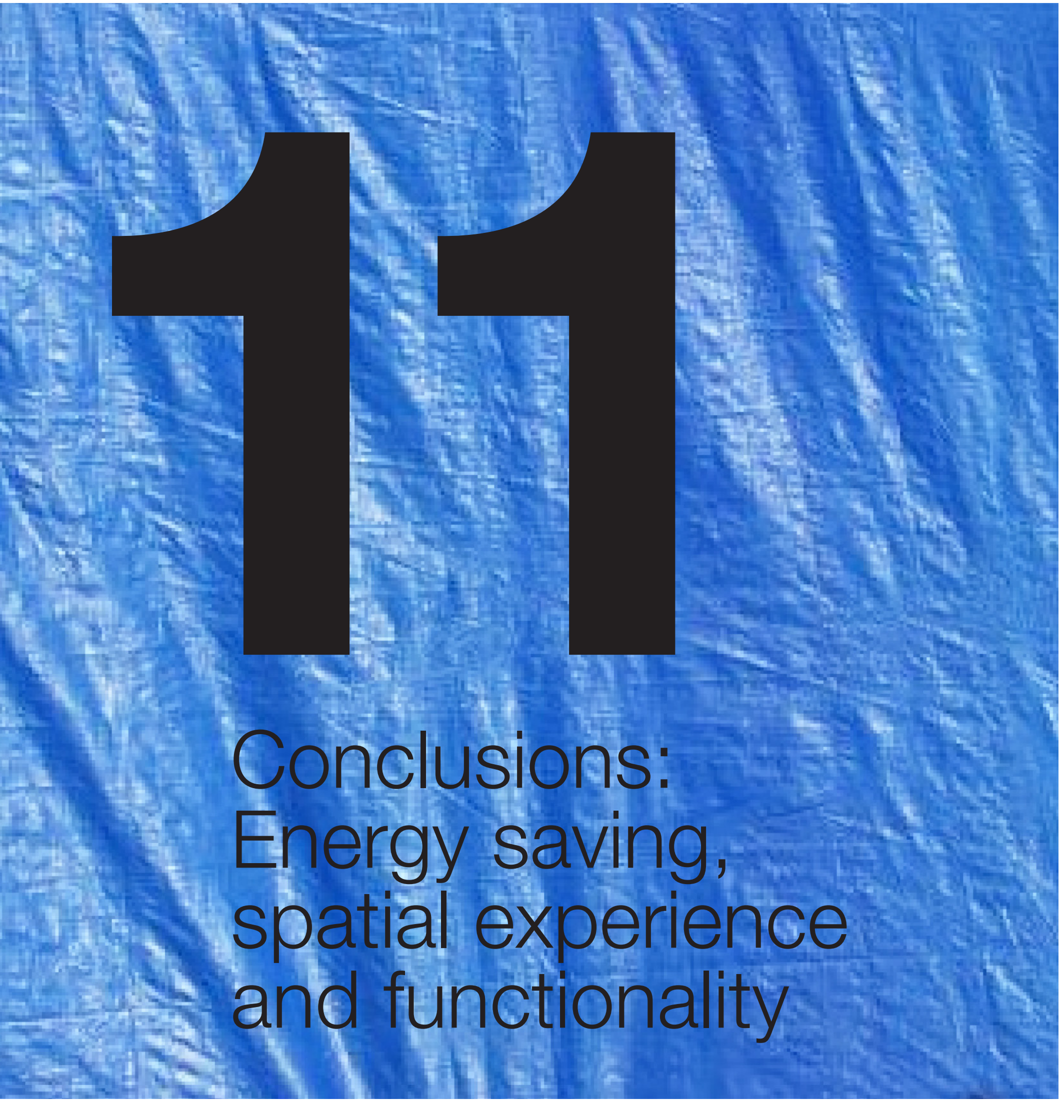
Maybe it would have been better not to try to make the room neutral, but instead to make it as normal and usual as possible, with furniture that is easy to associate with both a home and a public environment? Our motive for not choosing that option was that it could bring with it undesirable personal associations, and evaluations concomitant with these. After the evaluation discussion we now conclude, that even the newly made furniture resulted in uncontrollable associations and evaluations.
It may also be the case, that we, in our striving to create a room that feels genuine, raised the subjects' threshold
for what is acceptable. If this were a real room, to live or to work in, it would of course be very impersonal. If we had created a clear and strict test room, we might have gotten other types of answers, as one would have had much lower expectations there.

Conclusions about mood and atmosphere

The comments about mood and atmosphere in the different test rooms show that we did not achieve the positive room experiences that we aimed at. Neither could we, with the help of colour and light, create rooms with specifically different moods: dynamic and stimulating (room 1:1), and calm and harmonious (room 2:1 and 2:2), respectively. The reasons for this have to a large extent already been discussed. They may partly be derived from the test situation in itself and the design of the room, irrespective of its colour and light. For example, the room was perceived as calm irrespective of the light and colour situation. Clearly, it is not enough to use strong colours to create an activating mood in the room.

The intensity, quality and distribution of light play a large role in how a room is experienced and evaluated. If one experience vision difficulties, this is certainly a negative aspect of the entire situation. Light being perceived as logical has also been shown to have a large significance for the experience and evaluation of the room. Probably, we are here rather governed by conventions and by the patterns given by daylight through windows. Spotlights directed towards the floor, or towards what seem like randomly chosen parts of the wall, may be experienced as irritating, while it is seen as positive if they illuminate special objects worthy of our attention. Also, an intelligible orientation of light is preferred, with gradual transitions between more strongly and more sparingly lit parts of the room.

The contrast range between colours has a significant importance for the room to be experienced as distinct or not, and it also influences the experience of light or dark. Too small a contrast range easily makes the room diffuse or "washed out", and it is perceived as dark. Therefore, even if a coloration with similar colours is chosen, it is important that there are details both in black and white, and also details with relatively strong chromaticness and distinctly different hues.



11 Conclusions: Energy saving, spatial experience and functionality

The basis for the project OPTIMA is the need to reduce the energy consumption for illumination purposes and the current transition to more energy efficient light sources. To investigate how light and colour can interact in providing good spatial qualities together with a low energy consumption, we have chosen illumination solutions with very low power. In three different room versions, we used illumination with the power of 5, 3 and 2 W, respectively, per square meter room area.

These power levels are very much lower than the level recommended by the illumination industry and the Swedish Energy Agency. In the planning guide LJUS OCH RUM (LIGHT AND ROOM)[27] it says, for example, that small recreational rooms in offices should be lit with a power of at the most 10 W/square meter, and that well planned premises should be able to make do with 8 W/square meter. The low power levels used by us are only recommended for such as garages and industrial store houses. See Table 10.

The evaluation of the test rooms shows that they were perceived as too dark. Thus, we did not succeed in achieving rooms with a good functionality and room experience. There is, however, a fairly large possibility to increase the illumination of the rooms and still be very far below the recommended values. This should be tested in coming studies.

