Study of light patterns on interior surfaces

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I don't understand light. It gives me the feeling there's something beyond me,
something beyond all understanding. And I am very glad,
very grateful that there is such a thing

- Peter Zumthor, *Atmospheres*

1. Introduction

1.1 Visual effects of Light

The process of perception informs humans about the world that surrounds them, and, subsequently, visually perceived surroundings have a profound effect on the physical well-being and emotions of men and women[1,2,3]. Lighting has a large influence on how objects and the spatial environment will appear. The play of light and shadows is multifaceted by nature. Artifical lighting, when shaped competently, can provide luminous conditions that can recall experiences known from natural light.

1.2 Perception of light patterns

Visual effects of lighting have been studied by artists and scientists for more than 500 years and nowadays are still of high interest. If, as recently suggested by Tiller and Veitch, the distribution of luminances within a space will influence perceived brightness[4], then a study of the range of variation is a logical step forward. Earlier works of Kemenade and Reker studied light patterns projected by lamps. Based on characteristics of the perceived light patterns they introduced a description of the visual beam angle and gradient function. In their study, Kemenade and Reker compared different light sources and optical systems: parabolic reflector lamp 38E 120W flood and spot or bowl reflector lamp 100W in a 19 cm reflector. To simplify comparison they suggested categorise the

[1] Suresh Sethi, *Light play* 10th Generative Art Conference GA2007
[2] Baron RA, Rea MS, Daniels SG. *Effects of indoor lighting (illuminance and spectral distribution) on the performance of cognitive tasks and interpersonal behaviors: The potential mediating role of positive affect.* Motivation & Emotion 1992; 16: 1-33
[3] McCloughan CLB, *The impact of lighting on mood* Lighting Research and Technology, 1999, 31(3): p.81-88
[4] Tiller D K, Veitch J A, *Perceived room brightness: Pilot study on the effect of luminance distribution*. Lighting Research and Technology, 1995. 27(2): p. 93-101

light pattern produced according to a so called K-factor, ranging from K1 to K5 (see appendix).

Categorisation of the sharpness of a contour plays an important role in describing the performance of lighting equipment used for accent lighting. The various reflector types and light sources available can be used to provide light distributions that create specific visual effects. In general, characteristics of spotlights are defined by the maximum intensity of the beam and the beam angle. The most commonly used beam angle is measured between two diametrically opposite points with half-power intensity. This definition aligns poorly with what is perceived, as Kemenade pointed out. He suggested therefore the use of “visual beam angle”. This definition is based on the idea that luminance changing beyond a certain change rate is visually perceived as a contour and that the visual beam is dependent on the contour with the maximum change rate or gradient value. The visual beam angle is defined as the angle between those points in a luminance profile that feature the maximum gradient value. A perceptually optimized description of the performance of a spotlight for accent lighting thus contains:

- Centre beam luminous intensity, I_{max} in cd
- Visual beam angle (angle at which the visible contour of the beam is perceived)
- Contour sharpness (determined by the gradient function of the luminance profile)

2. Light pattern description

2.1 Beam angle

Next to the commonly used “half beam width”, in certain fields of application the beam angle is measured at 10% of the maximum intensity and called “field angle” (Fig.1). Both definitions are formal descriptions that do not tell enough about the visual perception and appearance of a light spot.

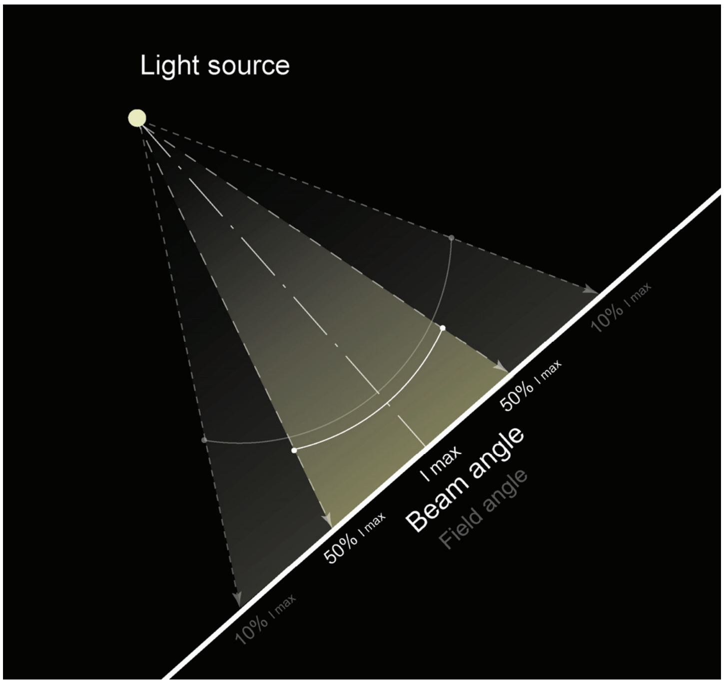

Fig.1. Beam and field angles

To facilitate the work of lighting designers and luminaire manufactures in the creation of effective lighting solutions, Kemenade proposed the Visual Beam System[5]. “This classification system is therefore directly related to the actual visual perception of the beam, which allows its effect in practical lighting situations to be predicted”. The visual

[5] van Kemenade, J, *A visual beam definition.* International Lighting Review, 1986(2): p. 53-56

beam angle enables more accurate prediction of the size of the visual contour, in those cases where a contour is visible, than the widely used "half beam width". Together with the luminous intensity of the light source, the apparent beam patterns influence how bright a situation is perceived. The actual perceived brightness is also influenced by the state of adaptation of the eye, the information content and surrounding contrast ratios[6].

