Energieffektiv belysning gennem fotorealistisk visualisering

Energy efficient lighting through photorealistic visualization

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Danish summary	Rapportens hovedformål er at undersøge forskellige belysningstyper for seks scenario i henholdsvis kontorlandskaber, mødelokaler, skoler, hospitaler og atrium. De forskellige belysningstyper evalueres i forhold til deres energi forbrug (W/m2) og deres belysningskvalitet bedømmes af et panel af observatører. Derved vurderes de bedste belysningstyper som scorer højest i begge kategorier og dermed både har en høj lyskvalitet samt er højst effektive. Ved metoden blev der identificeret følgende resultater/strategier: Ved effektiv bordbelysning kan man reducere strømforbruget i loft armaturer ved at skrue belysningsstyrken ned. Brug af ”vægvasker” belysning er generelt effektivt til at få rum til at virke større og kan styrke arkitektoniske træk uden at påvirke strømforbruget betydeligt. Ved at ændre lysets farvetemperatur kan man opnå interessante rum opfattelser, effekten på energiforbrug er dog ikke blevet fastsat.

Key words	Lighting, lighting schemes, lighting quality, highly efficient lighting systems, photorealistic imaging, lighting simulation
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Abstract

This report describes various steps of a study aimed at exploring successful energy efficient lighting solutions including description of the method, testing campaign, and analysis of the results.

It has benefitted from subsidies from Elforsk (PSO project no. 346-046).

Various ways to light buildings (with electric lighting) have been investigated, with a double objective: reducing electric power density and improving user satisfaction.

The selected approach was the projection of photorealistic images of indoor spaces to panels of observers. Each photorealistic image was a calibrated scene relevant to one lighting scenario. For each configuration, the exact electric power consumption of the lighting installation was calculated. The panel of observers was asked to compare lighting scenes one to one and to express their preferences, leading to the classification of the perceived quality of lighting installation.

This technique led us to identify lighting techniques allowing improving the quality of indoor spaces, and simultaneously reduce the electric power density.

We selected the following case studies: office space, atrium, hospital rooms (patient, wake-up room), shopping centre, meeting room, and classroom.

The participants proposed various ways to reduce energy consumption of artificial lighting and simultaneously increase user satisfaction. Most of them dealt with adding a small complement of light on specific surfaces in a way that largely compensates for a reduction of the power to general lighting. In this case, the number of light sources tends to increase, but global electric power used for general lighting decreases most of the time.

Various successful strategies were identified:

- Deploy efficient task lamps in combination with reduction of power to ceiling luminaires
- Insert thin LED wall washers to increase wall luminance (mainly in meeting rooms, classrooms, and circulation areas)
- Insert thin cove lighting at edges of walls to strengthen architectural value (circulations, commercial centres)
- Play with the spectrum of colour variations: Use two light spectra in the same room

- Increase variation of light variations in space and on surfaces. This increases contrasts and allow for some darker areas.
- Use suspended luminaires in meeting rooms (not in offices)
- Light large spaces by increasing wall luminance (and reduce overall lighting)
- Apply miniaturized light sources to bring the exact amount of light where needed
- Supply right lighting of human faces, especially in spaces where service is important (hospitals)

In addition, we identified the need for developing specific innovation lighting products:

- Very efficient task lamps
- Thin Led based (recessed) wall washers
- Luminaires made of groups of independent recessed LEDs in ceilings
- Stand-alone luminaires for large indoor spaces
- Wall mounted luminaires for improving quality of lighting during visits in hospitals

A large database of images has also been produced, to be used by the authors and their partners.

Introduction

Artificial lighting and energy are not topics that easily will catch the Danish architects' interest. Nevertheless, the architects' influence on energy-saving, functional and aesthetic lighting can be tremendous.
This project aims to generate interest, knowledge and tools for visualization of energy efficient lighting solutions. Energy demand in a light installation depends not only on the chosen luminaires, but also on lighting scenarios, which must be tailored to user needs and support the building design.
LED fixtures are becoming more and more popular in indoor lighting, and provide new opportunities for precise lighting control, dimming and tuning of the colour temperature. Unfortunately, the new technology often leads to unforeseen problems, e.g. in the form of glare, because the new light sources are used in new ways and have light distributions that cannot be simulated in the traditional lighting software.
Consequently, it is important to use tools that give credible evidence that energy efficient lighting solutions and user comfort can go hand in hand.
This project aims at visualizing and comparing lighting options in typical indoor environments, and at identifying directions in lighting design that could lead to both reduction of electric power consumption for lighting, and to indoor luminous environments that are more user friendly and attractive.

The project relies on a process with multiple steps:

- Design of various energy efficient lighting schemes, for comparison
- Detailed simulation and production of calibrated photorealistic images
- Presentation of images in pairs to observers to rate the lighting quality
- Full technical documentation of technical aspects of simulated scenes with rating of energy efficiency
- Graphical display of results, allowing identification of win-win scenes: Offering high energy performance and high quality for the occupants
- Identification of possible lighting equipment to develop for high performance.

3D pipeline for an agile calibrated testing process

Several steps were implemented to ensure portability and the possibility for a flexible calibration process. Calibrations of screens are often vital parts of setting up projection systems and ensuring a correct image involves several steps. These steps vary from single screen calibration to multiple projector overlay calibrations. Most critical is the calibration of luminance to ensure photometrical uniform displays (Majumder & Stevens, 2004).

Photometric lighting in computer graphics

For the purpose of this project we needed a way to simulate physically accurate lighting, as well as visualize it in a photorealistic way. The state of the art tool that is widely spread in the industry and meets these requirements is the render engine “V-Ray” developed by Chaos Group.
Being a physically based render engine and being famous for the image quality production, it was an already reliable tool to work with. However, for the purposes of this project, further validation was needed. A review done by Villa, Parent, and Labayrade (2010) of different rendering engines V-Ray proved to be the most effective in terms of creating photorealism in scenes with different lighting atmospheres. The particular research was done using a subjective method. In this study we would like to combine subjective metrics with objectives such as lux levels, luminous output, power consumption etc. To do this we performed test in order to validate the measurement of such objective metrics.
The first and foremost features that needed validation were light behaviour and material properties. To achieve this, we recreated an experiment often used by engineers in the industry. This experiment would validate the interaction between material properties and light. In particular, a virtual integrating sphere was created. The fact that the sphere was virtual, allowed us to beam collimated light onto a sample inside, without needing to have an opening. That increases the accuracy of the calculations compared to a real life integrating sphere. The image of the sphere can be seen in Figure 1.

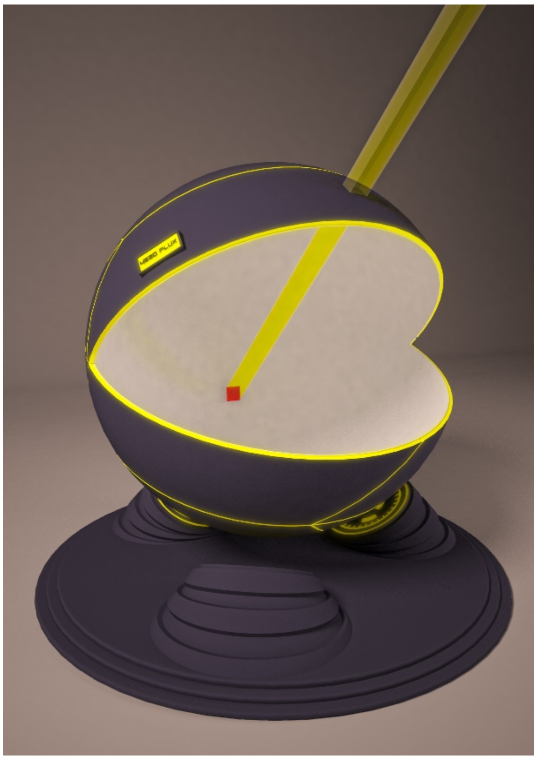


Figure 1 3D simulation of the integrated sphere used in the validation experiment (diffuse reflectance characterization). The light is being directed "through" the outer shell of the sphere

The light beam is angled toward a materials sample inside the sphere. When the light hits this sample we can measure the reflected light of the sphere material following this formula (Fontoynont, 2010):

$$E = \frac{1}{4\pi r^2} \cdot \frac{\rho}{1-\rho}$$

Where *E* is the flux, *r* is radius of the sphere, and *ρ* is the reflectance of the integrating sphere.

If one were to measure the flux in the darkest area (i.e. just next to the parallel light source entrance), it is possible to determine if the final renderings need any type of correction. If, for example, the readings showed a deviation in lux as the glossiness was varied, one would have to correct this in order to get correct light distribution. The method for measuring illuminance in V-Ray was to use an illuminance pass, which renders an image with lux values for a given pixel. To get correct results one has to use an un-biased rendering algorithm, which in V-Ray is called "brute-force". The renders were sampled with a brute-force subdivision at 512 sample and 5 bounces. Even though the resolution was very low (128x128) it still took around 2 hours per render, due to the extremely precise algorithm. Some noise was apparent in the renders. To remain consistent between sampling of the measurements the renders were scanned for lowest pixel value and which then was recorded. Theoretically there should be no change in lux levels when you change the glossiness/reflectivity.

Reflectivity \ Glossiness	0	0.2	0.5	0.7	1
0	0 lux	0 lux	0 lux	0 lux	0 lux
0.25	14.3 lux	14.1 lux	13.6 lux	13.5 lux	13.5 lux
0.5	28.9 lux	27.9 lux	27 lux	26.7 lux	27.4 lux
0.75	43.5 lux	41.7 lux	40.2 lux	40 lux	40.9 lux
1	57.2 lux	55.5 lux	53.3 lux	52.9 lux	53.1 lux

Figure 2 Measurements of the illuminance levels of the sphere, the values for reflectivity and glossiness have been normalized.

From the values in Figure 2 we can see a small decline in lux values as the glossiness decreases on the sample, yet spikes a very little as the glossiness parameter approaches one. It was decided that due to little variation no correction was necessary. Another validation test was of an outdoor environment with an CIE overcast sky and horizontal illuminance of 10 000 lx. The hypothesis was that, if V-Ray behaves in a physical fashion, the vertical illuminance on the buildings would be half of that. In the render below in Figure 3 it can be observed that this is true.

Figure 3 Rendering output of outdoor environment with a CIE overcast sky

The centre of the square on the images shows 10000 lx and the facades on the side show values around 5000 lx.

The next step of the validation process was to investigate the material properties and their behaviour using the V-Ray material input settings. Using virtual diffuse light source angled at 45 degrees and a camera at 45 degrees opposite of the light source the following images with the respective settings were created:

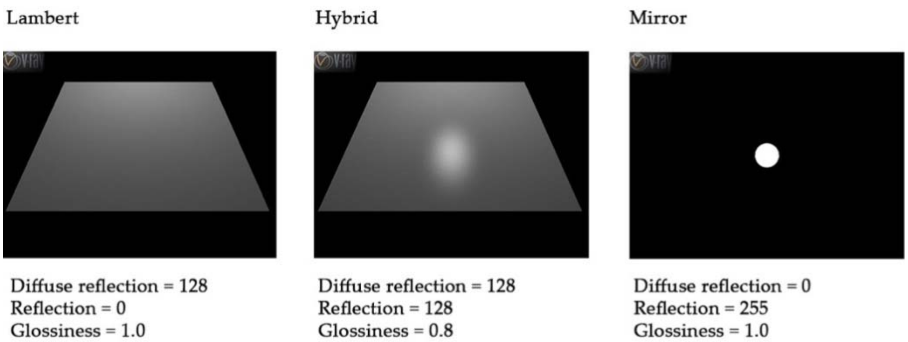


Figure 4 Some material properties and their behaviour using V-Ray (diffuse, glossy, specular)

This validates the possibility to create a wide range of materials in a controlled fashion as well as to create the perfect mirror in an isolated environment, thus producing the last image where only the light source is visible and no scattered light is present.

Far field photometry and light distribution files

To correctly recreate lighting supplied by a specific luminaire, we used the standardized format of IES files often publicly available from manufacturers websites, see figure below. The standard was created in order to accurately describe photometric properties of luminaries and ensured a standard for describing light distribution of light sources with a possibility for simulation software to read such files and accurately recreate the light distribution.

Figure 5 A sample IES file from a luminaire

One of the major drawbacks of the IES file format is that the light distribution is described as far-field photometry, essentially resulting in a point source light when luminaries often have a volume (Labayrade, 2010). This can fortunately be adjusted in V-Ray by applying a physical shape to the IES file which distributes the luminance in accordance with the shape and area of the particular shape. The resulting new shape of the IES light creates significantly softer shadows which are expected of any luminaire with a given volume, Figure 6 is a comparison.

Figure 6 Comparison of the far field photometry problem in a standard IES file (right) and the approximate grid divided area light shape used to counter this (left).