The investigation shows that the colour design of the room has a great significance for its experienced lightness and functionality. This not only regards the relatively self-evident fact that lighter room surfaces give a lighter room, if the illumination is constant, but also much more complex correlations between the illumination and the colour of surfaces. This provides a basis for specific hypotheses, which, if they are proven to be reliable, may deepen the knowledge about how colour design and illumination may cooperate in saving energy without losing other qualities. This is developed in section 13 of the report.

The development of LED technology has been governed by a desire to save as much energy as possible. The quality of the light that is provided with LED:s not only depends on the light source itself – the diode – but also to a high degree on the fitting, where

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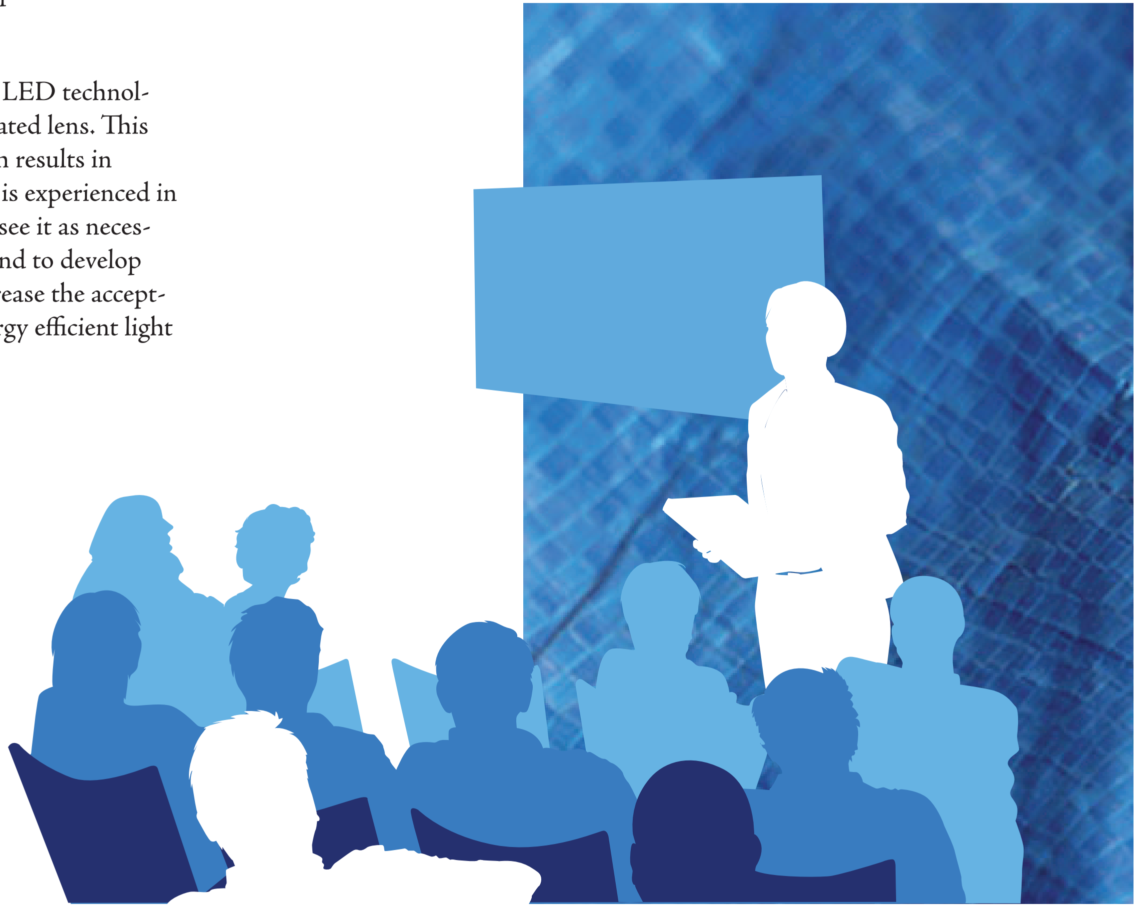
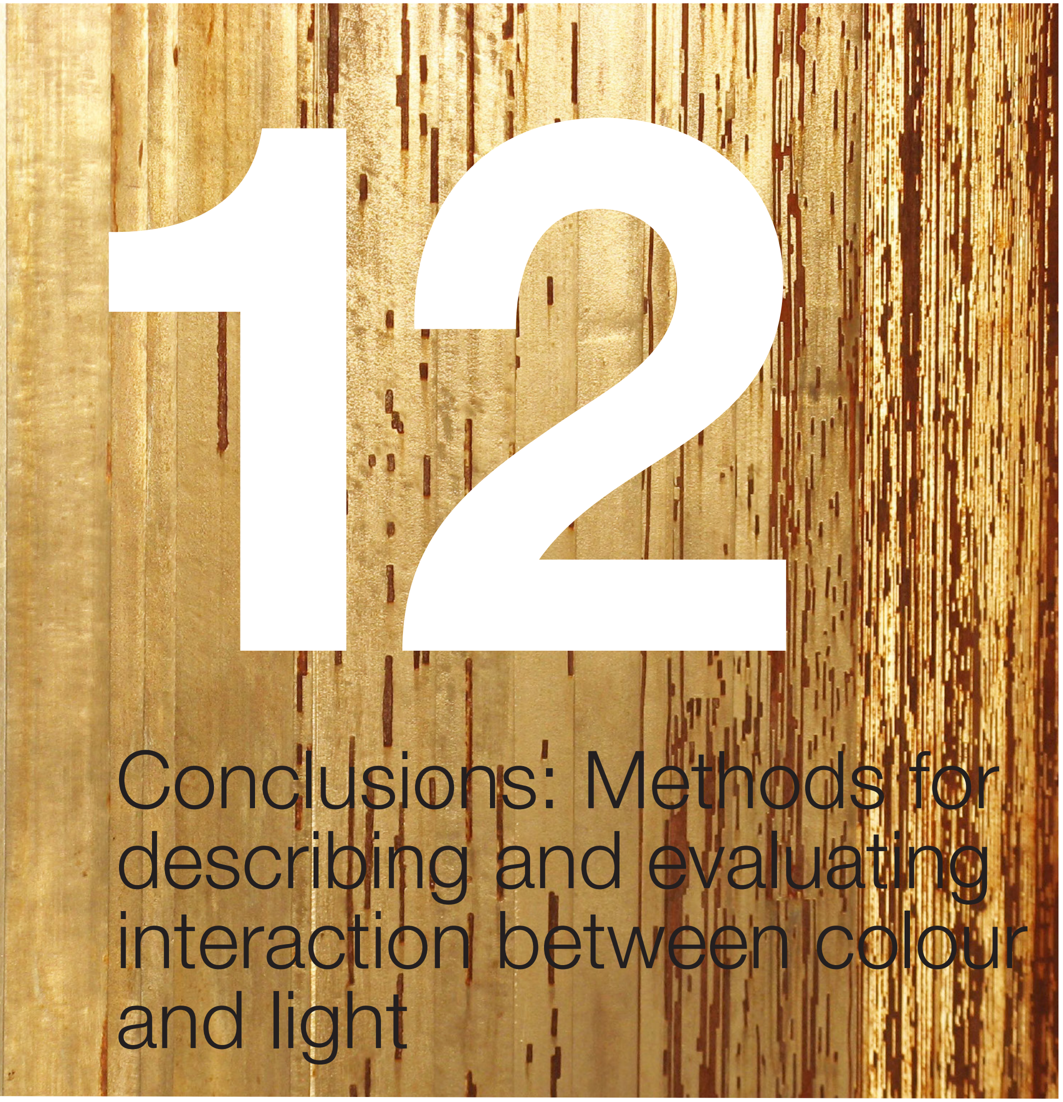
several diodes are mounted together. The diode as such provides light that is oriented in one direction only, and a "pack" of diodes normally has a light oriented directed within a sector of 120-160 degrees. Outside of this angle there is no "light spill" of the kind we are used to from traditional directed light sources.[28] This contributes to an uneven light distribution with sharp boundaries between light and dark, something which in our test rooms was experienced as irritating and deteriorating to the experience of the room.

