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Adaptable classroom lighting for pedagogical activities

Pupil-centred lighting for options in bodily orientation and health

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Abstract

Classroom lighting has been installed in the same way since the 1960s, in straight lines of fluorescent tubes, even if the teaching values have changed remarkably. There is a need for knowledge exchange that bridges lighting design theory and pedagogy and studies on how the current situation impacts education. Furthermore, there are few studies on new ways of illuminating classrooms. This thesis explores two case studies: one standard classroom built in the 1960s and a classroom redesigned in 2020 with adaptable lighting. The two case studies are used to derive a design concept that can be installed in any standard classroom. Moreover, during the autumn and winter in Sweden, electric light is crucial to support circadian rhythms, and there is a need for adaptability and change throughout the day.

Keywords

Pupil-centred lighting, adaptable lighting, dynamic lighting, illumination hierarchy, socio-spatiality

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Introduction

Currently, fluorescent tubes or LED panels illuminate standard Swedish classrooms. This illumination strategy is based on two common practices: creating a grid and calculating average uniformity according to the standard SIS SS-EN 12464-1, Light and lighting - Lighting of indoor workplaces.[2] This thesis will compare a standard classroom, Case I, to a designed classroom with adaptable modes, Case II. *Figure 1* presents the structure of the thesis.

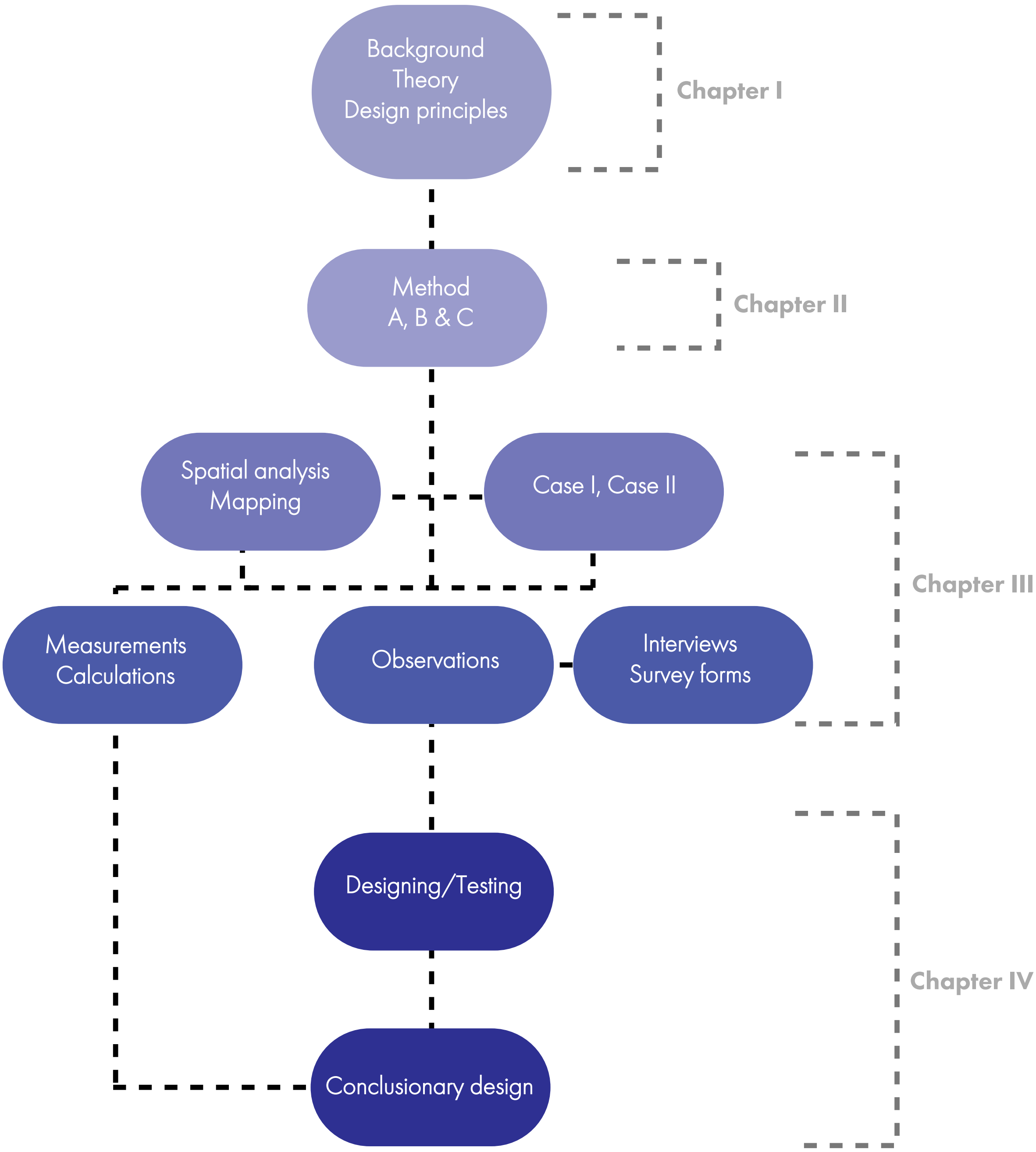


Figure 1 Model of structure of the thesis

Chapter I Background

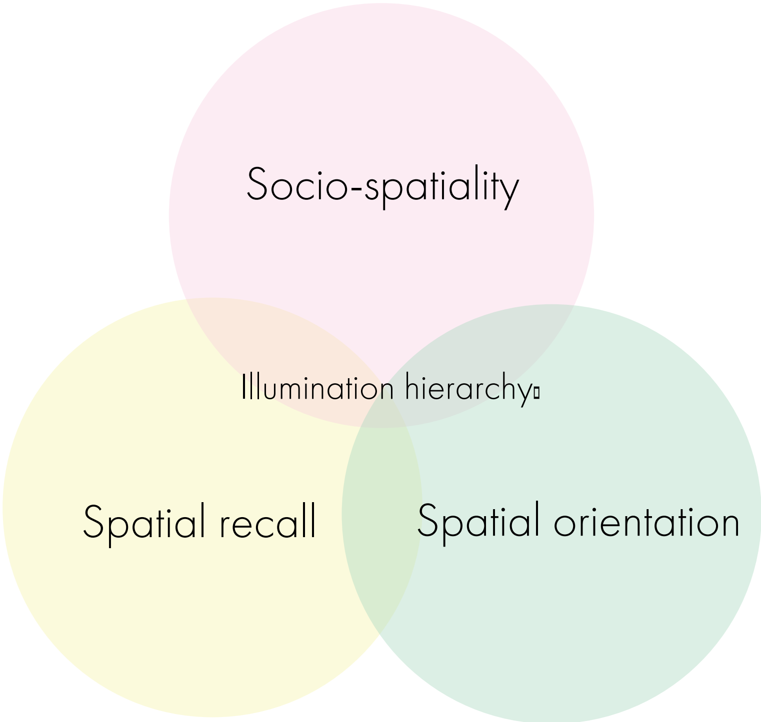


Figure 2 The image shows a model of combined theories used in this thesis concerning illumination hierarchy

This thesis reviews theory on illumination hierarchy on socio-spatiality, pedagogy theory, environmental psychology correlated to spatial recall, and phenomenological theory on bodily orientation—furthermore, the thesis review theory on physiology and circadian health.

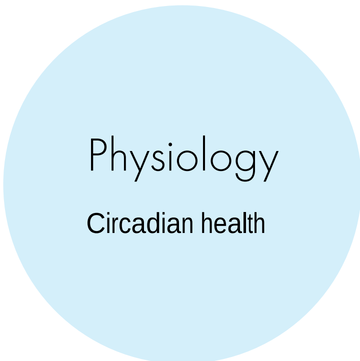


Figure 3 Physiology and circadian health

1. Pedagogical activities

Dovey & Fisher (2014) emphasise the uneven power relations due to teacher-centred pedagogies and propose pupil-centred pedagogies as an alternative; floorplan topology and layout maintain either teacher-centred- or pupil-centred pedagogical topologies.[3] Taking inspiration from the work of Dovey & Fisher (2014), four main pedagogical activities are derived to support the study of this thesis; discussion, interpersonal/relational, reading and writing, presenting, and creating, *see figure 5.*

Figure 4 Main pedagogical activities

Figure 5 Pedagogical activities →

1. Discussion (relational/interpersonal) 2. Doing a horizontal task (reading/writing) 3. Presenting 4. Creating

1.1. Orientation and spatial light distribution

Bolt (2021) applies Sara Ahmed's interpretation of Merleau Ponty's theory on bodily orientation.[4]

"*spatial forms or distance are not so much relations between different points in objective space as they are relations between these points and a central perspective—our body*" -Merleu Ponty, on bodily orientation in Bolt (2021). [4]

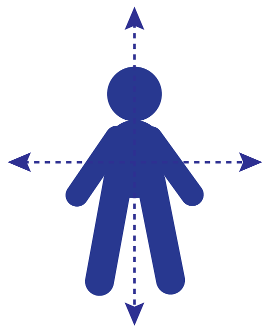


Figure 6 How the body and gaze can orient in different directions

In Bolt (2021), a theory of Ahmed is derived and described as; a spatial awareness, a sense related to kinaesthetic and psychological theories regarding how the spatiality orients bodies — a spatiality is seen as interwoven with social actions. The study in Bolt (2021) found that pupils oriented differently depending on how light sources were directed. Furthermore, a standard lighting solution was examined within a pedagogical space. The lack of direction caused the pupil's gazes in the study to orient towards the floor and lower part of the room. Conclusions formed by the study led to questions regarding the social implications of the downwards gaze.[4] This thesis takes inspiration from the theories in Bolt (2021) to form an analysis category to investigate the social implications of spatial light distribution.

1.1.2. Illumination hierarchy

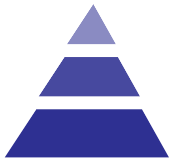


Figure 7 Illumination hierarchy where the brightest is furthest up

Section *1.1.2* presents other theories of inspiration that are the base of the illumination hierarchy analysis of this thesis. When a room is illuminated uniformly, all the elements appear equally important, with little to no contrasts. In Cuttle (2008), lighting design theory describes how the principle of illumination hierarchy can emphasise what needs to be seen as more relevant by illuminating selectively.[5]

If spaces are horizontally illuminated, the spaces will be experienced as horizontally dominating. In Millet (1996), the spatial organisation can be vertical or horizontal: depending on where and how the light is spatially distributed.[6]

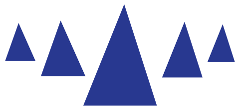


Figure 8 Elements of contrast creating rhythm

Millet (1996) describes how the repetition and distinction between illuminated elements and shadow create rhythm, depth, and a sense of distance.[6]

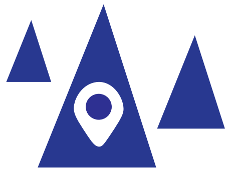
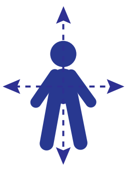


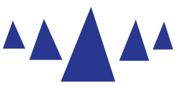
Figure 9 Landmark and distance between elements

In Bell (2002), findings show that children could benefit from using workstations of varying scales when doing different tasks—for example, using a workstation the size of a desk or using whole rooms as workstations. Moreover, the scale of the workstation can impact spatial recall. Children are more likely to recall spaces with landmarks. Landmarks are spatial aspects that stand out in contrast. [7]

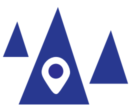
In Neumann (2010), lighting designer Richard Kelly's three principles are ambient luminescence, the play of brilliants, and focal glow. [8] These are categories used for analysing and designing meaningful illumination hierarchies in this thesis.



- Ambient luminescence generally illuminates and is the overall ambience that contributes to the awareness of the surroundings.



- Play of brilliants creates rhythm and contributes to visual interest and delight.



- Focal glow draws attention to task areas or elements of relevance.

1.1.3. Physiology and health

The body's circadian rhythm is the cycle of sleeping and waking, and the body must know what time it is to maintain health. In Soler & Voss (2021), light transitions from sunrise through intense midday to sunset are important cues of time for the body, which are lost in the increasingly indoor-based lifestyles.[9]

Figure 10 The exterior conditions and time

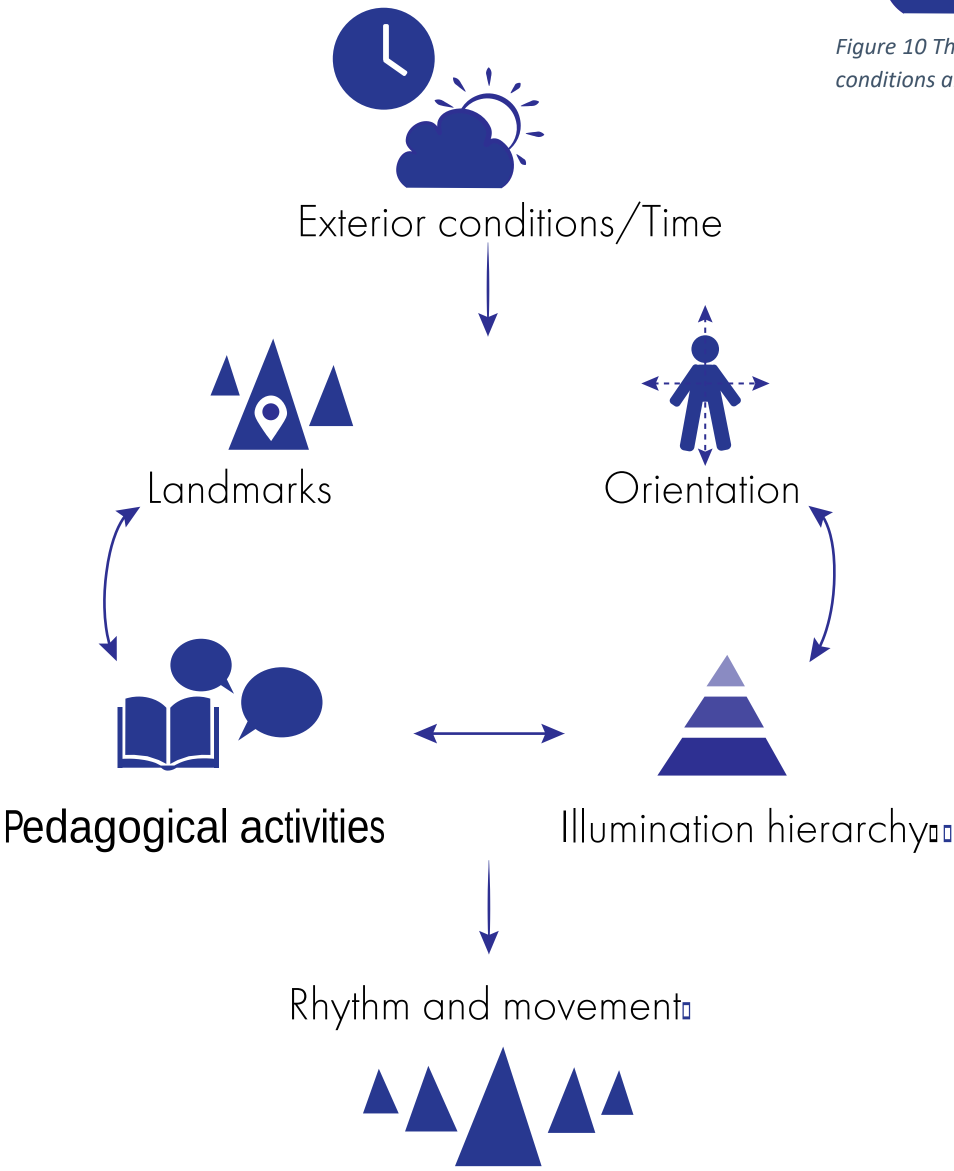


Figure 11 A model of the categories stated in this thesis and how they correspond

2. The visual and physical tools for light evaluation

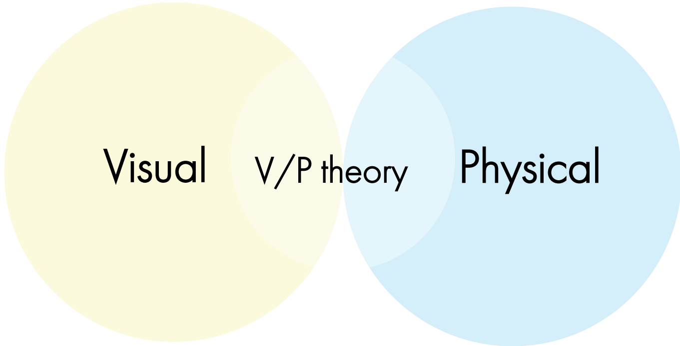


Figure 12 The visual/physical theory model based on Liljefors (1999)

The V/P (Visual / Physical) theory, developed by Liljefors & Ejhed at KTH, is a cornerstone of this thesis. The visual part regards the experience of light, and the physical part consists of the physical science of light. The visual and physical theories are of equal importance, see *figure 12.*

2.1. The seven factors

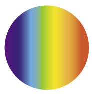
In Liljefors (1999) and Ejhed's work, seven factors are presented based on a subjective visual evaluation of the quality of light.[10] The seven factors are used to evaluate light quality.

1	Level of light	How is the general light level in the space?
2	Spatial distribution of light	Is the light evenly, uniformly distributed, or is there variation in the spatial light distribution?
3	Shadows	Are the shadows sharp, soft, defined, or undefined?
4	Reflections	Is there any glitter, sharpness in reflections, or are the reflections vague or non-existent?
5	Glare	Are there solid contrasts and glare? Is it intolerable or bearable?
6	Colour of light	How is the general colour tone of the light? Is it cold ashen grey or warm like sand?
7	Colour of surfaces	Do the surfaces appear muted, dull, ashen, or saturated, colourful, and prosperous? Is it a warm or cold hue?

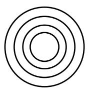
Figure 13 A table over the seven factors derived from a KTH evaluation sheet based on Liljefors (1999) and Ejhed

2.2. Physical factors

Figure 14 Central categories of physical aspects of light derived from the V/P theory in Liljefors (1999)



- In Liljefors (1999), the spectral power distribution graph (SPD) is measured with a spectrometer and contains wavelength radiation information of the light in nanometre (nm). The visible optic radiation is between 400-700 nm.[10]



- The pool of light reflected from a surface is measured in candelas per square meter (*cd/m^2*), using a luminance meter. [10] The luminaire topology impacts the *cd/m^2* due to the shaping of the beam. See *figure 15* of luminaire topologies.

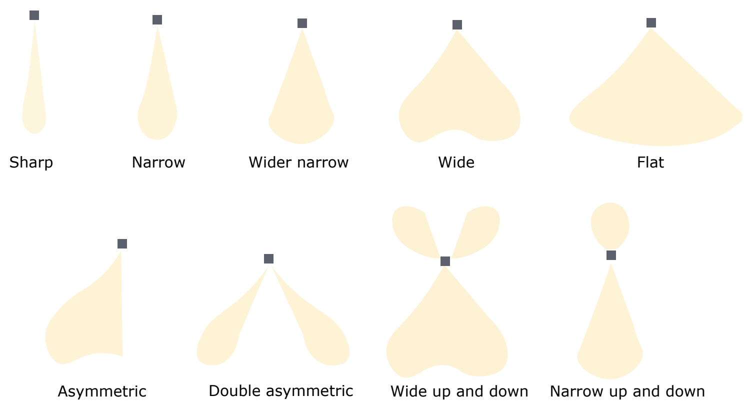
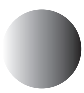
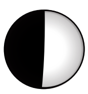


Figure 15 Diagrammatic explanation of beam angle and topologies; these can be directed towards walls as well as downwards or upwards



- The light intensity that hits a surface is called illuminance and is measured in Lux(lx) with an illuminance meter. The capacity of a light source is quantified in Lumen(lm) and indicates how much light the light source emits.[10]



- Contrasts can be colour-based or the transition between light and dark. [10]

- Light meeting material has three central aspects: absorption, reflection, and transmission. [10] Glossy white reflects light while matte black absorbs light; surface gloss and colour impacts absorption and reflection, which influence *cd/m^2*.

3. Problem Statement and objectives

The primary objective of the standard SIS SS-EN 12464-1 is to provide visual acuity on the horizontal plane with little to no contrasts for visual performance and less eyestrain risk.[2] However, the standards create identical solutions that are fixed and unadaptable. Fixedness and inadaptability do not support different pedagogical activities due to the standard's sole focus: performing tasks on the horizontal plane.

Furthermore, there is a recommendation of having '5:3:1', 500 lx, 300 lx, and 100 lx at and around the workstation. In Arbetsmiljöverket (2020), 500 lx is in the work area, 300 lx is in the close-by space, and 100 lx is in the outer surrounding area of the room. Arbetsmiljöverket (2020) recommends adaptable lighting.[11] However, floors in schools tend to have higher light levels, and classroom lighting is usually not adaptable.

Moreover, our bodies need brighter days and darker afternoons/nights to support circadian health, and electric light is crucial during the dark seasons in Sweden.

To focus the research, the following questions are asked:

- ***How can spatial light distribution be adapted for pedagogical activities and options in orientation in elementary school classrooms?***
- ***How can lighting be adapted for small scale-activities (reading) and big-scale activities using the whole classroom (discussions in the whole classroom)?***
- ***How can light be designed in an elementary classroom to support circadian health?***

4. Theory analysis

The following sections, *4.1.-4.3.*, will further analyse the introduced theories. Section *4.1.* contains theory related to vision and physiology, while section *4.2.* consists of theory connected to phenomenology and psychology. Section *4.3.* contains pedagogy theory and tools for socio-spatial analysis. The theories are applied in Chapter II and Chapter III regarding two case studies. Case I is a standard classroom with a layout installed in the 1960s, and Case II consists of a redesigned classroom installed in 2020. The redesigned version is adaptable and gives possibilities for variation in contrast to the fixed standard solution of Case I.

4.1. The vision and scale of activities

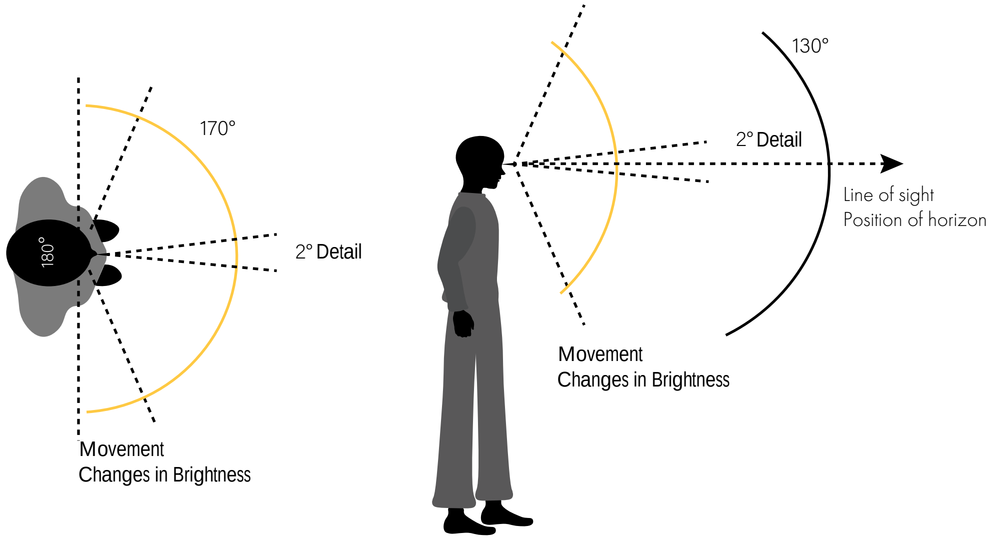


Figure 16 Explanation of the field of vision

Foveal vision and reading – Small scale vision

Standards on uniformity rely on the 2° of the visual field, see *figure 16.* It is located in the centre of the visual field and is responsible for visual acuity. In Liljefors (1999), visual performance tests speed and results when performing small detail tasks. According to Liljefors (1999), higher illuminance levels improve visual performance.[10] The 2° of the visual field is named the foveal vision; it is the small-scale vision.

Peripheral vision and orientation – Big scale vision

Contrasts are one of the main reasons one can distinguish spatiality and orient within it. In Liljefors (1999), 170° of the visual field, see *figure 16*, is the peripheral or retinal vision. Our sense of orientation depends on peripheral vision; it is the big-scale vision.[10]

Peripheral vision is crucial for understanding spatiality, and it is essential for big-scale activities such as discussions. The peripheral vision impacts the sensation of space and is sensitive to both movement and changes in brightness.[10]

4.1.1. Circadian light, line of sight and spatial light distribution

There is a line of sight in the horizon's position, as seen in *figure 16* and *figure 17*. In Soler & Voss (2021), the vertical illumination bouncing off walls in the horizon's position provides more circadian stimulus than the downlight distribution. The horizontal illuminance standards do not prioritise circadian health; its sole purpose is visual performance.[9]

Soler & Voss (2021) mention a cell type in the human eye that is partly responsible for regulating our circadian rhythm. The cell is called The Intrinsically Photosensitive Retinal Ganglion Cell (ipRGC), and it is sensitive to 480-490 nm wavelength light. The ipRGC impacts our circadian synchronisation, tracking of seasonal changes, acute alertness, working memory, and mood. Measuring circadian light is done using a meter weighted to the ipRGC, and it can be measured in equivalent melanopic lx (EML).[9]

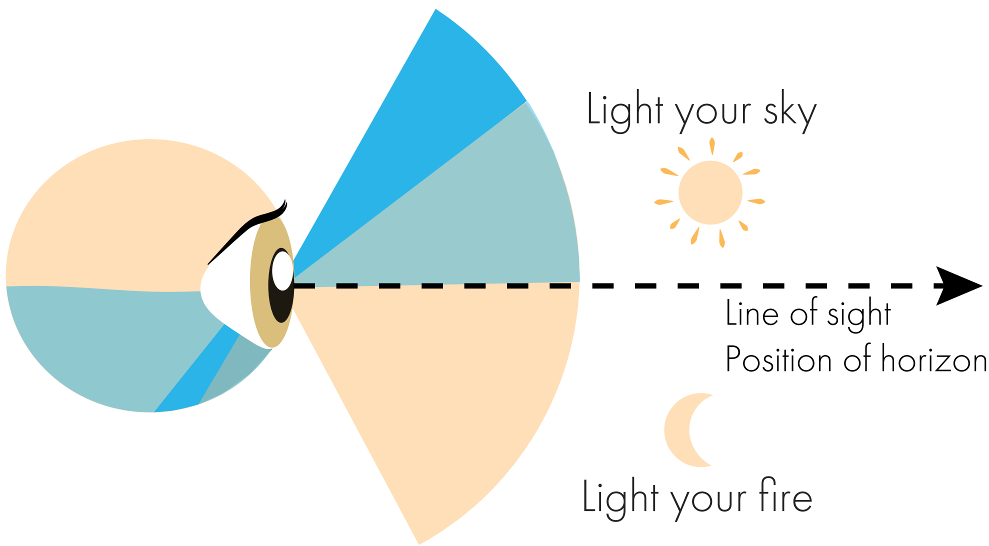


Figure 17 Diagrammatic explanation of how intense blue light enters the eye from above the line of sight during the day, and the warm dim light from below during the night

4.2. Spatial recall and orientation

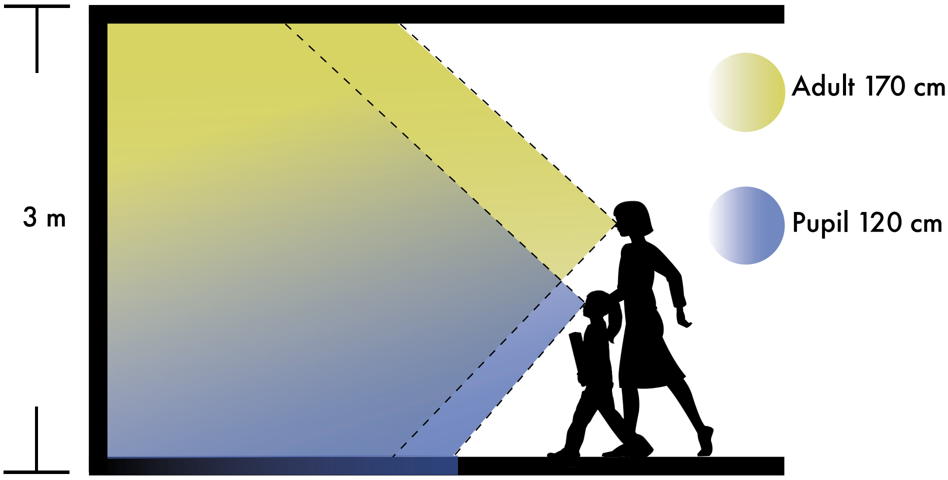


Figure 18 Visualisation of an adult's visual field and a pupil's visual field

The expression "human scale" in architecture is an approach to a scene from the eye-level perspective. Radaelli (2016) explores the child's perspective by studying the environment from a child's height. [12] Implementing this strategy when analysing spatial light distribution can increase the awareness of the pupil's experience. From the child's perspective, and in this case, the pupil's perspective, the horizontal spatial dominance overwhelms the scene due to the visual field being closer to the floor. The standard solution uniformly illuminates the floor, creating even further visual dominance.