Screen calibration

In order to ensure portability and the possibility for a flexible calibration process several steps were implemented to accommodate this. Calibrations of screens are often a vital part of setting up projection systems and often use multiple steps in order to correctly ensure a correct image. These steps vary from single screen calibration to multiple projector overlay calibrations, most prominent are the calibration of luminance to ensure photometrical uniform displays (Majumder & Stevens, 2004).
The DELL U2713H 27-inch monitor is supplied with calibrated sRGB colour space, which for this calibration process has been disabled and is used in a "standard" pre-set mode instead. The brightness has been set to max (100) and "Uniformity Compensation" (UC) has been turned on. UC ensures brightness uniformity across the screen albeit with a slight bias in the very left side of the screen (101%).
The screen's maximum luminance is 354 cd/m^2 measured with a Konica Minolta luminance meter, which corresponds well to the theoretical limit of around 350 cd/m^2.
For the calibration with V-Ray light systems a series of light sources were displayed in a grid structure. Each light source was 1x1m and emitted from 1 cd/m^2 to 275 cd/m^2 at 25 cd/m^2 intervals (except from 1 to 25 cd/m^2). The data was rendered using the V-Ray physical camera system with a default f-stop and shutter speed value of f/8.0 and 100 respectively. White balance was set to white (255,255,255). The varied variable was the ISO speed, which controls the overall light sensitivity. The measurements of the light sources were done using the luminance meter from equal distance of 1.5 meters from the screen. The renders were displayed in a 2,2 gamma corrected colour space (sRGB) and luminance measurements were done in this colour space. Due to the UC setting in the screen the maximum luminance was measured at around 220 cd/m^2

The results from the measurements shows a linear tendency of the light distribution (this is mainly due to the sRGB gamma correction). Measurements were done for each light source with three different ISO speeds (1000, 2000, 3000). Given the linearity it is possible to calculate a theoretical ISO value for correctly exposing the correct luminance on the screen, which would happen at 3750. Measurements were done with these settings and resulted in the following data:

Table 1 Data compiled from different light sources

Light source Luminance (cd/m2)	ISO 3750 measured luminance (cd/m2)	Deviation in percentage
1	1,025	3%
25	25,05	0%
50	48,1	4%
75	69,98	7%
100	97,1	3%
125	128	2%
150	151,8	1%
175	182,4	4%
200	209,1	5%
225	219	3%
250	219,1	12%
275	219,2	20%

There is some noise in the measured data, which in any case is below 10 % until the 220 cd/m2 point where the error exceeds the limit of 10 % that is due to the screen's brightness limit.

Projector calibration

The Epson EB-G6650WU has a maximum luminance of 6000 ANSI lumen and projects in a native 1920x1080 resolution. The projector comes with no factory calibration in colour space or luminance uniformity correction. The throw range of the projector was 2,75 meters from the wall with approximately a 100 inch diagonal (16:10 aspect ratio).

A luminance irregularity, or hotspot, correction is necessary to achieve a uniform luminance distribution and occurs due to the optical properties of the lens and due to the relative difference in length from the projected plane to the projector lens. To correct the hotspot, we used a process of recording a white screen using a DSLR camera. The picture contains pixel information, which can be extracted to get an idea of the hotspot. The recorded image was processed into an 8-bit version using a Reinhard tonemapping technique, and then processed into a greyscale image, which had its histogram stretched to contain as much data as possible. This is essentially the hotspot in an exaggerated state. Inverting the image will result in a correction expression for the hotspot (Rhee, Schulze, & DeFanti, 2010).

To verify the hotspot correction a purely white image was projected and measured and then compared to the same image with hotspot correction overlay. Measurements were done by projecting a completely white image resulting in measurements ranging from 535 cd/m^2 to 390 cd/m^2 giving a max difference in

luminance of 27.1%. After the hotspot correction was applied measurements were made, which ranged from 415 cd/m^2 to 391 cd/m^2 resulting in a maximum luminance difference of 5.7%.
To display images with correct luminance values a calibration process was needed as the projector may be in different distances from the projected surface. To accommodate this, we used a calibration chart rendered in V-Ray using 3ds Max with light sources emitting a known luminance, see the figure below. This luminance was then measured using a luminance meter and correlated. Any correction necessary was done using an exposure control where one may correct in terms of exposure levels. A drawback for this is due to the nature of exposure corrections where the whiter values are more affected of possible errors because of the relatively bigger pixel difference compared to low pixel values.

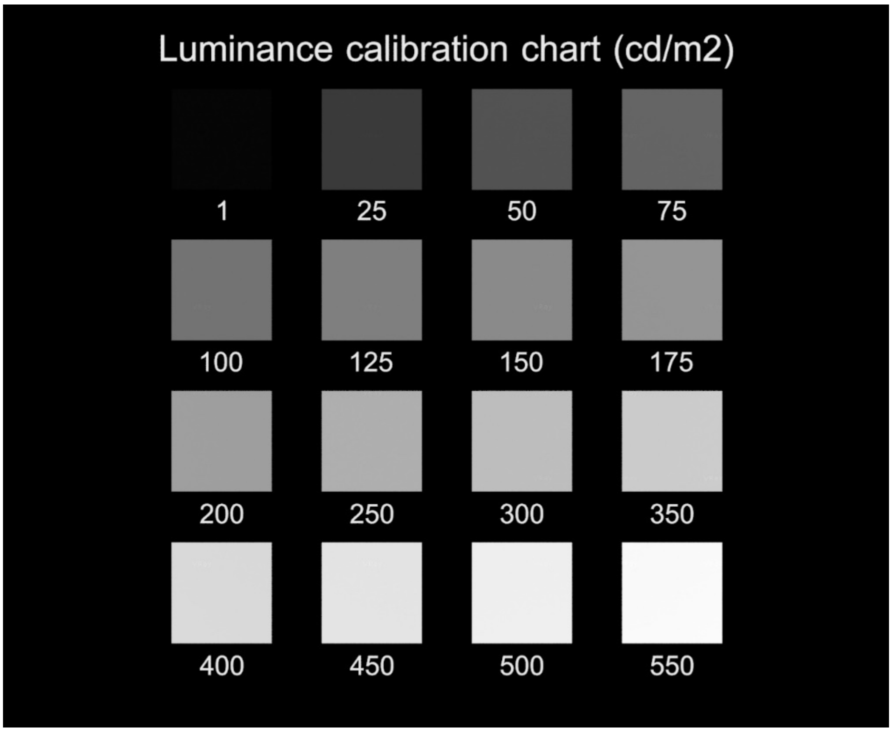


Figure 7 Calibration chart used to calibrate the projector. The values are corresponding to the brightness from the simulation software (luminances) . A script was created to calibrate a batch of images to fit this range of brightness.

Once the projector was calibrated to an acceptable level, one may batch the procedure on many rendered images reducing the possible human errors and to reduce the overall calibration time. The batch process was a custom made script used to work with Photoshop. The script applied the hotspot correction and the exposure correction. Any changes to either correction could easily be changed using the script on site.

Sources of error

All the measurements were done by projecting on a completely diffuse surface (wall), which due to the small amount of reflectance may have had an impact on the luminance measurements. To counter this, all the measurements where done from the same spot behind the projector. The calibration may change if the projected media is slightly reflective, therefore a very diffuse projection surface results in the best calibration with little variance. The room, where the calibration was completed, should be as dark as possible.

Method

When assessing the light schemes it's simply not enough to ask a user whether they think a lighting scheme is “good” or “bad”, simply because humans tend to be very subjective when it comes to assessment where they are having different preconceptions of the presented stimuli, in other words people see things differently. As an example people might have a hard time rating a lighting scheme when they have nothing to compare it with. For this exact reason we implemented a setup where assessors were given the opportunity to compare lighting in the same scene without any other variables being manipulated (Jones, Peryam, & Thurstone, 1955).

We implemented a test setup based on an approach based on an A/B testing method where assessors are able to choose from two options based on a comparison. The assessors chose the preferred scheme based on an assessment criterion which for example could be “in which of the schemes would you prefer to work?”. This way the user can make a choice for each configuration by comparing the setups rather than just judging a single scheme. This approach does have pitfalls associated with it, especially in the case where the assessors do not have preference for either option, for this reason we gave an option to option for a “no preference” when assessing a pair.

Ideally, this method should include all possible pair combinations, but due to the sheer number of combinations this would result in, we made a randomized setup where for each assessment the stimuli would be randomized prior to the assessment by the panel. All of the stimuli were numbered in pairs, e.g. pair 6a and 6b, this way the assessors would always have an identification possibility of the pair number if doubt occurred.

In most cases, the stimuli were structured in one long assessment of the lighting scenarios. For each scene, the assessors would experience a number of different lighting schemes, typically 8 scenarios, which were structured in pairs. For each testing scenario, any given scheme would appear three times in total. A description of the assessors/observers of the schemes is mentioned in the chapter Communication / dissemination at the end of the report.

Calculation of watt consumption

For each scene, we went through a process of calculating the objective measurement of energy consumption. This was done by calculating the size of the reference area of interest. This could typically be the entire room, but in some larger scenes, we made a section of interest where the calculations were done. To find the power consumption of each scheme, we used data received from the data files used in the visualization. This could i.e. be a photometric file (IES, LDT) and we used the data from this to calculate the specific scenario's power consumption in W/m^2.

Data processing

For each of the assessments we would get a response of either "A", "B" or "No preference". This was processed into a binary data set (no preference would be blank) which then could be processed. The data would be summed into number of "wins" ending up with each scenario having a number of comparison wins, where the one with the most wins was the most preferred scenario. To compare all the tests consistently in the same way we choose to normalize all the subjective data from a range of 0 to 10. When we have the data in this manor, we can easily compare the subjective data to an objective metric such as energy usage. Figure 8 below shows a sample graph.

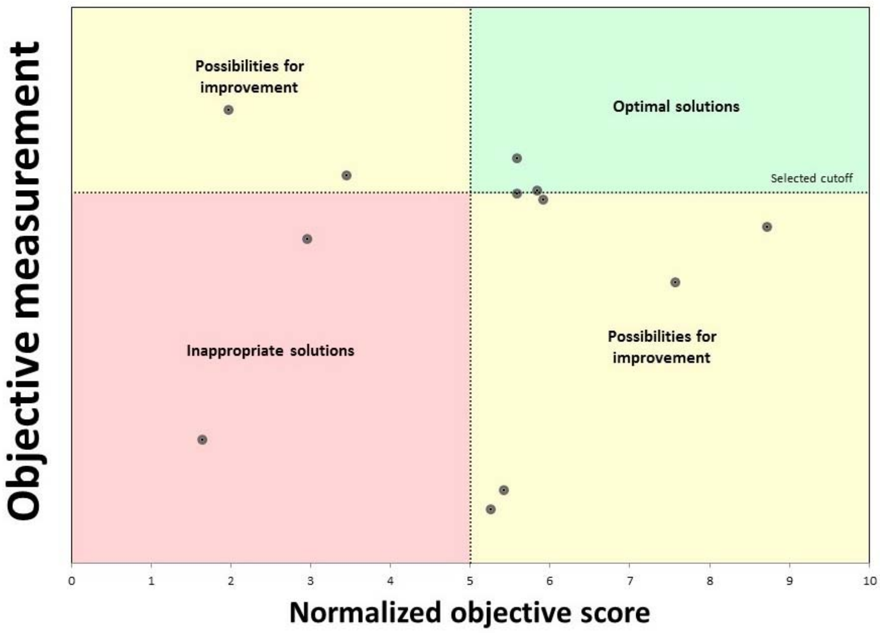


Figure 8 A Preference Efficiency Matrix (PEM), where the subjective score of a lighting installation is plotted against an objective measurement energy efficiency, cost, etc.)

By using this approach, it is possible to include many scenarios and still compare the relative preference score between schemes. This preference efficiency matrix (PEM) is used throughout the project.

Selection of case studies

Selection of case studies

The principle of this study is to explore possible lighting schemes and to rate them in regard to both energy performance and quality, as assessed by observers.

We have selected the installed electric lighting power density (W/m^2) as the major criterion for energy performance. It is the ratio of the installed electric lighting power (Watts, W) to the relevant floor area (m^2).

Typically, electric power density ranges between 3 and 15 W/m^2 depending for most applications on using rather efficient lighting equipment. The lowest values are obtained when priority for lighting is towards given tasks or functions, and the remaining lighting power is sized to maintain a reasonable “balance of luminance”. A uniform distribution of ceiling mounted luminaires is often considered as a good reference case, since this is very common in indoor lighting. Addition of wall washers and other decorative lighting tend to increase electric power density.

In this study, we have chosen to present a wide range of lighting solutions to offer the best possible choice for observers. We present these choices without any information on electric lighting power density to avoid influence on the comments. Our objective is to identify possible schemes that offer both high energy efficiency and high perceived lighting quality. For this reason, we did not restrict the analysis to study only very efficient lighting schemes. This allows identification of possible directions to improve the perception of indoor luminous environments. Below, we describe the various lighting schemes that have been selected as well as the reason to do so.

Office lighting

Most offices are usually lit from the ceiling and until recently “state of the art” has been to use fluorescent recessed luminaires with various shapes: Linear, rectangular, square or circular. Today, these luminaires are progressively replaced by LED based equipment.

Henning Larsen Architects proposed this case study as an office space located on their own premises. It is expected to house 16 work places. The total area of the scene is 112 m^2. The reason for choosing this case study was that this area of the office was to be included as an office working area and therefore needed to have enough light to fulfil the minimum standards while creating a friendly atmosphere.

Office iteration 1

We simulated the reference case, which is the actual situation using the linear fluorescent tubes. Then we proposed evolutions to the design using longer (but less powerful) linear light sources and we designed possible options using longer light sources, cove lighting (to make the ceiling brighter), recessed miniature LED light sources making luminaires almost invisible, and suspended luminaires for esthetical reasons.

In order to reduce global electric power density without reducing illuminance at tasks we also inserted some task lamps combined with reduced power of general lighting.

In the table below, lighting power densities vary between 3.25 W/m^2 and 10.85 W/m^2.