This uneven light distribution is, however, not a necessary result of the LED technology, but can be changed by distributing the light with such as an integrated lens. This entails that a certain amount of the energy is stopped by the lens, which results in slightly less energy efficiency. To achieve a light that functions well and is experienced in a positive way by the people that will live in the illuminated rooms, we see it as necessary to abstain from a part of the theoretically possible energy saving, and to develop fittings giving a softer distribution pattern. Such fittings also could increase the acceptance of LED light and thus contribute to an increased use of these energy efficient light sources.



28 Annell & Berggren 2011 page 41.



12 Conclusions: Methods for describing and evaluating interaction between colour and light

Test subjects in full scale rooms

The work with OPTIMA has taken place in full scale rooms, which were assessed and evaluated with the help of test subjects. This has resulted in a deepened understanding that could not have been achieved with other methods. Assessment of pictures, digital representations or scale models are well tried methods for investigating partial aspects of a room, but if you wish to capture the totality they are insufficient. A spatial situation cannot be fully experienced if you are not actually inside that space, and it is only by when being in this situation that you can formulate the relevant questions about the spatial totality and its causes. However, it proved difficult to find principles for the furnishing of rooms that would not draw the subjects' attention away from the questions investigated. It also became obvious that non-visual aspects, such as acoustics and the quality of air must be taken into consideration when designing the room

Successive approximation based on design experience

The work with OPTIMA shows that the method of successive approximation is very suitable for investigating the covariance of light quality, light distribution, chosen colours and their placing in complexly designed rooms. The most important element in this method is the evaluation discussions, where the project's participants, with differing competences between them, discuss the assessments of the subjects and, based on this, formulate a new understanding of the spatial situation and suggestions for changes before the next round of tests.

By using successive approximation, we have been able to define which aspects of the total design of the room that were important to the subjects' assessments and test results. In a longer test series, where time permits a greater number of rounds of evaluation and modification, based on an unchanged specification of requirements, this method can lead to more specific conclusions than were possible in this pilot study. With a slight modification, the method could also be used to initially vary only a few parameters, and to make developed expert evaluations of the totality. In a room optimised in this way, a larger group of subjects may then be used to investigate the room's qualities in a more traditional way.

Questions about the room's appearance and mood

The subjects were asked to answer questions regarding how the room looked. In the revised questionnaire this was done by choosing at a maximum four out of twelve given words. The subjects' choice of words gave information about which colour and light qualities caught their attention, and how these were evaluated. Open questions about the appearance of the room were also asked. These methods proved to be suitable to catch what the individual deemed important and did not deflect attention to things that were not spontaneously perceived.

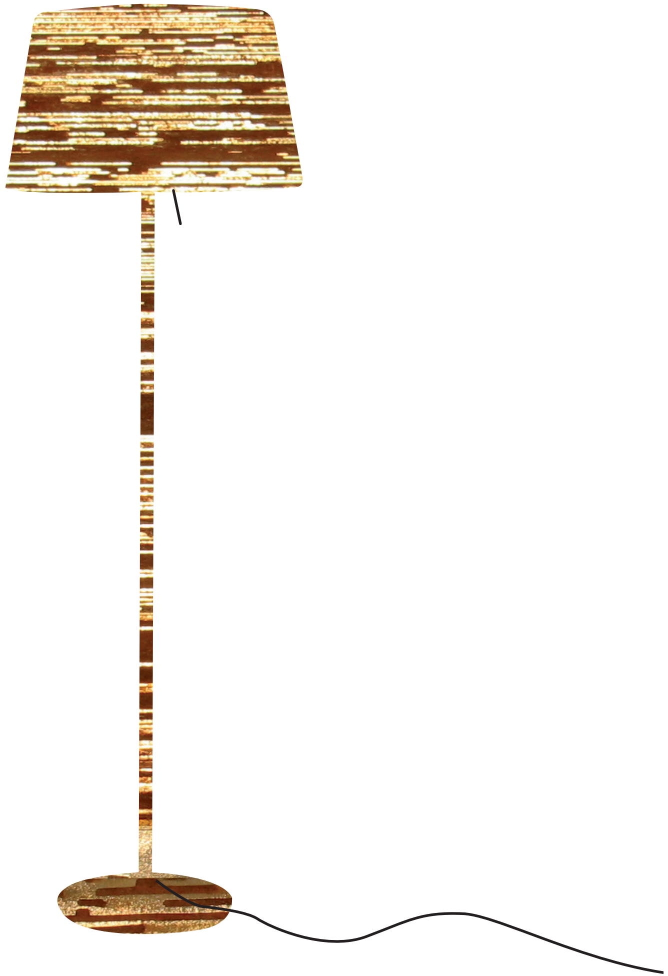
The subjects also answered questions about the mood they experienced in the room. Here also, the subject could choose at a maximum four out of twelve given words, and they also answered other questions regarding the mood of the room. The different ways of asking about the mood gave answers consistent with each other, which supports the reliability of the answers.

The words that the subjects may choose between can be adapted according to the goal of the individual study and provide a coarse check of the room's correspondence to the requirements. Open questions of the type "what is positive – what is negative – what is disturbing" are very valuable, as they give complementary, and often more exact, information about what catches the subjects' attention and how they evaluate different aspects of the room.

More controlled questions about the experience of colour or light prove to be less suitable to catch what is deemed essential, since the subject in this case is asked to look for and comment on things that they otherwise may have ignored. A distinct example is the question about glare – in most light situations a glare may be experienced if you look for it, but it may never come to a person's attention if the question is not asked.