2.2 Gradient value

According to Kemenade and Reker[7], the visual beam angle of a spotlight can be defined as the angle between the points at which the gradient function is at maximum. This is where greatest brightness contrast between adjacent areas in the light spot pattern is present. The gradient function is defined as a logarithmic function of the illuminance or luminance difference between two adjacent points relative to the distance between them. The formula to calculate the gradient value is: $\frac{\log E1 - \log E2}{R1 - R2} = \frac{d\log E}{dR}$, where d$\log E$ is the increment in illuminance and dR the corresponding increment in distance. The quotient d(logE)/dR gives the gradient of the illuminance profile. The maximum gradient value of the gradient function will describe the strongest defined contour (Fig.2).

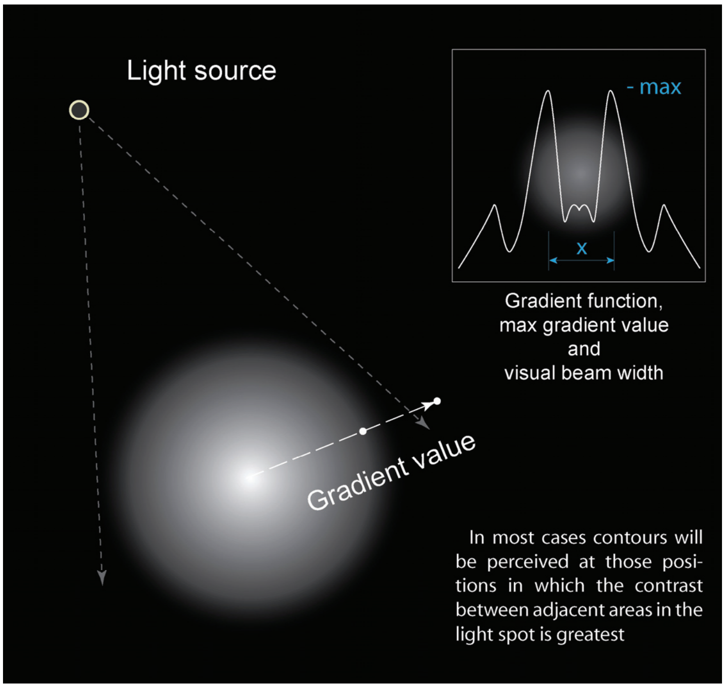

Fig.2. Light pattern and max gradient value. In most cases contours will be perceived at those points in which the contrast between adjacent areas in the light spot is greatest

2.3 K-Factor

The sharpness of the contour is determined by the gradient function. This visually observed contour sharpness can be categorised according to the K-factor in 5 classes. The five classes define five types of light beams[8]. They range from a very distinct contour (K1) up to a virtually uniform light distribution pattern with no visible spot (K5). The K-factor can be derived from the gradient value. In Table 1, gradient values are given in dB/cm for a reference distance of 1m, and the independent derived distance estimates are given in

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[6] Tiller D K, Veitch J A, *Perceived room brightness: Pilot study on the effect of luminance distribution*. Lighting Research and Technology, 1995. 27(2): p. 93-101

[7] van Kemenade J, Reker J, *Beam characteristics for accent lighting*, *IES Annual Conference*. 1987

[8] Philips Lighting, *Lighting and accent. A practical selection guide for light sources for accent lighting*. 1996

dB/degree (see Fig.3). Conversion is done by calculating the beam angle for two points around the centre that are at a reference distance exactly 1cm distant from each other. In Table 2, values are given for 1m and the actual distance from our experimental setup.

K-factor		Gradient value in db/cm in the reference of 1 m	Gradient value estimated in dB/degree
K1	=	> 4 dB/cm	> 7 dB/degree
K2	=	2-4 dB/cm	3.5-7 dB/degree
K3	=	1-2 dB/cm	1.75-3.5 dB/degree
K4	=	0.5-1 dB/cm	0.88-1.75 dB/degree
K5	=	< 0.5 dB/cm* *where dB = 10 Log E1/E2 With 1m distance	< 0.88 dB/degree