Figure 9 Office iteration 1 scheme 1

Figure 10 Office iteration 1 scheme 2

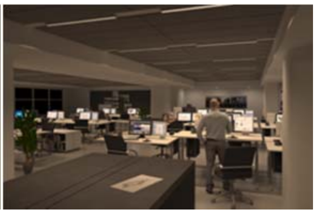


Figure 11 Office iteration 1 scheme 3

Figure 12 Office iteration 1 scheme 4

Figure 13 Office iteration 1 scheme 5

Figure 14 Office iteration 1 scheme 6

Figure 15 Office iteration 1 scheme 7

Figure 16 Office iteration 1 scheme 8

Figure 17 Office iteration 1 scheme 9

Figure 18 Office iteration 1 scheme 10

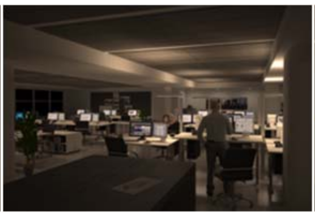


Figure 19 Office iteration 1 scheme 11

Figure 20 Office iteration 1 scheme 12

Table 2. Description of office iteration 1 lighting schemes

Scheme	Luminaire	Luminous flux/ luminaire (lm)	Power/ luminaire (W)	Number or length (m)	Total Power (W)	Electric Power Density (W/m²)
1: Reference lighting						3.25
	LED Back ceiling lighting	1116	15	3	64	
	LED 1 Central light fixture	2600	30	7	300	
2: Reference lighting + task lamps *						4.75
	LED 1 Central light fixture	2600	30	7	300	
	LED Task lamps	200	10.5	16	168	
3: Two ceiling light fixtures *						5.93
	LED 2 Central light fixture	2600	30	14	600	
4: Notor mounted ceiling lighting *						10.43
	LED 1 Central light fixture	2600	92	8	1104	
5: Central cove lighting *						9.35
	LED Central cove lighting	4000	43	16	982	
6: Central cove lighting + task lamps *						10.85
	LED Central cove lighting	4000	43	16	982	
	LED Task lamps	200	10.5	16	168	
7: LED strips *						4.02
	LED Strip lighting	50	0.5	540	385	
8: Three spot lights *						3.64
	LED Ceiling spot light	2600	30	8	342	
9: Pozzo pendants *						2.22
	LED Ceiling pozzo pendant	3300	43	3	184	
10: Notor suspended pendants *						3.97
	LED Ceiling notor pendant	3300	38	7	380	
11: Opur standing lights *						4.99
	LED Opur standing light	5280	99	5	495	
12: Aurilux ceiling lights *						4.15
	LED Aurilux ceiling light	700	10	28	400	

* LED back ceiling light remains unchanged

Office iteration 2

We proposed a second iteration aiming at strategies based on increasing luminance of vertical surfaces, using wall washers on the wall far away in the scene, or on the columns. Electric power density was slightly increased, with lighting power densities varying between 4.75 W/m^2 and 12.06 W/m^2. This lead to a second set of images and a second testing session.

Figure 21 Office iteration 2 scheme 1

Figure 22 Office iteration 2 scheme 2

Figure 23 Office iteration 2 scheme 3

Figure 24 Office iteration 2 scheme 4

Figure 25 Office iteration 2 scheme 5

Figure 26 Office iteration 2 scheme 6

Figure 27 Office iteration 2 scheme 7

Figure 28 Office iteration 2 scheme 8

Table 3. Description of office iteration 2 lighting schemes

Scheme	Luminaire	Luminous flux/ luminaire (lm)	Power/luminaire (W)	Number or length (m)	Total Power (W)	Electric Power Density (W/m²)
1: Reference lighting						4.75
	LED Back ceiling lighting	1116	15	3	64	
	LED Central light fixture	2600	30	7	300	
	LED Task lamps	200	10.5	16	168	
2: Central cove lighting *						10.85
	LED Central cove lighting	4000	43	16	982	
3: Central cove lighting + modified wall washers **						12.06
	LED Back wall lighting	2600	28	5	200	
	LED Central cove lighting	4000	43	16	982	
4: Column lighting at 40% dimming + modified wall washers **						5.57
	LED Back wall lighting	2600	28	5	200	
	LED Column fixtures	2600	28	16	256	
5: Reference with double amount of fixtures *						7.43
	LED Central light fixture	2600	30	14	600	
6: Reference with double amount of fixtures + modified wall washers **						8.64
	LED Back wall lighting	2600	28	5	200	
	LED Central light fixture	2600	30	14	600	
7: Reference at 50% dimming + modified wall washers **						4.63
	LED Back wall lighting	2600	28	5	200	
	LED Central light fixture	2600	30	7	150	
8: Reference + modified wall washers **						5.96
	LED Back wall lighting	2600	28	5	200	
	LED Central light fixture	2600	30	7	300	

* LED reference back ceiling lights and task lamps remain unchanged

** LED reference task lamps remain unchanged

Hospital room lighting

Based on a typical configuration of a hospital room, two points of view were selected:

- One from the patient lying in his/her bed, looking toward a nurse, a TV screen and a magazine.
- One describing the space from a standing observer looking at a patient with a visitor sitting on the side.

Various lighting systems located around the bed were tested, using either spot lamps or area lighting (in our case using a luminous image as a source of light).

The range of lighting power densities was quite significant: from 3.99 W/m^2 to 13.57 W/m^2

Point of view 1: from lying patient

Figure 29 Hospital room, patient POV scheme 1

Figure 30 Hospital room, patient POV scheme 2

Figure 31 Hospital room, patient POV scheme 3

Figure 32 Hospital room, patient POV scheme 4

Figure 33 Hospital room, patient POV scheme 5

Figure 34 Hospital room, patient POV scheme 6

Figure 35 Hospital room, patient POV scheme 7

Figure 36 Hospital room, patient POV scheme 8

Point of view 2: from standing visitor


Figure 37 Hospital room, visitor POV scheme 1


Figure 38 Hospital room, visitor POV scheme 2


Figure 39 Hospital room, visitor POV scheme 3


Figure 40 Hospital room, visitor POV scheme 4


Figure 41 Hospital room, visitor POV scheme 5


Figure 42 Hospital room, visitor POV scheme 6


Figure 43 Hospital room, visitor POV scheme 7


Figure 44 Hospital room, visitor POV scheme 8

Table 4. Description of hospital room lighting schemes

Scheme	Luminaire	Luminous flux/ luminaire (lm)	Power/ luminaire (W)	Number or length (m)	Total Power (W)	Electric Power Density (W/m^2)
1: Reference lighting						3.99
	LED Central ceiling light	2600	30	2	86	
2: Reference lighting with extra fixtures						7.97
	LED Central ceiling light	2600	30	4	172	
3: Reference + Pozzo circular ceiling fixture + bedside light spots						6.95
	LED Central ceiling light	2600	30	2	86	
	LED Pozzo ceiling light	3000	38	1	60	
	LED IKEA bedside light	70	3	1	4	
4: Reference + luminous picture						5.92
	LED Central ceiling light	2600	30	2	86	
	LED Luminous picture	1000	25	1	42	
5: Reference + bedside spots + Lithonia ceiling spots + Logotec spots						6.05
	LED Central ceiling light	2600	30	2	86	
	LED Logotec wall spot	400	4	1	6	
	LED Lithonia ceiling spot	1200	12	2	34	
	LED IKEA bedside light	70	3	1	4	
6: Reference with extra fixtures + Lithonia ceiling spots + luminous picture + wall side lamp						13.57
	LED Central ceiling light	2600	30	4	172	
	LED Lithonia ceiling spot	1200	12	2	34	
	LED Luminous picture	1000	25	1	42	
	LED Luis Poulsen wall lamp	370	40	1	44	
7: Reference with extra fixtures + Lithonia ceiling spots + luminous picture + new wall side lamp						11.76
	LED Central ceiling light	2600	30	4	172	
	LED Lithonia ceiling spot	1200	12	2	34	
	LED Luminous picture	1000	25	1	42	
	LED Wall lamp	300	5	1	5.6	
8: : Reference with extra fixtures + Lithonia ceiling spots + luminous picture						11.51
	LED Central ceiling light	2600	30	4	172	
	LED Lithonia ceiling spot	1200	12	2	34	
	LED Luminous picture	1000	25	1	42	

Hospital wake-up room

A wake-up room in hospitals is a room occupied by patients after surgery. They are lying on the bed and the viewing direction is mainly upwards. Rambøll engineering firm proposed this case study. The challenge was to propose a very comfortable environment for the patients combined with a lighting quality suited for the work of nurses. The proposed lighting schemes use three channels:

1. Ceiling mounted luminaires (circular down lighters)
2. Wall washers along the periphery
3. A central rectangular cavity creating an impression of daylight

In our tests, the light flux from ceiling mounted luminaires was fixed. Flux and colour temperature was varied, both for the wall washers and for the central lighting cavity. This was done to increase contrast and possibly raise interest in the scene.

We have presented views of a lying patient being observed by a nurse. In this configuration, observers can judge lighting quality through a double assessment: They judge both the luminous environment as well as the view of the nurse standing next to the bed.

Thirteen schemes where constructed with electric lighting power densities ranging from 6.26 W/m^2 to 10.26 W/m^2.

We made the colour temperature of the light from the wall washers and the central cavity variable between 2000 K and 5000 K.

The total area of the room is 151 m^2.

For all configurations, the electric lighting power density of the recessed ceiling luminaires was kept constant at 3.17 W/m^2.
In the scenarios, we only allowed adjustment of the light from wall washers and central cove with a power of up to 4.04 W/m^2 at full power. The central cove systems used 2.92 W/m^2 at full power.

The reference case used all channels at full power, for a maximum power density of 10.16 W/m^2.

Figure 45 Hospital wake-up room scheme 1

Figure 46 Hospital wake-up room scheme 2

Figure 47 Hospital wake-up room scheme 3

Figure 48 Hospital wake-up room scheme 4

Figure 49 Hospital wake-up room scheme 5

Figure 50 Hospital wake-up room scheme 6

Figure 51 Hospital wake-up room scheme 7

Figure 52 Hospital wake-up room scheme 8

Figure 53 Hospital wake-up room scheme 9

Figure 54 Hospital wake-up room scheme 10

Figure 55 Hospital wake-up room scheme 11

Figure 56 Hospital wake-up room scheme 12

Figure 57 Hospital wake-up room scheme 13

Table 5. Description of *hospital wake up room* lighting schemes

Scheme	Luminaire	Luminous flux/ luminaire (lm)	Power/ luminaire (W)	Number or length (m)	Total Power (W)	Electric Power Density (W/m^2)
1: Reference lighting						11.32
	LED Cove lighting	2450	25	22	785	
	LED Central cove lighting	1558	31	10	442	
	LED Ceiling recessed 1	1000	16	18	411	
	LED Ceiling recessed 2	1000	16	3	69	
2: Reference lighting + 30% dimming wall washers *						7.67
	LED Cove lighting	2450	25	22	235	
3: Reference lighting + 75% dimming wall washers and centred cove lighting *						9.28
	LED Cove lighting	2450	25	22	589	
	LED Central cove lighting	1558	31	10	332	
4: Reference lighting + 30% dimming on centred cove lighting *						9.26
	LED Central cove lighting	1558	31	10	132	
5: CCT 2000-5000 + 20% dimming wall washers **						7.15
	LED Cove lighting	2450	25	22	157	
6: CCT 2000-5000 + 40% dimming wall washers and 50% on centred cove lighting **						6.73
	LED Cove lighting	2450	25	22	314	
	LED Central cove lighting	1558	31	10	221	
7: CCT 2000-5000 + 35% dimming on centred cove lighting **						9.41
	LED Central cove lighting	1558	31	10	155	
8: CCT 3000-5000 + 25% dimming wall washers **						7.41
	LED Cove lighting	2450	25	22	196	
9: CCT 3000-5000 + 45% dimming wall washers and 50% on centred cove lighting **						6.99
	LED Cove lighting	2450	25	22	354	
	LED Central cove lighting	1558	31	10	221	
10: CCT 3000-5000 + 35% dimming on centred cove lighting **						9.41
	LED Central cove lighting	1558	31	10	155	
11: CTT 4000-3000 + 30% dimming wall washers **						7.67
	LED Cove lighting	2450	25	22	236	
12: CCT 4000-3000 + 55% dimming wall washers and 45% on centred cove lighting **						7.36
	LED Cove lighting	2450	25	22	432	
	LED Central cove lighting	1558	31	10	199	
13: CCT 4000-3000 + 25% dimming on centred cove lighting **						9.12
	LED Central cove lighting	1558	31	10	110	

** Remaining luminaires remain unchanged*

*** Only CCT is changed in remaining luminaires, which has no influence on power*

These calculations correspond with wall washers with 779 lm/m and 15.5 W/m.

Commercial centre

Rambøll Engineers suggested this case study. It consists of a hall in Frederiksberg Commercial Centre. Shops are located on two sides. Three families of lighting have been selected:

- Recessed ceiling luminaires
- Linear wall washers
- Central Area Cove lighting

The reference case was the lighting proposed by Rambøll Engineers. It dealt with a combination of circular ceiling mounted recessed luminaires, and cove lighting located on top of the walls, at the edge of the ceiling.

We thought it would be interesting to study the balance of lighting power between the ceiling luminaires and the cove lighting. This is aimed at finding the minimum power that should be provided by cove lighting to create the desired visual effect.

We also proposed to vary colour of cove lighting to explore possible benefits of using colour to reduce flux, and increase contrast.

Finally, we decided to explore an alternative way to give light from the ceiling using large cove lighting systems in the central area on the ceiling to increase brightness above occupants. Two options where then proposed: one with uniform white light, and another with a simulation of vision towards clear sky to increase the impression of depth.

The total area of the section of the commercial centre is 231 m^2.