4.2.1 Spatial recall

In Vasilyeva (2012), the understanding and use of landmarks undergo development during elementary school age, as does the understanding of spatial hierarchy. Pupils develop a viewer-dependent perspective relative to oneself and a viewer-independent perspective relative to external features – spatial recall. [13] Bell (2002) states that different spatial scales and landmarks can support pedagogical activities.[7] The sense of variation of scale and accentuation of landmarks can be enhanced with light.

4.2.2. Spatial orientation

In Bolt (2021), bodily orientation is described as restricted within lines of norms. The lines of norms uphold a self-evident way of orienting within a particular spatiality. The lines in a standard lighting solution enforce the actions of sitting vertically and gazing horizontally at the desk and floor.[4] The analysis used in this thesis concerns how lines of bodily orientation uphold patterns and how lines orient the gaze. Adopting the phenomenological point of view in the analysis can make the social boundaries of the space visible.

4.3. Tools for socio-spatial analysis

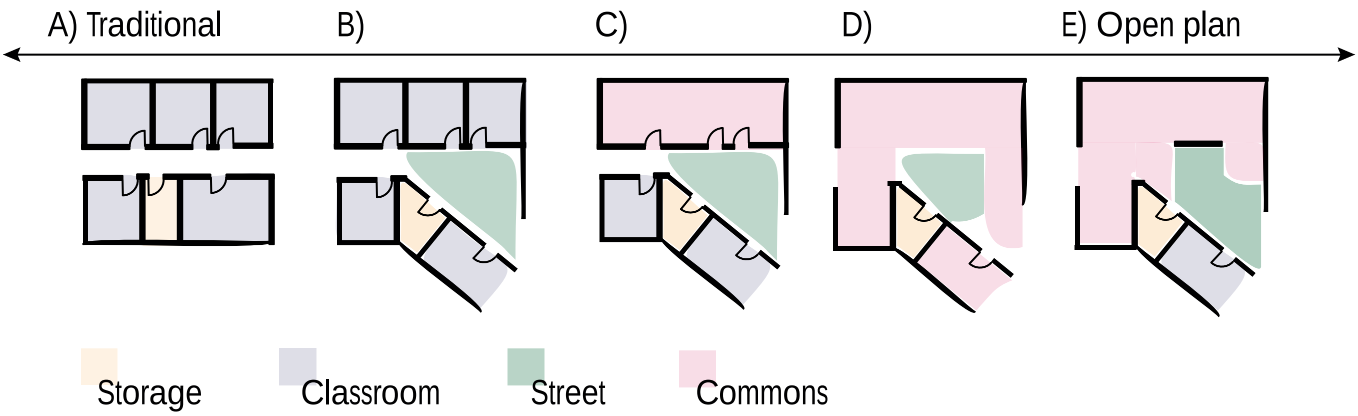


Figure 19 Floorplan topologies derived by Imms, Byers & Mahat (2017) originally by Dovey & Fisher (2014)

In Dovey & Fisher (2014), an open floorplan is seen as a pupil-centred spatiality that allows fluidity and adaptation.[3] The open floorplan is a step away from the fixed teacher-centred spatiality. Moreover, Imms, Byers & Mahat (2017) created an evaluation scale of the floorplan topologies. See topologies *figure 19*: Classrooms are traditional and closed areas where about 25 pupils fit, the street space is for learning and circulation, and the primary purpose of the common space is to enable in between pedagogical activities.[14] Dovey & Fisher (2014) emphasise the importance of multipurpose spaces with adaptability.[3]

Furthermore, in Imms, Byers & Mahat (2017), Dovey & Fisher's six different pupil-centred pedagogical topologies are further defined.[14] Teacher facilitated pedagogical topologies are where the teachers are active while the pupils are passive. When breaking out groups of pupils, the pupils can have an active role.

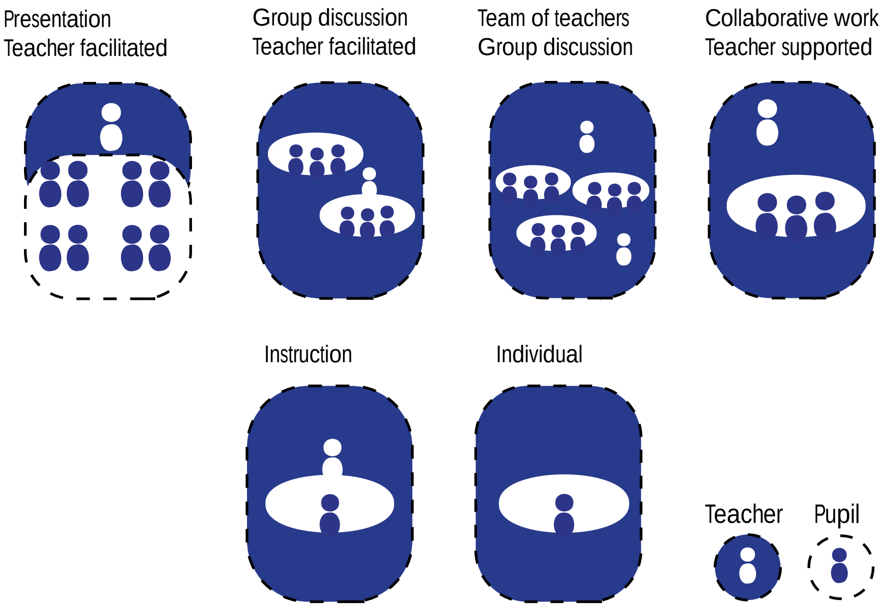


Figure 20 Pedagogical topologies inspired by Imms, Byers & Mahat (2017) originally from Dovey & Fisher (2014)

Moreover, taking inspiration from Imms, Byers & Mahat (2017), this thesis derives other topologies to analyse the classroom floorplan layout concerning light source topology. The passive layout relates to the teacher-centred topologies, and the collaborative layout concerns pupil-centred activating topologies, see *figure 21*. The optional space within a classroom enables further adaptability and options in orientation.

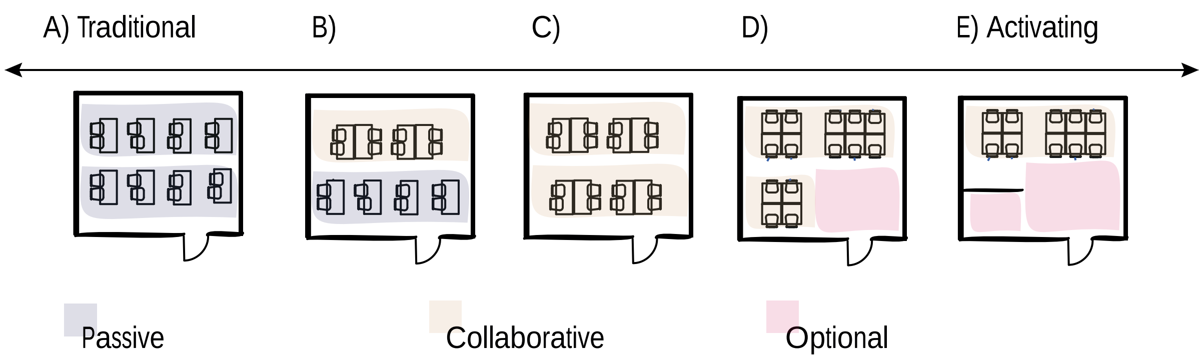


Figure 21 Floorplan topologies of classrooms derived from the theory of Imms, Byers & Mahat and Dovey & Fisher

In Frelin & Grannäs (2017), there is a need to balance learning spaces for pedagogical relationships and teaching content. If too much emphasis is placed on content, the relations needed for education are made invisible.[15]

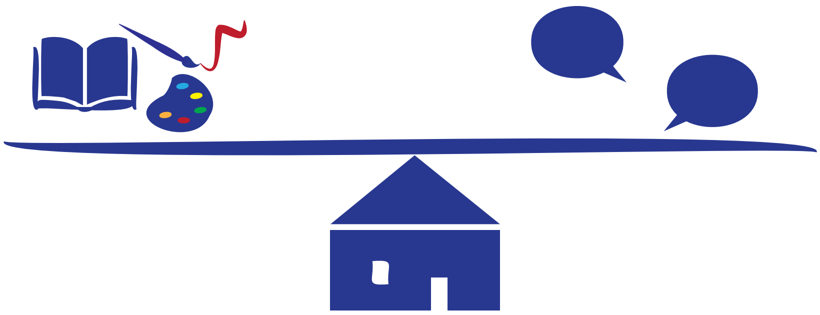


Figure 22 Visualisation of the balance between material and relational

Chapter II

Chapter II regards the methods used in the thesis. As mentioned in Chapter I, the thesis involves three main research questions. The three questions require three different methods. Question one regards orientation and pedagogical activities and requires an observational method (Method A). Question two includes the scale of activities and involves a method concerning observations and the seven factors (Method B). The third question considers measuring circadian stimulus quantities (Method C). The third method (Method C) also involves a quantitative analysis of the illumination hierarchy.

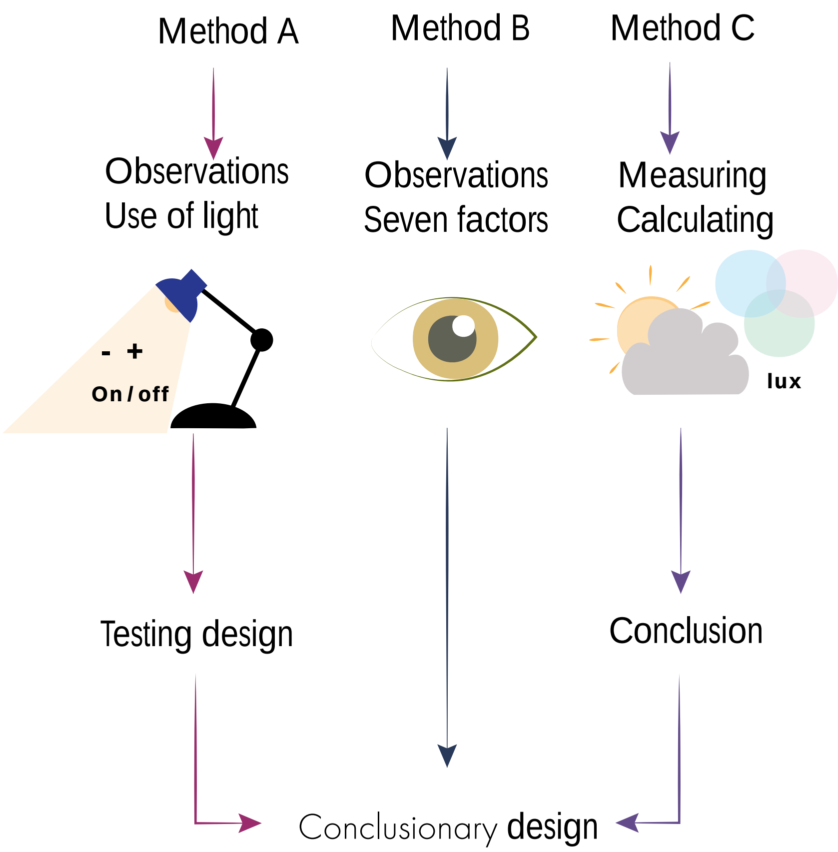
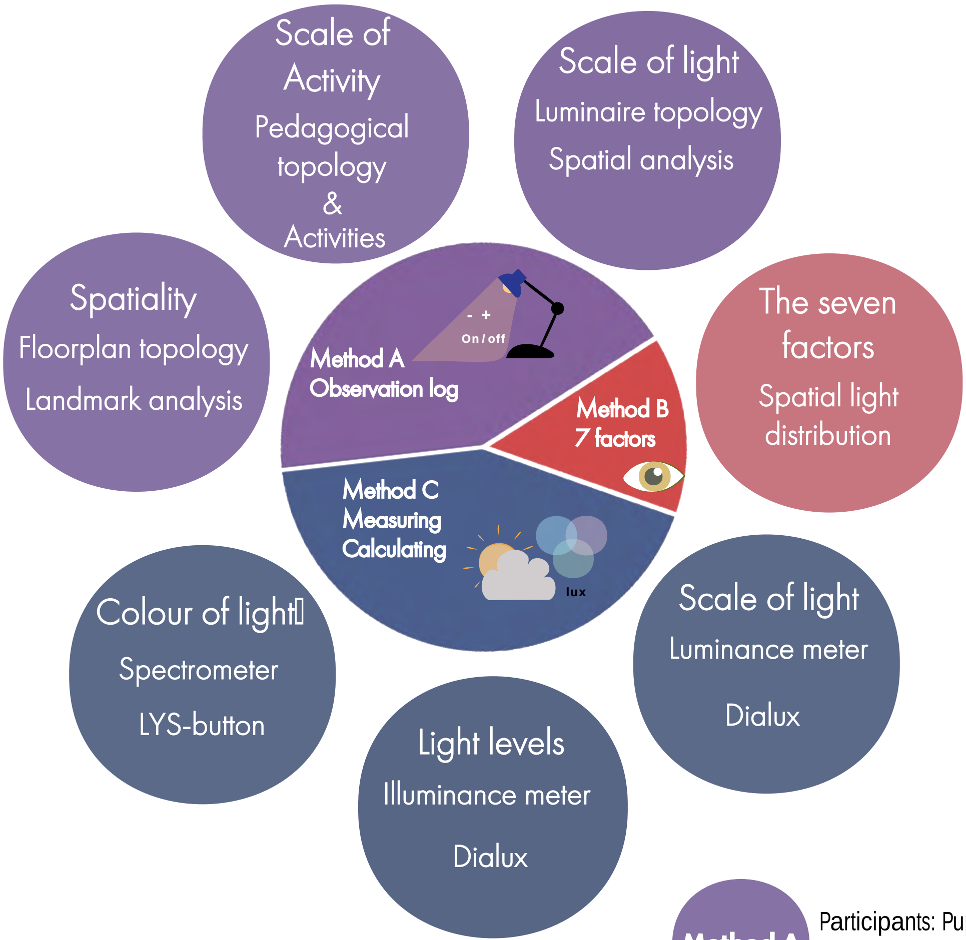


Figure 23 Three methods divided into categories

5. Methods

The methods are divided into three main categories, as demonstrated in *figure 23*. Method A considers the use of light and testing of pedagogical modes related to the theory of the thesis. Method B is a visual evaluation method. Method C contains quantitative light measurements regarding physical aspects and circadian health.



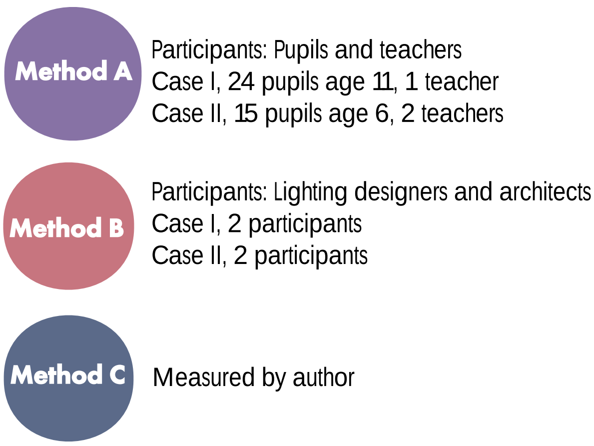


Figure 24 The model describes the tools used in methods. The different parts of the three methods are presented as the colour-coded components of the middle pie-chart connected to the smaller bubbles containing further information about the different equipment and analytical tools used in each method. The lower right division of three methods in the figure includes participant information

5.1. Method A: Use of light and spatial analysis

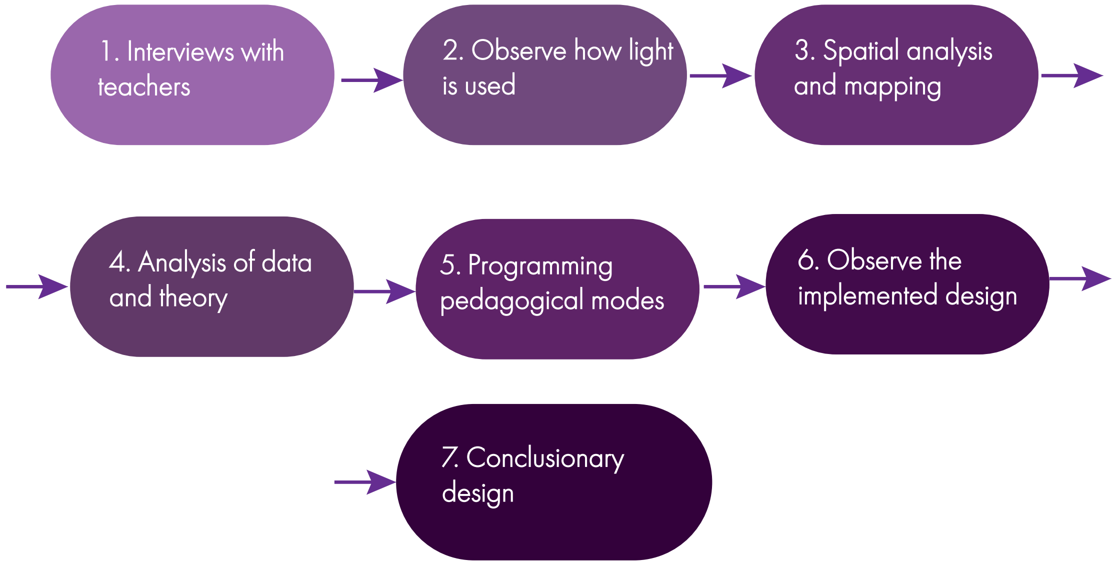


Figure 25 The figure shows the 7 stages of Method A

The following steps were made to support the programming of pedagogical modes, *see figure 25*:

1. Before the observations were initiated, the teachers were interviewed on how the pupils engage with-, prefer- and use light.

2. Consisted of observations on how teachers and pupils turned on and off the light and oriented in the existing light.

3. Spatial analysis and mapping included observing and mapping how the space was used and how the illumination hierarchy appeared.

4. Analysis of data and theory consisted of applying theory to the data and making conclusions on pedagogical modes in Case II.

5. The pedagogical modes' programming was based on past stages (1, 2, 3, 4) and theories in the thesis.

6. Observations regarding the implemented design were done to summarise how the settings were used; this step also involves interviewing a teacher.

7. Conclusionary design, a conceptual design correlated with Case II, was made in Case I.

Participants in Method A consisted of teachers and pupils.

5.2. Method B: The seven factors

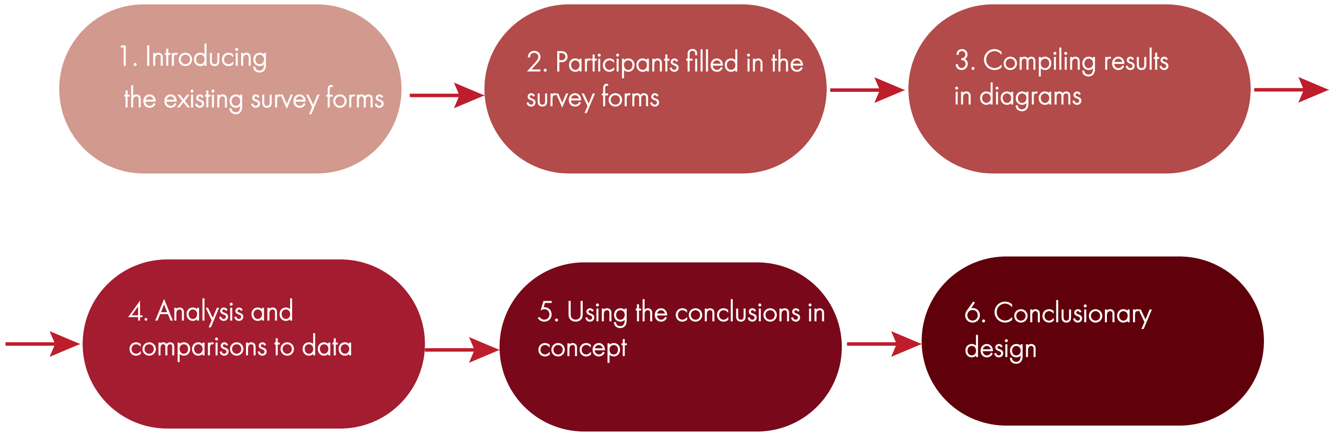


Figure 26 The figure shows the 6 stages of Method B

To assess the seven factors by Liljefors (1999), survey forms were developed and used at KTH (based on Jan Ejhed's work). These forms (see appendix) were used in this study.

1. The participants were introduced to the purpose and use of the survey forms.

2. The participants filled in the survey forms while in the case study classroom.

3. The results of stage **2** were compiled in diagrams using numeric scales.

4. The seven factor results were analysed with more data from the study.

5. The same process as in stage **2** regarding the seven factors was done during several pedagogical modes.

6. The conclusionary design aimed to improve existing flaws of the experience of the spatial light distribution found in the seven factors.

The participants in method B consisted of four lighting designers and architects.

5.3. Method C: Physical evaluation

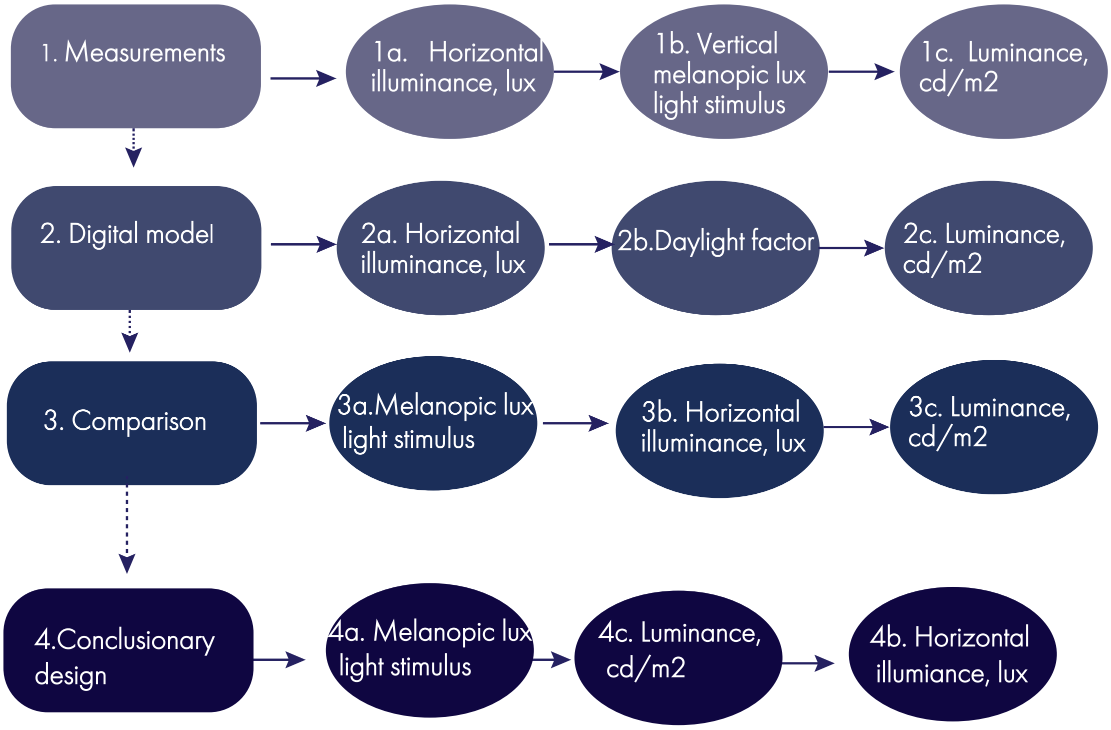


Figure 27 The figure shows the 5 stages of Method C

1. Measurements were made in the classrooms of the case studies.

1a. Horizontal illuminance measurements consisted of grid and on desk measurements. 1b.Vertical light stimulus regarded measuring from the occupants' (pupils') eye position in the space. 1c. Luminance *cd/m²* consisted of mapping luminaires beams' shape.

2. Consisted of a digital model on Case I, was used to analyse lx and *cd/m²* further.

2a. Horizontal illuminance, lx, was calculated to get a perspective on how much lx was on desks and the floor.