Functionality test – reading

The room's functionality for reading was tested by letting the subjects read a few pages in a paperback in two different light situations and answer questions about this. It turned out that all subjects, with a few exceptions, could read the book in both light situations. Reading thus did not contribute much to understanding the room's functionality. This means, in hindsight, that

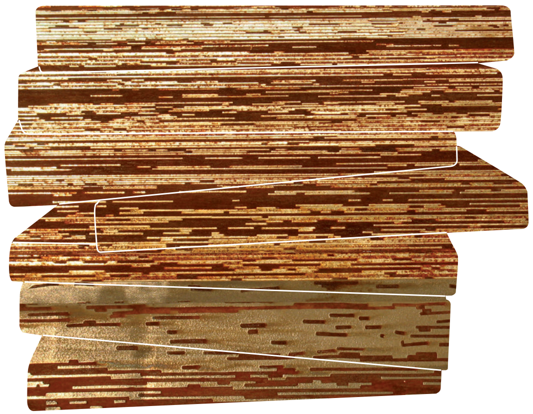


this task got an unnecessarily large part of the time for tests. It also turned out that the choice of book risked governing the subjects' entire idea about the test situation, and that this indirectly influenced their answers also to other questions.

Despite these objections the reading test had a great value as it led to comments, where the subjects compared the different situations and told how they experienced the light. To get this type of comments it is necessary to put the subject in an actual situation, where they are asked to evaluate the light. Possibly more suitable tasks may be found to start the same process – drawing, talking about pictures, building with Lego blocks, baking a cake?

Colour discrimination and categorisation tests

To demonstrate the colour qualities of the light situation two methods were used, the results of which complemented each other. The colour tests led us to conclusions we had not anticipated, and thus contributed significantly to a greater understanding of the effect of the chosen light sources in realistic spatial situations.
The use of the Farnsworth-Munsell 100 Hue Colour Vision Test turned out to be easy to understand and implement and gave results that could be interpreted. The test subjects were very different in being used to and capable of colour discrimination, but the effect of this was eliminated as we compared the performances of one and the same person in two different illumination situations. Thus the results of different test groups could be compared to each other. The selection of twenty different samples from four colour areas gave information about different parts of the colour circle, but it may be meaningful to test another selection, to see if this gives even more distinct results.

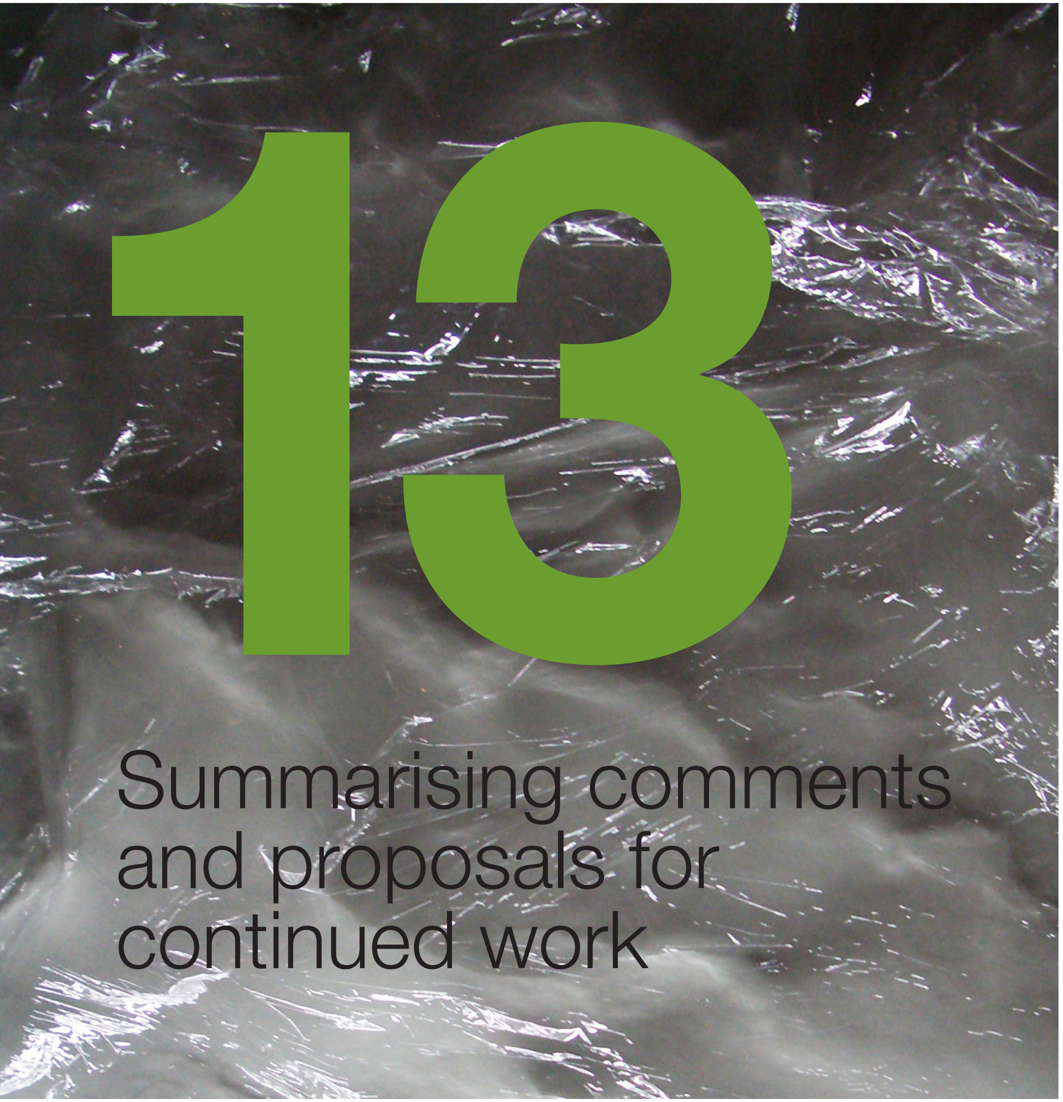


In the colour categorisation test the subjects made simple hue and nuance assessments of twelve colour samples in two illumination situations. The subjects' knowledge of the categories used differed significantly, but we counted on the effect of this being eliminated by only comparing an individual's assessment with their own assessment in the other situation. In many cases we could see that an individual made consistent errors compared with what an a person experienced in such assessments would have made, but these errors seemed to be constant during both test series, and they thus, as expected, did not impact the result. Despite this it would be desirable to be able to spend more time on an introduction, as well as performing a test round as a methodology training. It would also be valuable to have assessments of somewhat more than the 12 samples used in this study.
In both the colour tests the subjects first performed the task in the test room, and then in the light box. We do not judge that this made a difference for the result, but for a more reliable result we recommend that half the tasks are performed the other way around.

The person's own regulation of the light situation

The tests performed did not include any possibility to regulate the direction or strength of the light. For an increased understanding of how different individuals perceive the light situation it would, however, be valuable to have tests where the subjects themselves set the lighting to comply with their requirements for comfort and function, with a possibility of directly charting the choices made. This kind of test set-up needs other equipment than what we used in OPTIMA.

Interior details from the test rooms



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Summarising comments and proposals for continued work

OPTIMA has been carried out as a pilot project, where an important part of the result is to formulate questions for further research. Here, we can isolate three important areas associated with energy consumption and the new illumination technique:

- The possibilities to save energy through interaction between colour and light
- Increased understanding of how LED:s function in realistic spatial situations
- The relation between the illumination of different parts of a room

Energy saving through interaction between colour and light

Based on the tests that were performed, we posit the hypothesis that the contrast range of a room's colours is important for the experienced lightness of a room, meaning that a larger contrast range provides the experience of more light. Preliminarily this pertains both to the contrast range in lightness, from white to black, and to the contrast range between colours with different chromaticness and hue.