Table 1. K-factor and maximum gradient values

Distance	Corresponding degree
1m	0.57 degrees
1.56m	0.37 degrees

Table 2. Angles that correspond to a 1cm step at different distances

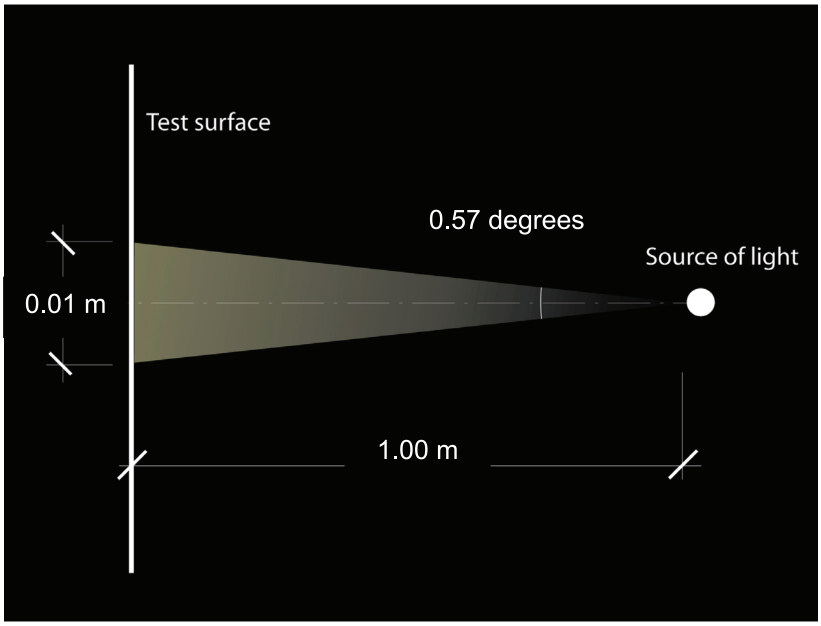


Fig.3. Angle that corresponds to a 1cm step at 1m distance from the light source

3. Study design

In our study we measured physical characteristics of a stimulus and related them to the behavioural responses of human observers. In the experiment we used psychophysical methods to investigate the perception of light patterns. On the basis of what is known about the gradient value of spotlights, we created light patterns that were perceived as uniform or non-uniform. The aim of the study was to quantify the threshold of just perceived uniformity and just perceived non-uniformity. This border is thought to coincide with transition from K-factor 4 and K-factor 5 for spotlights. Subjects in our experiment tuned the light in four scenes according the criteria of uniformity or non-uniformity. In two of the scenes, the subjects needed to create uniform perceived light patterns, and in the other two scenes they needed to create non-uniform perceived light patterns. Subjects tuned the scenes either by increasing the intensity of the diffuse light (to produce light patterns that are more uniform) or the directional lights (to produce light patterns that are less uniform). The dependent measure recorded was the vertical surface illuminance and the corresponding luminance profile and gradient function. The light emitted by all sources was controlled to minimize differences in correlated colour temperature. Scenes were tuned by adding a just sufficient amount of light to meet the perceptual criterion.

3.1 Experimental Set Up

The experiment was performed at the Lightlab of Philips Research Europe in Eindhoven. The laboratory space is a white painted room that is 3.75m by 6.27m and has a height of 3.00m. All light patterns to be tested on vertical surface were generated by light from two ceiling recessed halogen spots generating directional light (Philips Fugato 1xHAL - 45W 24D), and three ceiling recessed fluorescent luminaires emitting diffuse light (Philips Savio TBS770 ACMLO 6xTL5-14W) (Fig.4,5). Distance from light source to centre of the light pattern on the wall was 1.56m. The colour temperature of the fluorescent diffuse light source was trimmed for the initial condition to match the halogen light sources.

Fig.4. Perspective view of the laboratory and simulated in DIALux light distribution from Philips Savio

Subjects examined the light pattern from a position in the centre of the room, at a 3.00 meter distance from the light pattern. Subjects remained seated in this place during the whole experiment. Light pattern in scenes 'Stimulus 1' (Fig.7) and 'Stimulus 2' were initially to be perceived as non-uniform. The task of the subjects was to create a light pattern that was perceived as uniform. Scenes 'Stimulus 3' (Fig.6) and 'Stimulus 4' were initially to be perceived as uniform. The task of the subjects was to create non-uniform perceived light patterns. Stimuli 2 and 4 provided light patterns similar to Stimuli 1 and 3 but at half the luminance level. Detailed description of Stimulus 1 is given in the form of a computer rendered scene (Fig.7), luminance pictures (Fig.8), false colour illustration (Fig.9), luminance profile (Fig.10) and derived gradient function (Fig.11). Description of stimuli 2, 3 and 4 are in the appendix. In addition to the measured 2-dimensional distribution of luminance at the wall surface, the illuminance was measured at two points.

Stimuli were measured with the Spectroradiometer: PhotoResearch Spectra Duo (Fig.12) and the Luminancephotometer: Radiant Imaging PM Series Imaging Colorimeter Model: PM-1423-1. Lenses: Nikon 20mm 1:2,8D (Fig.13).

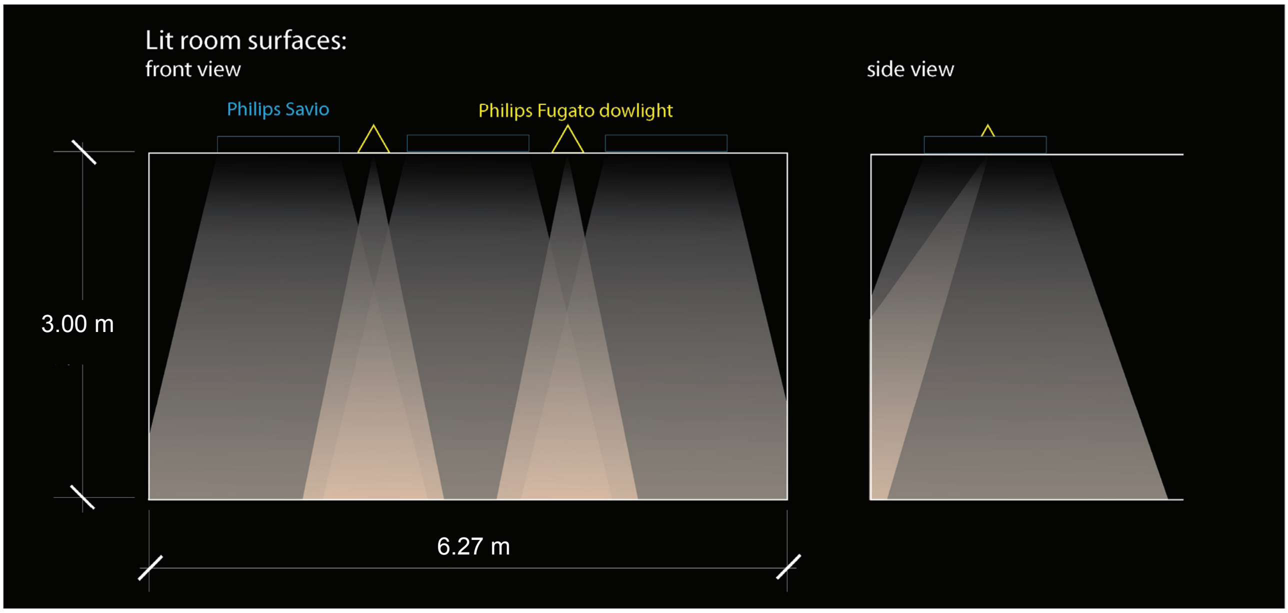


Fig.5 Scheme of Luminaire positions and light distribution on the vertical surface.