2b. The daylight factor was calculated to see how much daylight entered the room to see if the room lacked daylight.

2c. Luminance *cd/m²* regarded the distribution and was mapped to create false colour images of how much *cd/m²* was spread.

3. Compared stages 1 and **2**, emphasising spatial light distribution.

3a. The melanopic lx and light stimulus was compared to see differences in electric lighting stimulus.

3b. The light levels were compared.

3c. Luminance *cd/m²* and beam shapes were compared and related to other data on spatial light distribution.

4.The different aspects were concluded into a design proposal in the order presented in *figure 27*.

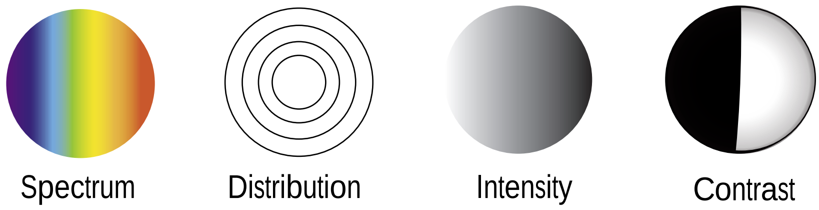
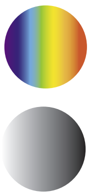


Figure 28 Physical factors from the V/P theory, Liljefors (1999).

5.3.1. Description of equipment in Method C



- Circadian metrics in this thesis regards EML. Measuring EML is relevant to the question regarding circadian health. Due to the long dark seasons in Sweden, most of the light stimulus is provided by electric light during autumn and winter.

  Circadian measurements were made vertically in the occupants' (pupils') eye level using a spectrometer *see figure 29.*

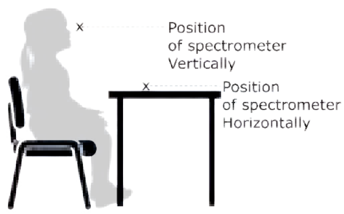
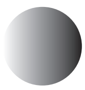
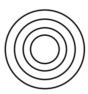


Figure 29 General diagrammatic image of where the spectrometer was held – at the eye level of the pupil

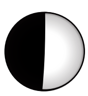
The spectrometer measured spectral power distribution graphs (SPD's) and equivalent melanopic lx (EML). The LYS-button measured light stimulus (ls) according to LYS-technologies; the LYS-button further provided RGB values. [16]. The button was attached to the author's shirt.
The illuminance meter measured horizontal lx.



- Task areas were measured with horizontal lx, putting the spectrometer at the desk, as seen in *figure 29*. Afterward, to further analyse illumination, a digital model was built to analyse lx levels in Dialux.



- The luminance meter was for calibrating the Fusion Optix app. The app was used for analysing luminaires beams using an android phone. To further analyse and investigate the spatial light distribution, calculations were made in a digital model in Dialux.



- Dialux was used to calculate uniformity and the SS-EN 12464-1 formula. Uniformity was also measured manually using an illuminance meter.

Chapter III Case studies

In Chapter III the case studies will be presented and analysed. Case I is of interest for designing a circadian solution conceptually, and the daylight and changes in sky conditions are essential for the conclusionary design. Case II was analysed concerning how the solution impacted sensations of changes in sky conditions. Case II involves circadian metrics due to the interest in how the luminaires in the redesigned school, in contrast to the standard school, provide different melanopic stimuli at different seasons and at various times of the day.

Figure 30 A map of Sweden with the two locations of the case studies

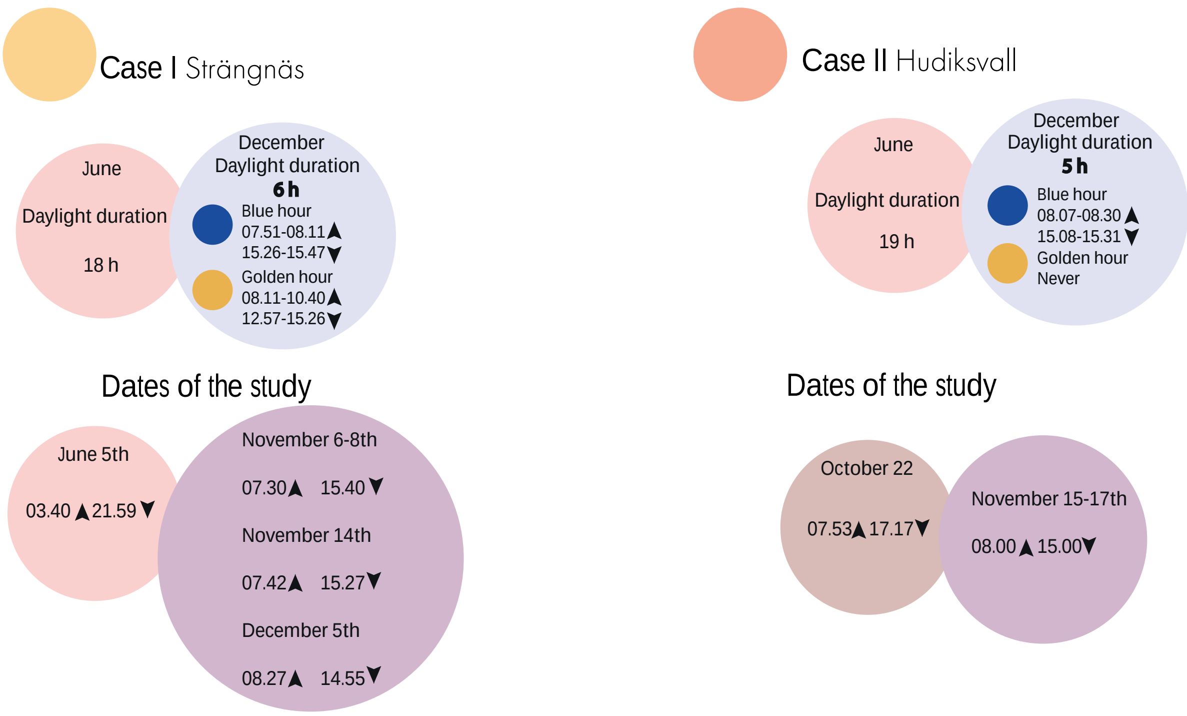
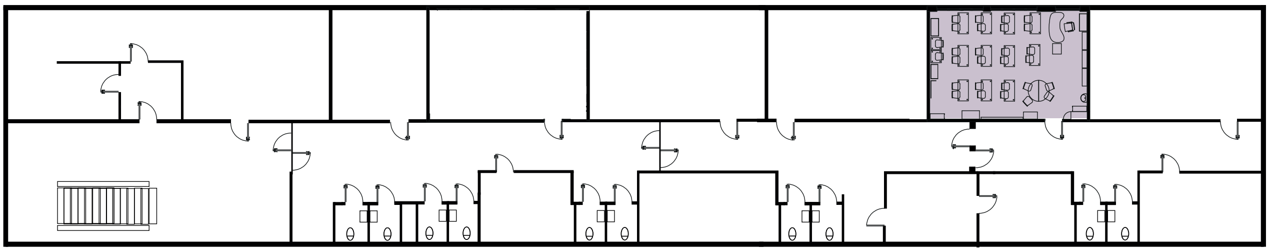


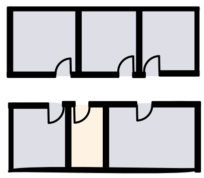
Figure 31 Sunset and sunrise data derived from https://www.suncalc.org/ 2021-12-05

Case I

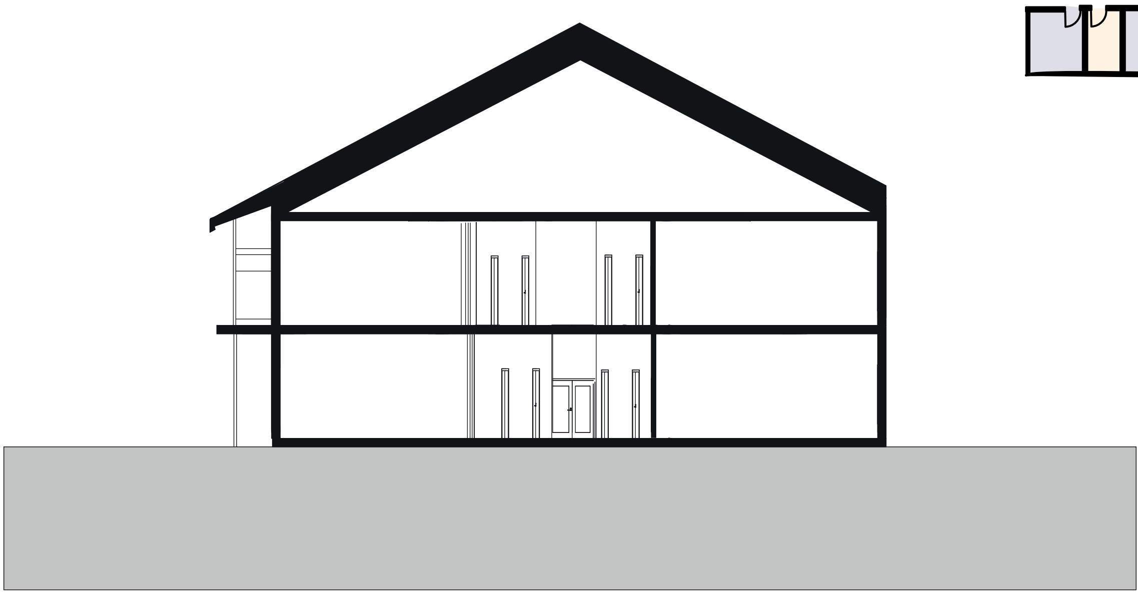
1. Floorplan topology



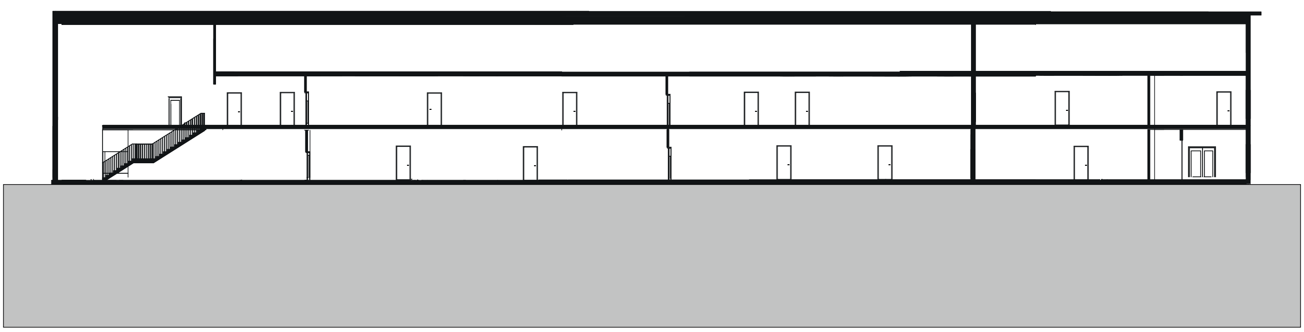
A) Traditional



Case I consists of a traditional school built in the 1960s with corridors; it is currently used by pupils ages 6-12. It is in category A), Traditional floorplan.



Section A-A

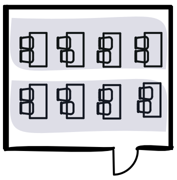


Section B-B

Figure 32 Floorplans, sections, and topology A) Traditional

2. Spatial analysis of a standard classroom

A) Traditional



The observed classroom had 24 eleven-year-old pupils and one teacher. *Figure 34* shows how pupils and teachers circulated in the classroom throughout the day.

Furthermore, the use of spatial elements is shown in a bubble diagram, *see figure 33*.

Student's and teacher's movement in space

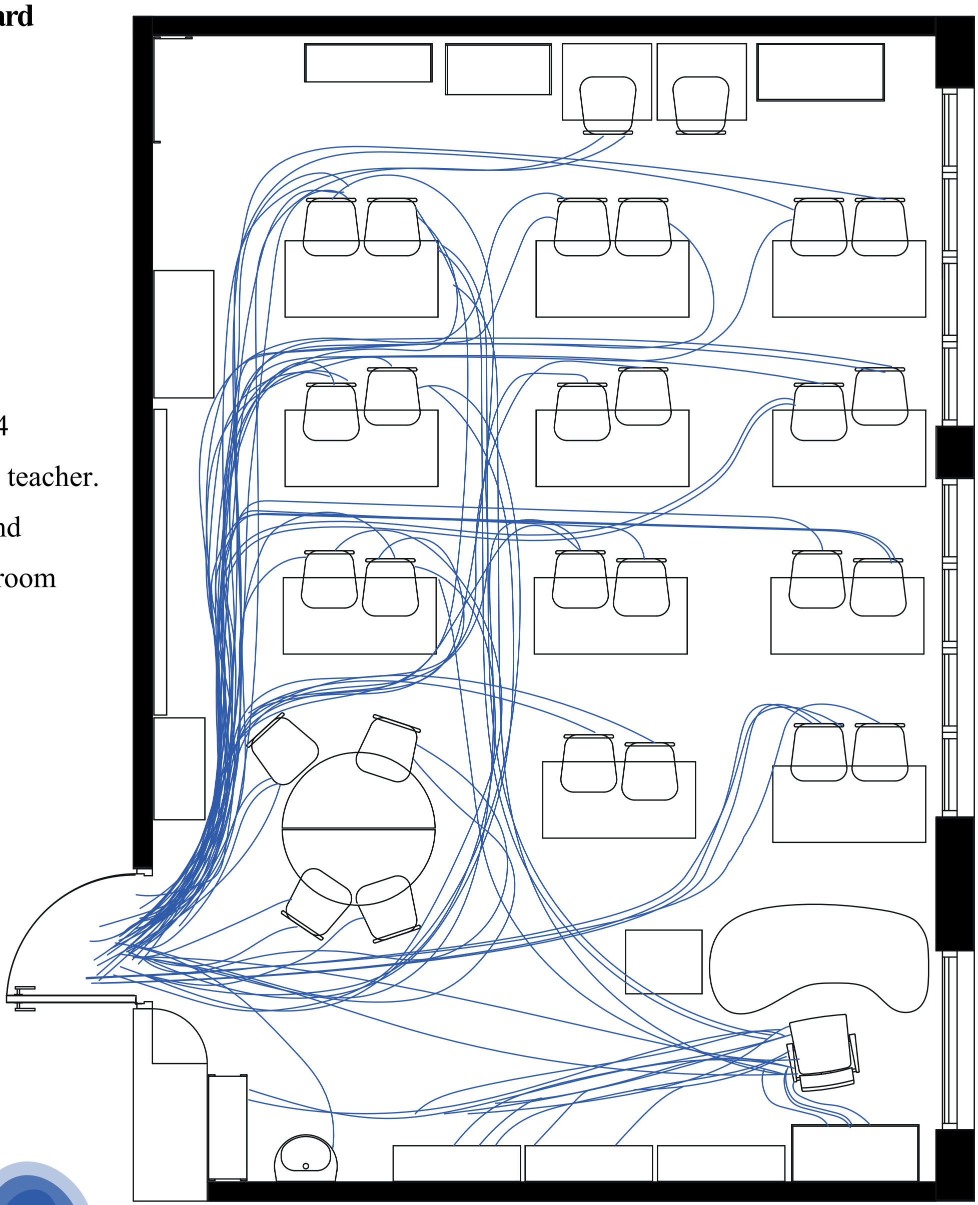


Figure 34 Floorplan and pupils' and teachers' circulation

How pupils and teachers circulate between spatial elements

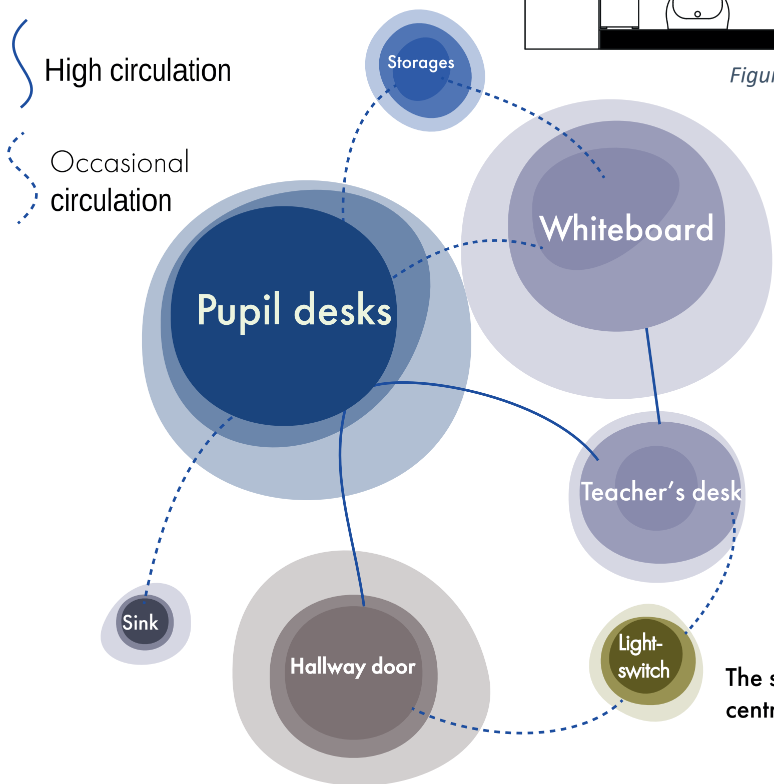


Figure 33 A bubble diagram showing central spatial elements and how often circulation occur there

The size of the bubbles indicate how central spatial elements are during class

2.1. Interview with teacher

Teacher quotes on the use of the classroom,

8th of November 2021.

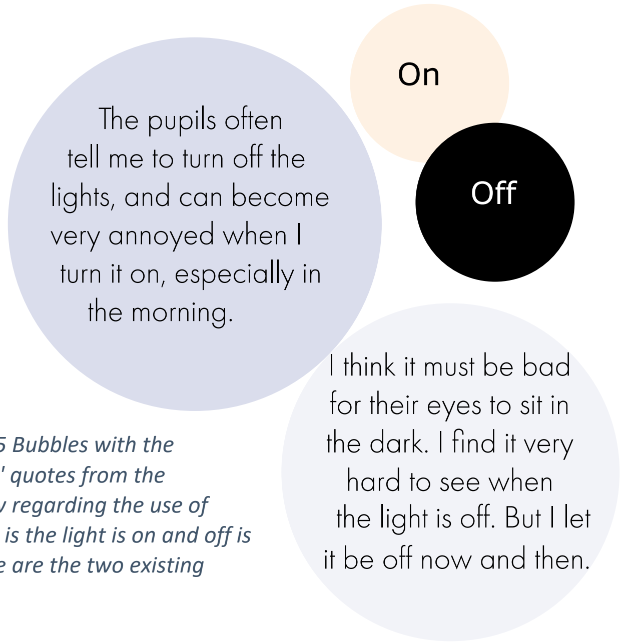


Figure 35 Bubbles with the teachers' quotes from the interview regarding the use of light. On is the light is on and off is off, these are the two existing options

2.2. Pedagogical activities

When reading, the lights can both be on or off. Most of the activities in this classroom consist of reading or writing.

Most of the relational activities happen at the teacher's desk when pupils walk there and ask the teacher a question.

Most activities involve a presentation at the start. The light can be on or off during presentations.

It is primarily a teacher-facilitated pedagogical topology with an orientation towards the whiteboard and a one-to-one instruction topology at the teacher's desk. Pupils primarily work individually.

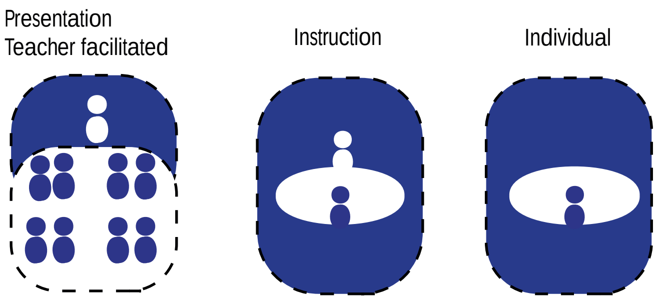


Figure 36 Pedagogical topologies occurring in the observations

2.3. Illumination hierarchy

November 8-9. Observation log: 0% electric light, dim daylight only. Reading hour 08.00-09.00.

Figure 37 Photograph of dim daylight in the Case I classroom

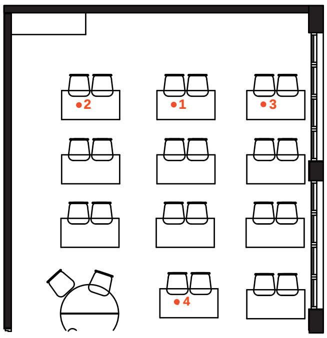
- Pupils are oriented vertically, with the gaze oriented on desks or towards windows.
- There is a spatial dominance towards areas close to the windows.
- There are faint shadow patterns between windows.
- The desks close to the windows are prominent, while the inner part of the classroom is covered in shadows.
- It is a dark overcast sky that barely illuminates the room.

November 8-9. Observation log: Electric light after sunset. 15.30 presentation and independent work.

Figure 38 Photograph of electric light while dark outside in the Case I classroom

- Pupils orient in a vertical position with a horizontal gaze. Due to an increased luminescent ambience, there is no directionality towards spatial elements but a direction towards the lower part of the space due to the horizontal illuminance. The pupils partly orient towards the whiteboard when the teacher presents, although most pupils orient their gaze down at the desk.
- There is a horizontal organisation of the space, and the floors and desks are spatially dominant.
- There is no rhythm of shadow and light.
- There are no prominent aspects illuminated with a focal glow.
- It is dark outside, and the brightly illuminated room is mirrored in the windows.

3. The seven factors: spatial light distribution and light levels



In Method B, regarding the seven factors, the participants are lighting designers and architects. Two participants answered on a scale of 1-6 on how they experienced the brightness and the spatial light distribution.

In *figures 40,42,45*, both participants' numbers are averaged and presented. The factors are written in the following way: Homogenous/Variegated. The low number is towards the homogenous, and a higher number the towards the variegated.
The participants experience the front desk as more confining, less variegated, and dimmer than the rest of the space. The inner desk is experienced as more confining during the winter than in the summer.

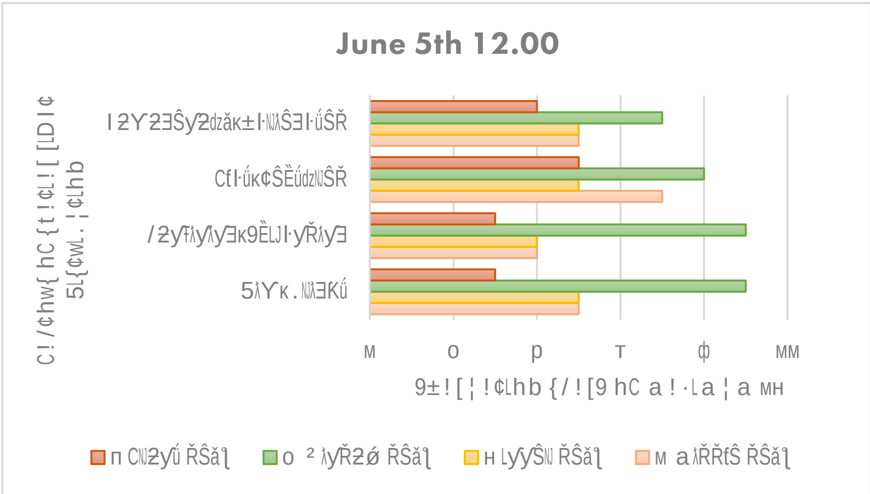


Figure 40 A diagram on experienced daylight light levels and spatial light distribution

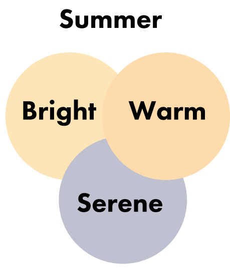


Figure 39 Words chosen by participants for describing daylight during summer put in bubbles

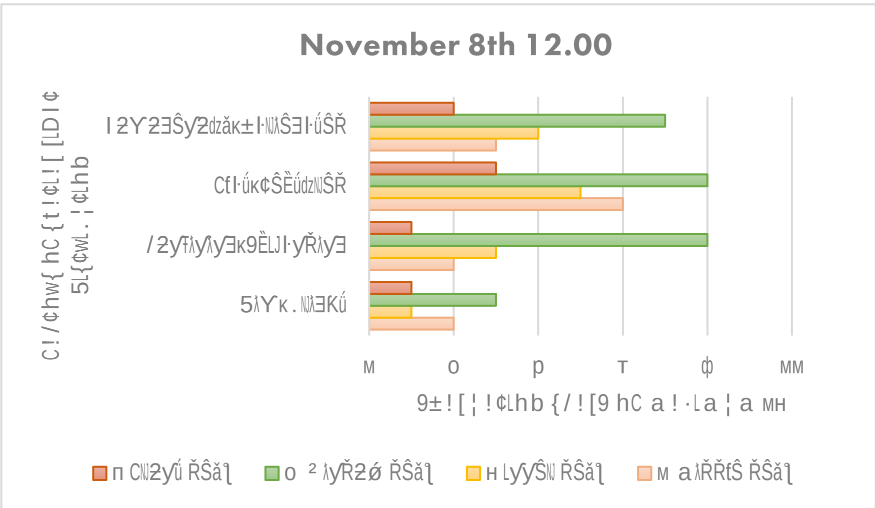


Figure 42 A diagram on experienced daylight light levels and spatial light distribution

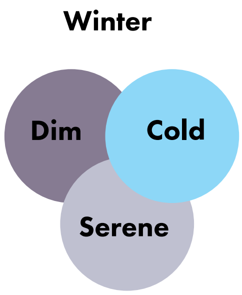
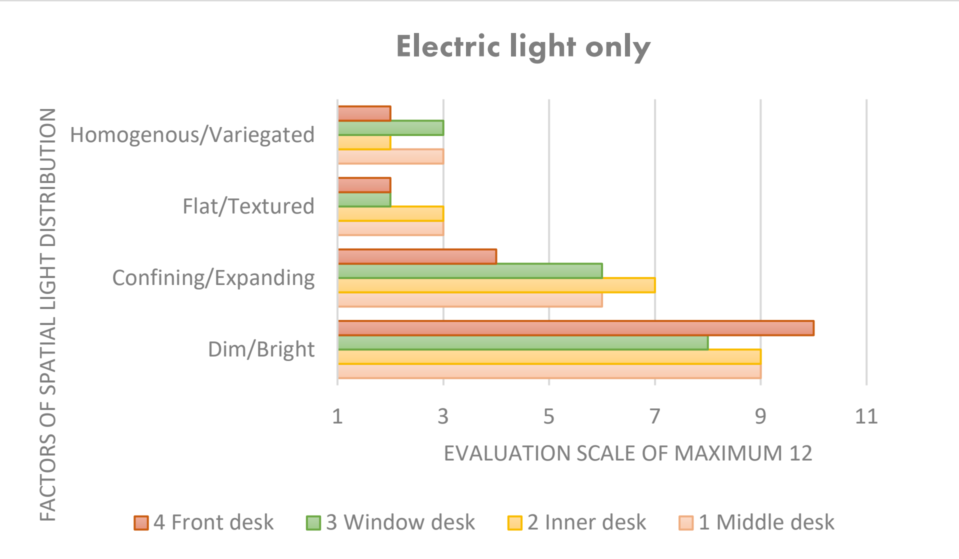


Figure 41 Words chosen by participants for describing daylight during winter put in bubbles

1	Level of light	Intense and overpowering
2	Spatial distribution of light	Flat, monotone and uniform
3	Shadows	Undefined, faint shadows

Figure 43 Three factors out of seven factors regarding the level of light, spatial light distribution, and shadows



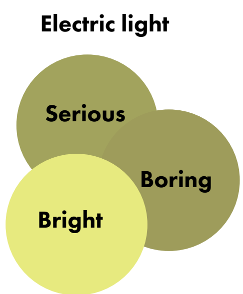


Figure 44 Words chosen by participants for describing the electric light put in bubbles

Figure 45 Diagram on experienced light levels and spatial light distribution in electric light without daylight, blinds were used

Furthermore, the participants experienced the electric light as bright, increasingly confining, and homogenous.