We also put forward the hypothesis that the spatial distribution of colours can interact with the real or expected distribution pattern of light, in a way that enhances the experience of light. Distinct borders between different fields of colour and between surfaces with differing orientation are essential to give the room a distinct shape and counteract the merging of colours. We posit the hypothesis that such a distinctiveness in the room contributes to the experience of a good illumination.

If these hypotheses could be verified, it could lead to actively using colour design to reduce the need of illumination, with a maintained experienced light level. The hypotheses, however, concern only the total experience, that is to say what is observed with peripheral vision. If the contrast range of the room also influences the prerequisites for a good central vision is an open question. These hypotheses should be tested in full scale studies, possibly with preliminary studies in scale models.

It can also be envisaged that energy can be saved by adapting the reflection curves of the room surfaces to the spectral distribution of the light sources and eventual coated window panes. This possibility has not been explored within OPTIMA, but could be formulated as a project, where lighting industry, paint industry and the glass producers could cooperate, using their respective specialist knowledge

LED:s in spatial situations

The OPTIMA tests have shown colour rendering effects (a shift towards blue), which could be due to the spectral distribution of the diodes used but could have also have other reasons. This is a question that should be investigated further.
Sometimes people experienced difficulties focussing in the LED-illuminated rooms. There were different theories about what could be the reason for this: chromatic aberration, flicker in the electronics, multiple shadows, adaptational effort at the border between a sharply delimited light cone and its dark surroundings.

We also experienced diodes with the same nominal colour temperature giving a visually cooler light when they had a stronger illuminance and/or a narrower distribution pattern. This resulted in wall colour being perceived in a distinctly different way in different parts of the room. One theory is that this has to do with the design of the LED fittings, but effects should also be tested with applicable knowledge in colour theory, regarding such phenomena as the Bezold-Brücke effect.

What we observed about LED:s in spatial contexts may possibly be partly explained by already existing specialized technical knowledge. Further understanding can be gained by laboratory tests, designed with specific questions in mind. This may lead to hypotheses that then could be tested in full scale rooms.

The relation between the illumination of different parts of a room

During the discussion about the OPTIMA rooms, 5-3-1 was often mentioned as a frequently applied recommendation for perceived light relationships in a room. In Ljus och Rum(Light and room)29 there are similar recommendations for luminance relationships between a work area and its surroundings at different distances. It may be assumed that these recommendations are based on experiences of traditional light sources. An interesting task for continued studies would be to, with the help of test subjects, test these recommendations in rooms illuminated with LED:s, and to compare the results with the studies upon which the recommendations are based..

29 Ljuskultur 2010, page 103.

References

Annell, S & Berggren, L, 2011: *Våra vanligaste ljuskällor*. Stockholm: Annell Ljus+Form.

Billger, M, 2006: 'Rummet som färgernas mötesplats' in Karin Fridell Anter (red): *Forskare och praktiker om FÄRG LJUS RUM*. Stockholm: Formas.

Billger, M, 1999: Colour in Enclosed Space, Göteborg: Dep. of Building Design, Chalmers University of Technology

Derefelt G & Berggrund U, 1994: *Färg som informationsbärare*. Stockholm: FOA

Fridell Anter, K, 2000: *What colour is the red house? Perceived colour of painted facades*, Stockholm: Arkitektur, KTH

Fridell Anter, K, 2008a: Aktuell svensk litteratur om ljus och färg. *Annoterad bibliografi 2007*, SE RUM, web publication www.explicator.se

Fridell Anter, K, 2008b: Ljus, färg och deras samverkan i rummet. *Kunskapsöversikt 2007*, SE RUM, web publication www.explicator.se

Fridell Anter, K & Billger, M, 2010: 'Colour research with architectural relevance: How can different approaches gain from each other?' *Color Research and Application* 35:2 sid 145-152

Green-Armytage, P, 2006: 'The Value of Knowledge for Colour Design' *Color Research and Application* 31:4 sid 253-269

Hein, P, 1985: 'Att formulera ett problem är att lösa det'. In *Forskning och Framsteg* 6/85

Hård, A & Svedmyr Å, 1995a: *Färgsystemet NCS. Tanke, tillkomst, tillämpning. Färgantologi bok 1*, Stockholm: Byggforskningsrådet

Hård, Küller, Sivik & Svedmyr, 1995b: *Upplevelse av färg och färgsatt miljö. Färgantologi bok 2, Stockholm*: Byggforskningsrådet

Hårleman, M, 2007: *Daylight Influence on Colour Design. Empirical study on perceived colour and colour experience indoors*, Stockholm: Axl Books

Klarén, Ulf, 1997: 'Varför skrattar femåringen' In Ulf Klarén: *Diverseartiklar*. Stockholm: Konstfack

Kronqvist, A, 2010: 'The influence of the Lighting Environment on Performance and Well-being in Offices'. in Zennaro, red: *Colour & Light in Architecture. International Conference Venice 11-12 November 2010*. Verona: Knemisi.

Lillo, Aguado, Moreira & Davies, 2004: 'Lightness and hue perception: The Bezold-Brücke effect and colour basic categories' *Psicológica* 25 sid 23-43.

Liljefors, A, 2006: 'Ljus och färg i seendets rum' in Fridell Anter, red: *Forskare och praktiker om FÄRG LJUS RUM*, Stockholm: Formas

Ljuskultur, 2010: Ljus och Rum. *Planeringsguide för belysnings inomhus*.

Matusiak, B, 2006: 'The impact of window form on the size impression of the room. Fullscale studies'. *Architectural Science Review*, 49:1

Mårtensson, Bertil. 1980: 'Falsifiering eller förändring genom vetenskapliga revolutioner Popper versus Kuhn', i Bengt Hansson (red): *Metod eller anarki – moderna teorier om vetenskapens väsen och metoder*. Lund: Bokförlaget Doxa

Sandström, Bergqvist, Küller, Laike, Ottosson & Wibom, 2002: *Belysning och hälsa. En kunskapsöversikt med fokus på ljusets modulation, spektralfördelning och dess kronobiologiska betydelse*. Arbete och hälsa, Stockholm: Arbetslivsinstitutet