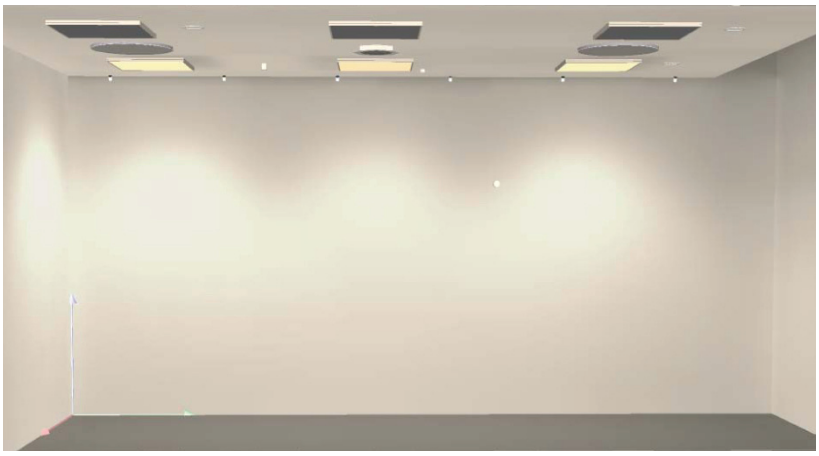


Fig.6 Computer rendered scene of Stimulus 3 with high amount of diffuse and low amount of directional light

Fig.7 Computer rendered scene of Stimulus 1 with high amount of directional and low amount of diffuse light

Fig.8 Luminancephotometer measurement. 1.53 x 1.02 m

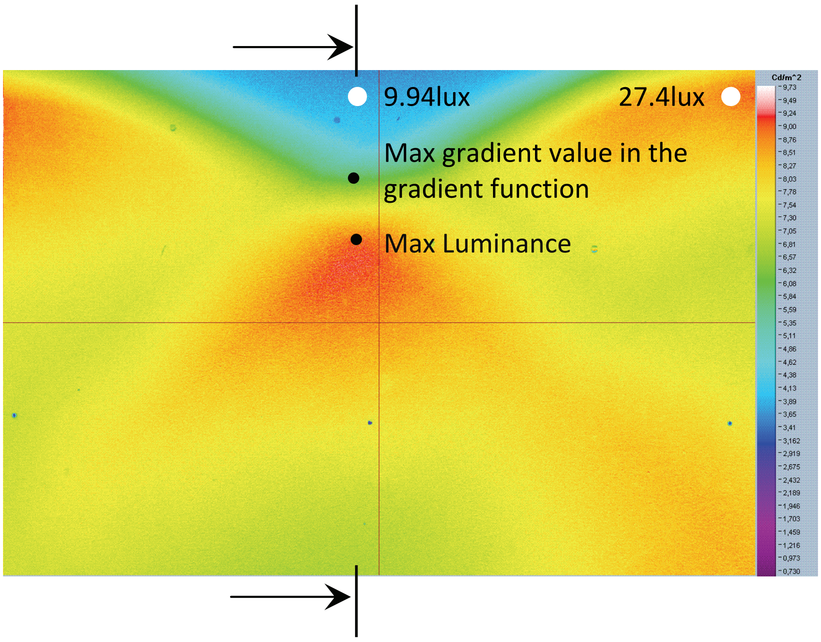


Fig.9 False colour representation of luminance measurement.
Max gradient value.
Max Luminance.
1.53 x 1.02 m