Figure 58 Commercial centre scheme 1

Figure 59 Commercial centre scheme 2

Figure 60 Commercial centre scheme 3

Figure 61 Commercial centre scheme 4

Figure 62 Commercial centre scheme 5

Figure 63 Commercial centre scheme 6

Figure 64 Commercial centre scheme 7

Figure 65 Commercial centre scheme 8

Figure 66 Commercial centre scheme 9

Figure 67 Commercial centre scheme 10

Figure 68 Commercial centre scheme 11

Figure 69 Commercial centre scheme 12

Figure 70 Commercial centre scheme 13

Table 6. Description of *commercial centre* lighting schemes

Scheme	Luminaire	Luminous flux/ luminaire (lm)	Power/ luminaire (W)	Number or length (m)	Total Power (W)	Electric Power Density (W/m²)
1: Reference lighting						11.82
	LED Cove lighting wall	1200	24	9	308	
	LED Fixed lighting 1	1000	16	25	571	
	LED Fixed lighting 2	3200	36	12	617	
	LED Fixed lighting 3	2400	36	24	1234	
2: Reference lighting + double power for cove lighting (dim level 200%) *						13.16
	LED Cove lighting wall	1200	24	9	617	
3: Reference lighting + cool cove lighting *						11.82
	LED Cove lighting wall	1200	24	9	308	
4: Reference lighting + warm cove lighting *						11.82
	LED Cove lighting wall	1200	24	9	308	
5: Central cove lighting						19.67
	LED Cove lighting wall	1200	24	9	308	
	LED Fixed lighting 1	1000	16	12	274	
	LED Central cove lighting	2275	33	84	3960	
6: Central cove lighting + 50% dimming on cove lighting along wall **						19
	LED Cove lighting wall	1200	24	9	154	
7: Central cove lighting + 150% dimming on cove lighting along wall **						20.33
	LED Cove lighting wall	1200	24	9	462	
8: Central cove lighting + cool cove lighting along wall **						19.67
	LED Cove lighting wall	1200	24	9	308	
9: Central cove lighting + warm cove lighting along wall **						19.67
	LED Cove lighting wall	1200	24	9	308	
10: Central cloud cove lighting						19.67
	Same as scheme 5: Central cove lighting					
11: Central cloud cove lighting + 0% dimming on cove lighting along wall **						18.33
	LED Cove lighting	1200	24	9	0	
12: Central cloud cove lighting + cool cove lighting along wall *						19.67
	LED Cove lighting	1200	24	9	308	
13: Central cloud cove lighting + warm cove lighting along wall *						19.67
	LED Cove lighting	1200	24	9	308	

** Remaining luminaires remain unchanged*

*** Central cove lighting and fixed lighting 1 remain the same as scheme 5*

Cove lighting along side corresponds to wall washers with 2275 lm/m and 33 W/m.

Atrium

Henning Larsen Architects designed The Southern University of Denmark in Kolding was designed by Henning Larsen Architects. In the central atrium of the building, the floors of the upper levels are staggered and frame the atrium boundary. From the ground floor, a wide staircase connects the floors of the building. It was therefore a design decision to incorporate a uniform and discrete lighting design created from down lights integrated in the ceiling.

In the shown renders, the indoor atrium is presented at night time, in order to only evaluate the artificial light distribution in the atrium. The total area
The total area of atrium is 2000 m^2, which includes a total of five floors.

The objective of the set of simulations was to investigate the possibility of avoiding lamps above the atrium (to simplify maintenance and reduce energy consumption), and to explore the possibility changing the space by using linear energy efficient light sources: wall washers and architectural cove lighting.

The images use three light channels: Ceiling lighting, wall washers, and cove lighting along the stairs.

A fourth scenario was also investigated with light produced from stand-alone luminaries.

In total, two iterations were presented to observers, each of them using 5 scenes (total 10 scenes)

The first iteration used the existing ceiling luminaires as a reference, the second proposed to dim the ceiling luminaires (down to 30% of its initial power) and compensate with actions on the other channels.

Please note that when dimming levels are displayed in the tables below, it is the final power used for the simulation in comparison to the maximum power.

Lighting power densities vary from 4.05 W/m^2 to 6.28 W/m^2. This variation is rather small, since most of the scenario concern compensation of lighting: When the power of one channel is decreased, the power of another channel is increased.

Atrium iteration 1

Figure 71 Atrium iteration 1 scheme 1

Figure 72 Atrium iteration 1 scheme 2

Figure 73 Atrium iteration 1 scheme 3

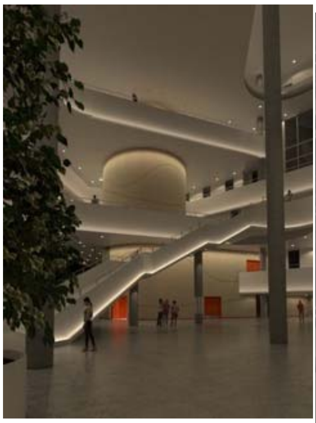


Figure 74 Atrium iteration 1 scheme 4

Figure 75 Atrium iteration 1 scheme 5

Table 7. Description of atrium iteration 1 lighting schemes

Scheme	Luminaire	Luminous flux/ luminaire (lm)	Power/ luminaire (W)	Number or length (m)	Total Power (W)	Electric Power Density (W/m²)
1: Reference, Existing lighting						5.31
	LED Lunis ceiling light	1200	18	374	9617	
	LED Easy med LED ceiling light	498	8	18	206	
	LED Pleiad ceiling light	885	20	28	800	
2: Reduced existing fixtures + 30% dimming wall washer						4.92
	LED Lunis ceiling light	1200	18	306	7868	
	LED Easy med LED ceiling light	498	8	18	206	
	LED Pleiad ceiling light	885	20	28	800	
	LED Wall washer Dim level 30%	2400	30	75	964	
3: Reduced existing fixtures + 60% dimming wall washer *						5.4
	LED Wall washer Dim level 60%	2400	30	75	1928	
4: Reduced existing fixtures + lines of light + 30% dimming wall washer *						5.04
	LED Lines of light Dim level 19%	391	6.9	128	239	
	LED Wall washer Dim level 30%	2400	30	75	964	
5: Standing light fixtures + 60% dimming wall washer						4.05
	LED Easy med LED ceiling light	498	8	18	206	
	LED Pleiad ceiling light	885	20	28	800	
	LED Wall washer Dim level 60%	2400	30	75	1928	
	Standing light poles	1000	19	163	5162	

* Reduced existing fixtures are included and remain unchanged

Atrium iteration 2

Figure 76 Atrium iteration 2 scheme 1

Figure 77 Atrium iteration 2 scheme 2

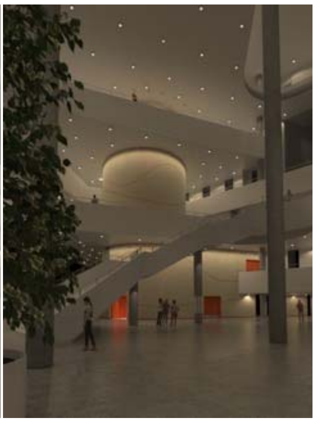


Figure 78 Atrium iteration 2 scheme 3

Figure 79 Atrium iteration 2 scheme 4

Figure 80 Atrium iteration 2 scheme 5

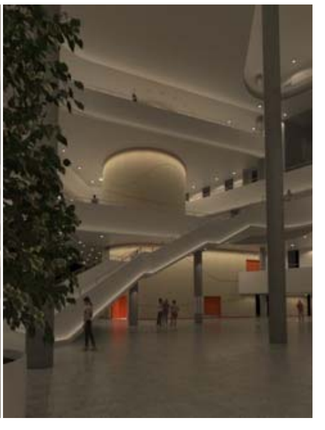


Figure 81 Atrium iteration 2 scheme 6

Figure 82 Atrium iteration 2 scheme 7

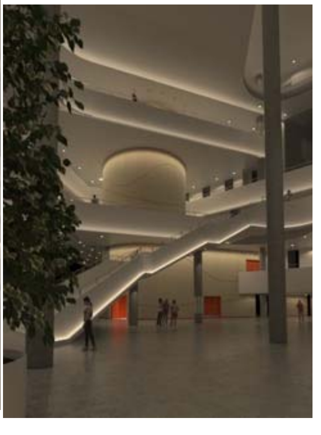


Figure 83 Atrium iteration 2 scheme 8

Table 8. Description of atrium iteration 1 lighting schemes

Scheme	Luminaire	Luminous flux/ luminaire (lm)	Power/ luminaire (W)	Number or length (m)	Total Power (W)	Electric Power Density (W/m^2)
1: Reference, Existing lighting						5.31
	LED Lunis ceiling light 1	1200	18	348	8948	
	LED Lunis ceiling light 2	1200	18	26	669	
	LED Easy med LED ceiling light	498	8	18	206	
	LED Pleiad ceiling light	885	20	28	800	
2: Reference lighting + 60% dimming wall washer *						6.28
	LED Wall washer Dim level 60%	2400	30	75	1928	
3: Reference lighting 30% dimming + 30% dimming wall washer						5.56
	LED Lunis ceiling light 1	1200	18	348	8948	
	LED Lunis ceiling light 2 Dim level 30%	1200	18	26	201	
	LED Easy med LED ceiling light	498	8	18	206	
	LED Pleiad ceiling light	885	20	28	800	
	LED Wall washer Dim level 30%	2400	30	75	964	
4: Reference lighting 30% dimming + 60% dimming wall washer						5.66
	LED Lunis ceiling light 1	1200	18	348	8948	
	LED Lunis ceiling light 2 Dim level 30%	1200	18	26	201	
	LED Easy med LED ceiling light	498	8	18	206	
	LED Pleiad ceiling light	885	20	28	800	
	LED Wall washer Dim level 60%	2400	30	75	1928	
5: Reduced existing fixtures 30% dimming + 30% dimming wall washer + 30% dimming lines of light						5.24
	LED Lunis ceiling light 1	1200	18	306	7869	
	LED Lunis ceiling light 2 Dim level 30%	1200	18	26	201	
	LED Easy med LED ceiling light	498	8	18	206	
	LED Pleiad ceiling light	885	20	28	800	
	LED Wall washer Dim level 30%	2400	30	75	964	
	LED Lines of light Dim level 30%	391	6.9	128	442	
6: Reduced existing fixtures +30% dimming wall washer + 30% dimming lines of light						5.14
	LED Lunis ceiling light 1	1200	18	306	7869	
	LED Lunis ceiling light 2	1200	18	0	0	
	LED Easy med LED ceiling	498	8	18	206	

	light					
	LED Wall washer Dim level 30%	2400	30	75	964	
	LED Lines of light Dim level 30%	391	6.9	128	442	
7: Reduced existing fixtures + 60% dimming wall washer + 30% dimming lines of light**						5.62
	LED Wall washer Dim level 60%	2400	30	75	1928	
	LED Lines of light Dim level 30%	391	6.9	128	442	
8: Reduced existing fixtures + 60% dimming wall washer + 100% dimming lines of light**						6.14
	LED Wall washer Dim level 60%	2400	30	75	1928	
	LED Lines of light Dim level 100%	391	6.9	128	1472	

* Reference lighting remains unchanged

** Reduced existing fixtures remains unchanged from scheme 6

Meeting room

A meeting room was selected, because there are many such spaces in office buildings and there is an opportunity to adjust lighting design in these rooms according to use. One danger is that such an adjustment would lead to extra electric lighting power densities.

Our study deals with the exploration of lighting schemes that would be more attractive than standard solutions (uniform lighting from ceiling) by increasing contrast and possibly reduce energy consumption.

The total area of meeting room is 40 m^2. Table below shows power densities of various lighting schemes.

The reference lighting configuration is a solution providing 500lx uniformly in the table, with an electric power density of 5.1W/m^2.

We have explored solutions that tend to concentrate light on the table and increases the luminance from the walls. This is done with the use of wall washers or with a combination of ceiling lamps and wall washers. Relevant power densities vary from about 2 to 9 W/m^2.

Figure 84 Meeting room scheme 1

Figure 85 Meeting room scheme 2

Figure 86 Meeting room scheme 3

Figure 87 Meeting room scheme 4

Figure 88 Meeting room scheme 5

Figure 89 Meeting room scheme 6

Figure 90 Meeting room scheme 7

Figure 91 Meeting room scheme 8

Table 9. Description of meeting room lighting schemes

Scheme	Luminaire	Luminous flux/ luminaire (lm)	Power/ luminaire (W)	Number or length (m)	Total Power (W)	Electric Power Density (W/m²)
1: Reference lighting						6.63
	LED Central ceiling lights Dim level 80%	2890	29	8	265	
2: Reference lighting + wall washer						10.88
	LED Central ceiling lights Dim level 80%	2890	29	8	265	
	LED Wall washer 1	440	21	3	90	
	LED Wall washer 2	2600	28	2	80	
3: Three ceiling light fixtures						2.49
	LED Central ceiling lights Dim level 80%	2890	29	3	99	
4: Three ceiling light fixtures + wall washer						6.74
	LED Central ceiling lights Dim level 80%	2890	29	3	100	
	LED Wall washer 1	440	21	3	90	
	LED Wall washer 2	2600	28	2	80	
5: Three ceiling light fixtures + 30% dimming wall washer						3.76
	LED Central ceiling lights Dim level 80%	2890	29	3	100	
	LED Wall washer 1 Dim level 30%	440	21	3	27	
	LED Wall washer 2 Dim level 30%	2600	28	2	24	
6: Hanging ceiling lamps						3.07
	LED Central hanging lamps	3300	43	2	123	
7: Hanging ceiling lamps + wall washers						7.32
	LED Central hanging lamps	3300	43	2	123	
	LED Wall washer 1	440	21	3	90	
	LED Wall washer 2	2600	28	2	80	
8: Hanging ceiling lamps + 30% dimming wall washer						4.35
	LED Central hanging lamps	3300	43	2	123	
	LED Wall washer 1 Dim level 30%	440	21	3	27	
	LED Wall washer 2 Dim level 30%	2600	28	2	24	

Classroom

A classroom was also considered as an important case study. Classrooms are rather generic with shape mostly being rectangular with areas between 46 and 70 m^2.

General lighting is normally provided with uniformly distributed ceiling luminaries and a line of wall washer to light the blackboard.

However, several experiences demonstrate that by increasing the wall luminance, you tend to increase alertness, suggesting to explore possibilities to use longer wall washers along the blackboard and possibly along the side walls. We have explored if such features could allow reduction of electric power density from ceiling lighting.