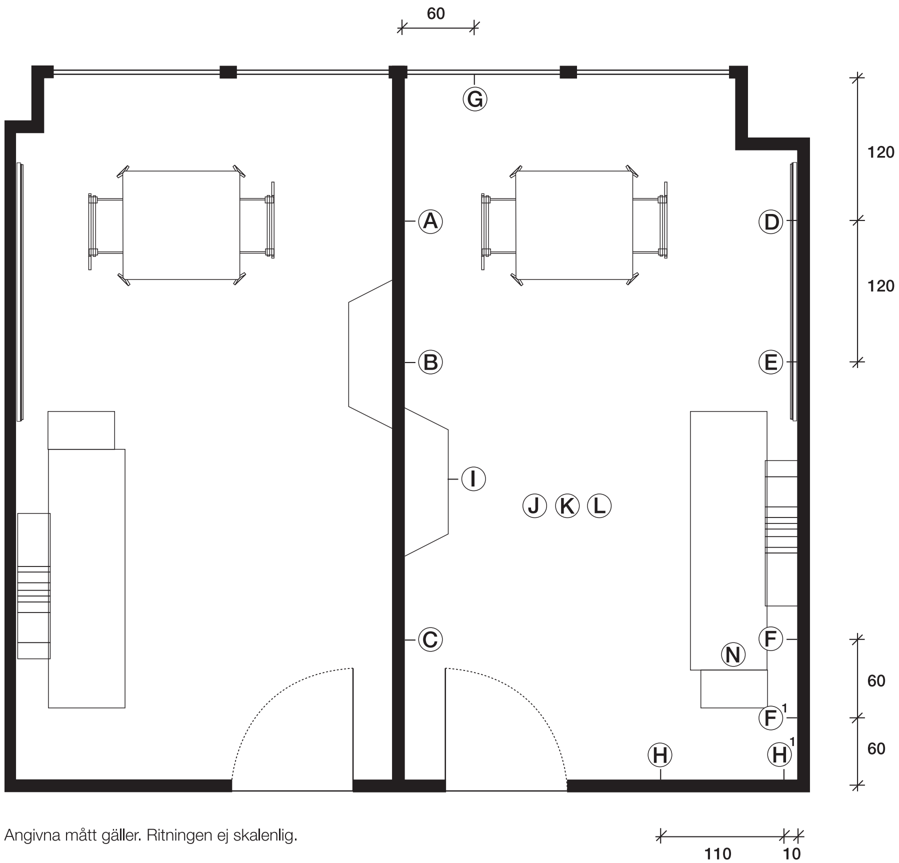
Starby, L, 2006: *En bok om belysning*. Ljuskultur.

Vogels. I, 2008: 'Effect of coloured light on atmosphere perception' *Proceedings from AIC Interim Meeting Colour - Effects and Affects, Stockholm June 2008*, web publication http://www.aic-colour.org/histo.htm

Technical specifications

Drawing with measuring points

In each of the room versions 1:1, 2:1 and 2:2 the illuminance was measured on walls and floors. See the plan below for measuring points. The measurements on the walls were in most cases performed on three heights – 60, 120 and 180 cm above the floor. Based on the lux values and the reflectance of the surfaces, luminance values were calculated for all points.
On the following pages a selection of the values for the respective room versions are presented. All measured values, including comments about the measuring situation, are found on pp. 65-67.



Angivna mått gäller. Ritningen ej skalenlig.

Measured values, room 1:2

Calculated energy consumption appr. 5 W / square meter

Measured illuminance (rounded to the nearest 5 lux, except for values below 10)

Walls, height 180 cm	55-95 lux
Walls, height 120 cm	35-70 lux
Walls, height 60 cm	35-50 lux

The most illuminated wall section was in the corner behind the sofa, directly lit by the spotlight above the sofa. The least illuminated wall section was the shadow below the shelf above the sofa.

Floor, most illuminated part (on the red carpet)	360 lux
Floor, centre, between light cones (on beige linoleum)	65 lux
Floor, in shadows from furniture	not measured
Yellow cupboard, most illuminated part (glossy surface)	160 lux
Yellow cupboard, least illuminated part (glossy surface)	50 lux
White table, most illuminated part	605 lux
White table, least illuminated part	155 lux

Calculated luminance values	
Grey side walls	6-15 cd/m2
White wall with window	23 cd/m2
White back wall	13-27 cd/m2
Red board on the wall	1-2 cd/m2
White table	43-170 cd/m2
Red carpet	12 cd/m2
Floor, outside of cast shadows	10-11 cd/m2

The yellow cupboard was glossy and reflective, and therefore its luminance could not be calculated.
The highest luminance was found in the light cone on the table, the second highest on the directly spot lit blanket in the sofa.

Measured values, room 2:1

Calculated energy consumption appr. 2 W / square meter

Measured illuminance
(rounded to the nearest 5 lux, except for values below 10)

Walls, height 180 cm	10 - 120 lux
Walls, height 120 cm	10 - 50 lux
Walls, height 60 cm	7 - 25 lux

The most illuminated wall section was near the right-hand corner at the window, on and around the board.

Floor between cupboard and sofa	10-235 lux
Greyish green cupboard, most illuminated part (glossy surface)	110 lux
Greyish green cupboard, least illuminated part (glossy surface)	11 lux
White table, most illuminated part	1040 lux
White table, least illuminated part	40 lux
Blanket in sofa, directly below spotlight	1100 lux

Calculated luminance values	
Grey side walls	2 - 9 cd/m2
White wall with window	11 cd/m2
White back wall	3 cd/m2
White board on the wall	6-61 cd/m2
White table	10-291 cd/m2
Floor, outside of cast shadows	2-37 cd/m2
Blanket in sofa (assumed reflectance 50 %)	175 cd/m2

The greyish green cupboard was glossy and reflective, and therefore its luminance could not be calculated.
The highest luminance was found in the light cone on the table, the second highest on the directly spotlit blanket in the sofa.

Measured values, room 2:2

Calculated energy consumption appr. 3 W / square meter

Measured illuminance
(rounded to the nearest 5 lux, except for values below 10

Walls, height 180 cm	25-90 lux
Walls, height 100 – 120 cm	25-100 lux
Walls, height 60 cm	25-35 lux
Floor between cupboard and sofa	30-680 lux
Green cupboard, most illuminated part (glossy surface)	215 lux
Green cupboard, least illuminated part (glossy surface)	25 lux
White table, most illuminated part	1600 lux
White table, least illuminated part	115 lux

Calculated luminance values	
Grey side walls	5-12 cd/m2
White wall with window	17 cd/m2
White back wall	9 - 28 cd/m2
White board on the wall	25-26 cd/m2
White table	32 - 450 cd/m2
Floor, outside of cast shadows	9-108 cd/m2

The green cupboard was glossy and reflective, and therefore its luminance could not be calculated.

The highest luminance was found in the light cone on the table, the second highest in a light cone on the floor

Room 1:2 Measured illuminance values and calculated luminance values

The table shows measured lux values on a series of points according to plan (p. 63). Measurements were performed on the heights of 60, 120 and 180 cm if nothing else is said. The luminance was calculated for the lightest and the darkest parts of each surface, respectively.