In *figure 46*, two participants answered on a scale of 1-5 how they perceived the electric light as satisfactory for the context; the seven factor analysis shows that it is poor and not satisfactory. The shadows are experienced as too soft and poor for the context.

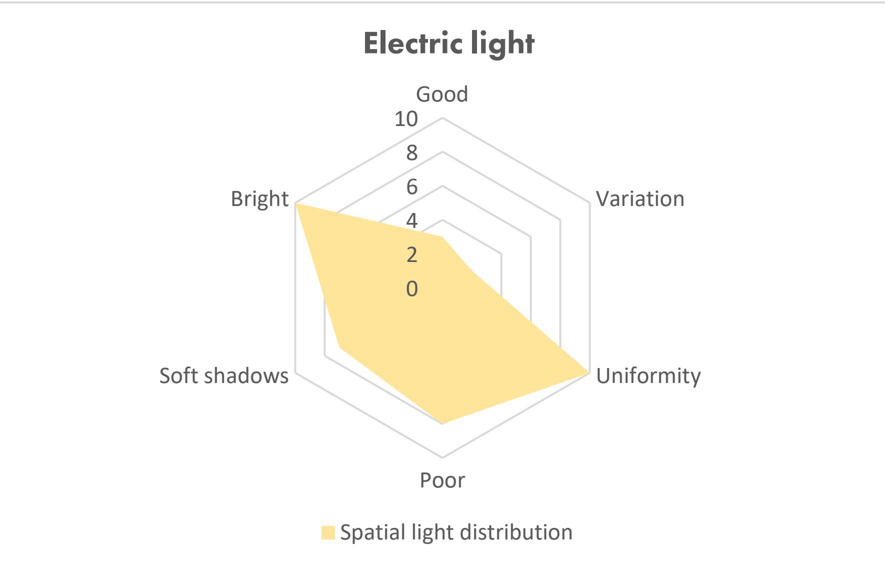


Figure 46 The diagram shows the experienced light quality for the context, the factors close to good are experienced as good while the factors close to poor as poor

4. Light source topology

There are ceiling-mounted T8 fluorescent tubes situated in the ceiling in Case I. The shape of the beams from the luminaires is flat and spreads a diffuse uniform light.

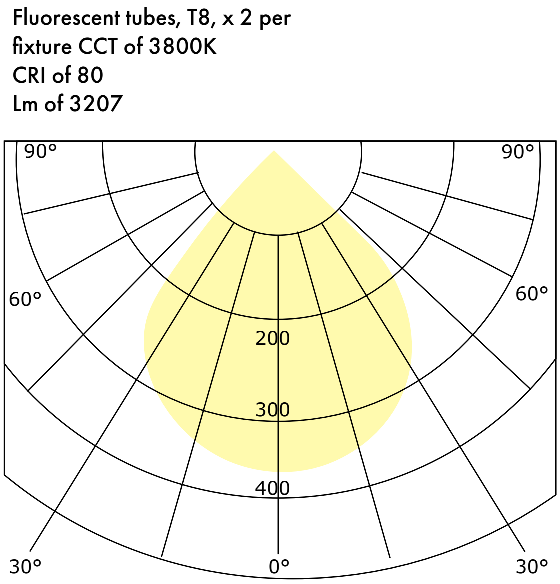


Figure 47 A polar diagram showing cd

Figure 48 Photograph of Case I T8 fluorescent tube fixtures mounted in the ceiling

Figure 49 Reflected ceiling plan (RCP) indicating where the luminaires are situated

4.1. Physical light analysis

The walls are in plaster and painted with matte white paint, while the floor consists of a light grey linoleum carpet with a semi-matte surface. Desks are in wood-coloured matte plastic, see *figure 50.*

Figure 50 Material and colour palette of the classroom

Approximate light reflectance values according to Dialux:

Desks and chairs: 26%

Walls: 84%

Floor: 30%

Calculations on a digital classroom model are presented on *pages 34 and 38* to examine light levels, distribution and materials further. The calculation date is on the 11th October 11.00; see *figures 52-58*.

Figure 51 Photographs of the Case I classroom during daylight in summer with and without electric light

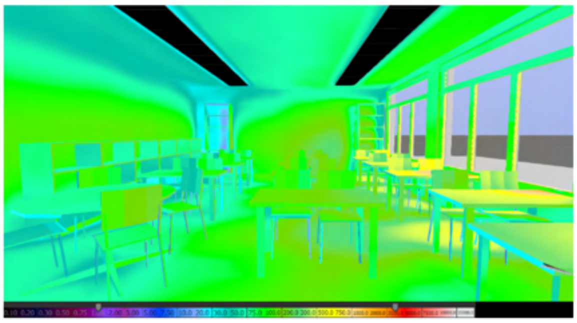


Figure 52 Daylight light levels in lx illustrated in false colour, date is 11th October 11.00

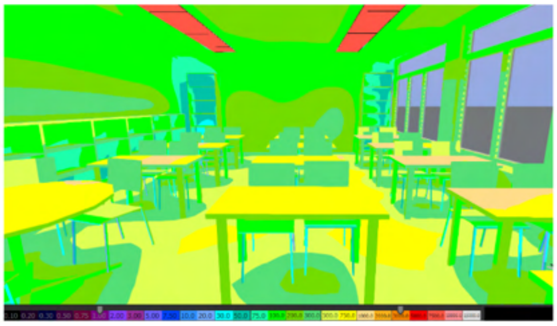


Figure 53 Daylight and electric light levels in lx illustrated in false colour, date is 11th October 11.00

In *figure 52*, the illuminance consists of daylight only, while in *figure 53,* it is from daylight and electric light. As shown in *figure 52*, it is approximately 200 lx in the inner part of the classroom without electric light. Moreover, in *figure 53,* with the electric light on, it is 750 lx in the inner part and 1000 lx by the window desks.

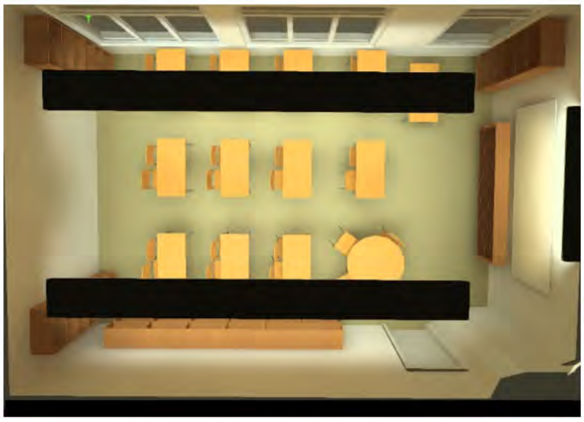
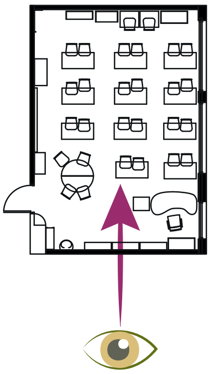


Figure 55 Electric light only

Figure 54 Electric light only shown in false colour

In the current situation, without daylight, the average lx levels are 700 lx. Furthermore, the levels at the working areas are around 750 lx, and the maximum lx level is at 1018 lx. The uniformity is 0.5, close to the standard of 0.6.[2] It is 500 lx on the floor in the middle of the classroom. The lx levels on the floor are equivalent to recommendations for a workstation.[11]



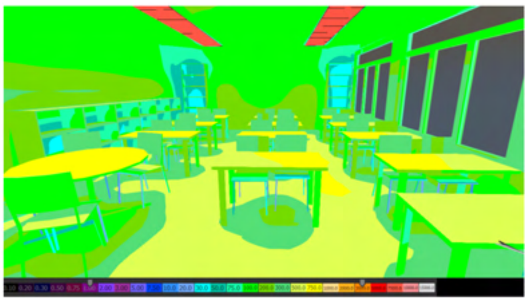


Figure 56 False colour illustration of lx levels from perspective

4.2. Daylight factor

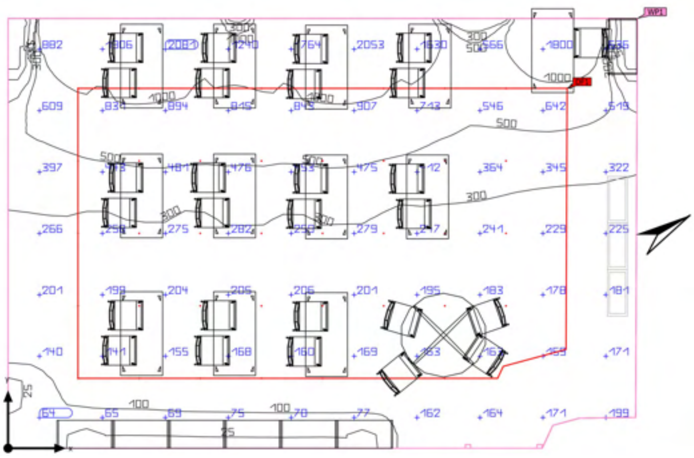


Figure 57 Daylight light levels in the classroom

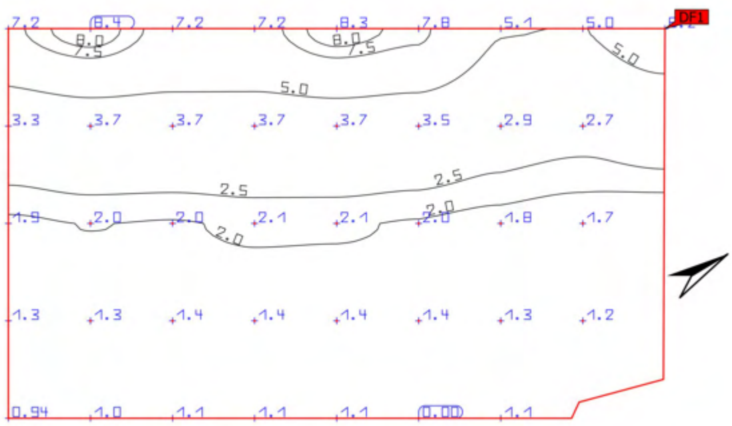


Figure 58 Daylight factor in the classroom

As seen in *figure 58*, it is an average of 3% daylight factor (DF) in the room. It is 5% in DF by the window, and then further into the room, the DF falls to 1%. There is less daylight in the front of the classroom due to the wall between windows and the smaller window by the teacher's desk, see *figure 57*.

4.3. Horizontal measurements

Calculating the measuring grid using the standard EN 12464-1.[2]

$P = 0.2 \times 5^{\log(d)}$

P: the distance between the measuring points.

d: is the longest side of the surface.

Uniformity:

$U_1 = E_{Min} \div E_{Average}$

$U_2 = E_{Min} \div E_{Maximum}$

$E_{Min} = 376{,}77\ lx$
$E_{Maximum} = 966.39\ lx$
$E_{total} = 52\ 569{,}64$

$$E_{Average} = \frac{\mathbf{Etotal}}{\mathbf{\#Measurements}} = \frac{\mathbf{52\ 569{,}64}}{\mathbf{70}}$$

=750,994

$$U_1 = \frac{\mathbf{376{,}77}}{\mathbf{750{,}994}} \approx 0{,}5 \quad U_2 = \frac{\mathbf{376{,}77}}{\mathbf{966{,}39}} \approx 0{,}4$$

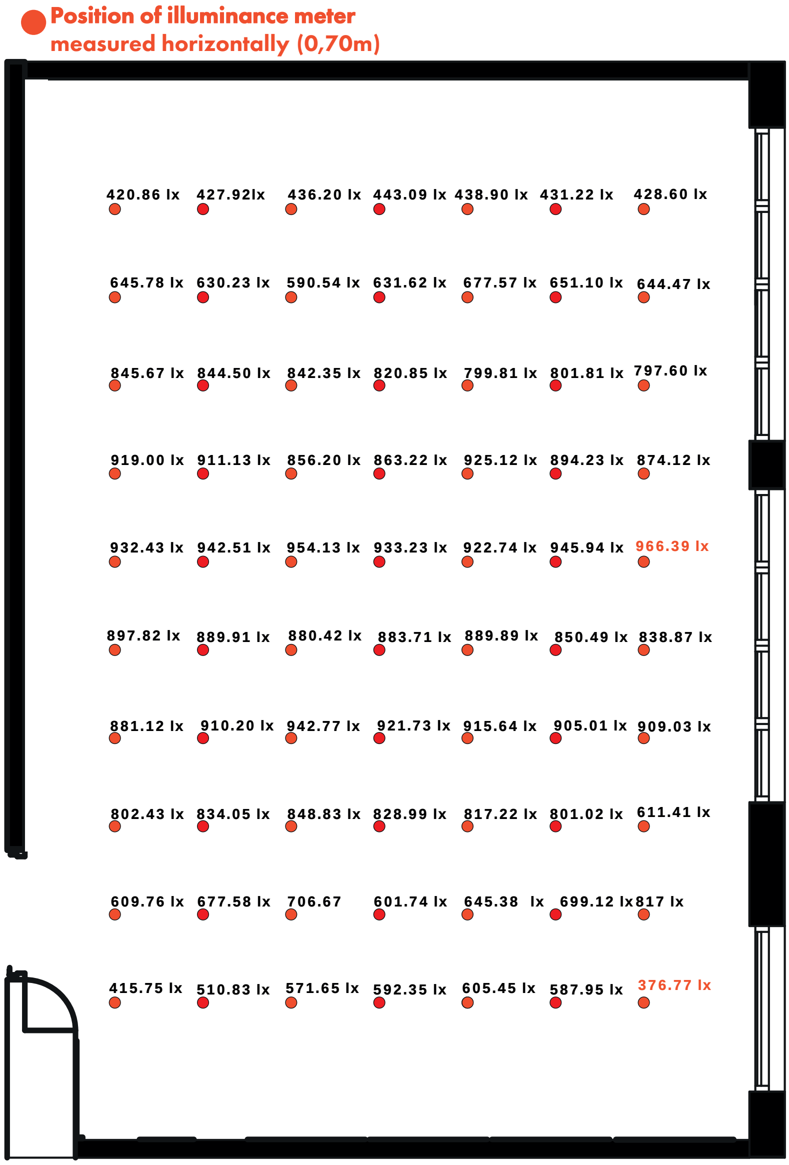


Figure 59 The uniformity grid, each point is measured with the illuminance meter

Figure 59 shows the manual measurements using a uniformity grid calculation on the electric light. The uniformity is 0.5, close to the standard of 0.6 [2], and the overall lx level is around 750 lx. *Figure 60* shows desk illuminance. The level of light varies between desks, all desks complies with the standards.[2,11]

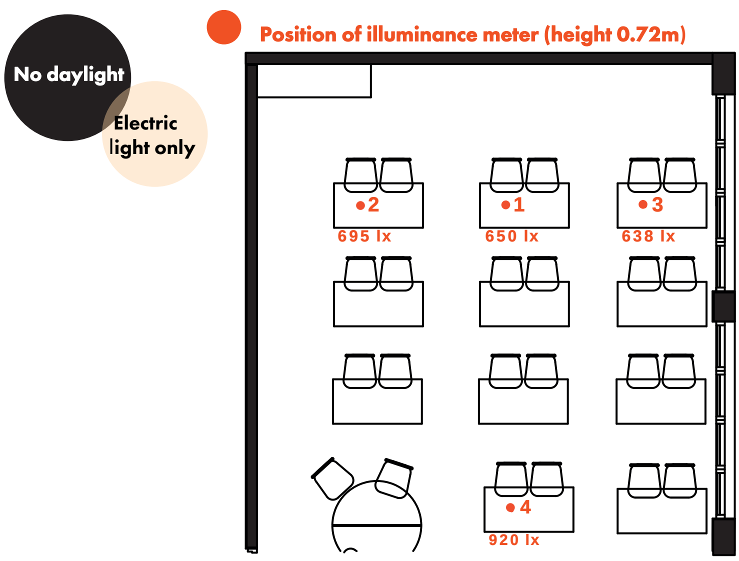


Figure 60 On desk measurements in electric light only

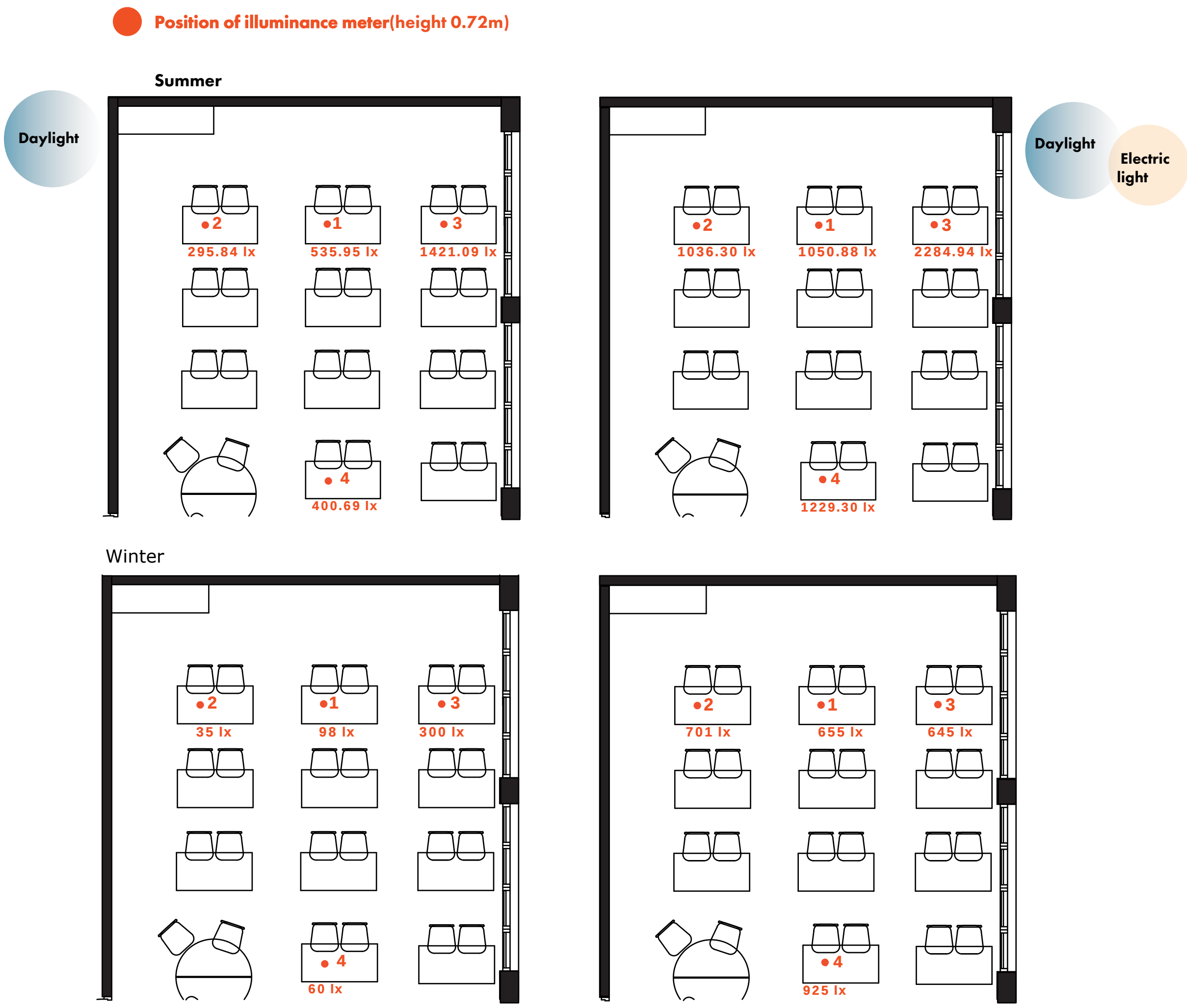


Figure 61 On desk measurements with daylight only and daylight with electric light

The daylight levels differ significantly from the window desk to the inner desk, see *figure 61*. The levels are measured at approximately 14.00 in summer and winter; the electric light combined with daylight becomes very intense during summer. Nonetheless, light levels are drastically lower than the recommended light levels in terms of visual performance and circadian health during the winter when using daylight only. [2, 11] The front desk and the inner desk get less daylight than the window desk.

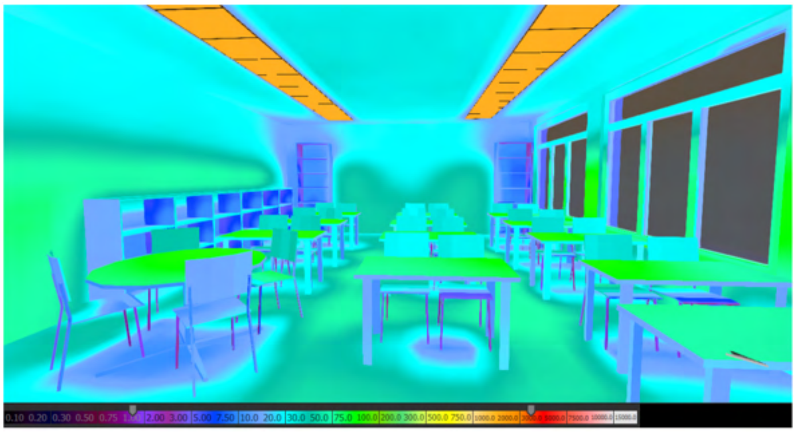


Figure 62 Cd/m² meter false colour illustration from Dialux

It is about 150 *cd/m²* on the oak-coloured desks when illuminated with 750 lx. It is impacted both by material, intensity, and distribution. The walls have matte white paint that reflects more light. Nevertheless, the lower light levels on the walls cause between 10-30 *cd/m²*, as seen in *figure 62*. It complies with the recommendations of 30 *cd/m²* on the walls.[11] It is up to 250 *cd/m²* on the floor.

Figure 63 Colour and material palette of Case I

4.3.1. Vertical measurements with a luminance meter

Figure 64 is a false-colour image presenting the beams *cd/m²*. The image is taken post-sunset and without daylight. The beam is flat and evenly covers the floor and the desks.