Video projection is also used in class rooms, and it appeared interesting to adjust power from ceiling luminaires to maintain enough light on tables to take notes, and to allow good visibility of projected images.

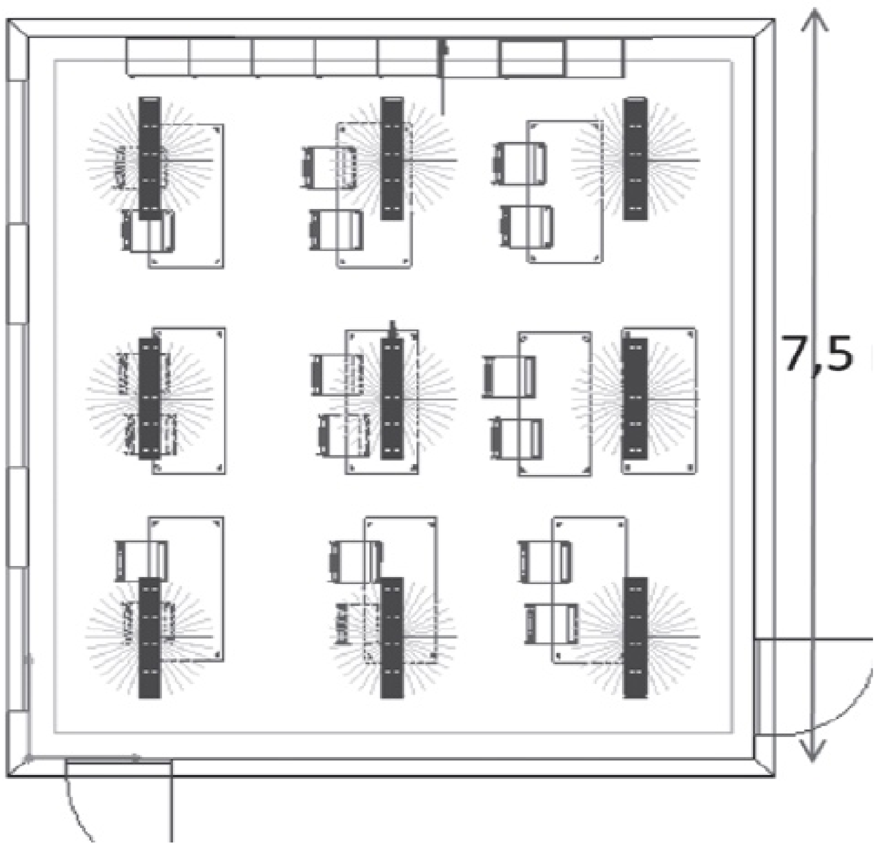


Figure 92 Illustration of classroom dimensions

Figure 93 Classroom scheme 1

Figure 94 Classroom scheme 2

Figure 95 Classroom scheme 3

Figure 96 Classroom scheme 4

Figure 97 Classroom scheme 5

Figure 98 Classroom scheme 6

Figure 99 Classroom scheme 7

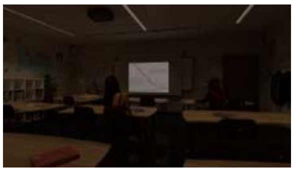


Figure 100 Classroom scheme 8

Figure 101 Classroom scheme 9

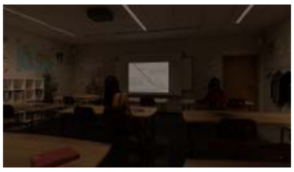


Figure 102 Classroom scheme 10

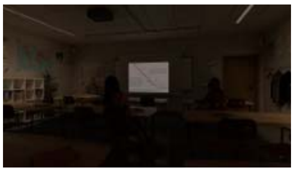


Figure 103 Classroom scheme 11

Table 10. Description of classroom lighting schemes

Scheme	Luminaire	Luminous flux/ luminaire (lm)	Power/ luminaire (W)	Number or length (m)	Total Power (W)	Electric Power Density (W/m^2)
1: Reference lighting						4.44
	Central lighting Dim level 55%	2890	29	9	205	
2: Reference lighting moved						4.44
	Central lighting Dim level 55%	2890	29	9	205	
3: Reference lighting + wall washers recessed *						6.62
	Wall washers Dim level 84%	2600	28	3	101	
4: Reference lighting + wall washers suspended *						6.44
	Wall washers Dim level 77%	2600	28	3	93	
5: Reference lighting + LED recessed lighting *						7.00
	LED Central recessed Dim level 92%	2600	30	3	118	
6: LED strips + wall washers recessed						7.08
	LED strips Dim level 55%	320	4.8	60	226	
	Wall washers Dim level 84%	2600	28	3	101	
7: Projector on						0.73
	Central lighting Dim level 9%	2890	29	9	34	
8: Projector on + LED strips						1.07
	LED strips Dim level 12%	320	4.8	60	49	
9: Projector on + LED strips on sides						0.95
	LED strips Dim level 16%	320	4.8	40	44	
10: Projector on + LED strips + LED wall washers						1.31
	LED strips Dim level 12%	320	4.8	20	17	
	LED wall washer Dim level 16%	320	4.8	40	44	
11: Projector on + LED wall washers						1.37
	LED wall washer Dim level 23%	320	4.8	40	63	

* Reference lighting remains unchanged

Results of tests (rating and comments)

Principle

We have presented the images in pairs to observers using a calibrated video system showing the exact same luminance on surfaces as in reality. We did not simulate visible point sources due to the difficulty of simulating their exact luminance. The limitation of the power of the projector lead to a limitation of luminance to maximum 350 cd/m^2.

We have presented the results with the x-axis showing the normalized preference score (between 1 and 10). We drew a vertical line at value of 6. This was done to express that we consider that the situations with scores higher that 6 are definitely interesting, since they "won" at least 60% of their comparisons.

We also drew a horizontal line with a specific lighting electric power density in W/m^2. Configurations above this line are clearly best in class and considered to be above standard practice.

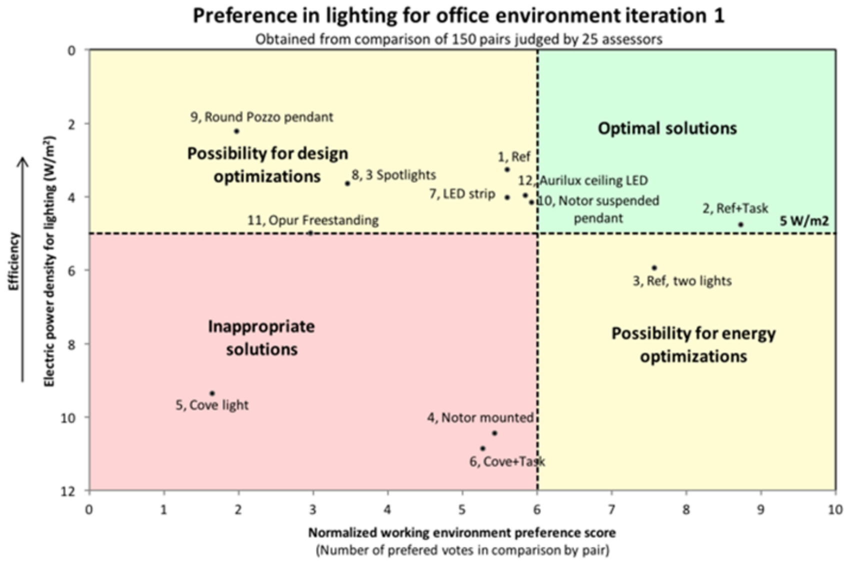
Office lighting

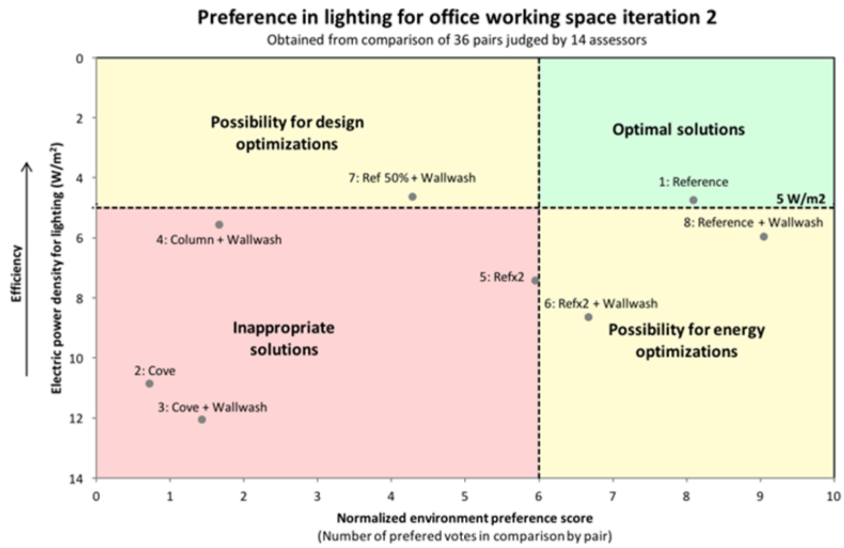
Twelve configurations were presented for iteration 1 and eight configurations for iteration 2.
Twenty-five observers for iteration 1 and fifteen observers for iteration 2.

The two iterations for offices clearly show key facts:

- Adding a task lamp leads to gaining up to 3 points in the lighting quality scale
- Adding a task lamp leads to an increase of lighting power of less than 1.5 W/m^2 for these lamps, suggesting that power for ambient lighting should be decreased by the same amount to maintain efficiency (below 5 W/m^2). In this case ambient lighting should use less than 3.5 W/m^2 for 200 – 300 lx [EN 12464-1] which is achievable
- Cove lighting is hard to make efficient (light is lost in reflections on surfaces), and tends to be judged poorly
- The selected central pendant light was not preferred, although is uses little electric power
- Linear pendant light (T5 or LED) was judged fine by 60% of the observers.
- Adding wall washers (40 W/m^2) lead to gaining 1 point on the preference scale.

- Increasing consumption associated to wall washers lead global efficiency to be just lower that the 5 W/m^2 line. This suggests that wall washers are still interesting, but that their consumption should be below 30 W/m^2.
- In our examples, wall washers appear to be a good supplement to rather neutral and uniform ceiling mounted luminaries.





Comments by participants to the tests:

The comments indicated a focus on the immediate surrounding space around the user's desk. It appears that observers first looked at the possible quality of the work place as if they had to work there. This suggests strategic importance of an energy efficient local lamp.

Observers also stressed the importance of the even distribution of light on the desk (avoid narrow beam task lamp), and the avoidance of reflection on computer screens.

Another interesting aspect was the desire to light vertical surfaces and contours to strengthen the architectural quality of the space.

The overall light distribution in the room should also have a focus on lighting vertical planes to create contours between the work space and surrounding walls and columns.

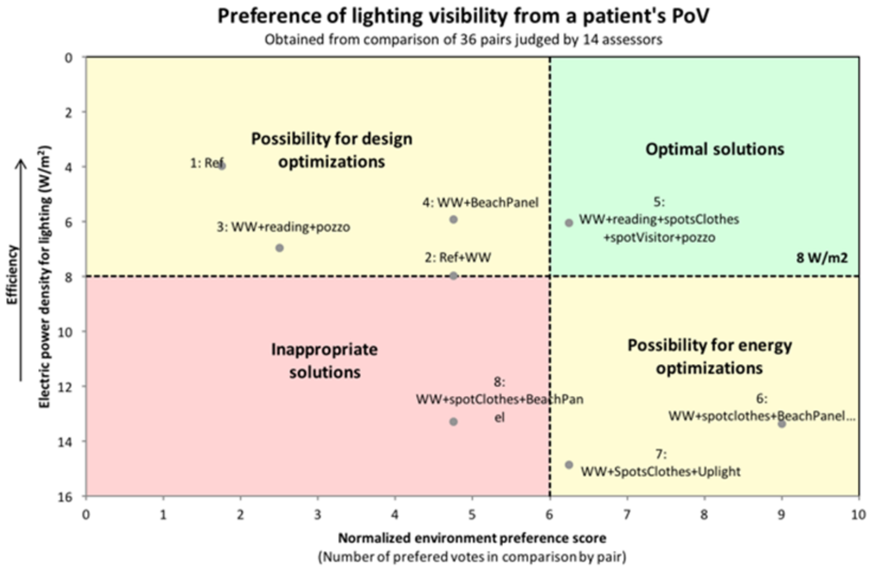
Hospital room lighting

Eight configurations were presented to 13 observers.

Only one configuration led to an electric power density below 8 W/m^2.

One configuration clearly jumps out: No. 7 from the patient point of view, because it facilitates reading and allows good perception of the nurse. However, power density is far too high (above 11 W/m^2).

Point of view 1: from lying patient



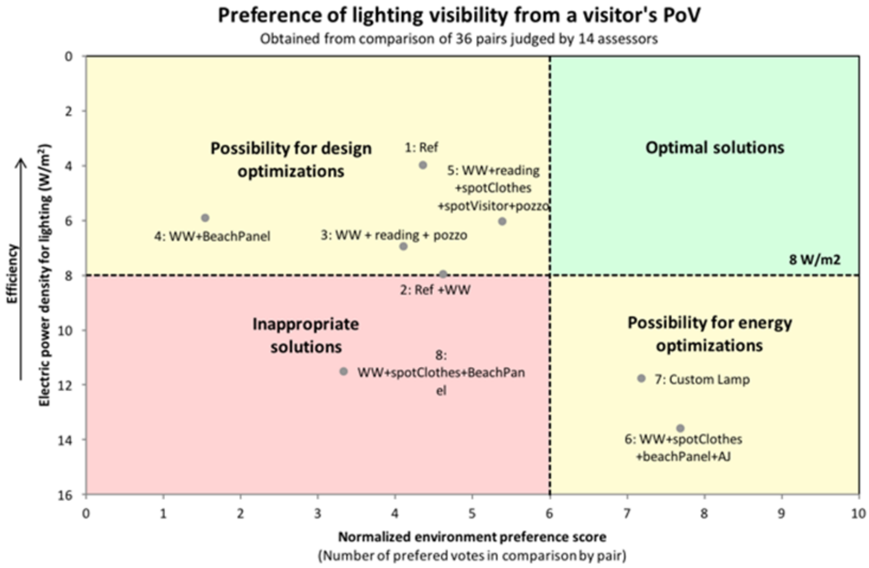
Comments by observers:

From the position of a patient lying on his/her bed, it appears that the priority is the light quality of the immediate surrounding, more particularly lighting quality for reading, and also the perception of the face of the visitors, such as the medical staff. This suggest a very efficient light source close to the head of the patient.