Measure point	Measured lux values, height above floor					Luminance calculation for selected measuring points					
See page 63	Floor	60cm	120cm	180cm	Comment	Description	Point	Reflectance	Lux	cd/m^2	Comment
A		49	68	85		Grey wall max	A 180	57%	85	15	
B		40	52	68							
C		36	41	54							
D		47	55	81	180=at board	Red board max	D 180	6%	81	2	
E		44	48	62	180=at board	Red board min	E 180	6%	62	1	Darkest
E1											
F			38		Not in shelf shade						
F1			34		Not in shelf shade	Grey wall min	F1 120	57%	34	6	
G				81	Height 164 cm	White window wall	G 164	88%	81	23	
H			45			White back wall min	H 120	88%	45	13	
H1			59	96		White back wall max	H1 180	88%	96	27	
H2											
I			162		Lightest part. Height not specified						
I1			50		Lightest part. Height not specified						
I2											
J	362				Middle of carpet	Red carpet	J	10%	362	12	
J1											
K	72				Lit	Floor, light area	K	50%	72	11	
L	64				Between light beams	Floor, dark area	L	50%	64	10	
L1											
L2											
M	607				Lightest part	Table max	M	88%	607	170	
M1	153				Darkest part	Table min	M1	88%	153	43	Lightest
N											

Room 2:1 Measured illuminance values and calculated luminance values

The table shows measured lux values on a series of points according to plan (p. 63). Measurements were performed on the heights of 60, 120 and 180 cm if nothing else is said. The luminance was calculated for the lightest and the darkest parts of each surface, respectively

Measure point	Measured lux values, height above floor					Luminance calculation for selected measuring					
See page. 63	Floor	60cm	120cm	180cm	Comment	Description	Point	Reflectance	Lux	cd/m^2	Comment
A		15	32	38							
B		7	20	22							
C		12	11	12							
D		23	48	117	180=at board	Grey wall max	D 120	57%	48	9	
E		13	19	23	180=at board	White board min	E 180	88%	23	6	
E1				216	Lightest at board	White board max	E1 180	88%	216	61	
F			11		Not in shelf shade						
F1			9		In shelf shade	Grey wall min	F1 120	57%	9	2	Darkest
G				41	Hight 164 cm	White window wall	G 164	88%	41	11	
H			12			White back wall max	H 120	88%	12	3	
H1			10			White back wall min	H1120/180	88%	10	3	
H2											
I			108		Lightest part. Height not specified						
I1			11		Darkest part. Height not specified						
I2											
J	13				Middle of carpet	Beige carpet	J	40%	13	2	Darkest
J1	235				Lightest on floor	Floor, light area	J1	50%	235	37	
K	52				Lit at sofa						
L	13				Not directly lit	Floor, dark area	L	50%	13	2	Darkest
L1											
L2											
M	1038				Lightest at table	Table max	M	88%	1038	291	Lightest
M1	37				Darkest at table	Table min	M1	88%	37	10	
N		1100			Blanket at sofa, under spot light						

Rum 2:2 Measured illuminance values and calculated luminance values

The table shows measured lux values on a series of points according to plan (p. 63). Measurements were performed on the heights of 60, 120 and 180 cm if nothing else is said. The luminance was calculated for the lightest and the darkest parts of each surface, respectively.

Measure point	Measured lux values, height above floor					Luminance calculation for selected measuring					
Se sid. 63	Floor	60cm	120cm	180cm	Comment	Description	Point	Reflectance	Lux	cd/m^2	Comment
A		33	66	67		Grey wall max	A 180	57%	67	12	
B		33	55	61							
C		26	25	27		Grey wall min	C 120	57%	25	5	
D		36	38	92	120 in shelf shade, 180 at board	White board max	D 180	88%	92	26	
D			60		Höjd 100 cm = not in shelf shade						
E		27	28	88	180=at board	White board min	E 180	88%	88	25	
E1					Lightest at board					61	
F			25		In shelf shade						
F1			46		Not in shelf shade					2	
F2			53		Not in light beam from floor lamp						
G				62	Hight 164 cm	White window wall	G 164	88%	62	17	
H			32		Not in light beam from floor lamp	White back wall min	H 120	88%	32	9	
H1			38		Not in light beam from floor lamp						
H2			99		In light beam from floor lamp	White back wall max	H2 120	88%	99	28	
I		27			Lower part cupboard						
I1				214	Upper part cupboard						
I2											
J	31				Middle of carpet	Beige carpet	J	40%	31	4	Darkest
J1					Lightest area, floor						
K	679				In light beam, cupboard	Floor, light area	K	50%	679	108	
L	54				Between light b. cupboard	Floor, dark area	L	50%	54	9	
L1	214				In light beam, floor lamp						
L2	130				In light beam, at table						
M		1605			Lightest at table	Table max	M	88%	1605	450	Lightest
M1		113			Darkest at table	Table min	M1	88%	113	32	
N											

Spectral distribution graphs

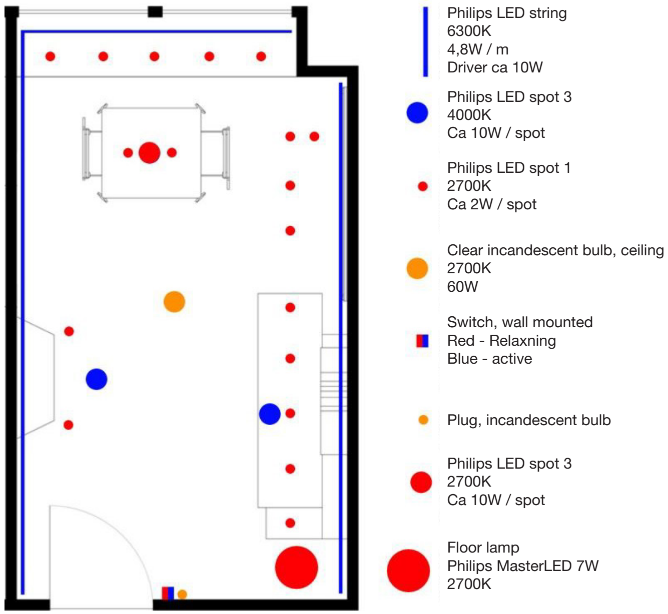
Spectral distribution of used light sources and on different parts of the walls were measured on February 10:th 2011 with AvaSpec-2048 Fiber Optic Spectrometer from Avantes. The measuring of the ceiling mounted light sources was done vertically below the light source, about 70 cm above the floor. The measurement of the floor lamp was made from above and from the side, directly outside the lamp shade, in both cases about 30 cm from the light source .For each light source the room/rooms where it was used is noted.

The measurements in the daylight room were done about 2.30 PM and represent one of many possible daylight situations in the room. Half of the eight window panes had lowered, but not angled, blinds, while the others had the blinds pulled up. The weather was cloudy, the ground was covered with snow. The daylight from the window was measured directly inside the window, with the meter lying on the table. The illuminance there was about 220 lux.

The reflected light from the walls in the daylight room and room 2:2 was measured as the average along vertical lines on several planar positions, according to the figure on p. 63.

As an illustrative example spectral graphs from the flourescent tubes of the daylight room and from a clear incandescent bulb of 60 W are shown.