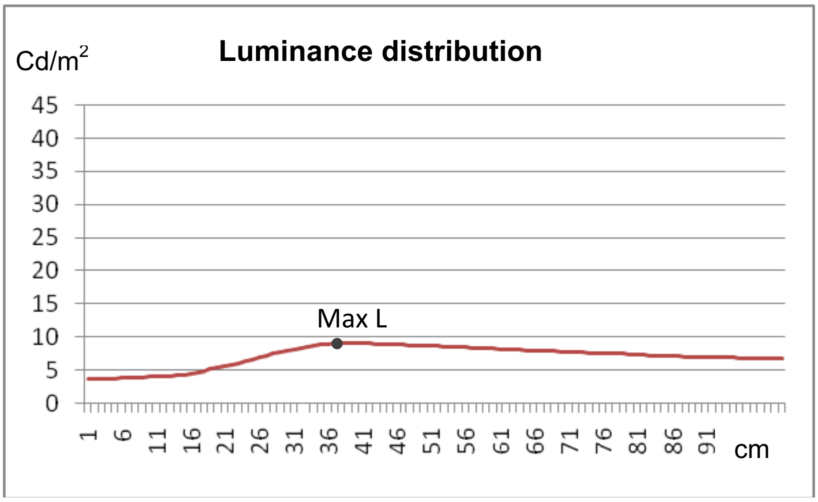


Fig.10. Luminance distribution scan for the section with the max value

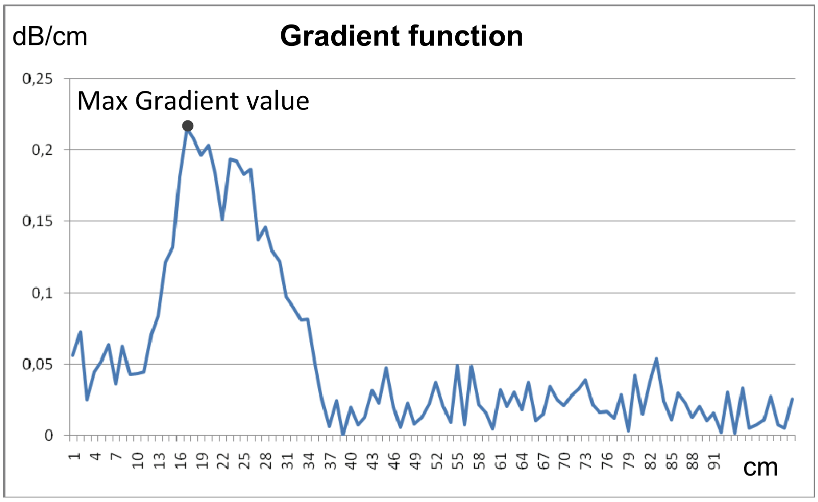


Fig.11. Graph of the gradient function for the section with the max value

Fig.12. Spectroradiometer

Fig.13. Luminancephotometer

3.2. Procedure

Six subjects, three male and three female, participated in the experiment. All were drawn from the staff of Philips Research. None of them have reported any visual dysfunctions. The following instructions were given to each subject.

"This experiment is concerned with how lighting can influence the appearance of the room. You will see four different scenes with neutral situations in between.

- *In the first two scenes your task will be to arrange the luminance pattern on the wall to a uniform appearance,* ***the point at which you think the wall is evenly illuminated****.*
- *In the second two scenes your task will be to arrange the luminance pattern on the wall to a non-uniform appearance,* ***the point at which you think the wall is unevenly illuminated****. "*

After reading the instructions, subjects were given some test trials to get acquainted with the task. Those trials presented the range of conditions subjects would see in the experiment. The procedure used for the experiment was identical to the procedure used for the trials. Scenes were tuned by adding just a sufficient amount of light to meet the perceptual criterion. The dimming level of the lights was controlled with a computer by the experimenter according to the subject's commands. The experimenter stayed in the room during the whole experiment. Each subject tuned four scenes (Stimuli 1 to 4). When each scene had been completed, results were recorded. On average, it took about 15 min for each subject to tune lights for 4 experimental conditions.

3.3 Results and discussion

Subjects showed consistent behavior in tuning each situation to similar thresholds. Graphs below show the average amount of light needed to tune non-uniform situation to uniform (Figures 14, 15) and uniform to non-uniform situations (Figures 16, 17). Stimuli 3 and 4 turned out to be close to threshold value. The resulting differences after tuning have therefore been rather small and limit the conclusion we can draw from it. The brightness gradient function was taken from a vertical profile in the middle of the wall. It was calculated as $10\frac{\log L1-\log L2}{R1-R2}$. Subjects tuned the high intensity and the low intensity conditions towards the same gradient values. Tuning towards non-uniform perceived appearance has demonstrated clearly a threshold value of 0.16 dB/degree (0.06 dB/cm) under given test conditions (see table 1 and 2 for reference value and conversation). The tuning results for non-uniform perceived appearance indicated threshold at approximately the same level.

The difference between our result (0.16 dB/degree) and results obtained by Kemenade (0.88dB/degree) are supposedly due to differences in the setup. Tests by Kemenade were done in a dark surrounding and using a single isolated spot pattern; we tested with general light and a pattern composed of more sources. Also, illuminance levels were more than a factor of 20 higher in the study by Kemenade than in ours. In our setup, adding of general light caused a fading of contours. As a result, the steepness of the gradient is decreased and thus the perceived brightness[9].

Comments were collected from subjects after each experiment. A common difficulty experienced was caused by the presence of scallops (hyperbolic shaped light pattern typically produced by spotlights or downlights).