Observers also express that a criterion was the luminance contrast between the face of the visiting nurse and the background, reinforcing the interest of having production of light from the wall next to the bed, and a darker background (opposite wall).

Warmer colour temperatures are preferred to create a cosy atmosphere instead of a clinical effect.

Point of view 1: from standing visitor



Comments by the observers:

The comments indicate a general appreciation for a soft, well-lit room from this perspective and therefore rejects harsh light and extreme contrasts. This could be obtained with large area diffusers among various solutions.

Hospital wake-up room

Thirteen configurations were presented and judged by 28 observers.

Below is the graph showing the results. We set up the maximum electric lighting power density of lighting at 7 W/m^2. Results show a clear preference for warm colour light in wall washers (3000 K) in combination with cool white central lighting from the rectangular cove (5000K).

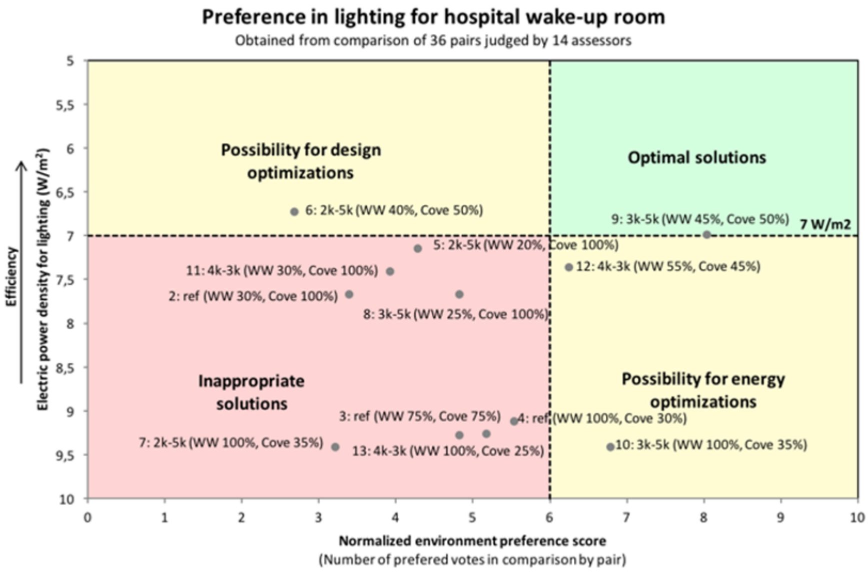
However, a colour temperature of 3000 Kelvin was preferred to 2000 Kelvin, which was judged to be too orange.

Surprisingly, the second optimal configuration was using cooler light from wall washers and warmer lights from central cove, which shows an opposite result from the best case. This suggest that difference in CCT is probably the major interesting feature. For that optimal configuration, electric power was set to the medium position. We note that the two following preferred schemes use rather high power on the wall washers. These lead to an electrical power density above 8 W/m^2.

Some configurations were judged inappropriate: The ones using very low colour temperature on walls in combination with high colour temperature in the central cove, and all configurations using rather high power in the central cove, and low value on the wall washers.

For this space the message could be summarized as follows:

1) Provide medium power to wall washers and central cove: 350 lm/m along the wall (with 7 W/m) and provide 1558lm in the centre
2) Use two colour temperatures (one rather cool in the centre and one rather warm in the periphery)
3) Explore solutions using wall washers with a consumption less than 15 W/m^2.



Comments by observers:

The criteria for judgement was lighting on the face of the nurse next to the patient, suggesting the importance of light being reflected by the wall above the patient head.

Concerning colour temperature observers expressed that, in principle, it was mostly favourable to have warm colours of light on walls.

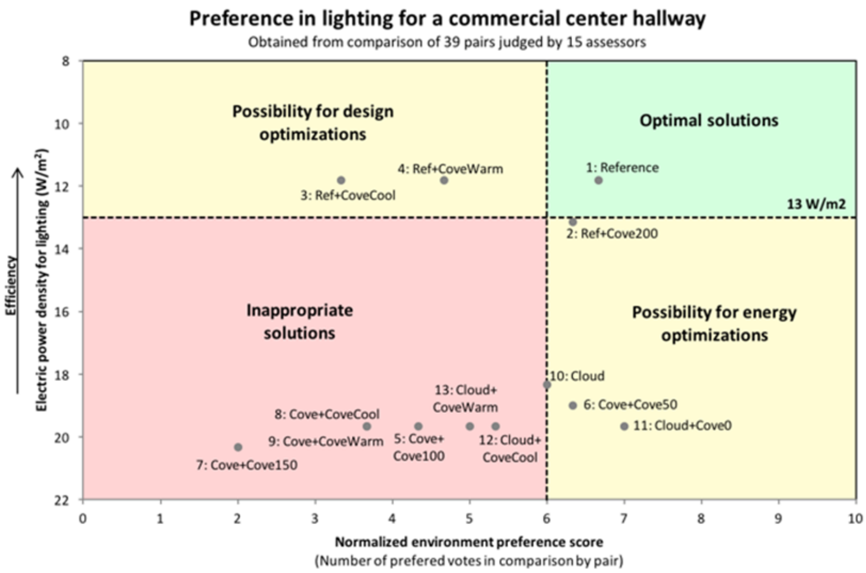
Commercial centre

Thirteen configurations were presented to 15 observers.

Selected cases have electric power densities ranging between 12 and 22 W/m^2. The reference case proposed and built by Rambøll combines very discreet down lighters and a cove light. We should note that no other adjustment of the cove lighting in power and colour improved the quality. This suggests that the power and the colour of the cove lighting as proposed by the designers was appropriate.

However, this solution was slightly outperformed by a configuration adding sky images in the ceiling, but the associated added energy costs appeared excessive.

Cove lighting with images of clouds was judged attractive, but led to lighting power above 18W/m^2. This suggests investigation of large imaging systems using LEDs behind the screen (not in the periphery) to reduce the power consumption significantly.



Comments by observers:

Observers preferred warmer colour temperatures and low intensities to create a cosy environment and contrast between the hallway and the well-lit shops. This suggests that if shops are powerfully lit, lighting at the central area could be minimal.

Artificial skylights may be implemented but should be designed to fulfil aesthetics in relation to surrounding luminaires and real-life conditions. From this comment, and the desire for rather cosy environment, this suggests that possible daylight penetrations (or simulation of daylight) should have rather small dimensions, to avoid excessive interference with the visual impact of the shops.

Atrium

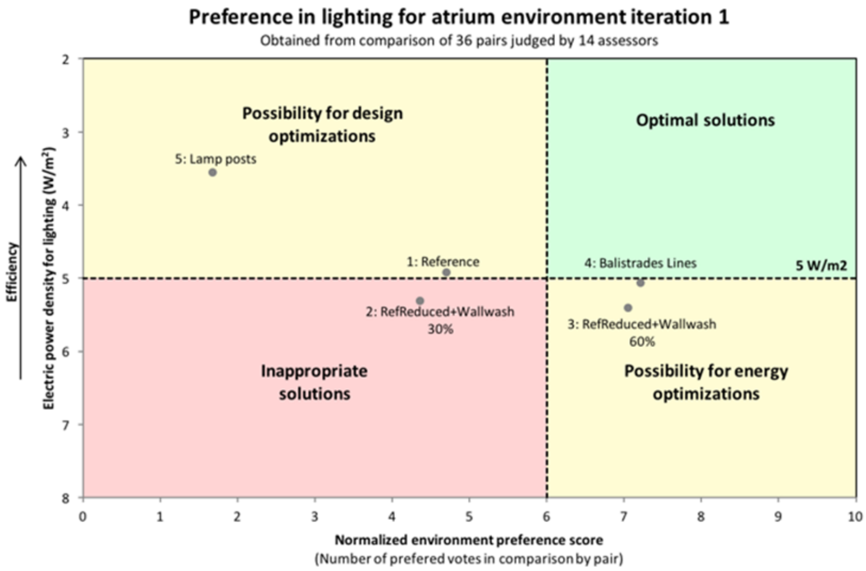
Five configurations were presented for iteration 1 and eight configurations for iteration 2. Twenty observers participated in the judgement for both iterations.

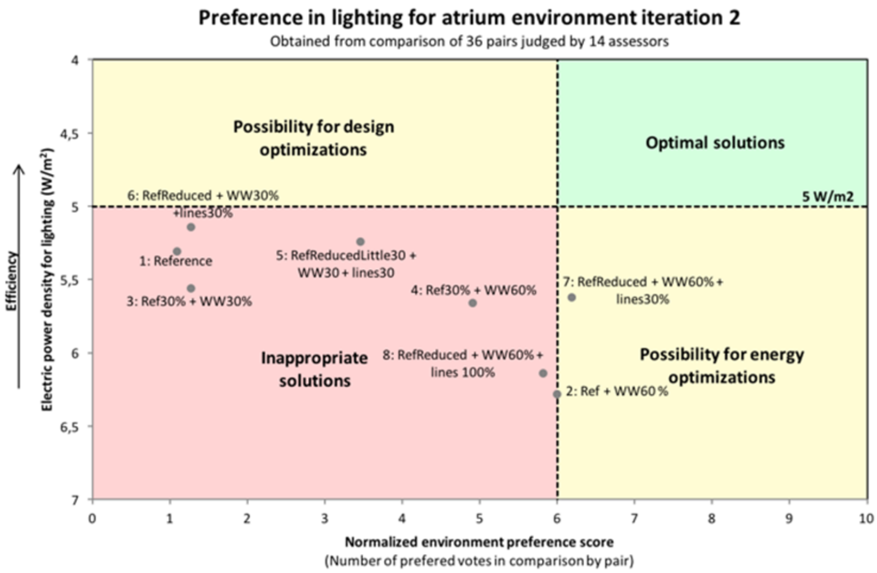
We have investigated solutions proposing suppression of light sources in the centre of the ceiling (high above the ground) for maintenance, and reduction of energy usage. We have then investigated how this could be compensated by bringing light to other surfaces (wall washers, or stand-alone luminaires).

We have also investigated mainly lighting architectural functions (lines on the stairs) and tested if this could allow a reduction of the global electrical power.

Results show that it is difficult to reduce the electric power density in the reference case. Addition of lampposts is the most efficient measure, but effect and design was disliked, suggesting a re-thinking of the design.

Compensation for decreased output from ceiling luminaires by architectural lighting along the stairs lead to an increase of the satisfaction level from 45% to 73%. Adding wall wash lighting on vertical surfaces increased interest, but lead to excessive increase of electric lighting power.





Comments by the observers:

There was a general desire to have a well-lit atrium but not with evenly distributed lighting.

Observers tend to appreciate interesting luminous effects with shadows and highlights in different areas and thus adding more contour/contrasts to the space.

Observers appreciated the principle of wall washers.
However, observers stated that it is important that the different lighting fixtures work well with the overall visual design (good integration with the architecture).

Some fixtures were particularly appreciated: The uniform distribution of ceiling spots, and the lighting lines along the stairs.

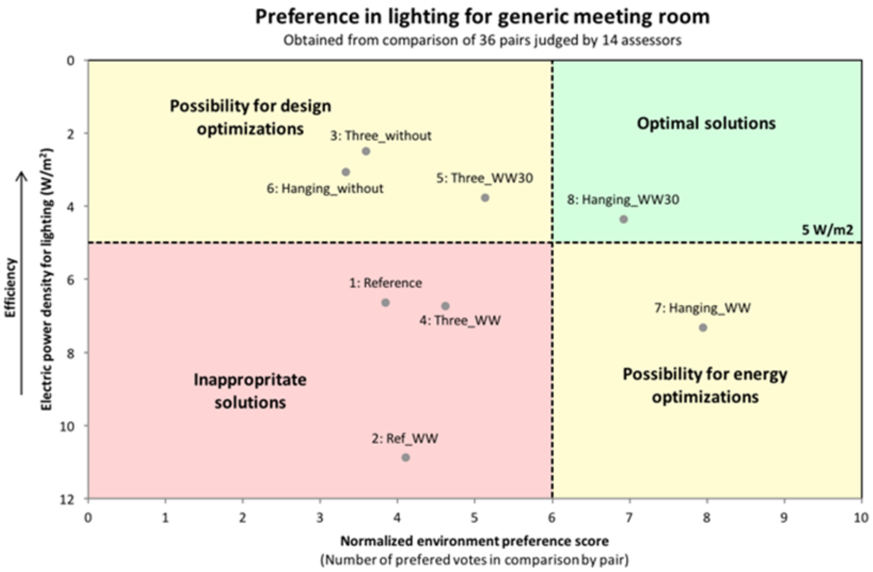
However, many observers disliked the freestanding lampposts.

Meeting room

Eight configurations were presented to 13 observers.

A suspended luminaire above the table is definitely preferred, and a reasonable addition of wall washers allows for energy consumptions below the 5 W/m^2 limit.

Brighter wall washers are preferred (satisfaction level 80%) but electric power reaches then 6.5 W/m^2.