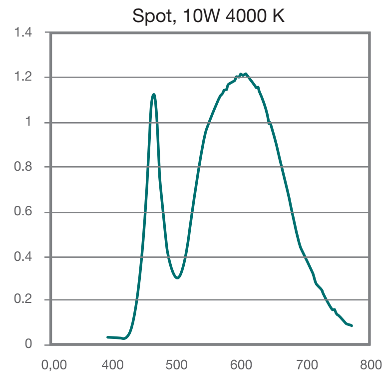
Note that the scale varies between the different charts!

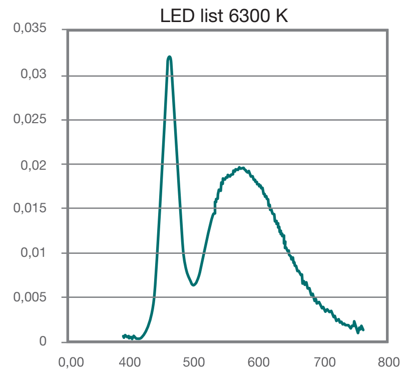


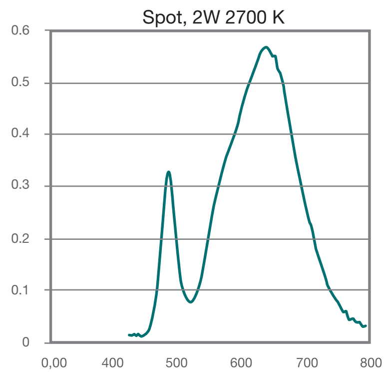
Lighing plan (Svante Pettersson - Philips AB, Lighting)

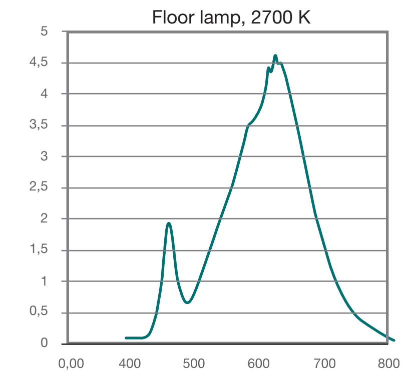
Spectral distribution curves for the light sources used in the studies

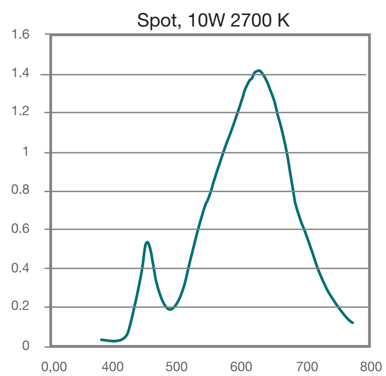
Spot 10W, 4000 K - Room 1:2, LED list 6300 K, Room 1:2
Spot 2W, 2700 K - Room 2:1 and 2:2
Spot 10W, 2700 K - Room 2:2, Floor lamp 2700 K - Room 2:2

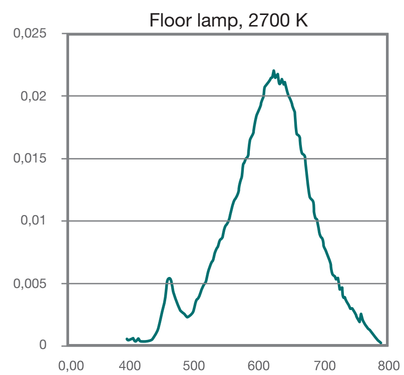






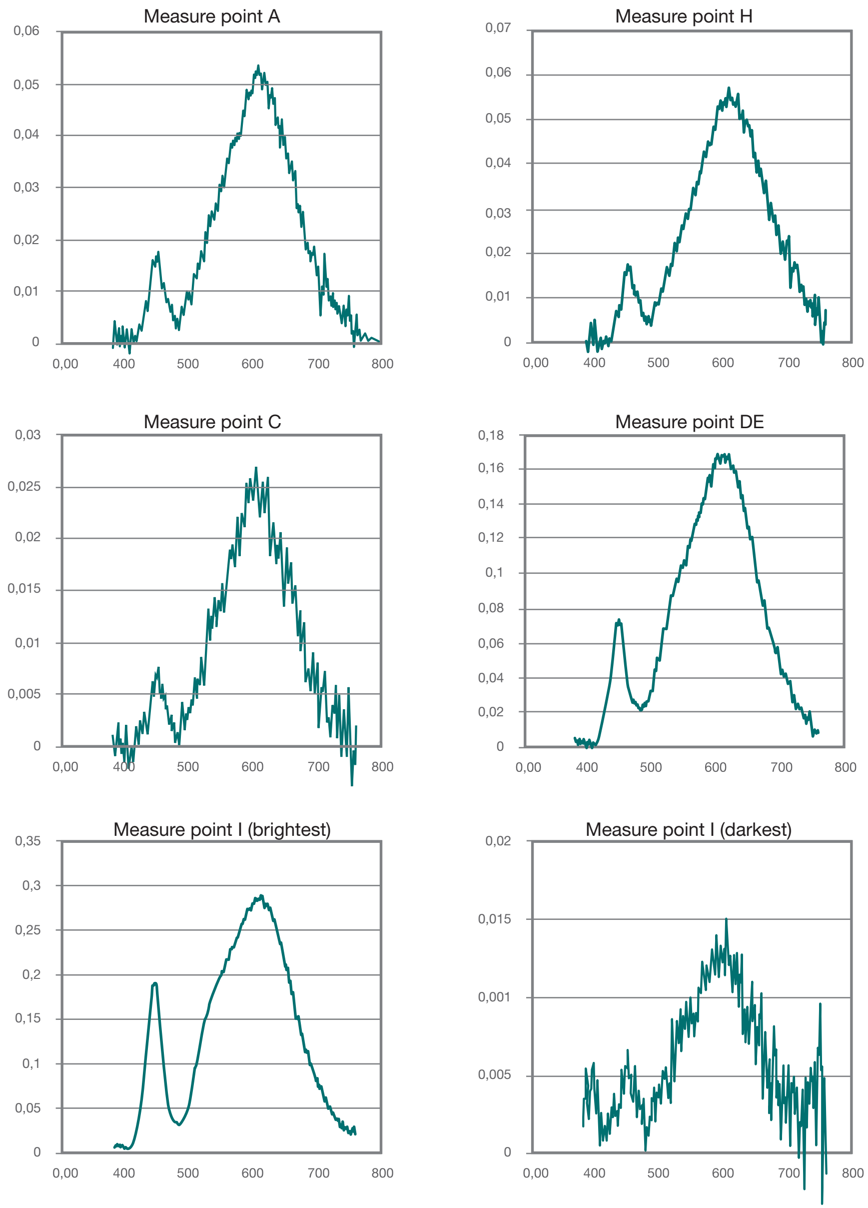






Spectral distribution of reflected light from the walls in room 2: 2 (see plan, page 63)

Measure point A (grey wall)
Measure point C (grey wall)
Measure point I (brightest parts, green glossy cabinet)
Measure point H (white wall)
Measure point DE (grey wall under board)
Measure point I (darkest parts, green glossy cabinet)



Spectral distribution in the daylight room and for the incandescent bulb