Figure 64 Fusion optix false colour photo to illustrate mark of the beam size of the fixtures of Case I

4.3.2. Vertical measurements with spectrometer and LYS-button

According to the WELL office standards, EML should be measured vertically to simulate the occupant's view. Between 09.00 and 13.00 daylight should, together with electric light, provide recommended EML of 200, see *figure 65.* The recommended EML needs to be fulfilled every day of the year for at least 75% of the workstations. Electric light should provide 150 EML or greater for all workstations, see *figure 65*.[1]

The electric light fulfils the recommendation for the electric light, see *figure 65.*

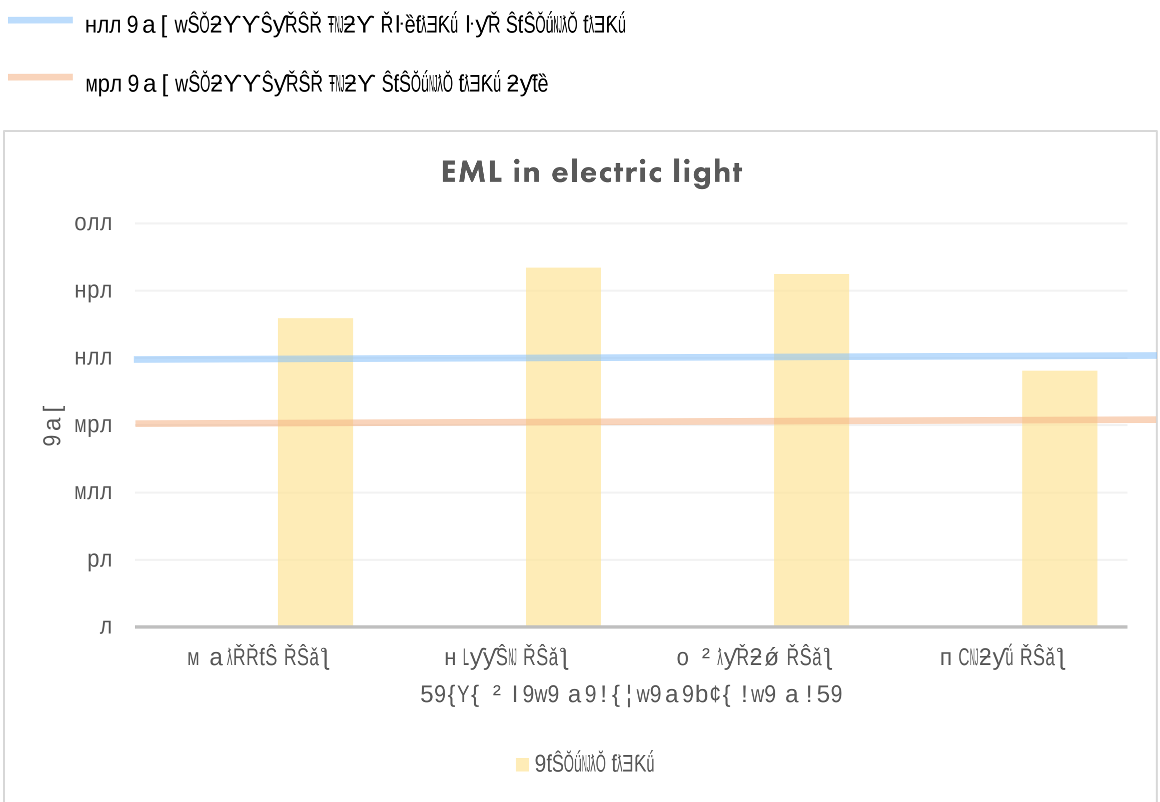
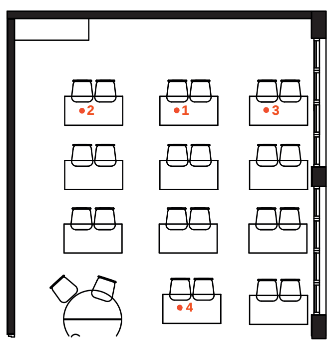


Figure 65 Diagram showing EML levels in electric light and two lines indicating the recommendations and below desks 1, 2, 3 and for as referred to in diagram



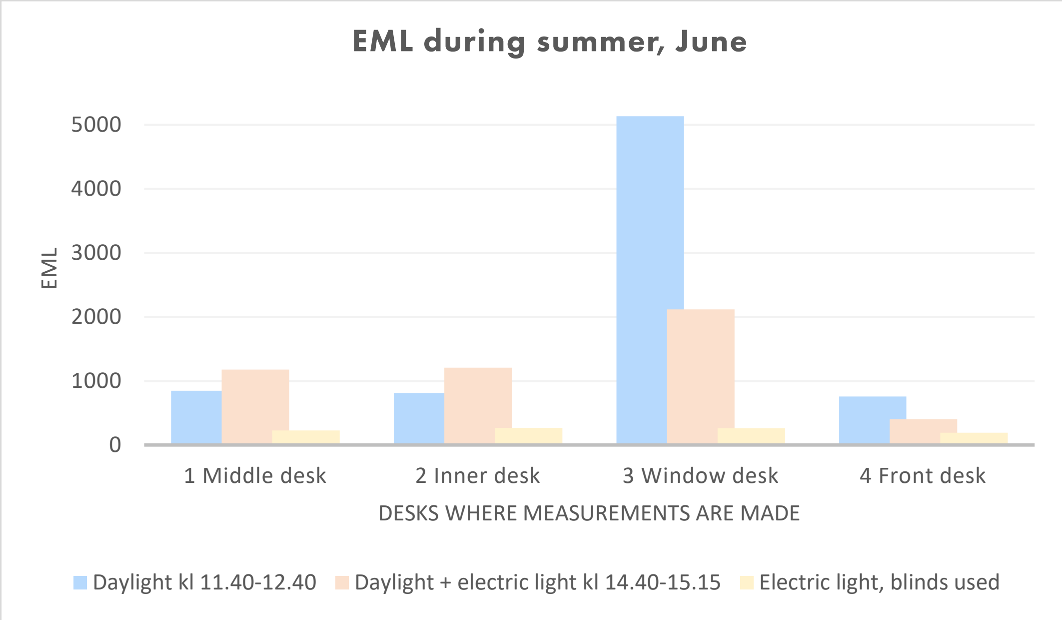


Figure 66 EML levels during summer

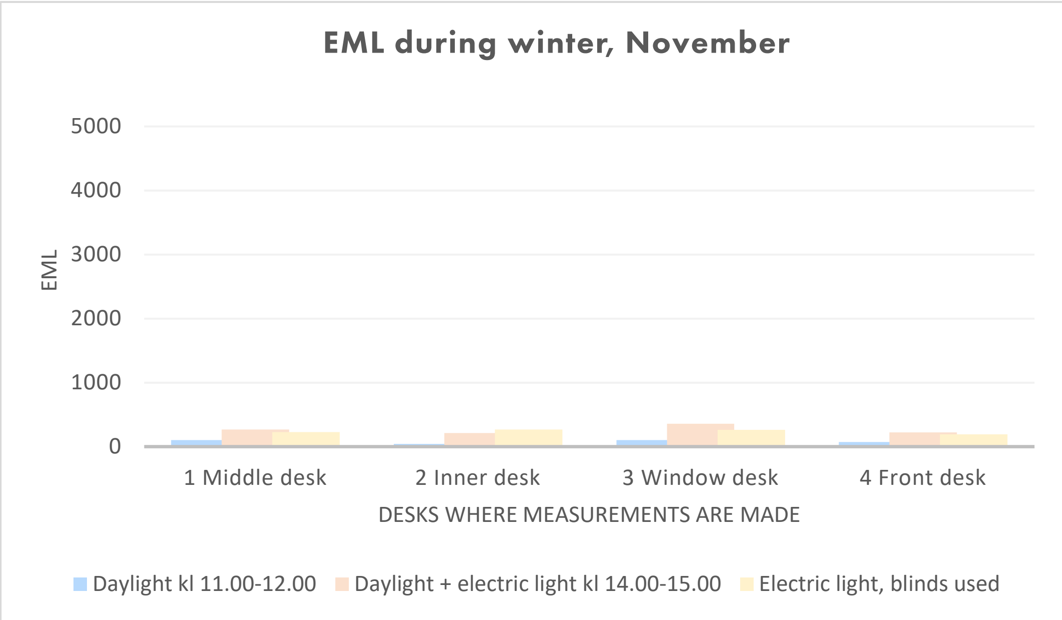
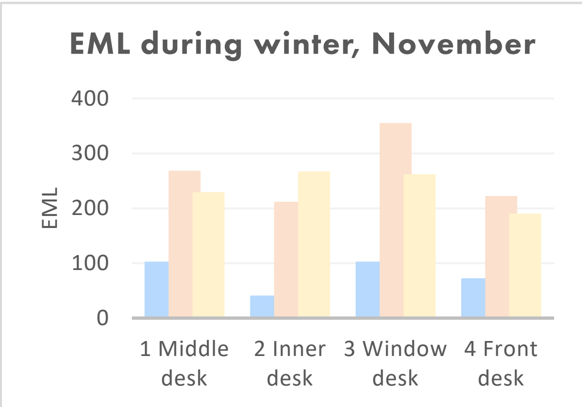


Figure 67 EML levels during winter both in relation to 5000 EML and zoomed in in relation to 400 EML

There is sufficient EML in the daylight alone during summer, see *figure 66*. The front- and inner desk is below WELL standards during the winter, see *figure 67*. The inner desk gets less daylight than the other desks generally. The front desk gets less electric light than the other desks, as shown in *figures 66 and 67*.



Figures 68-71 have imitated the colour of light shown in the LYS-app. The daylight during November, *figure 68,* provides more light stimulus (ls) (according to LYS-technologies[16]) than in December, *figure 70.*

The electric light provides around 63 ls on its own when positioned at desks 1, 2, and 3, while it emits around 46 ls at desk 4, *see figure 96.*

During December, desk 3 gets most of the ls from the window, while the rest of the space gets a remarkably lower amount of ls, see *figure 71*. Occupants obtain the most of the ls from the electric light during winter.

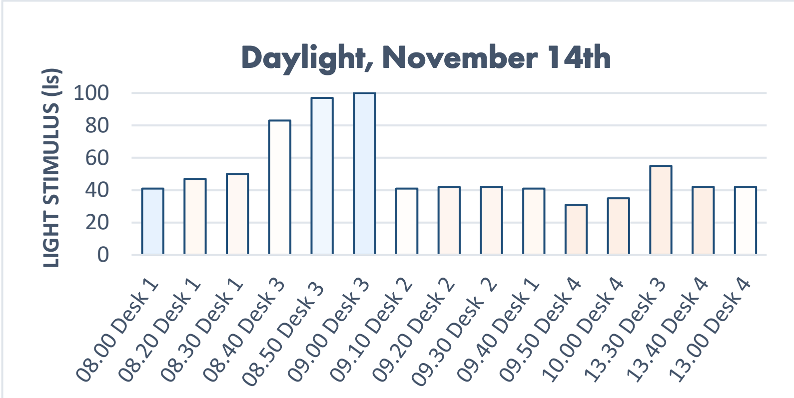


Figure 68 The diagram shows daylight light stimulus

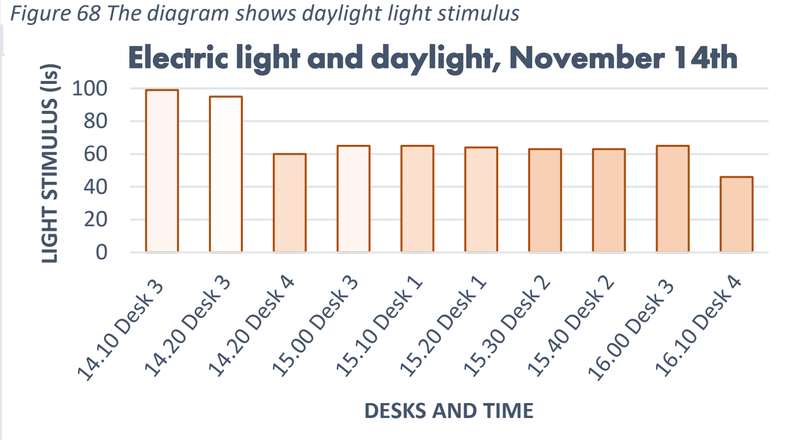


Figure 69 The diagram shows electric light stimulus

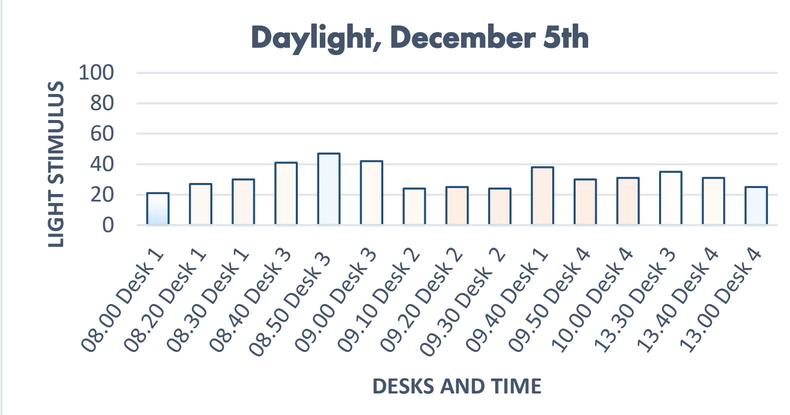
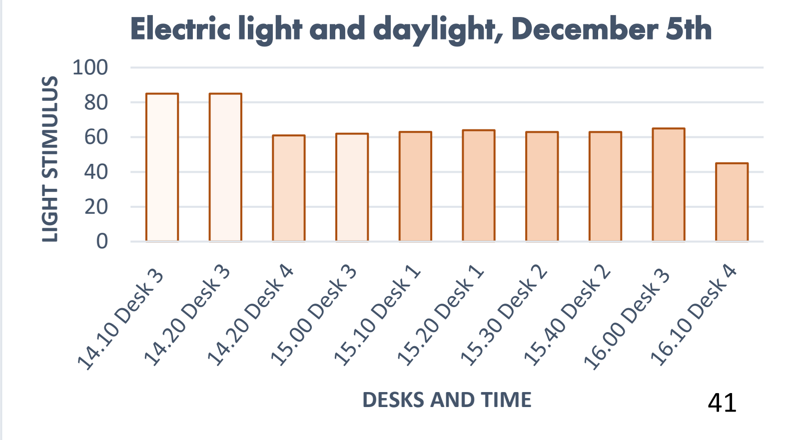


Figure 70 The diagram shows daylight stimulus



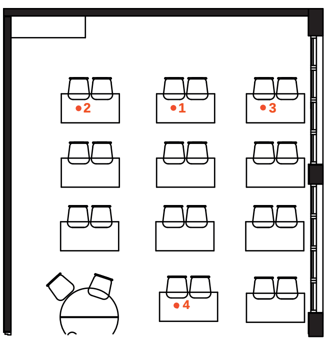


Figure 71 The diagram shows daylight, electric light stimulus and desk 1, 2, 3 and 4 as referred to in figures 68-71

5. Colour analysis: Seven factors and spectral content

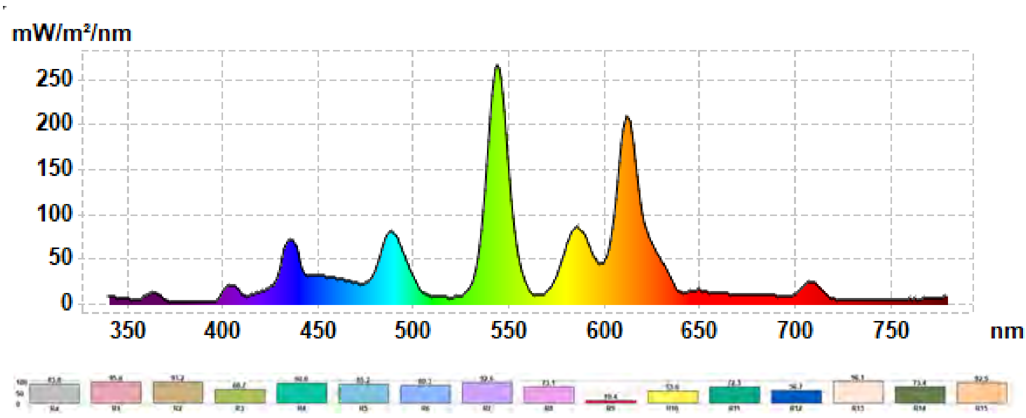


Figure 72 SPD measured close to luminaire and Ra indices (CRI) of the luminaire

The T8 fluorescent tubes hardly emit any of the redder longer wavelengths; it emits mostly the greenish-yellow 550 nm. Furthermore, in the Ra indices, the red is low, see *figure 72*.

6	Colour of light	The tone is dull lemon ash
7	Colour of surfaces	The surfaces appear desaturated and dull, and muted

Figure 73 Two factors out of seven regarding the experience of colour of light and colour of surfaces

The experience of the colour of light and surfaces is warm, dull, desaturated and pale, see *figure 73-74*.

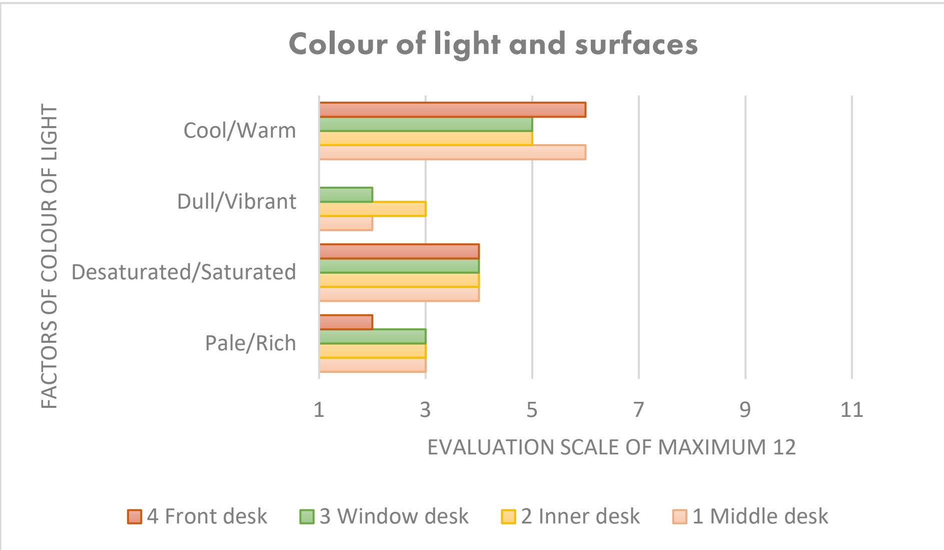
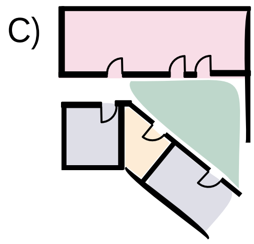


Figure 74 The diagram shows the experienced colour of light and colour of surfaces of two participants, it is read in the following way: a low number indicates a cool experience and a high number a warm experience

Case II

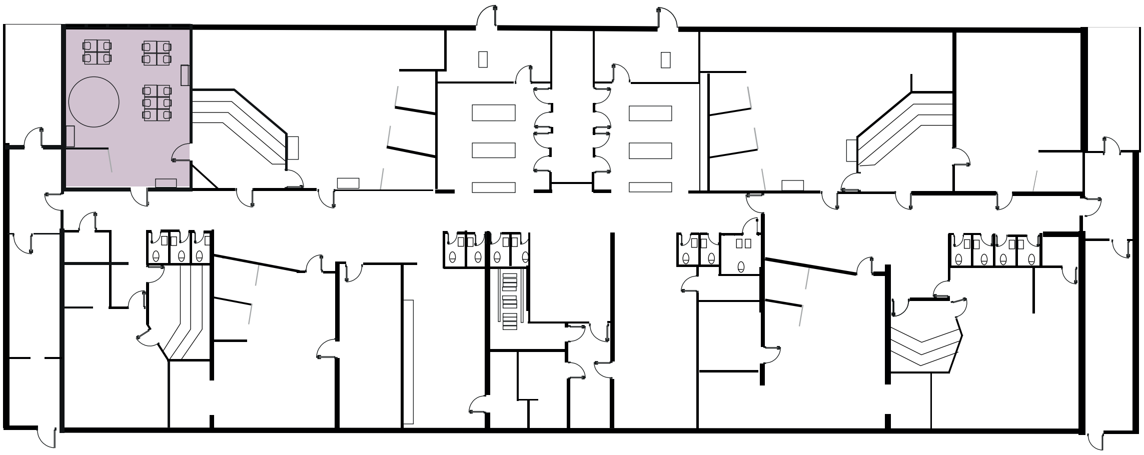
1. Floorplan topology

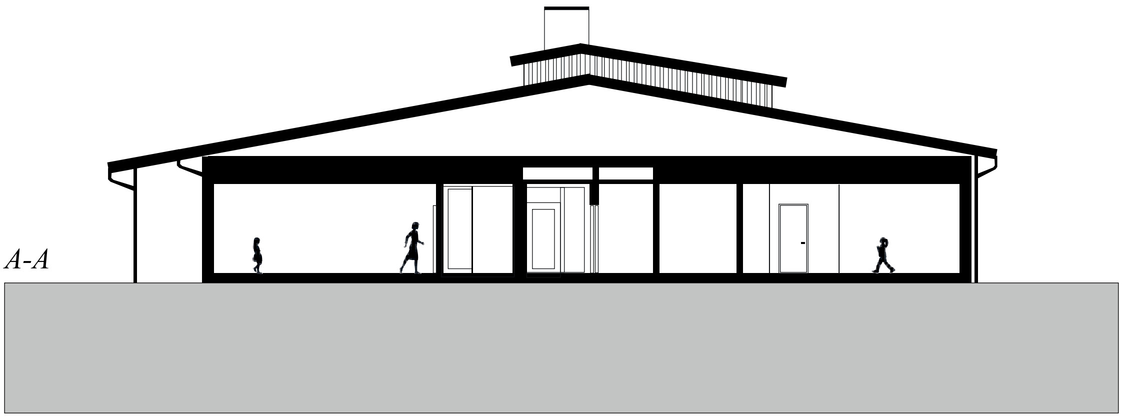
The school in Hudiksvall, Case II, is categorised as a C) and it was redesigned and renovated in 2020.



Architecture Firm: SWECO,

Project Lead: Åsa Machado & Jonas Kjellander





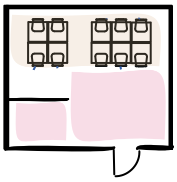
Section A-A

Section B-B

Figure 75 Sections, floorplan, and topology C) in floorplan openness

2. Spatial analysis of a designed classroom

E) Activating



The classroom has E), an activating topology. During the observations, 15 six-year-old pupils and two teachers were in the classroom. *Figure 76* shows how pupils and teachers circulated in the classroom throughout the day.

The use of spatial elements is mapped in a bubble diagram, see *figure 77.*

Figure 76 Mapping of pupils' and teachers' circulation

How pupils and teachers circulate between spatial elements

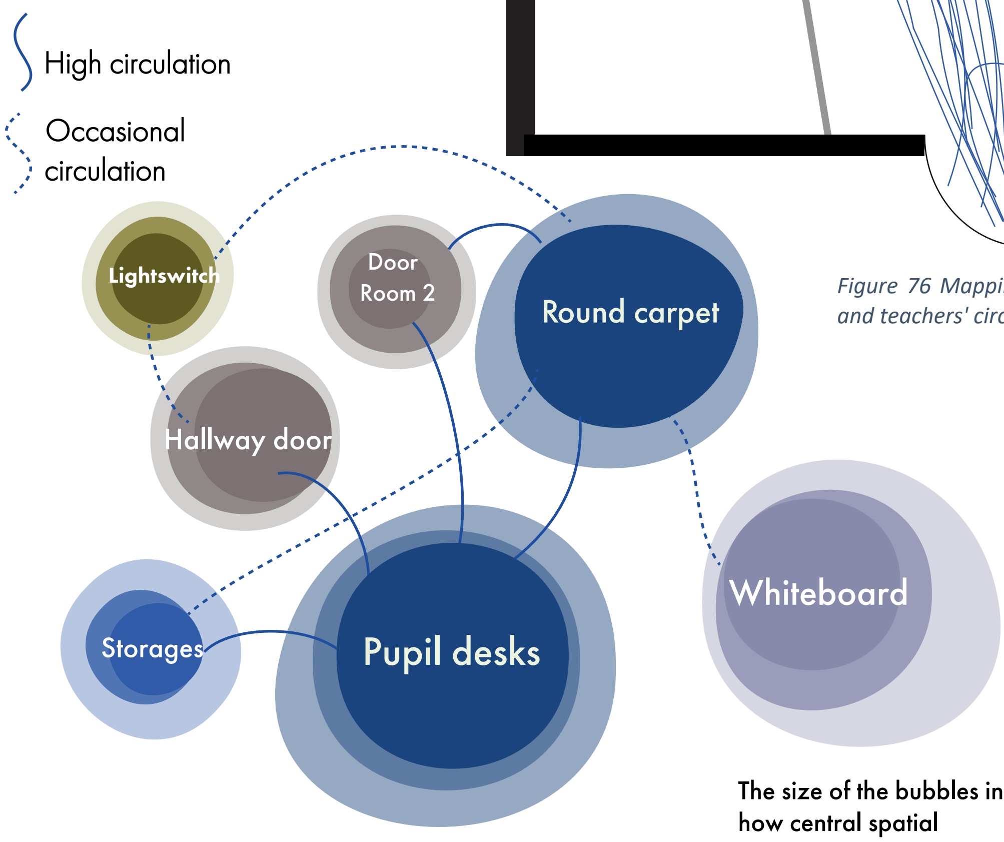
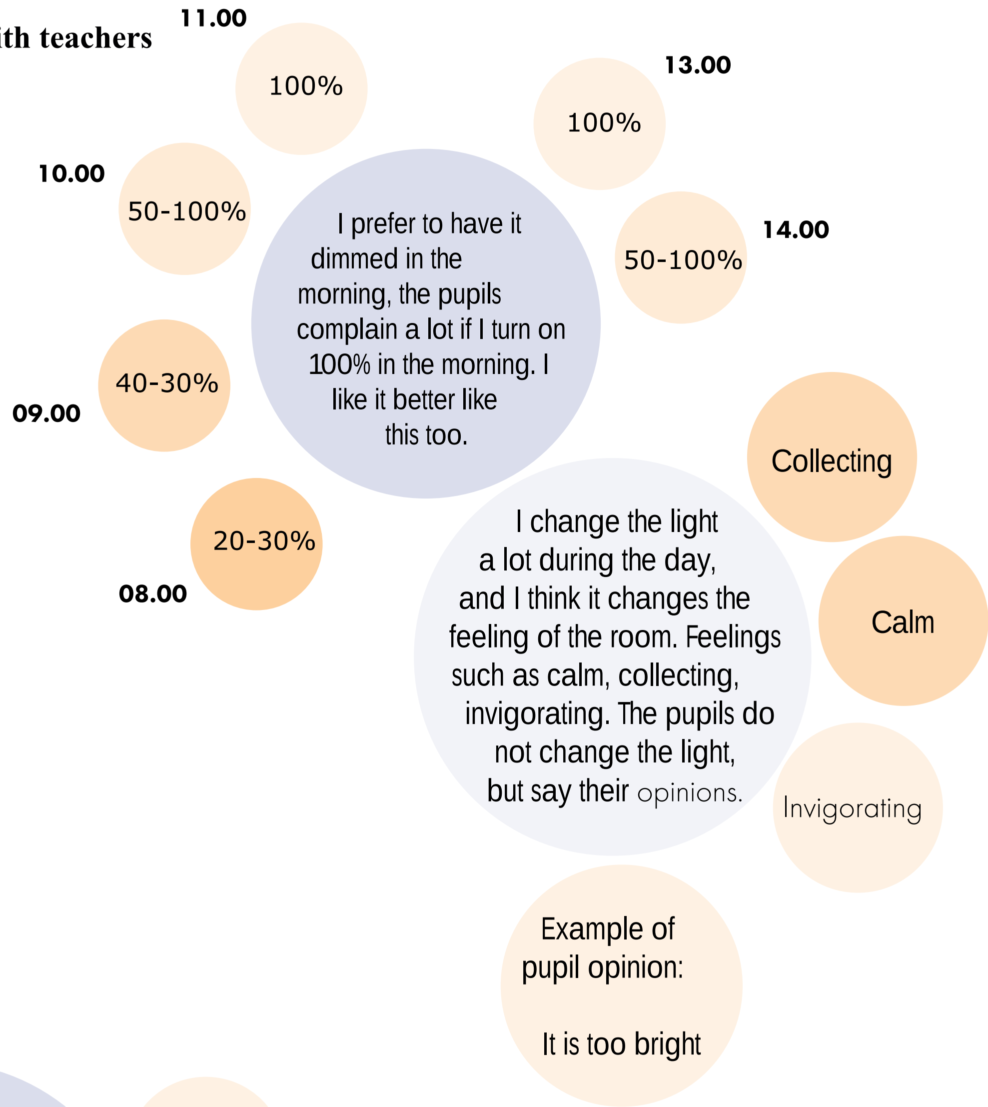


Figure 77 Bubble diagram showing central spatial elements and how often circulation happens there

The size of the bubbles indicate how central spatial elements are during class

2.1. Interview with teachers

Teacher 1 quotes



Teacher 2 quotes

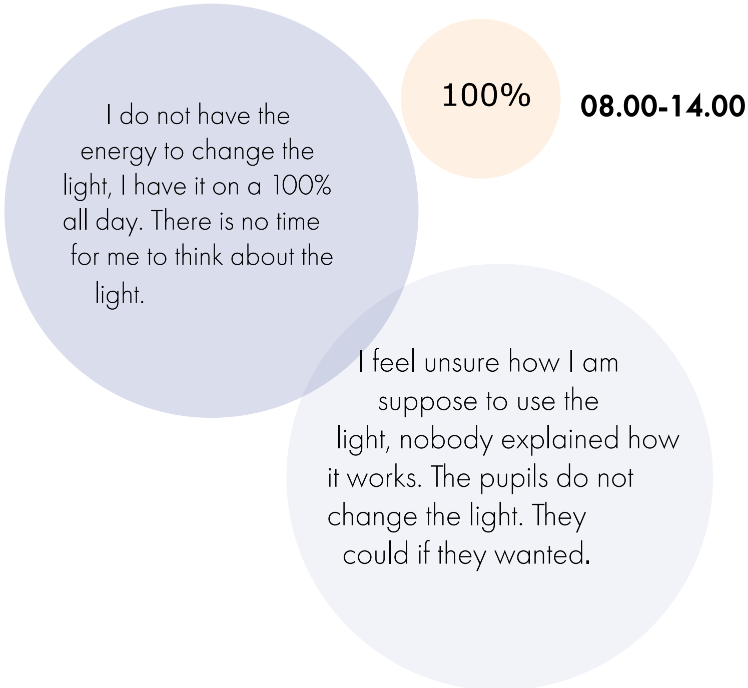


Figure 78 Teacher 1 and Teacher 2 quotes from interviews put in bubbles

2.2. Pedagogical activities

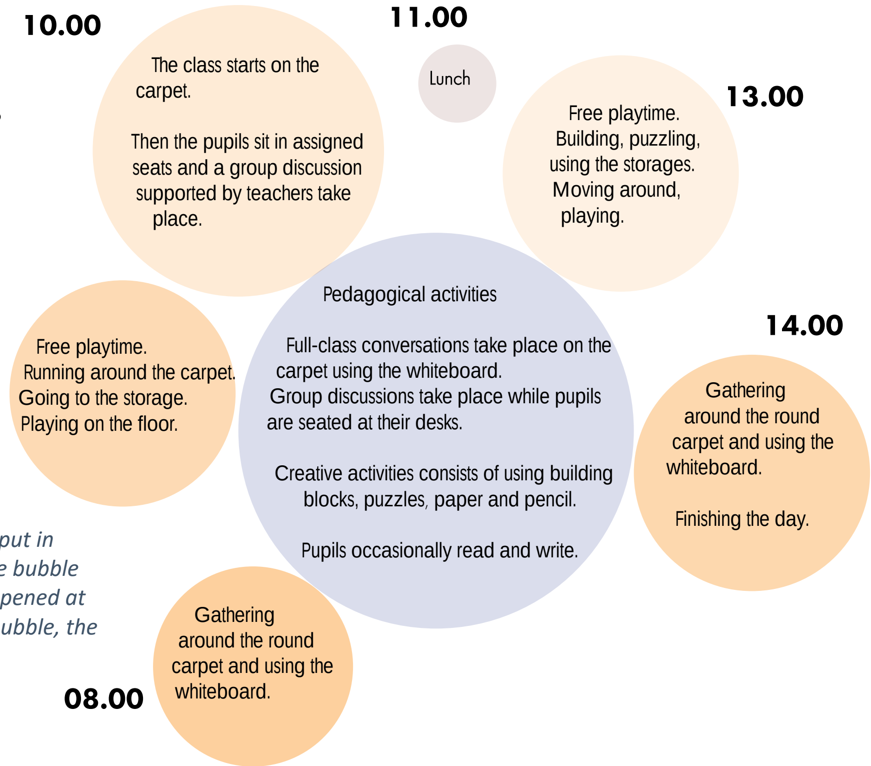


Figure 79 *Observation data put in bubbles; the time next to the bubble indicates that the event happened at that time; the brighter the bubble, the more lumen output was on*

The light is mostly fully turned on when reading and writing.