Fig.14. Stimulus 1. Vertical luminance profile and derived gradient function

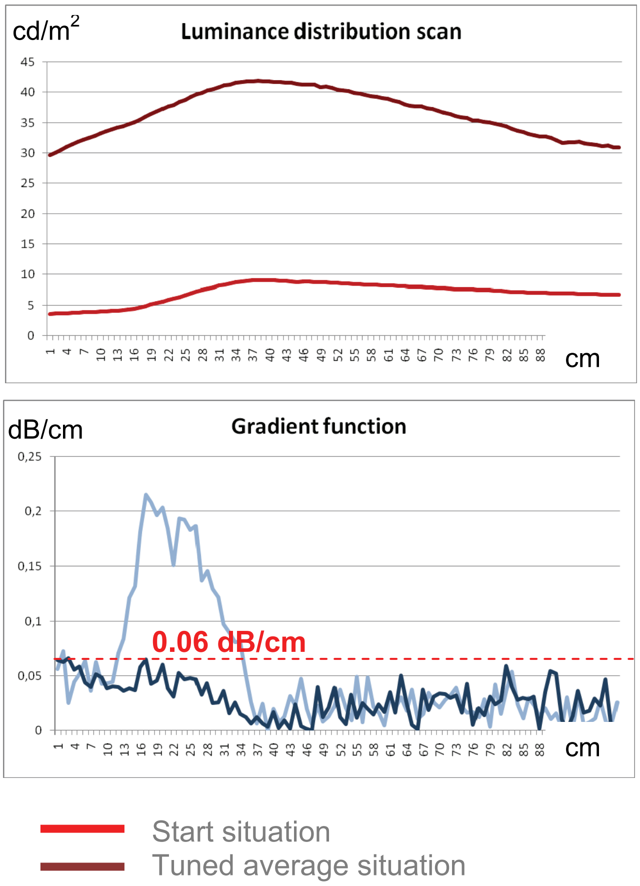
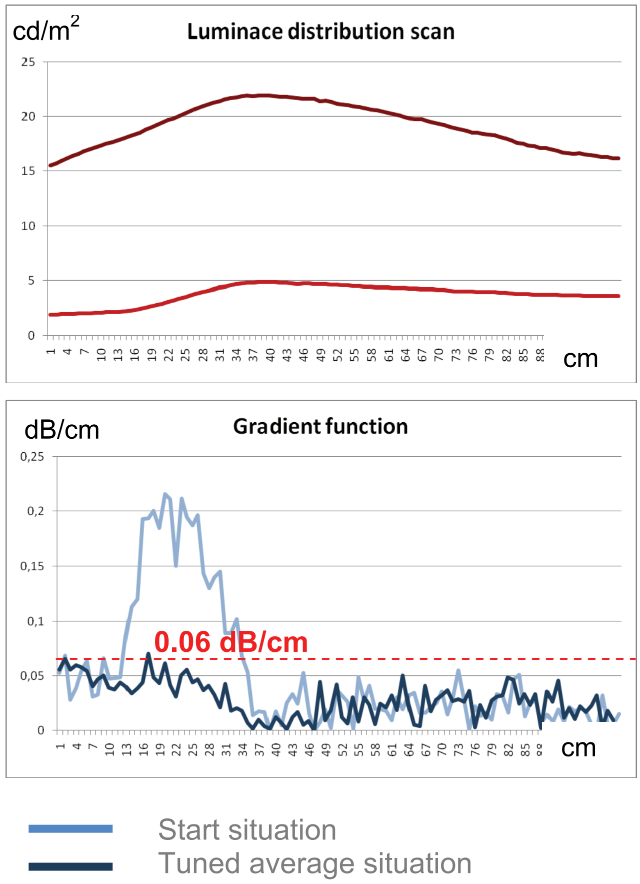


Fig.15. Stimulus 2. Vertical luminance profile and derived gradient function



4. Conclusion and Recommendations

One reason that lighting design has remained more an art than an engineering discipline is that it is hard to grasp perceptions objectively. Light beams create different light patterns depending on their maximum intensity, visual beam angle and gradient value. The performed study marks an attempt to acquire knowledge about the perception of uniform and non-uniform patterns on walls of interior spaces. The description of brightness gradient value was used to measure the transition of brightly illuminated areas to less brightly illuminated ones. There were no studies available concerning gradient

[9] Ngai, P. Y., *The Relationship between Luminance Uniformity and Brightness Perception*. Journal of the Illuminating Engineering Society, 2000. 29(1): p.41-47

values of lighting patterns on this scale. We derived a reference value from the contour sharpness definition used to determine the K-factor for accent lights. From this study, it can be concluded that conditions with lower gradient values are perceived as more uniform and conditions with higher gradient values are perceived as less uniform. The threshold is found well defined at the level of 0.16 dB/degree. The conditions under which this was apparent concerned an interior situation with light pattern created by spotlights and diffuse fluorescent office luminaires.

The findings can directly benefit light planning as they provide a quantified threshold that discriminates uniform from non-uniform perceived lighting conditions. Further research on the subject may specify in more detail characteristics of light pattern, their appearance and their effects on the well-being and emotions of humans.

5. Acknowledgments

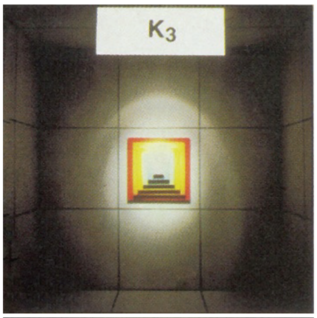
This work presents the results of my internship at Philips Research Europe in Eindhoven. I would like to thank the colleagues from Philips Research for their helpful suggestions and specifically Markus Reisinger for his guidance during the internship and his assistance with preparation of the manuscript.

Appendix

Five beam types

K1: a profile spot without any spill light. A mechanical or optical device is usually used to cut off spill light and allow the beam shape to be controlled exactly.

K2: a spot which has a sharp shift to a minimal amount of spill light, making this type of beam excellent for creating dramatic or theatrical lighting effects



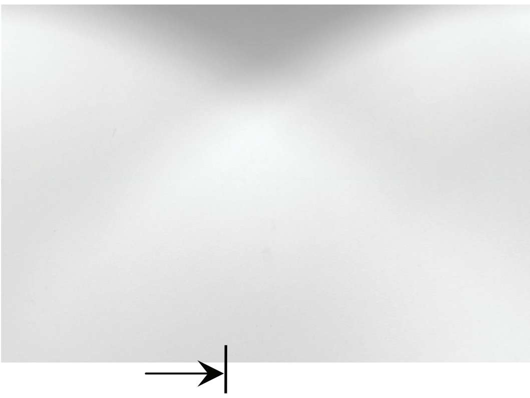
K3: a spot with a hard shift from a high-intensity spot to spill light, which is seen as a narrow ring around the spot

K4: a soft shift from a relatively strong spot to a great deal of spill light. The spill light reduces the contrast level, and assists considerably in lighting the general surroundings

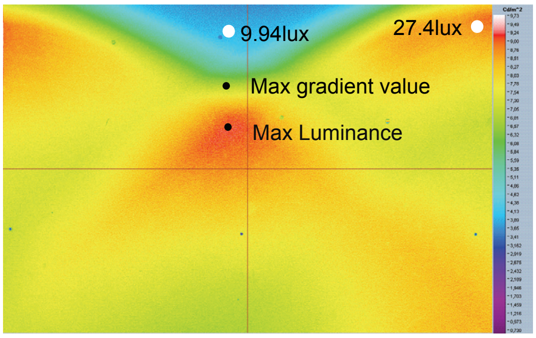
K5: this is a uniformly wide beam angle without any visible spot, and producing little or no contrast. As a result this beam is best suited for general or supplementary lighting