Comments by the observers

A well-lit meeting room is preferred with lighting that creates contrast between seating area and walls, with a good modelling of light. This can be accomplished by creating a dark area between the table and the walls.

Observers expressed their preference for luminaires suspended above the table, in combination with wall washers.

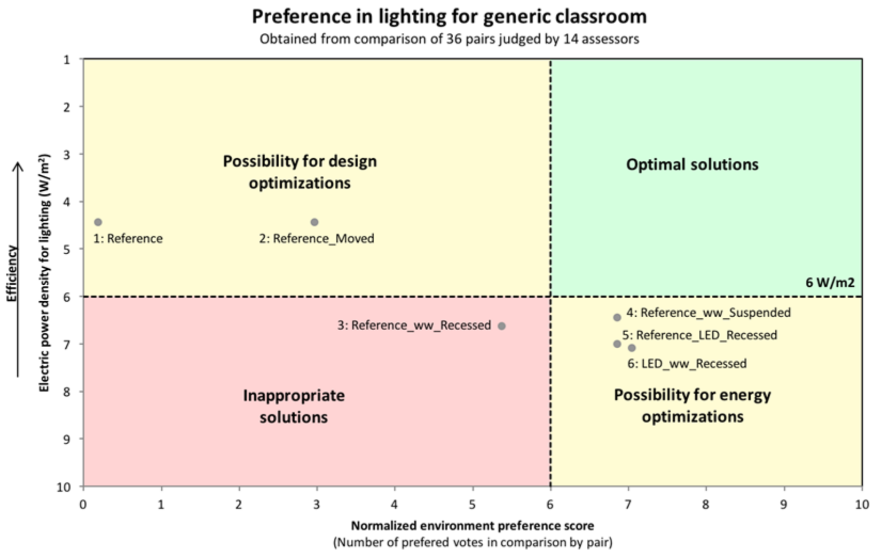
Classroom

Six configurations were presented to 14 observers for the classroom without the projector. Five configurations were presented to 14 observers for the classroom with the projector on.

The interior room dimensions are 6,6 m x 7 m, which is an area of 46,2 m^2.

The evolutions suggest that no scheme is defined as an optimal solution both in regard to electric power density and preference score from the observers. However, if scheme 4, 5 and 6 have a higher efficiency then they would be favourable.

Classroom without projector

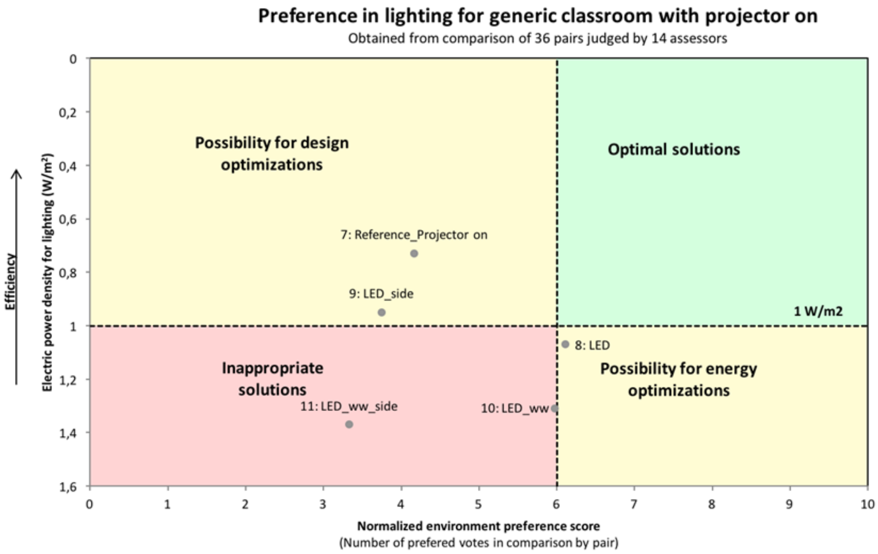


Comments by observers

The focus of the observers was mainly on the visibility of the blackboard. Enough light on the blackboard was preferred but not direct in order to avoid glare. A cooler temperature on the blackboard was favourable.

Diffuse wall washers were desired to have an intensity difference between the students and the blackboard. The observers expressed that this and a little shadow above the blackboard created an aesthetically pleasant look.

Classroom with projector on



Comments by observers

Most importantly the observers expressed a high appeal to being able to read and write at the work desks, while the teacher is presenting with the projector on.

Uniformity was favourable for the observers but a contrast between the board and the desk was also preferred. In regard to the contrast between lighting on the wall and the desk, the observers had split opinions. Some favoured the contrast to have a diversity in the room while others found it distracting.

There were no definitive answers on the appearance of the luminaires or the colour temperature.

Discussion

Results show that there are rather consistent and clear trends in the preferences, which offer good opportunities for designing lighting schemes with improved satisfaction by building occupants.

We should note that in most cases, we have found energy efficient solutions winning more than 70% of the comparisons by pairs.

Trends in preferences

- Added value of a task lamp above a work place, or pendants above a meeting room
- Added value of thin wall washers, or lines created by cove lighting, or accentuation of architectural features, to increase the perception of space (make it more interesting, more spacious)
- Role of illuminance of faces of occupants, suggesting that sufficient light is provided on face, and that contrast is obtained with a darker background
- The importance of deliberate lighting was stressed, with light focussing on specific functions (reading, vision of people, circulation, etc.)
- Globally, scenes with an increased number of light sources were preferred, and some of them with a lower global electric lighting power density.
- For general ceiling lighting there was a clear interest for discrete light sources, uniformly distributed over the ceiling (small LED based lighting)
- For large volumes, it seems that high efficient stand-alone luminaires (or lampposts) is a nice approach, but may lack correspondence to the overall visual design.

Challenges for product development

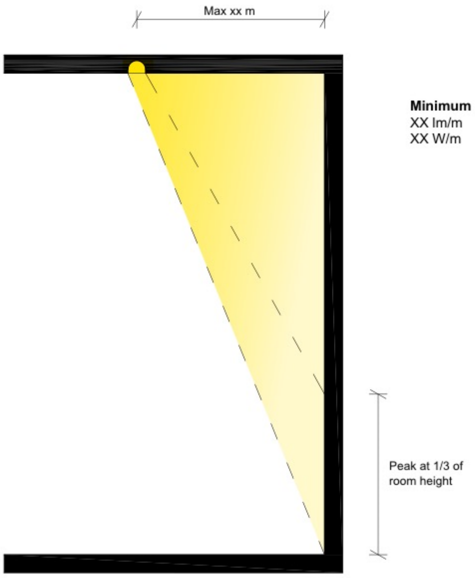


Figure 104 Specifications for an optimum wall washer

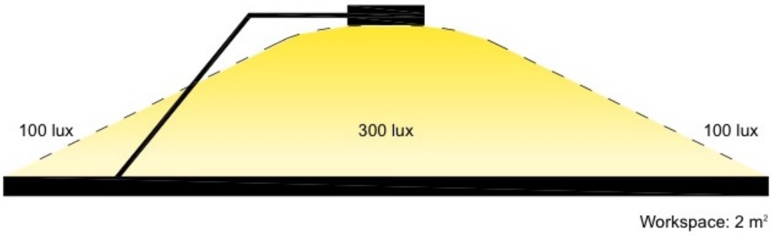


Figure 105 Specifications for a task lamp

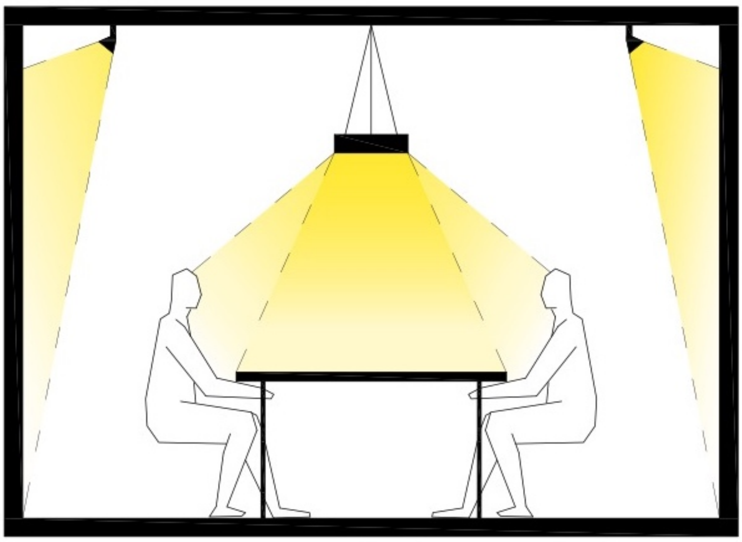


Figure 106 Specifications for pendant luminaries for meeting room

Figure 107 Specifications miniaturized LED systems

Figure 108 Specifications for lamp post design to light large volumes:
luminous power 2000 lm / 4000 lm , balance between diffusion and optical control

Communication / dissemination

Outreach to stakeholders

Originally, the project description defines the main target groups of the project as lighting professionals and architects, whereas the project does directly affect end users who are therefore not directly targeted (acc. to section 4 point "d" on page 11 in the Project Description, June 2013).

The main concern in the project thus is to reach lighting professionals and architects through *seminar activities* and *articles* in the professional magazine "Lys" published quarterly by Danish Lighting Centre (DCL). DCL has approximately 900 members who are mainly lighting professionals (e.g. lighting designers, architects, contractors, municipalities, electricians, engineers and light oriented students).

Finally, the project outlines ideas and results in a conclusive YouTube film that will be launched in social media throughout 2016.

In the following sections, it is described how the project progress and results have been disseminated and how the project's target groups/stakeholders have been informed during the project.

Involvement of professionals in the tests

Both DCL and AAU have been heavily involved in engaging test people in "live tests" with the purpose of showing visualizations using AAU's powerful video projector, which is capable of reproducing very high intensities of light and even can reproduce glare situations to some extent.

There has been a series of tests arranged by AAU at Henning Larsen Architects, AAU with students and Fagerhult over summer 2015 and further tests at the beginning of 2016 – all test persons relatively close to the project as "second party stakeholders".

During these tests, AAU showed several light scenarios: Twelve small versions of office lighting (shown to HLA, 25 test persons), office lighting with further extensions (shown to Fagerhult, 14 test persons) and hospital/patient situation (shown to AAU students, 14 test persons).

To have a larger data material for statistical validation of the result's significance, further tests were necessary at "third party stakeholders". It was not an easy task to engage third party lighting professionals and non-professionals in attending live tests of photorealistic visualization.

During September to December 2015 DCL reached out to possible companies and persuading them into participating in the live tests of visualizations. DCL has contacted thirteen companies with the aim of making two or three test sessions of each 10-20 test persons in groups of five people, over a period of around 45 minutes per group. Figure 109 shows the “teaser invitation” that DCL sent to the possible test attendees.

Fotorealistisk Visualisering – ELFORSK-projekt ved Aalborg Universitet i København

Virksomheder søges til test af visualiseringsteknikker til lysdesign

Vil du og din virksomhed være med til at udforske visualiseringer af lysdesignprojekter og give jeres mening til kende om, hvad I bedst kan lide?

I forbindelse med ELFORSK-projektet ”Energieffektiv belysning gennem fotorealistisk visualisering” søger vi testpersoner, som vil teste lysscenarier; minimum 10 personer pr. virksomhed og om muligt gerne 20 personer. Testpersonerne i jeres virksomhed behøver ikke at have nogen speciel viden om lys.

Testen foregår i grupper á 5 personer med 45 minutters varighed, således at hver person forventes at skulle afsætte ca. 45 minutter af til testen. I skal sætte et par timer til en halv dag af til hele testen, alt efter hvor mange personer, som deltager. Testen skal foregå i et mørklagt rum.

Vi ønsker at testen finder sted i oktober eller november måned 2015. En projektleder fra Aalborg Universitet møder op hos jer med udstyr, som kan fremvise fotorealistiske billeder. I skal vurdere forskellige billeder, og give jeres mening til kende.

Ved at deltage i projektet vil I få den sidste nye viden om fotorealistiske visualiseringer, og få afprøvet hvilken form for belysning, I synes fungerer bedst i et rum. Vi får værdifuld viden til forskningsprojektet og vil gerne høre jeres mening om, hvordan dette design- og beslutningsværktøj kan anvendes i praksis.

Projektet er beskrevet i LYS nr. 2, 2015 og du kan se mere om projektet på ELFORSK’s hjemmeside: http://www.elforsk.dk/ELFORSK/Projekter/ProjectSearch/ProjektInfo.aspx?proji=346-046

Er du interesseret kontakt Dansk Center for Lys: Thomas Maare: tm@centerforlys.dk (tlf.: 4266 0188) eller Mette Hvass: mh@centerforlys.dk (tlf.: 4717 2935).

Foto af testopstillingen

Vi ser frem til at høre fra jer ☺

Med venlig hilsen

Mette Hvass og Thomas Maare
Dansk Center for Lys

Figure 109 Teaser invitation sent to possible test attendees.

Finally, three test sessions were planned and two of them were merged into one test group – the third ended up being cancelled by the attendee due to a hectic period before Christmas 2015. The outcome ended up being one large test session in December 2015 at Citelum Denmark with 14 test persons divided into three groups. In total AAU has conducted six larger test sessions with a total of approximately 95 test persons showing various different light scenarios in numerous variations, amounting to 94 light settings.