Creative activities take place in all the light settings. A dimmed light setting is used when building and playing activities occur and higher intensity when activities such as laying puzzles or drawing occur.

The conversations between teacher and pupils are most noticeable when the teacher is close to the carpet and the whiteboard. The relational activities otherwise occur by teachers instructing one pupil at a time, often close to a working zone.

The teachers use the whiteboard often. The pupils look at each other and towards the whiteboard during the teacher's lecture. During lectures, 100% of the light is on most of the time.

Most of the activities in the classroom are either teacher-supported or in the form of one-to-one instructions, see *figure 80.*

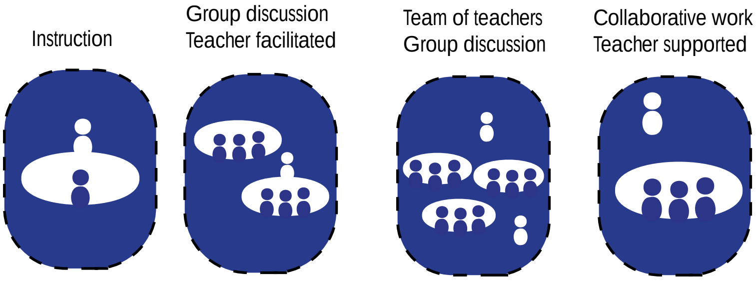


Figure 80 Pedagogical topologies taking place during the observations

2.3. Illumination hierarchy

Observations with 20-30% of the lumen output with two intense pools and one faint pool, 08.00.

- The pupils orient toward the two pools of light, playing close to or in the pools. Some sit, build, or draw horizontally, mainly on the floor and desks, while other pupils are oriented vertically, moving around and playing close to the toy train and the carpet.
- The main spatial elements in the illumination hierarchy are the carpet, and the toy train. There are dimly lit pools on the walls. The horizontally lit carpet and train area dominate and create horizontal domination with spatial boundaries.
- The rhythm in the room consists of two different distinguished light pools horizontally. The distance between the pools creates a slow rhythm giving an impression of the room being longer with connotations to an exhibition with pools of play of brilliants.
- The carpet and the toy train contrast from the rest of the space illuminated with focal glow, and they become two landmarks.
- The overcast darkish morning outside blends with the dimmed scenario inside.

Figure 81 Two photographs of the light when dimmed 20-30% together with daylight

Observations with 50-100% of the lumen output with vertically and horizontally lit surfaces, 10.30.

- Pupils are primarily oriented vertically. Moreover, there is an overall increased luminescent ambience.

- There are four main pools of light on the walls. Vertically lit surfaces create a vertical dominance. Some of the pools on the walls can appear illuminated with a focal glow when the light is at 100%.

- The rhythm between pools creates a pattern giving spatial boundaries. With the long walls and the corners accentuated with enough information, the rhythm is faster than the dimmed solution. However, it is a varied and noncontinuous rhythm without linear speed.

- The landmarks consist of the art, the toy train, and the green carpet, and they are equally lit and prominent in a focal glow when at 100% of the lumen output. The work areas on the desks and floor are illuminated with a focal glow.

- The overcast mid-day daylight is brighter than in the observation in *figure 81*, and it blends with the full light turned on.

Figure 82 Photographs of the light when at 50%-100% of the lumen output together with daylight

3. The seven factors and spatial light distribution

In Method B, concerning the seven factors, the participants are lighting designers and architects. Two participants answered on a scale of 1-6 on how brightness and spatial light distribution were experienced. In *figure 84,* values are added from both participants in each factor. The factors are to be read like this: Homogenous/ Variegated. The low number, the more homogenous, and the higher number, the more variegated.

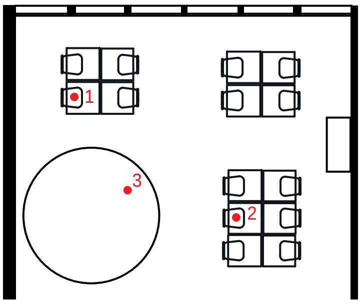


Figure 83 Desk 1, 3 and 2 referred to in the diagrams

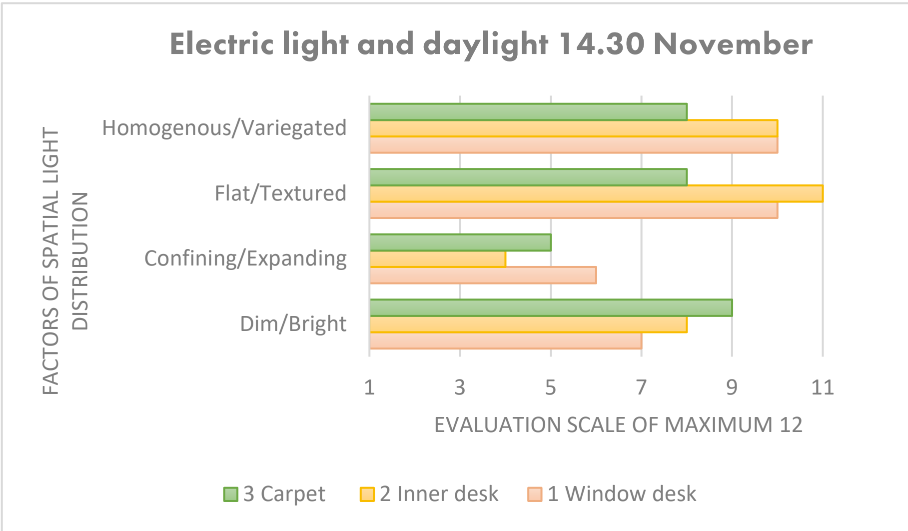


Figure 84 A diagram showing how participants experienced the spatial light distribution and level of light

In *figure 85*, two participants answered on a scale of 1-5 if they perceived the electric light as satisfactory for the context; the results show that it is satisfactory. Nonetheless, the sharpness in shadows is experienced as poorer for the context.

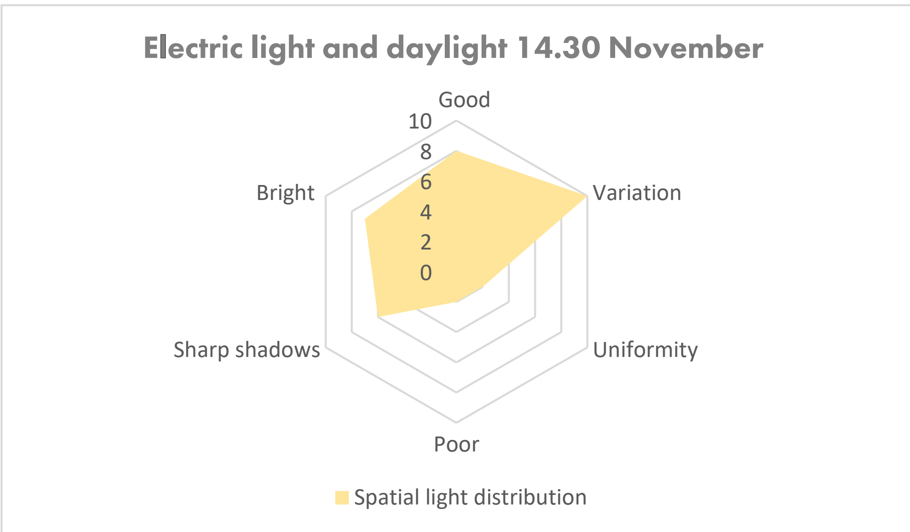


Figure 85 Diagram shows the experienced light quality for the context, the factors close to good are experienced as good while the factors close to poor as poor

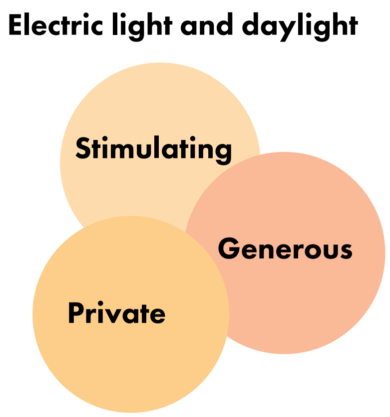


Figure 86 Words chosen by two participants used to describe the light put into bubbles

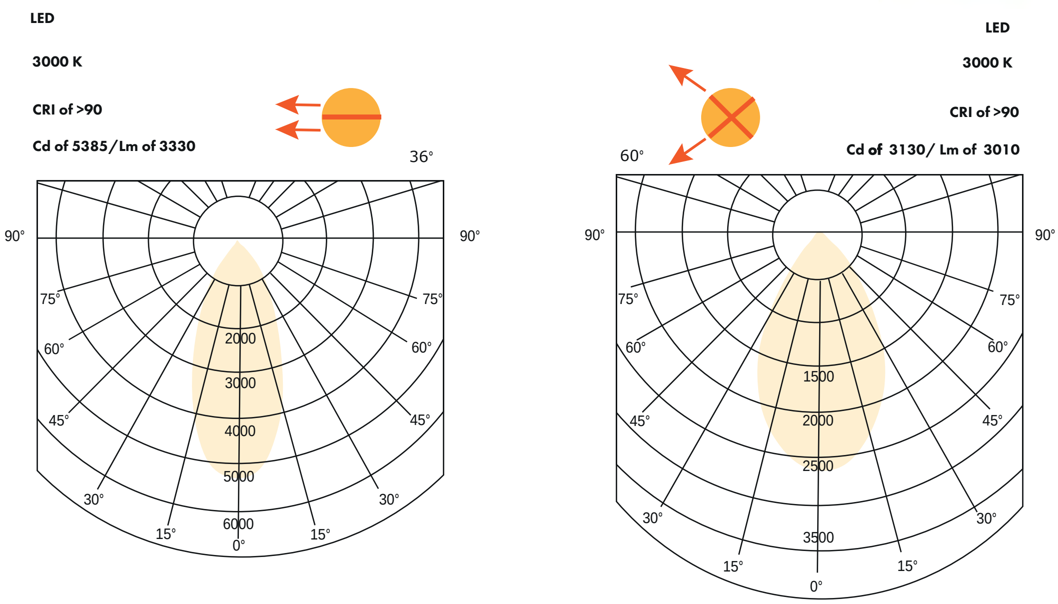
The seven factors show that the experience of the designed classroom, Case II, has a more harmonious and varied spatial light distribution and a more suitable light level for the purpose.

Level of light	Adapted, accurate
Spatial distribution of light	Harmonious, balanced, varied
Shadows	Sharp around the tables and softer in the overall room

Figure 87 Table showing words from two participants used to describe the light regarding the brightness and spatial light distribution during an overcast day around 15.00 with 90% of the lumen output on, this is a general experience of the space and not an experience from a certain point of view

4. Light source topology

Figure 88 Photograph of the light sources



Programmable with KNX/DALI

Can be moved on a track

Rotatable 360°

Tiltable 90°

Figure 89 A polar diagram showing cd

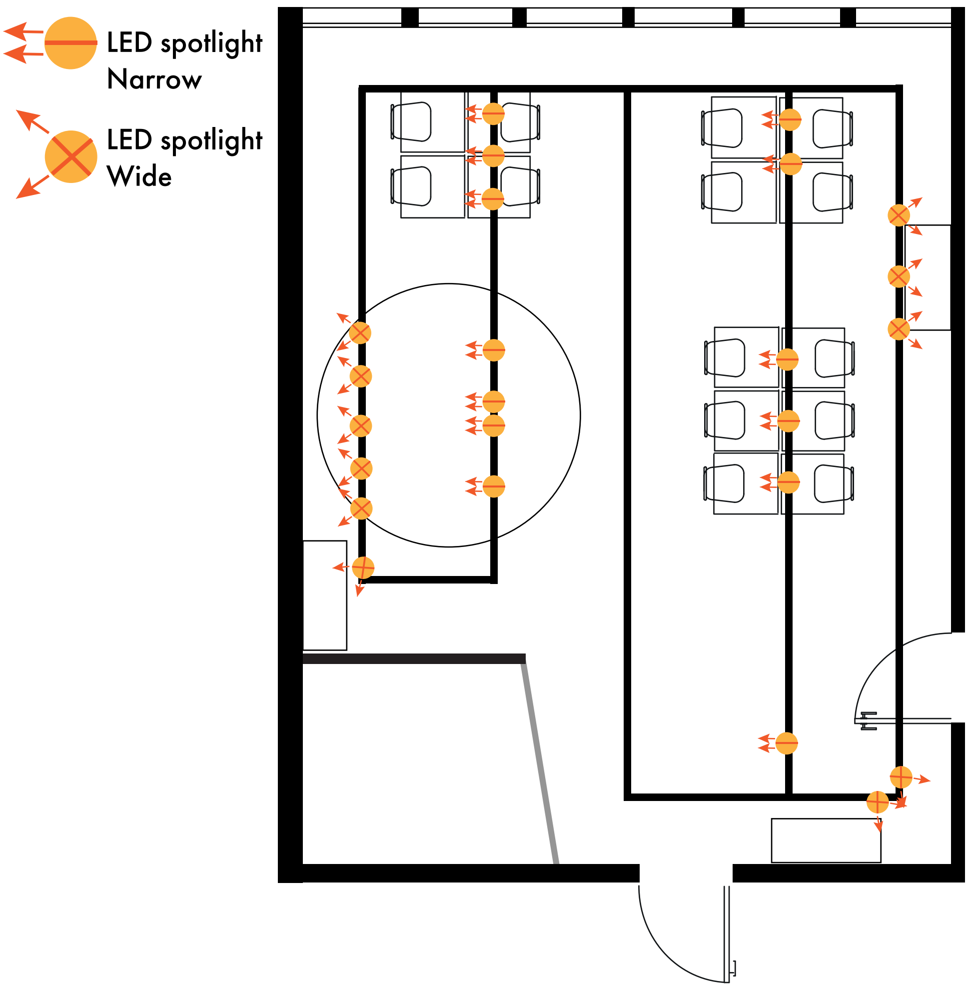


Figure 90 Reflected ceiling plan (RCP) indicating where the luminaires are situated

4.1. Physical light analysis

These are the approximate light reflectance values, in the Case II classroom, according to Dialux:

Desks: 20%

Chairs: 29%

Walls: 84%

Floor: 20%

Carpet: 16%

Figure 91 A colour and material palette of the classroom of Case II

Figure 92 Photograph of the Case II classroom

4.1.1. Horizontal measurements

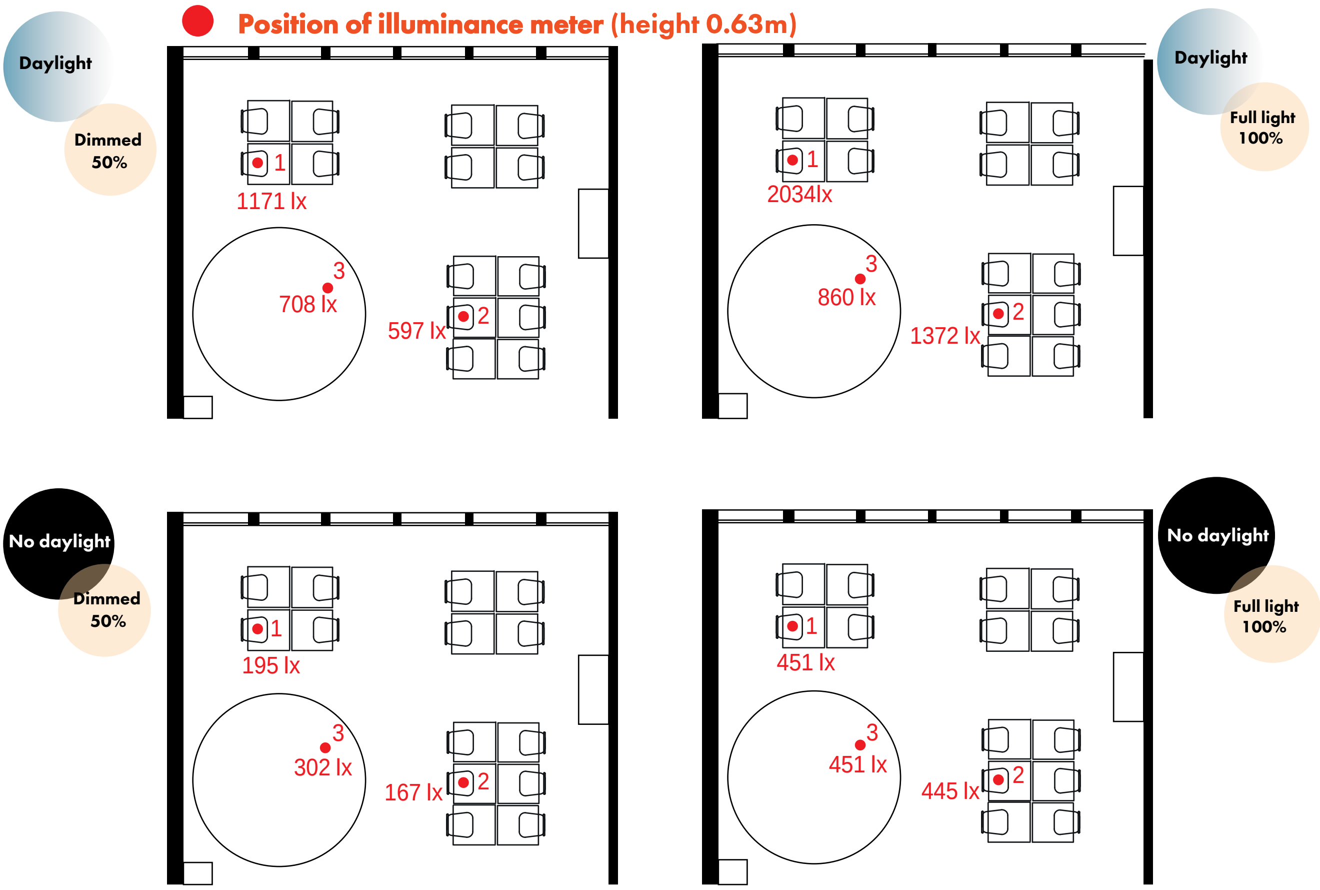


Figure 93 On desk measurements during different light conditions with and without daylight

When dimmed down to 50% of the lumen output without daylight, the light levels are drastically lower. The light levels are lower in Case II than in Case I, as seen in *figure 93* and *figure 60-61*. Nevertheless, in *figure 93* it is close to the recommendations of 5:3:1 when at 100% of the lumen output.[11]

4.1.2. Vertical measurements with a luminance meter

In *figure 94* the beam *cd/m²* measurements of the different light pools in the classroom are shown to map the spatial light distribution.

Figure 94 Fusion Optix false colour photographs to illustrate beam shape and photographs without fusion Optix

Both direct and indirect pools are defined and distinct, unlike the distribution of the standard solution, Case I, where it was a big undefinable pool, *see figure 64 and figure 94*. More luminaires are grouped to add to a bigger pool when needed. The beams are quite intense on the walls and the whiteboard while the light is on to 100% of the lumen output capacity; this is due to the high reflectance, distance of the luminaire and angle of the beam. Specifically, at some spots, the beams become very concentrated, see *figure 94*.