Stimuli description
Stimuli 1

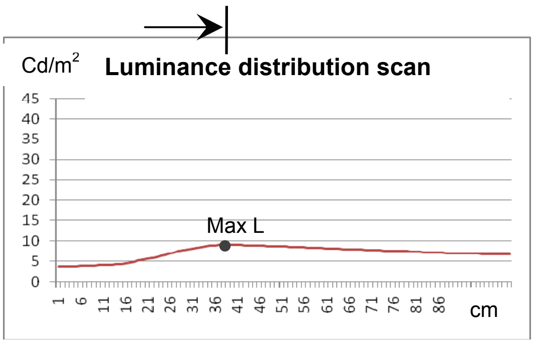
Computer rendered scene of stimulus with high amount of directional and low amount of diffuse light



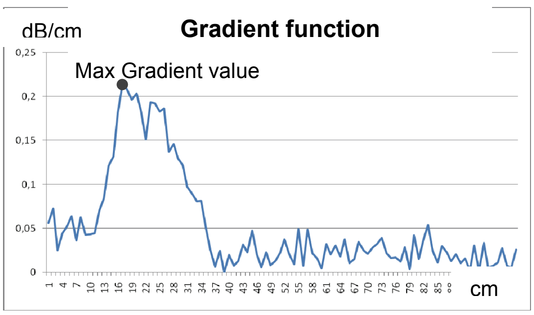
Luminancephotometer measurement.
1.53 x 1.02 m



False colour representation of luminance measurement.
Max gradient value.
Max Luminance.
1.53 x 1.02 m



Luminance distribution scan for the section with the max value

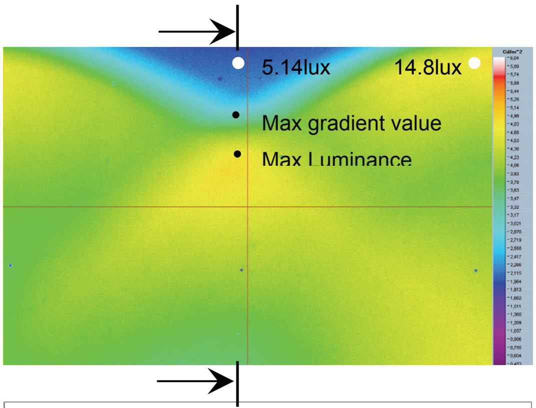


Graph of the gradient function for the section with the max value

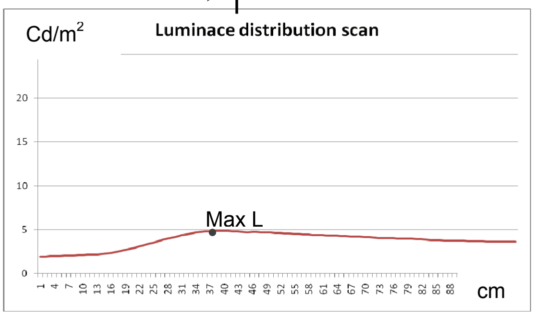
Stimuli 2

Computer rendered scene of the stimulus with high amount of directional and low amount of diffuse light

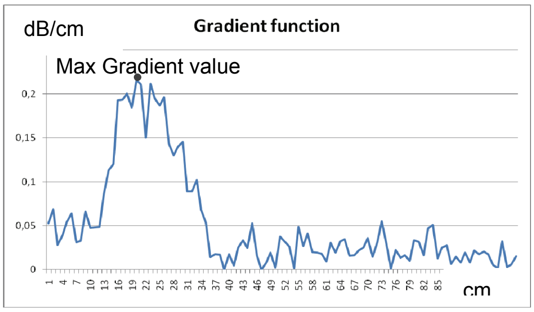
Luminancephotometer measurement.
1.53 x 1.02 m



False colour representation of luminance measurement.
Max gradient value.
Max Luminance.
1.53 x 1.02 m