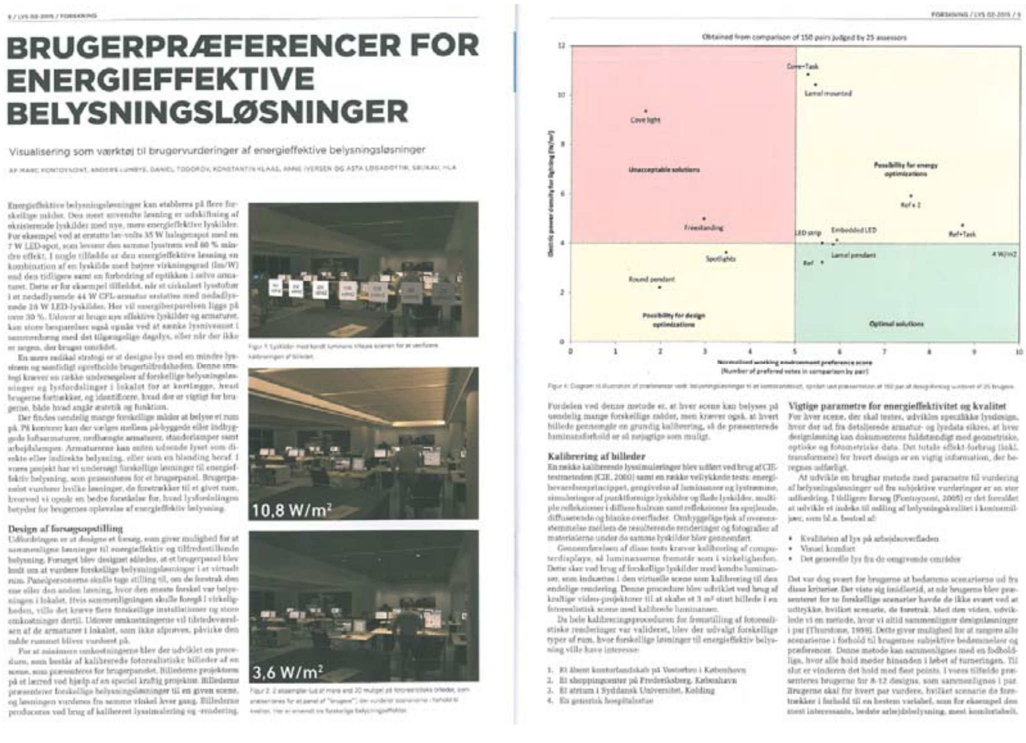
Communication of results

A communication package comprising articles, seminars and a YouTube film is the backbone in the dissemination of project progress and results deriving from the various tests and research in the photorealistic visualization project.

Articles in the professional magazine “Lys”

In the magazine “Lys, No. 2, 2015” the article “User Preferences for Energy Efficient Lighting Solutions” was written by the project team at SBi/AAU and Henning Larsen Architects: Marc Fontoynont, Anders Lumbye, Daniel Todorov, Konstantin Klaas, Anne Iversen and Asta Logadóttir.

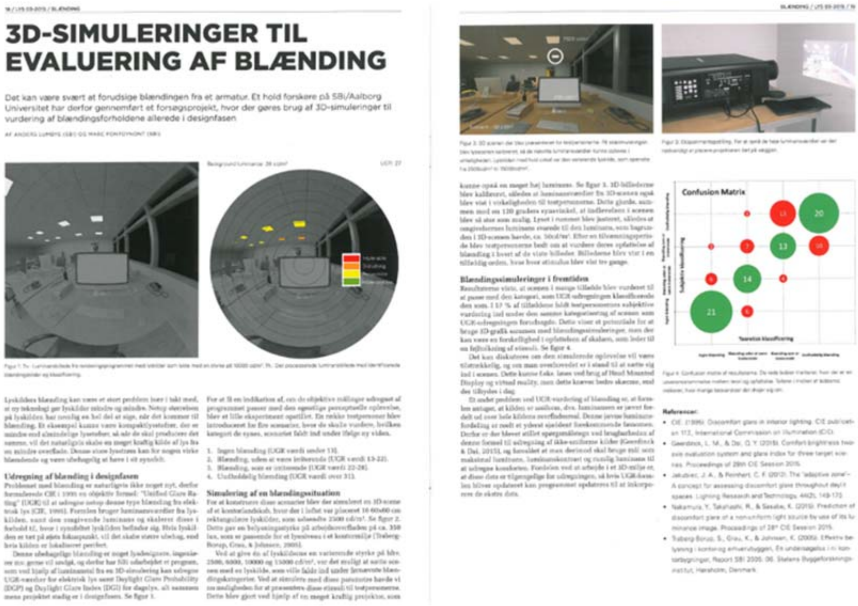
In this article, the main ideas behind the project are described: How calibrated photo realistic visualizations are used in test sessions to evaluate light preferences that can be compared to energy efficiency in the Preference/Efficiency Matrix.


BRUGERPRÆFERENCER FOR ENERGIEFFEKTIVE BELYSNINGSLØSNINGER

Visualisering som værktøj til brugervurderinger af energieffektive belysningsløsninger

Fig. 2: Article in Lys No. 3, 2015: “User preference of energy efficient lighting solutions”.

Anders Lumbye from AAU described the progress and discussed the outcome of the visualization project in the magazine “Lys, No. 3, 2015” in the article “3D simulations to evaluate glare”. The two-page article visualizes and discusses the possible confusion between theoretical classification and subjective classification of the perceived stimuli from the visualization in a so-called “Confusion Matrix”. Figure 110 illustrates this article.



3D-SIMULERINGER TIL EVALUERING AF BLÆNDING

Det kan være svært at forudsige blændingen fra et armatur. Et hold forskere på SBi/Aalborg Universitet har derfor gennemført et forsøgsprojekt, hvor der gøres brug af 3D-simuleringer til vurdering af blændingsforholdene allerede i designfasen

Figure 110 Article in Lys No. 3, 2015: “3D simulations for evaluation of glare”.

An article for the professional magazine Lys No. 2, 2016 after the project’s research finalization, will be written explaining the key findings in the project and showing examples of the visualizations, etc.

Press release

A press release presenting the product results in a hands-on way for e.g. electricians, architects and engineers to be produced as a part of the project in parallel to above-mentioned article in Lys No. 2, 2016.

Seminars for architects

During the project, two seminars have been organized. The first seminar (targeted at the lighting business) took place in June 2015 arranged in cooperation by AAU and Danish Lighting Innovation Network under the following articulation:
"How can we use media technologies to explore users' experience of different lighting scenes? Come, listen and play with media technologies for designing future lighting".

Figure 111 Programme for seminar on the 17th of June 2015 on visualization, virtual reality and augmented cognition.

The second seminar targeted at Danish architects was arranged in cooperation between the Danish Association of Architects (Arkitektforeningen) and Danish Lighting Center and took place on the April 4th 2016 in an auditorium at AAU in Copenhagen. More information is available on the seminar's web site: www.styrlysdesignet.dk, see Figure 112.

Figure 112 Web site for the second architect seminar on the 4th of April 2016.

The teaser for the seminar said: “Light is a prerequisite for the experience of architecture - and this applies to both artificial light and daylight. There are many impressive visualizations, but they are often a “pretty painting” of how light interacts with the building and its users. How is the actual light and how do you maintain your vision for the architectural experience throughout the design and construction process?”

Thus, the main target of the seminar was to hear how and when architects work with visualizations of light and to discuss and debate how to claim the ownership of the lighting design and related energy consumption throughout the project as an architect. Four key architects and lighting designers focusing on energy savings and good lighting in Danish architecture participated and gave presentations and participated in a panel discussion, lead by Marc Fontoynont, Professor AAU, on how to integrate energy savings and lighting design and visualizations /simulations throughout a project.

The feed back on the architect seminar the 4th of April 2016 was very positive and through the cooperation with between Danish Association of Architects (Arkitektforeningen) we succeed in reaching many new target group members as more than half of the almost 100 participants were architects and/or working in the architectural business area.

The contact with Danish Association of Architects is expected to bring new seminars on lighting in the coming years in cooperation with Danish Lighting Centre.

Figure 113 Pictures from the architect seminar on the 4th of April 2016 with happy participants, Lene Lene McNair/Danish Association of Architects (Akademisk Arkitektforening), Jesper Ravn/Gottlieb Paludan Architects and Merete Madsen/Sweco, Lighting.

YouTube film

During the winter/spring season 2015/2016, a film has been shot and directed by DCL. The video material has been edited into an approximately 7 – 8 minute long film explaining the key focus and outcome of the visualization project.

The film will be put on YouTube in spring 2016 as part of the project documentation and as a tool for communicating the project findings to the target group and other people interested in learning about the findings in the project and about possibilities with photo realistic visualizations.

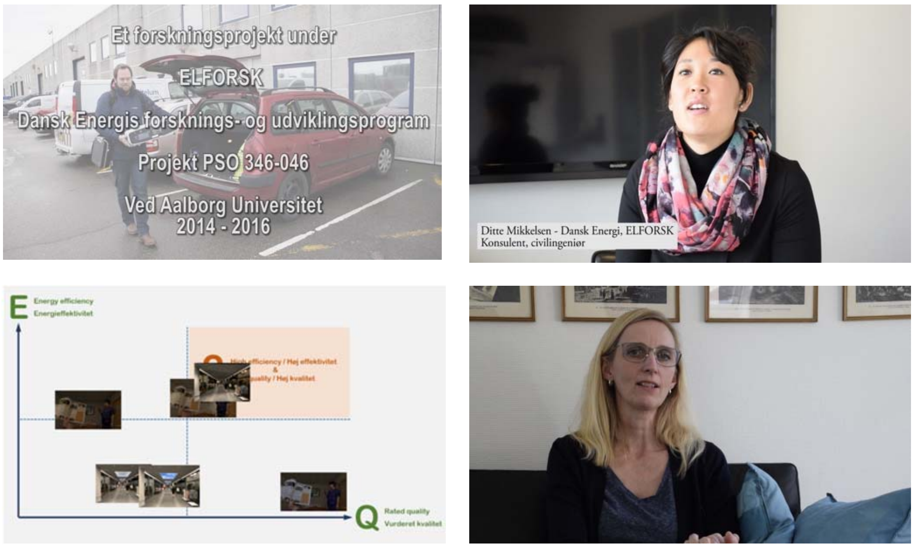


Figure 114 Screen shots from the YouTube film showing: Intro scene with title text, interview with Ditte Mikkelsen/Elforsk, photo realistic visualization scenarios put into the Preference/Efficiency Matrix and interview with Anne Bay/DCL.

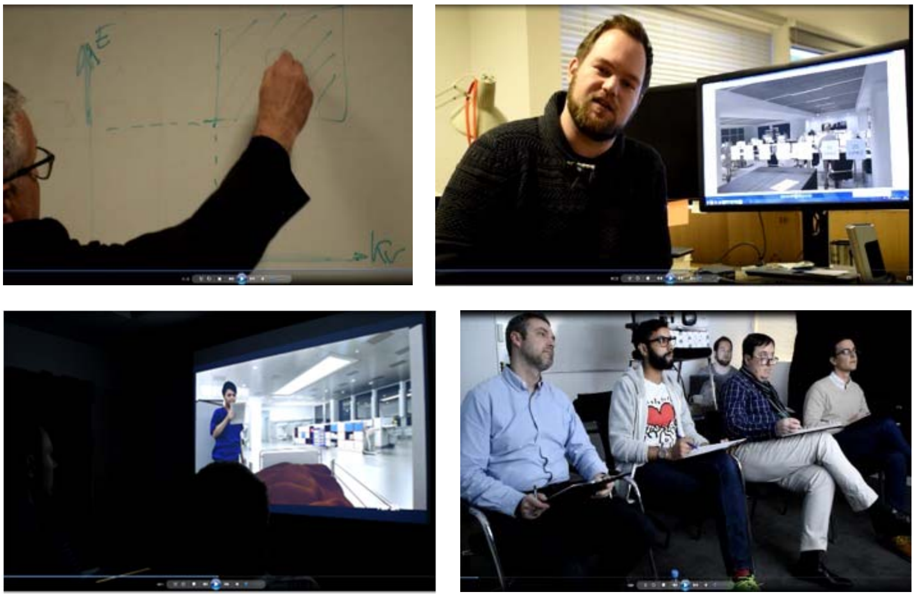


Figure 115 Screen shots from the YouTube film showing: Marc Fontoynont/AAU drawing the Preference/ Efficiency Matrix, Anders Lumbye/AAU explaining simulation of luminance levels and two test scenarios with test groups at Citelum Denmark.

The main purpose of the YouTube video is to show how to evaluate numerous different light settings objectively and compare these to the energy consumption by showing the evaluations in an easily overviewed “Preference/Efficiency Matrix” (also referred to as “the PEM”). The film explains how the project has come up with a way to make light simulations appear like photorealistic light visualizations that can be compared and evaluated in short time instead of walking around trying to remember the differences between relatively expensive live setups/ mock-ups. All this with the aim of encouraging well designed, high performance and energy friendly lighting projects. See Figure 114 and Figure 115: Screen shots from the film material.

As the YouTube film is not finalized by the editing of this report, it is not possible to show the link to the film yet.

Conclusion

The results are clearly linked to the quality of the calibrated photorealistic scenes, which have been presented to the observers. Although they judged the experience positively after the testing sessions, it is clear that the exercise would be more realistic by improving further the realism:

1. through improving the immersive aspect
2. through making the scene livelier (animation and sound)

The improvement of the immersive aspect is being tested presently at SBI-AAU: Head Mounted Displays (HMD) allow observers to explore freely the space around them, and improve comfort to answer the questions. Calibration is less precise since resolution and dynamics of luminance tend to be lower than with projected images. However, the experience is more powerful.

It seems also that with the VR approach, we could be more specific in the questions, and more specific in the adjustments, which are proposed: specific to the given direction of visions, to light effects, or conditions of observations (sited at work place, standing, entering a room, etc.) This requires to adjust the VR-equipment to fit each user to make it “feel like the users own sensations”.

Presentations to professionals during the three major events, which we organized, show that these techniques should also facilitate exchange between lighting professionals, architects, engineers and clients. This could leverage obstacles for some innovative energy efficient lighting proposals, and contribute to raise interest towards them.

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