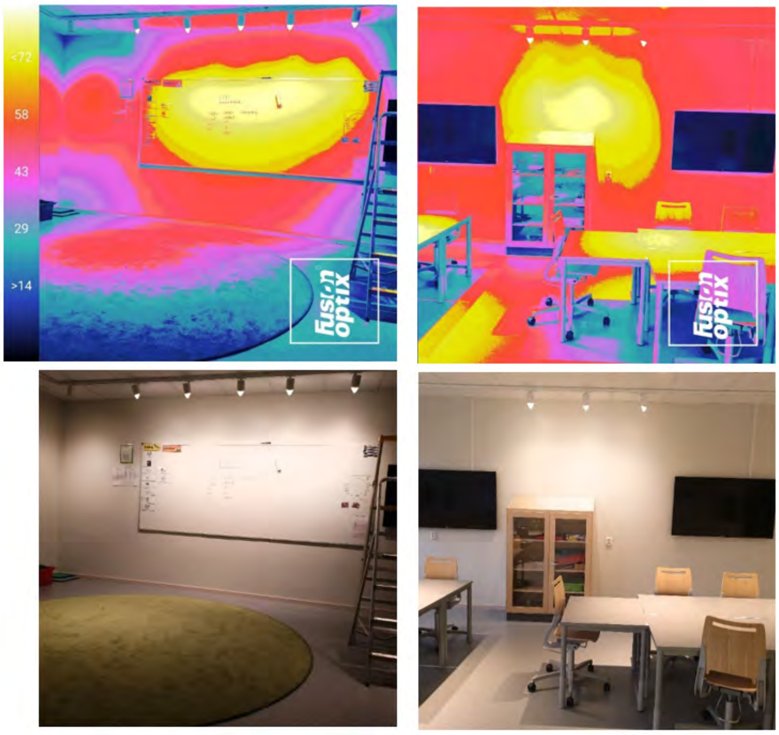


Figure 95 Fusion Optix false colour photographs and regular photographs while at 100% lumen output

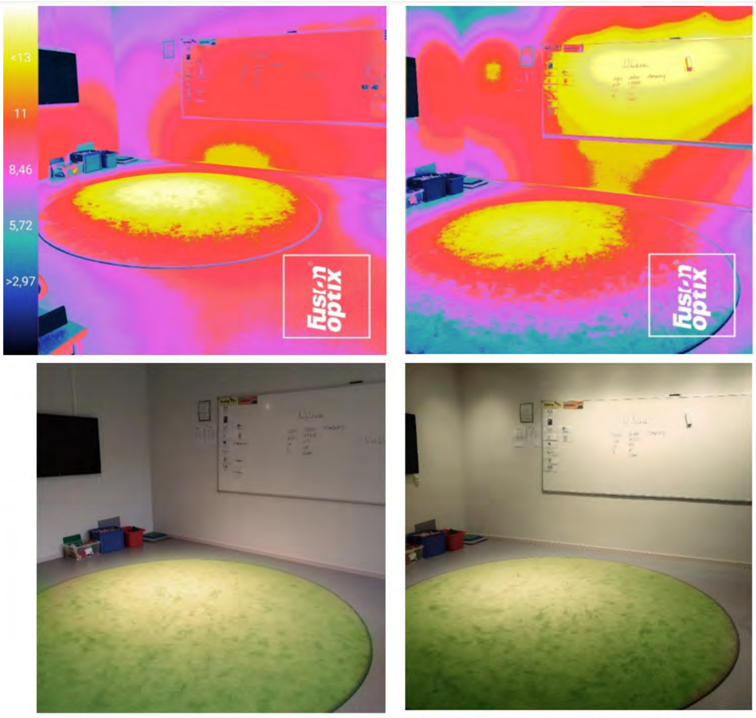


Figure 96 Fusion Optix false colour photographs to illustrate beam shape and photographs, carpet and whiteboard

80%-100% of lumen output

4.1.3. Vertical measurements with spectrometer and LYS-button: Overcast conditions

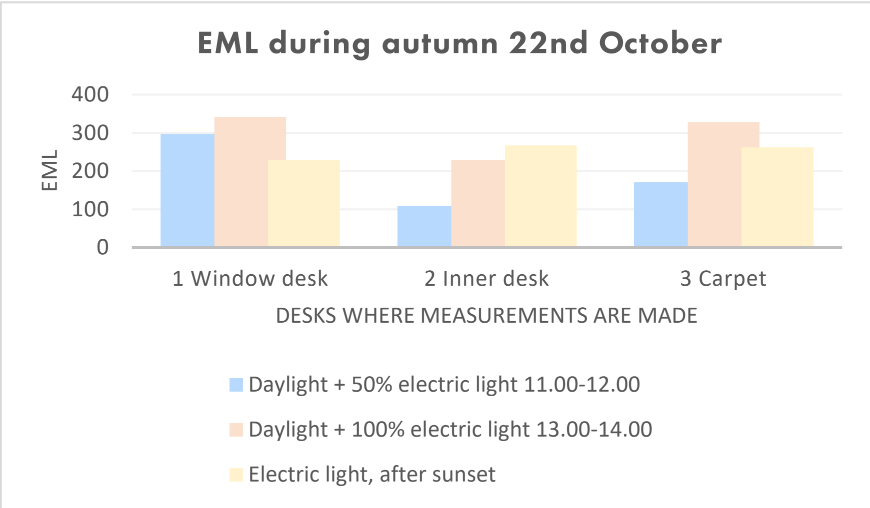


Figure 97 EML values during October with and without daylight

In *figure 97,* the light levels did not reach the WELL recommendations[1] of 200 EML between 09.00-13.00 (when using the 50% dimmed mode in the morning). With 100% of the lumen output on the EML recommendations are reached together with daylight. The electric light on its own does not provide the recommended EML on three of the workstations, see *figure 99.*

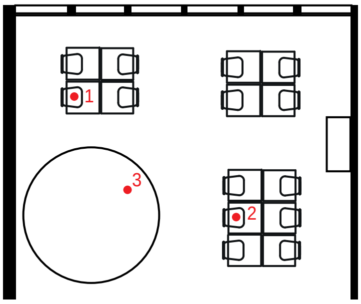


Figure 98 Desk 1,3 and 2 as referred to in diagram 97 and 99

200 EML Recommended from daylight and electric light

150 EML Recommended from electric light only

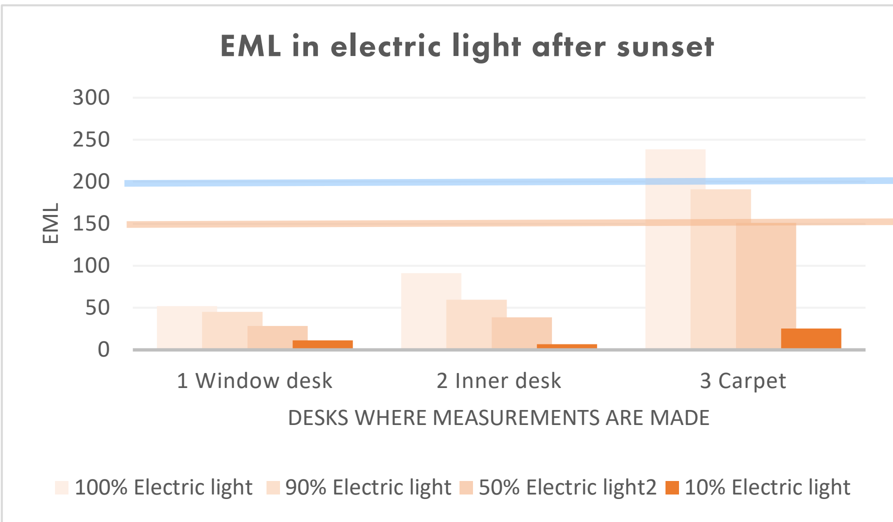


Figure 99 EML levels in electric light when dimmed or fully on and two lines indicating WELL recommendations[1] percentages refer to lumen output

In *figures 100-104,* daylight and electric light data from the LYS-button is conducted; the colour imitates the colour in the app. Ls refers to LYS-technologies definition of light stimulus.[16]

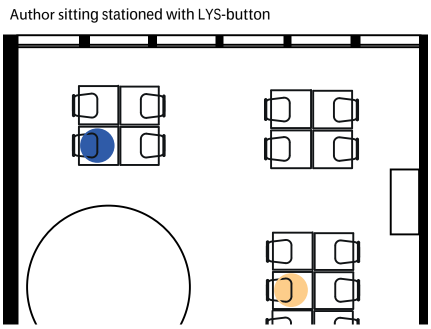


Figure 103 Positions during the measurements of figure 100,102

Around noon most of the middle area of the classroom, see *figure 104*, get sufficient ls when moving around. However, in November, a decrease in ls can be seen from 14.00, see *figure 101*.

The electric light provides approximately 40 in ls when turned on to 100% without daylight.

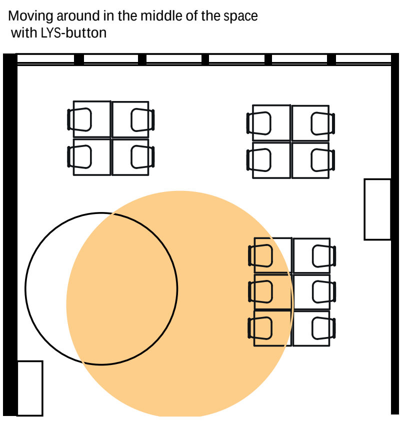


Figure 105 Area where the measurements are made for figure 104,101

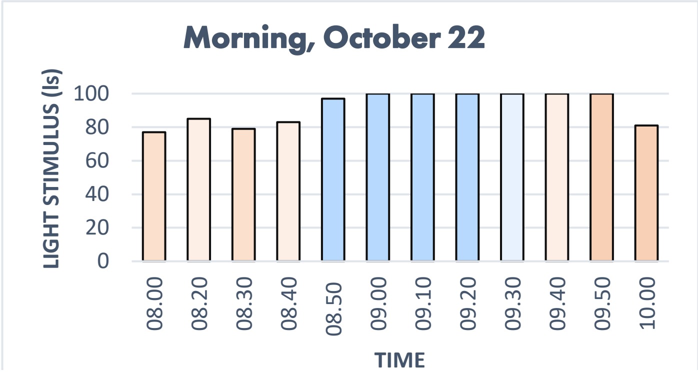


Figure 100 Light stimulus from daylight and electric light

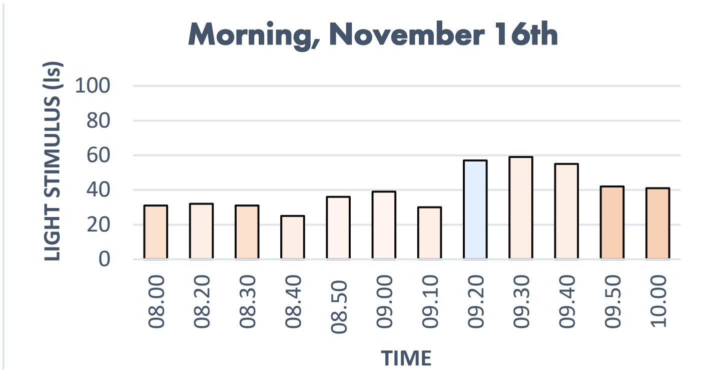


Figure 102 Light stimulus from daylight and electric light

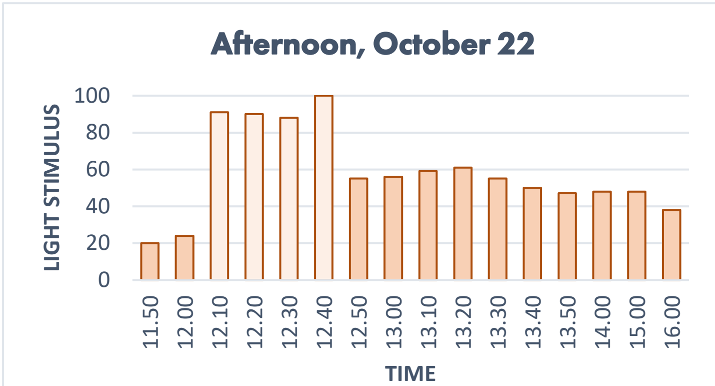


Figure 104 Light stimulus from daylight and electric light

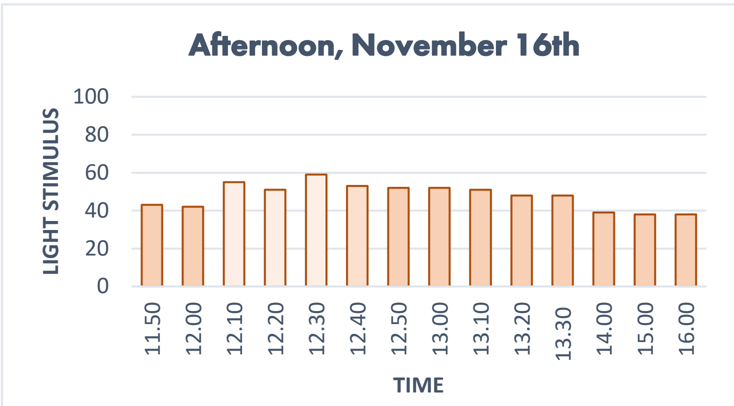


Figure 101 Light stimulus from daylight and electric light

5. Colour analysis: Seven factors and spectral content

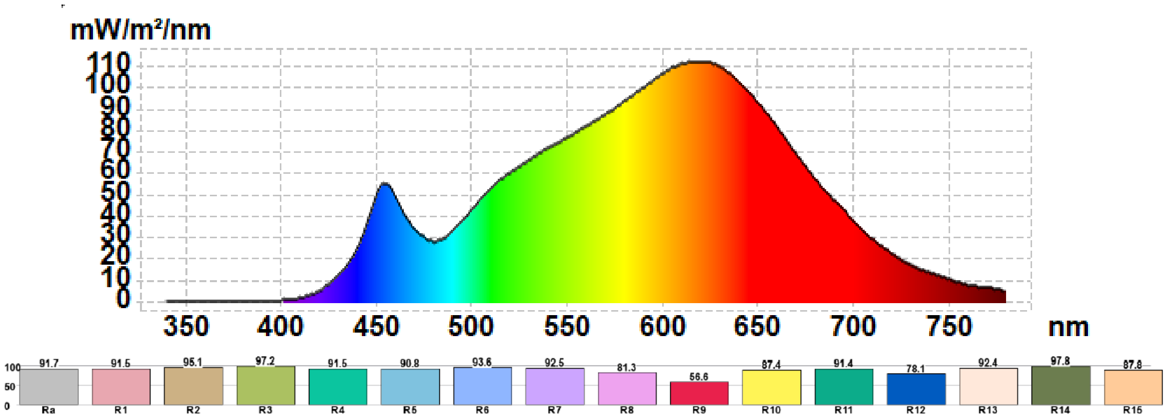


Figure 106 SPD measured close to luminaire and Ra indices (CRI) of the luminaire

The SPD of the LED spotlights admits more of the longer red wavelengths. Overall, the luminaires have a higher CRI, as seen in *figure 106*, of the SPD and Ra indices, where red is higher than the Case I luminaires in *figure 72.*

Colour of light	The tone is honey warm
Colour of surfaces	The colours appear rich and warm

Figure 107 Words presenting two factors out of seven; chosen by two participants to describe the colour of light and surfaces

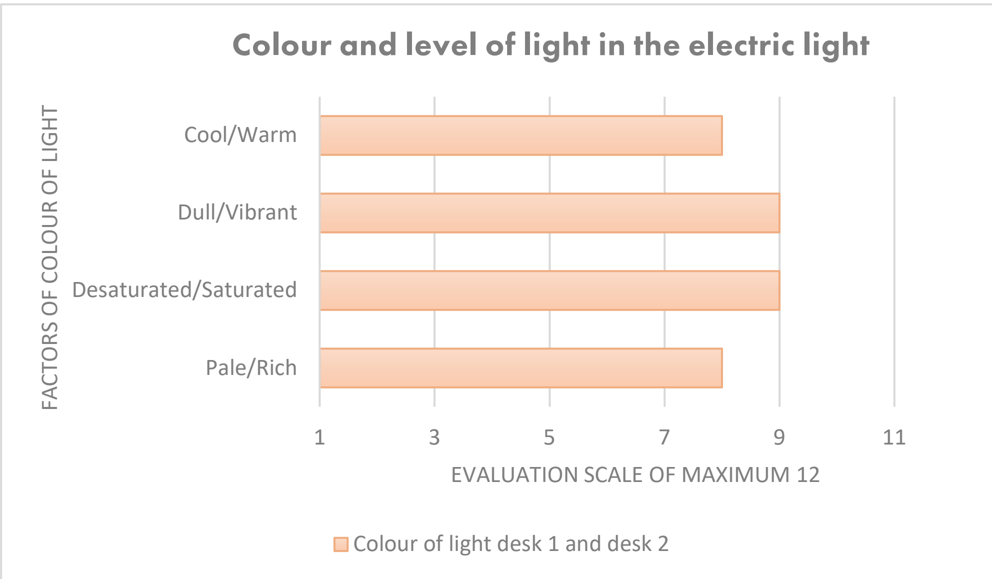


Figure 108 A diagram of experienced colour of light of two participants, it is read in the following way: a low number is experienced as cool, and a high number is experienced as warm

Chapter IV Designing pedagogical modes in Case II

As previously presented in Case II, *1. Floorplan topology,* the light was installed in 2020 in the redesigning of a school in Hudiksvall by SWECO (Lead: Jonas Kjellander and Åsa Machado). Moreover, for this thesis, several pedagogical modes were programmed based on theories of the thesis together with the lead Kjellander and Machado. There are several buttons to change the light within the classroom. Each button reaches a group of luminaires programmed with DALI/KNX.

6. Socio-spatial aspects and pedagogical modes

The four pedagogical modes programmed for Case II are; presentation, discussion, focus and gathering, see *figure 109*.

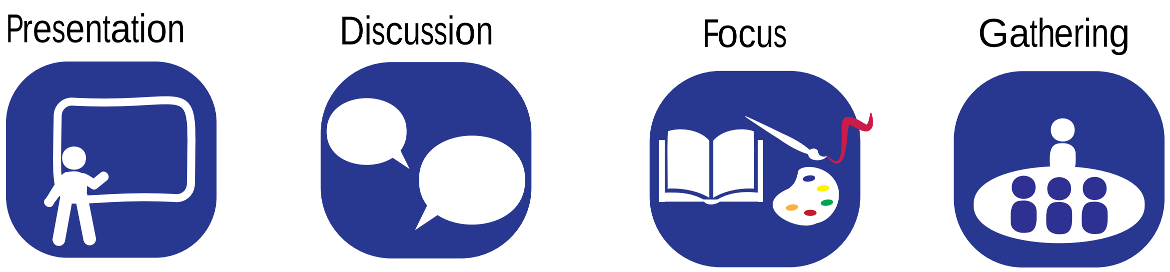


Figure 109 Pedagogical modes; Presentation, discussion, focus and gathering

Based on the theoretical review of this thesis, interviews with teachers, and observations, the author suggested programmable modes for the existing design. The modes are programmed for pupils and teachers to predict and use during class. The theoretical review concluded that adaptive light for different pedagogical typologies and analysis of gaze orientation is relevant regarding the socio-spatial aspect.

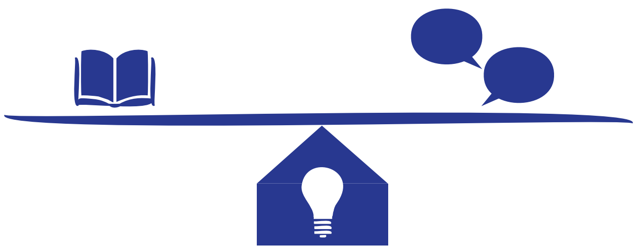


Figure 110 The balance between material and relational

The modes emphasise both material and interpersonal/relational activities; as illustrated in *figure 110*, both interpersonal and material pedagogical activities matter.

The different modes are divided into four main categories, see *figure 111*. The presentation mode focuses on teacher-supported and facilitated topologies. The discussion mode emphasises all pedagogical topologies regarding group discussions. The focus mode supports three topologies; teacher to pupil instruction, individual- and collaborative work supported by teachers. The gathering activity is a form of collaborative meeting at the beginning and end of the day and classes; therefore, it needs to be a pedagogical mode on its own.

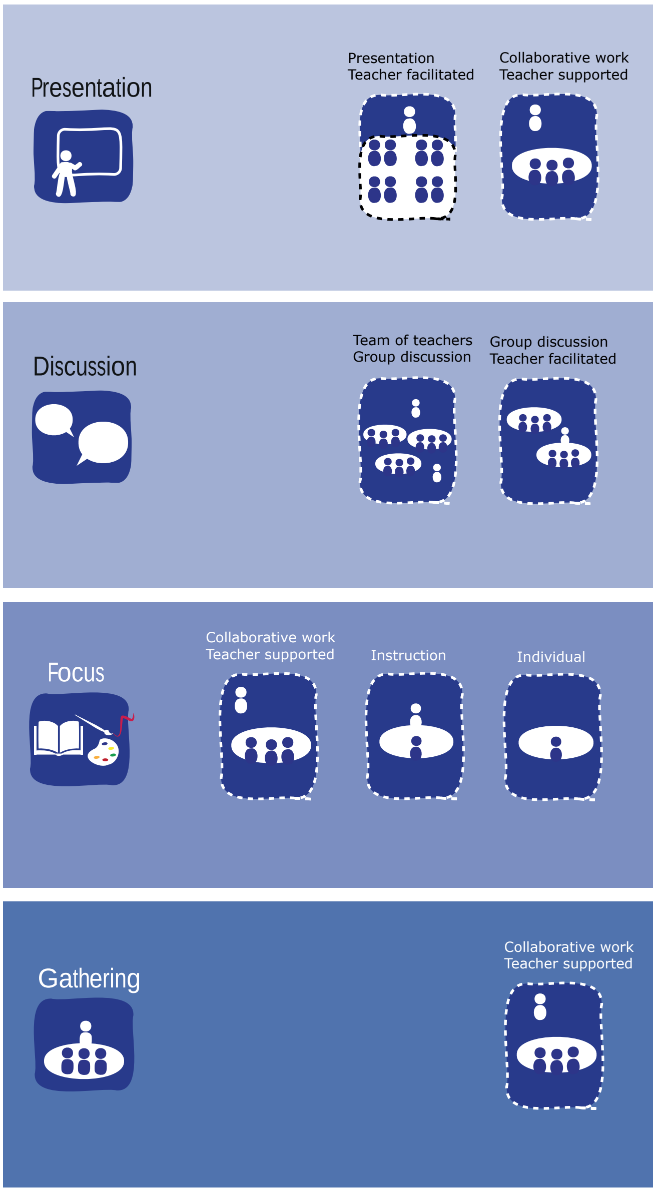


Figure 111 The pedagogical topologies that the modes are meant to support

6.1. Illumination hierarchy and bodily orientation

- The discussion mode is meant to support a gaze direction upwards, and this is both based on observations in this thesis and Bolt (2021).[4]

- The illumination hierarchy in the different modes organises the space either horizontally or vertically and selectively illuminates important aspects.

- The play of brilliants is the landmark illumination and rhythm.

- The carpet and the toy station are the primary landmarks due to the pools of focal glow. The art distinguishes itself from the rest of the walls because the cd/m^2 is more concentrated, similar to a focal glow beam.

  The focus mode emphasises landmarks and small-scale workstations, and the discussion mode creates a sense of the whole space and supports the big-scale activities. In Bell (2002) different scales and spatial distinctions can further assist different pedagogical activities.[7]

6.1.2. Sky transitions

- During the winter, the blue hour takes place around the time of the gathering activity. To let the sky transition in and avoid reflectance of the windows, the mode therefore decreases the ambience by only illuminating the carpet and leaving the rest of the space dim.

Figure 112 Times the sun rises and sets

6.2. Scale of activities

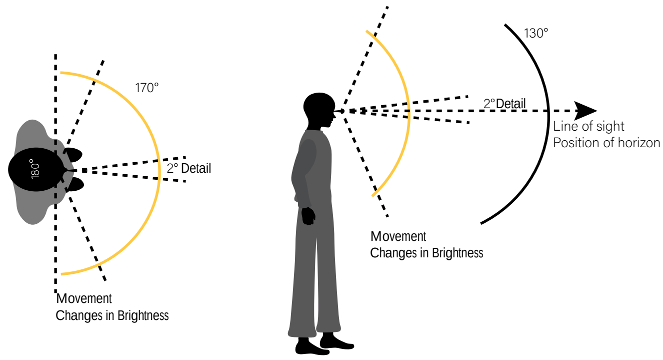


Figure 113 Image of the visual field

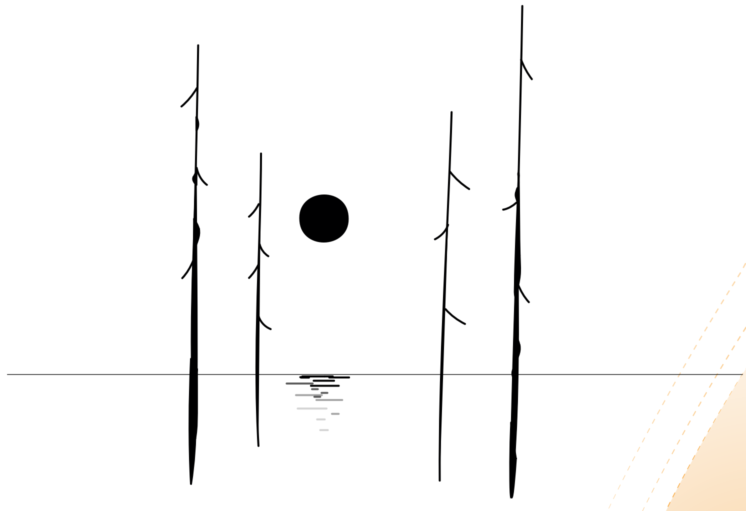
In Liljefors (1999), 170° of the visual field is the peripheral vision responsible for the big-scale vision that sees spatiality.[9] Moreover, the 2° is the foveal vision, and it is the small-scale detail vision that sees, for example, text in a book.[9]

Presentation: small- and big-scale activity – The mode is designed with a vertical pool of light on the whiteboard, creating directionality towards the learning content while casting pools of light on desks supporting notetaking.

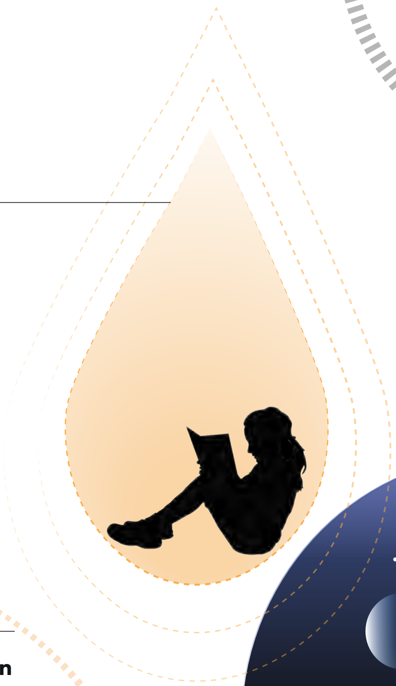
Discussion: big-scale activity –This mode is designed to make the interpersonal and relational visible with vertical pools of light on the walls to create a sensation of spacious scale and encourage orientation of the gaze upwards.

Focus: small-scale activity – This mode is designed to facilitate all small-scale activities like reading and writing. The focus mode is made with horizontal pools of light on the desks and workstations to decrease the light in the periphery. Furthermore, a light pool to work in creates a sensation of closedness and a smaller scale. It makes the desk the area of relevance.

Gathering: small- and big scale activity – The mode is designed with one horizontal pool of light to create a sensation of a small room within the room, exclude information from the rest of the space, and naturally give more attention to the gathering space.



Focal glow on landmarks can give spatial boundary-support and contribute to spatial recall



6.3. Concept and vision

Outdoors the line of sight is focused on the position of the horizon,

the vertical way of seeing comes natually and is
used to see both landscape and each other. The peripheral vision is the landscape vision, and it detects changes in our surroundings

When there is a need to focus on a small-scale task, peripheral changes are less significant, and a lot of informa-tion in the periphery can be distracting

A light pool on the workstation and lower ambience can contribute to focus on the task

A lower ambience in the space can create a connection to the exterior - during the blue hour

With a dimmed mode for the gathering activity, the teacher would not need to adjust the light settings manually

A collecting pool of light can create an atmosphere and support the focus on the group gathering

The light simulates a small room within the room, and at the end of the day it could create the feeling of having a ”kura skymning moment”

Figure 114 Image of concept and vision

The figure regards the feeling of looking towards the horizon outdoors, sitting in an enclosed light pool, and gathering around a fire. Moreover, it contains information about landmarks

6.4. Settings of the pedagogical modes

	Presentation	Discussion	Focus	Gathering
Whiteboard	90%	80%	10%	20%
Desks	70%	30%	90%	10%
Walls	20%	90%	10%	10%
Carpet	10%	10%	90%	90%
Toystation	10%	10%	90%	10%

Figure 115 A table showing how the modes are programmed to dim a percentage of the luminaire's lumen output, 10% is 10% of the lu luminaire's lumen output, and 100% is the total capacity

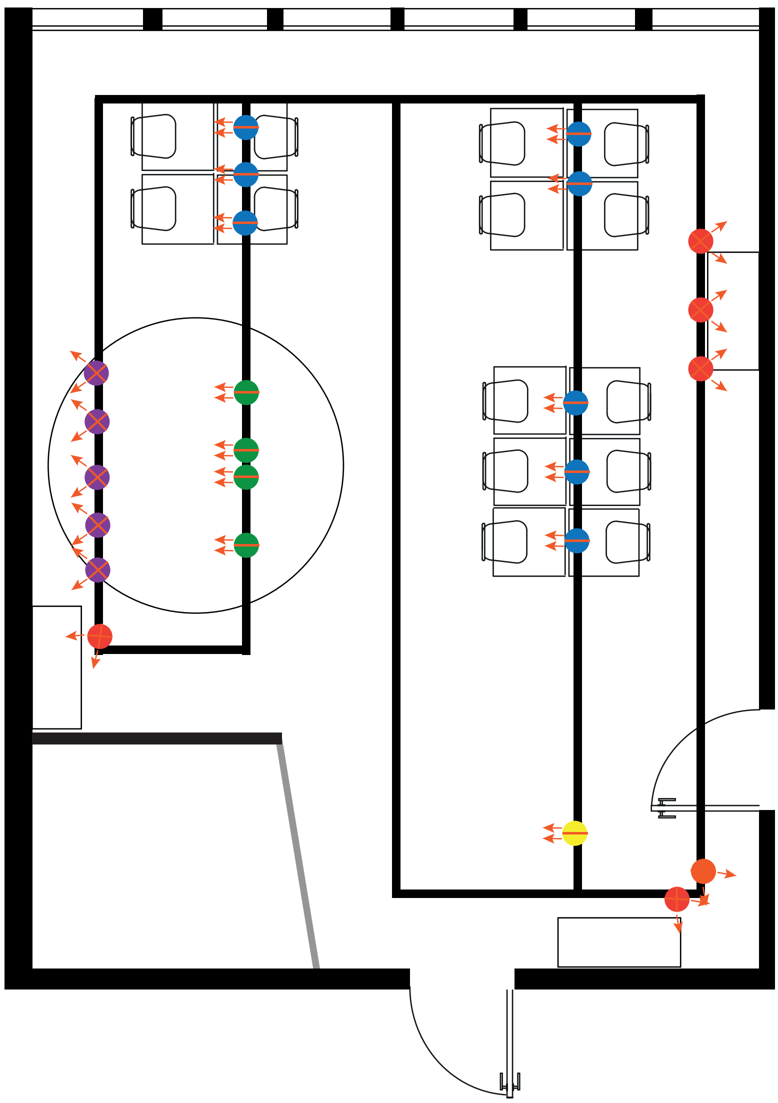


Figure 116-117, The colour coded groups represent how the luminaires are programmed into groups using DALI/KNX

6.5. Distribution of the pedagogical modes visually and physically

In *figure 18,* beam *cd/m²* measurements are shown to physically map the light pools to compare the light distribution using false-colour images. The coming pages, *pages 66-68*, will show the pedagogical modes with photographs and false-colour fusion Optix photographs.