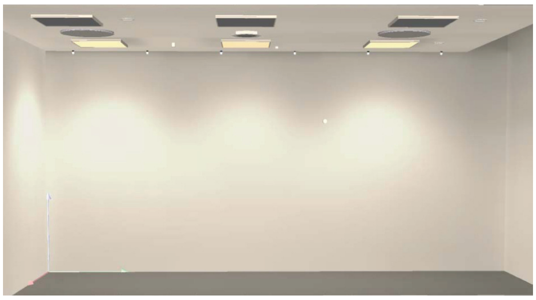


Luminance distribution scan for the section with the max value

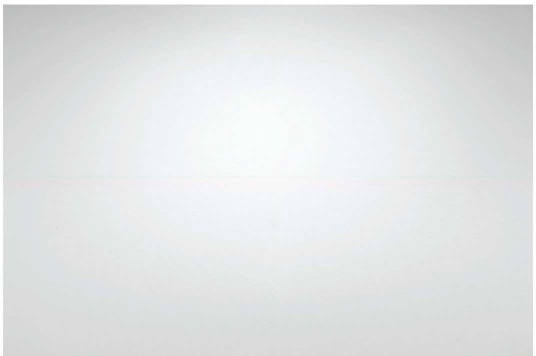


Graph of the gradient function for the section with the max value

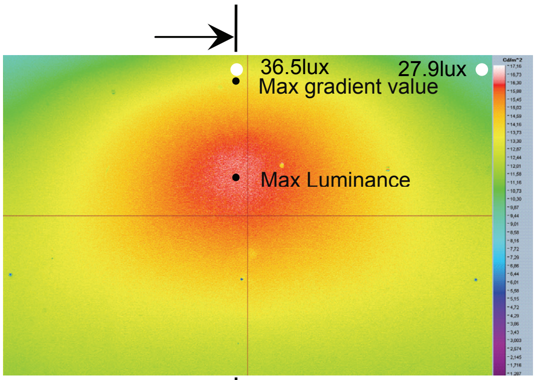
Stimuli 3



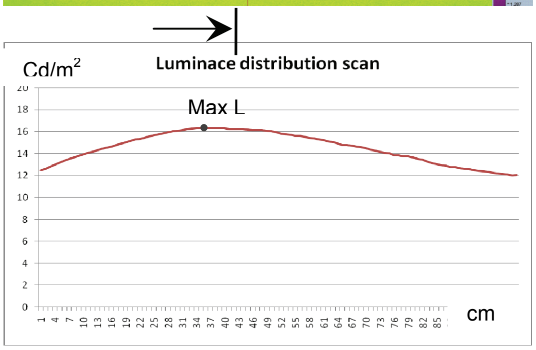
Computer rendered scene of the stimulus with high amount of diffuse and low amount of directional light



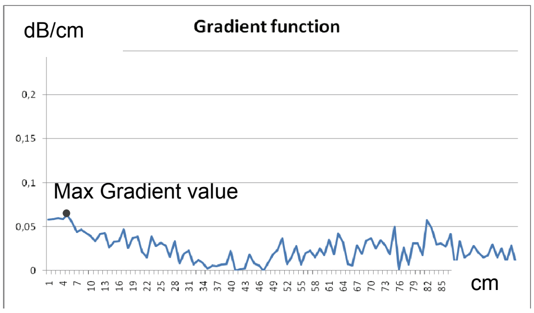
Luminancephotometer measurement.
1.53 x 1.02 m



False colour representation of luminance measurement.
Max gradient value.
Max Luminance.
1.53 x 1.02 m

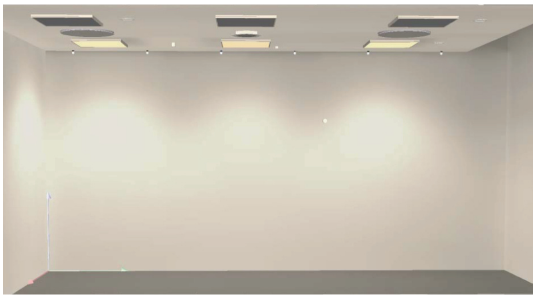


Luminance distribution scan for the section with the max value

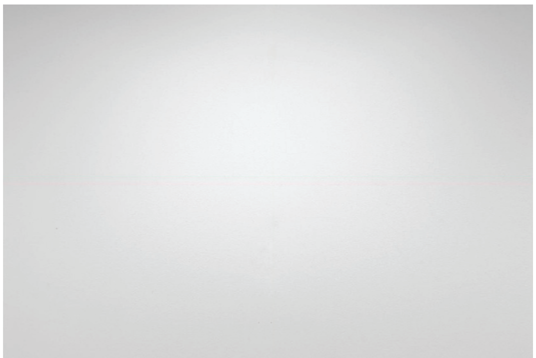


Graph of the gradient function for the section with the max value

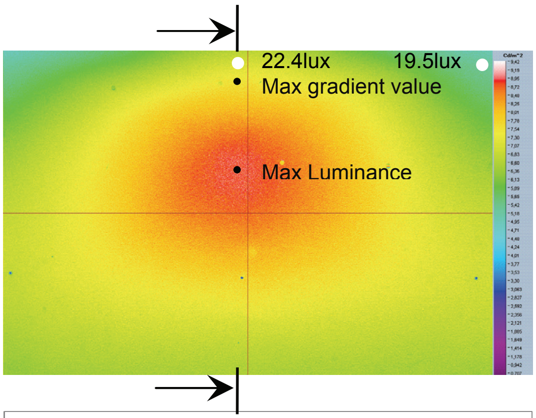
Stimuli 4



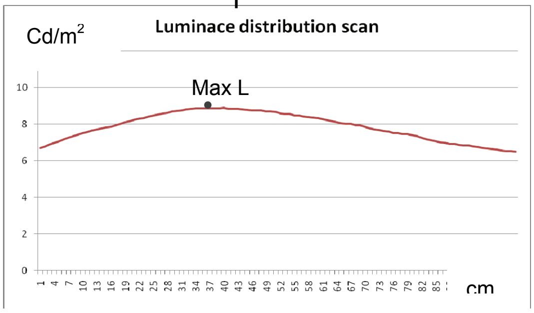
Computer rendered scene of the stimulus with high amount of diffuse and low amount of directional light



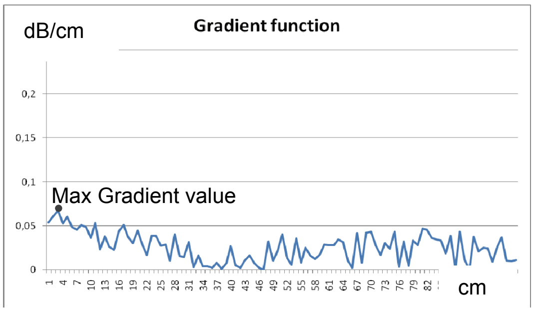
Luminancephotometer measurement.
1.53 x 1.02 m



False colour representation of luminance measurement.
Max gradient value.
Max Luminance.
1.53 x 1.02m



Luminance distribution scan for the section with the max value



Graph of the gradient function for the section with the max value