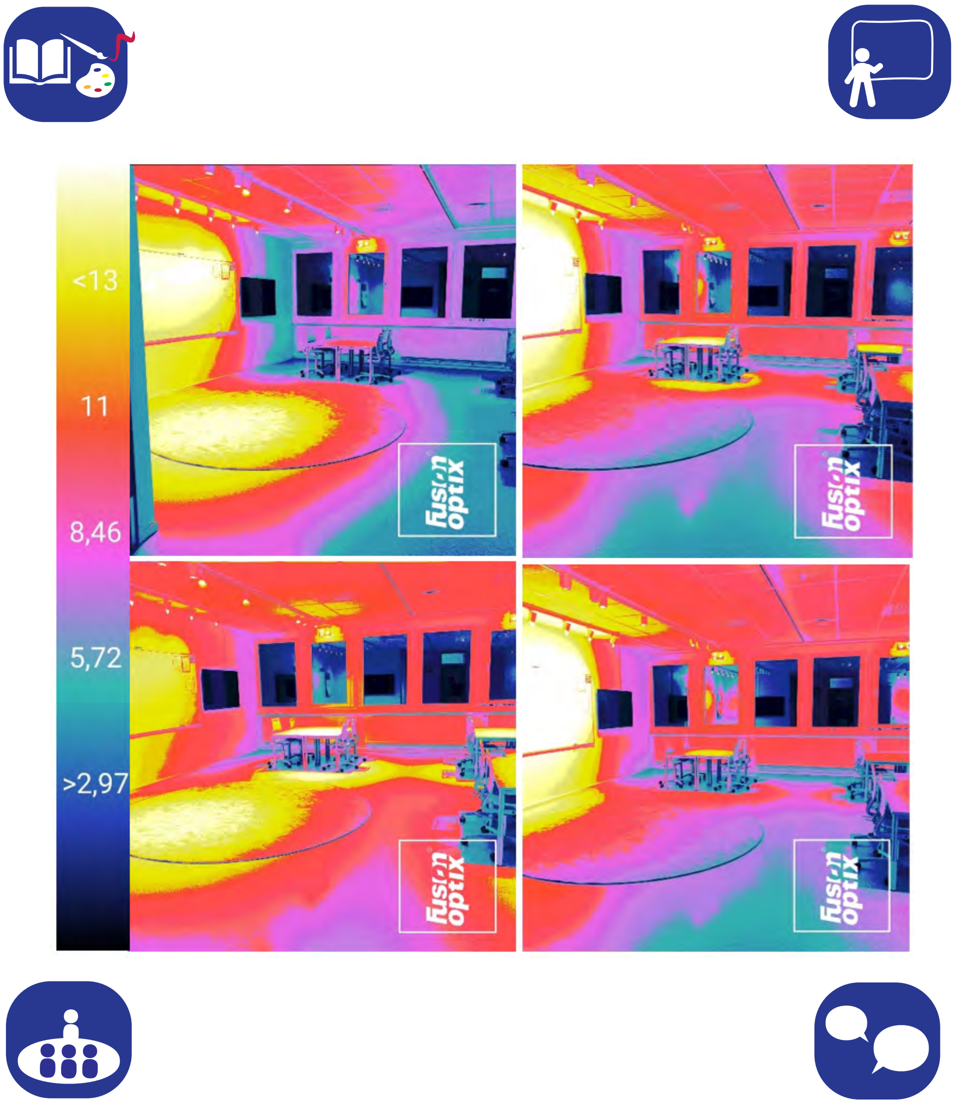


Figure 118 Fusion Optix cd/m² photographs of the different pedagogical modes

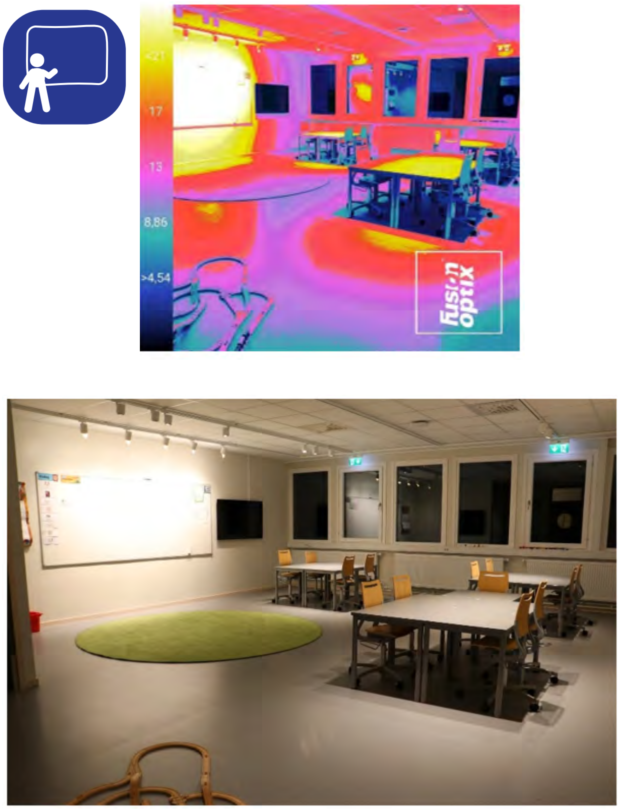


Figure 119 Fusion Optix photograph and photograph of the presentation mode

Figure 120 Fusion Optix photograph and photograph of the presentation mode

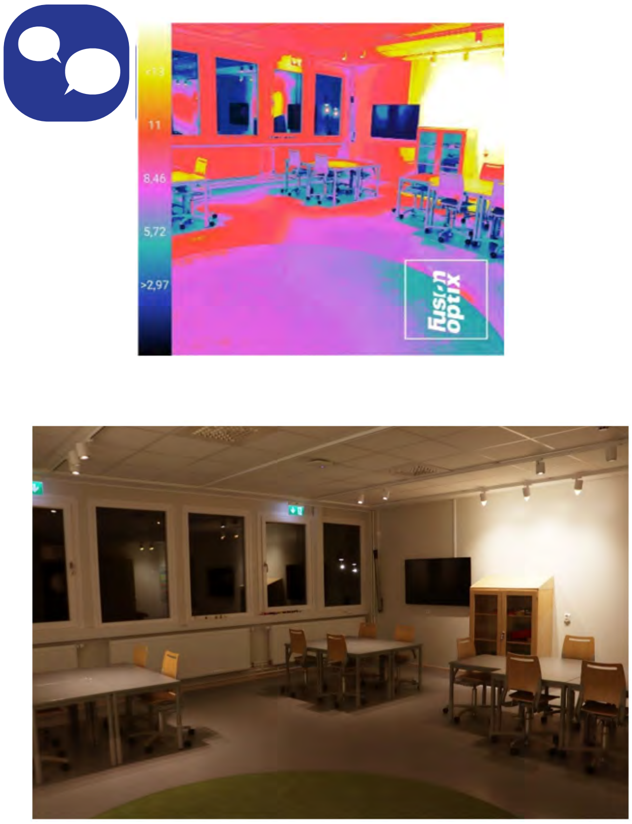


Figure 121 Fusion Optix photograph and photograph of the discussion mode

Figure 122 Fusion Optix photograph and photograph of the discussion mode

Figure 123 Fusion Optix photograph and photograph of the discussion mode

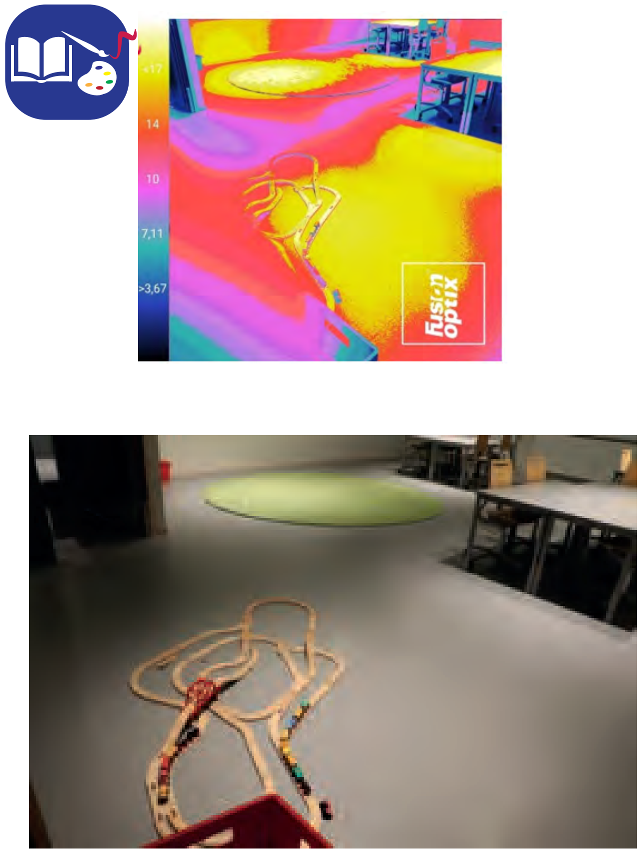


Figure 124 Fusion Optix photograph and photograph of the focus mode

Figure 125 Fusion Optix photograph and photograph of the focus mode

Figure 126 Fusion Optix photograph and photograph of the focus mode

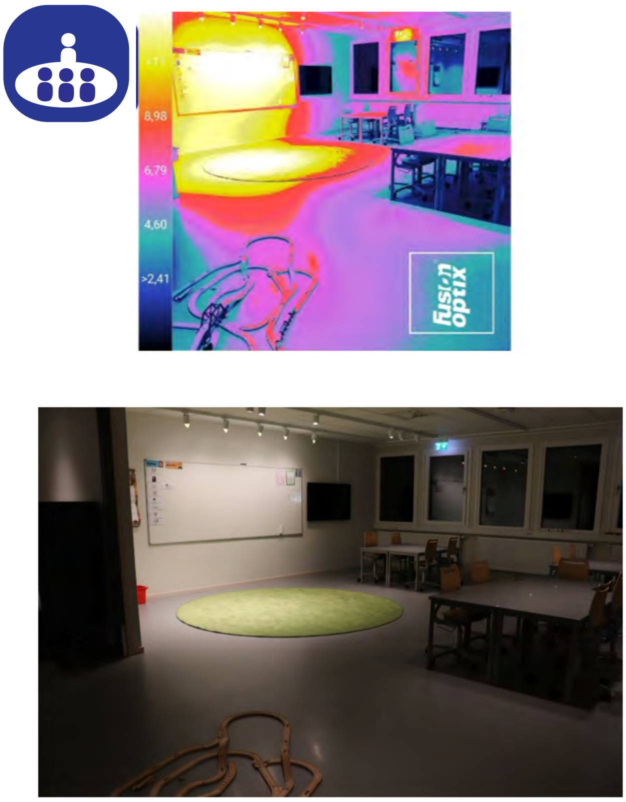


Figure 127 Fusion Optix photograph and photograph of the gathering mode

Figure 128 Fusion Optix photograph and photograph of the gathering mode

6.6. Observations and an interview with a teacher regarding the modes

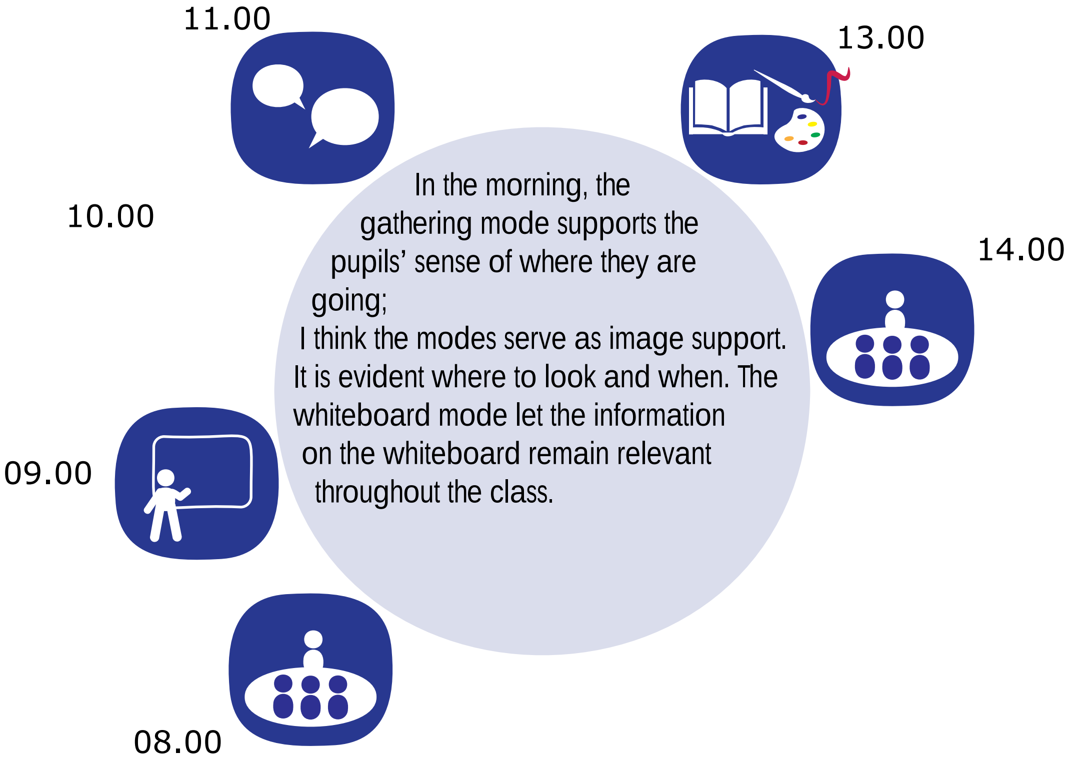
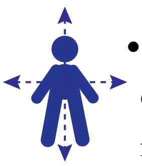


Figure 129 Teacher's use of and comments on the pedagogical modes through a day

The following information is based on interview and observation data from pupils and a teacher concerning the pedagogical modes. The author presented the modes to the teacher, and the teacher looked through them. The author suggested that the teacher could use them as they wanted. They used the whiteboard mode during teacher-supported pedagogical topologies. The discussion mode created an overall brighter ambient luminescence that worked for wrapping up the class before lunch in an end-discussion on the mornings presented topics.



- The discussion mode seemingly created a more vertical orientation in gaze. The orientation towards workstations was increased in the focus mode. In the presentation mode, gazes oriented towards the whiteboard, even when the teacher circulated through the classroom.

6.6.1. The seven factors and the pedagogical modes

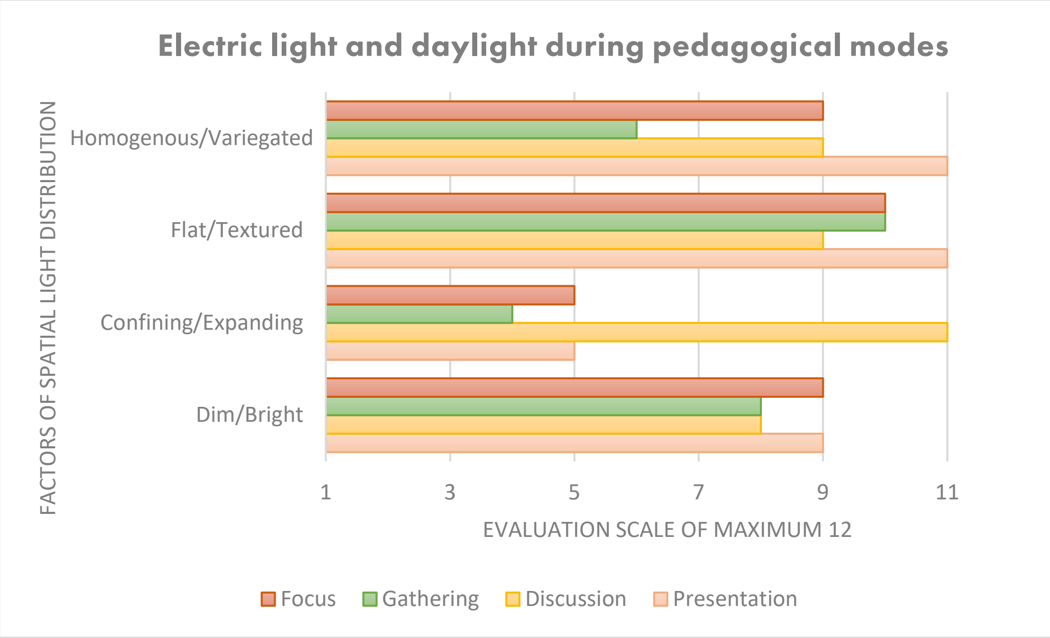


Figure 130 Diagram showing two participants answers regarding spatial distribution and level of light in the pedagogical modes

The aim with the pedagogical modes was to create a sense of varying scale by using either direct light pools on desks for a small-scale sensation or diffuse vertical illuminance throughout the whole room for a big-scale sensation; this appears to work. The participants experienced spaciousness in the discussion mode and closedness in the focus mode.

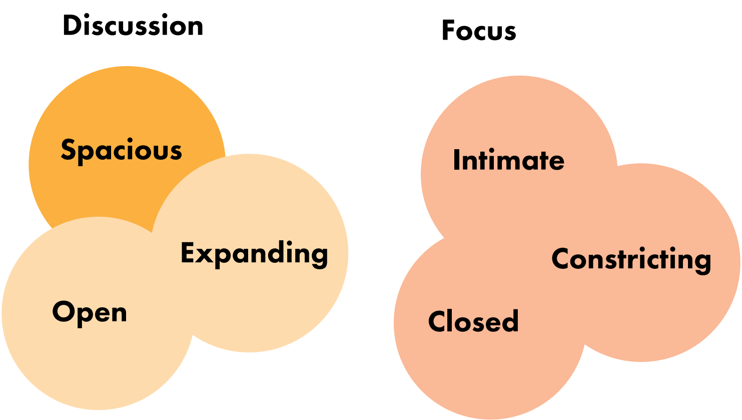


Figure 131 Words used by participants to describe the pedagogical modes, discussion- and focus mode, put in bubbles

7. Conclusionary design, Case I conceptual design

The following parts of the thesis, sections *7.1.-7.4.*, will explain the conclusions that underline the decisions for the conclusionary design. Afterward, in section *7.3*, a theoretical proposal on a circadian solution is presented and connected to the conclusions. Furthermore, the two cases are compared in section *7.4* before the conclusionary design proposal is described in section *7.4.1.-7.4.2.*

7.1. Conclusion on physiology from Case I and Case II

The daylight factor calculations show that the inner part of the standard classroom receives less daylight while the part close to the windows obtains more, see *figures 54-55*. Nevertheless, the T8 fluorescent tubes give sufficient light stimuli, see *figure 65*. The light is often off for half of the day during the winter, even when it is very dark, see *figures 70-71*. The light is off due to the pupils' complaints that it is too bright, see *figure 35*. The light is on during the afternoon instead; this results in low stimulus during the day and morning and higher stimulus during the afternoon, see *figures 70-71.*

In Case II, the light is on during the morning, often dimmed, while on a total capacity during the hour before lunch, see *figure 78*. The electric light never meets the recommended EML at desks 1 and 2, see *figures 97-98.* However, even if the standard solution gives a higher light stimulus due to the higher lumen output, the pupils prefer to turn the light off in the standard solution. In the designed solution, it is never off.

7.2. Conclusions on the seven factors

The findings show that the standard solution gives a fixed and flat experience that participants evaluate as poor for the context regarding spatial light distribution. Furthermore, the designed classroom and the pedagogical modes varied the experience, creating a spacious sensation from the vertical illumination and a sensation of closedness and intimacy using light pools on the desks. Participants evaluate it as good concerning spatial light distribution. Nevertheless, sharp shadows around the desks in Case II were noted; these could cause eyestrain.

7.3. Light shower mode proposal

The fluorescent tubes provided more light stimulus than the LED spotlights due to their overall higher lumen output. Strategies to improve the spectral quality and support circadian health can be to add the sky blue 480-490 nm and to use vertical illuminance. The sky blue component contributes to a higher light stimulus with less lumen output. Furthermore, the eye receives light stimulus more efficiently when light enters the eye vertically (from the horizon's position).[9]

The light can be dimmed down to a warm spectrum and turned up to a sky-blue spectral content when in a "Light shower mode".

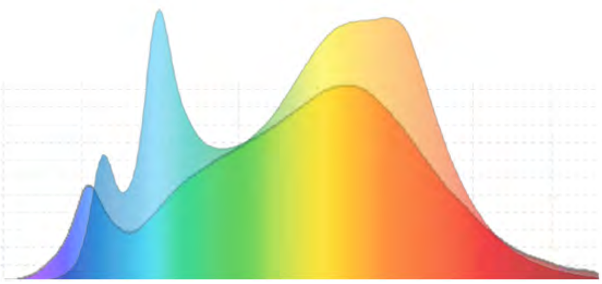


Figure 132 The luminaires of Case II SPD combined with a sky-blue component that activates during ''Light shower mode''

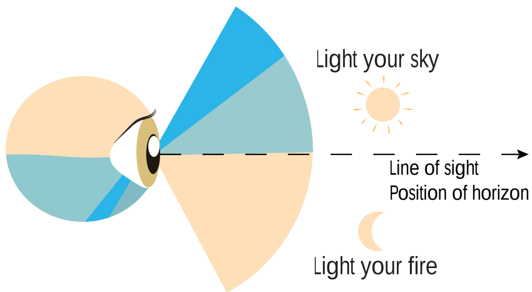


Figure 133 Diagrammatic explanation of the eye and light entering from the position of the horizon

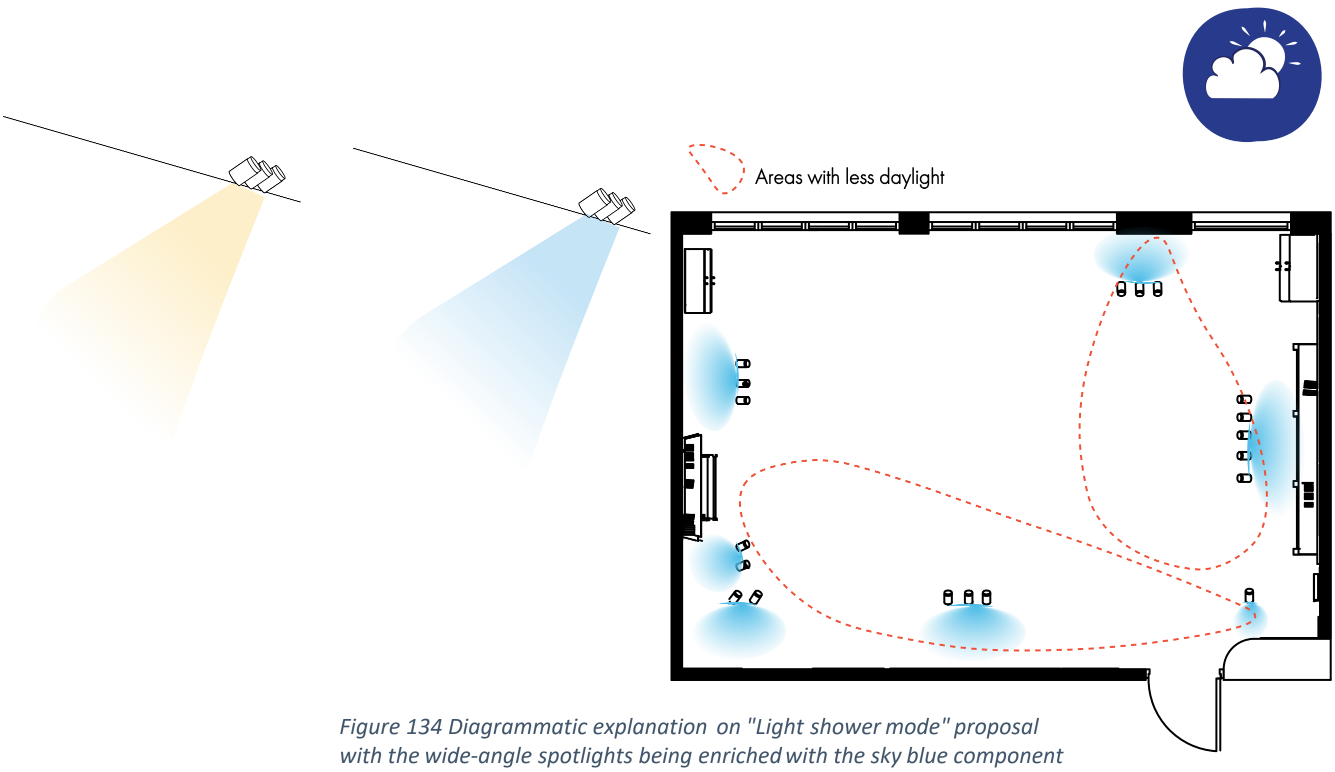


Figure 134 Diagrammatic explanation on "Light shower mode" proposal with the wide-angle spotlights being enriched with the sky blue component

7.4. Conclusions on applied theories

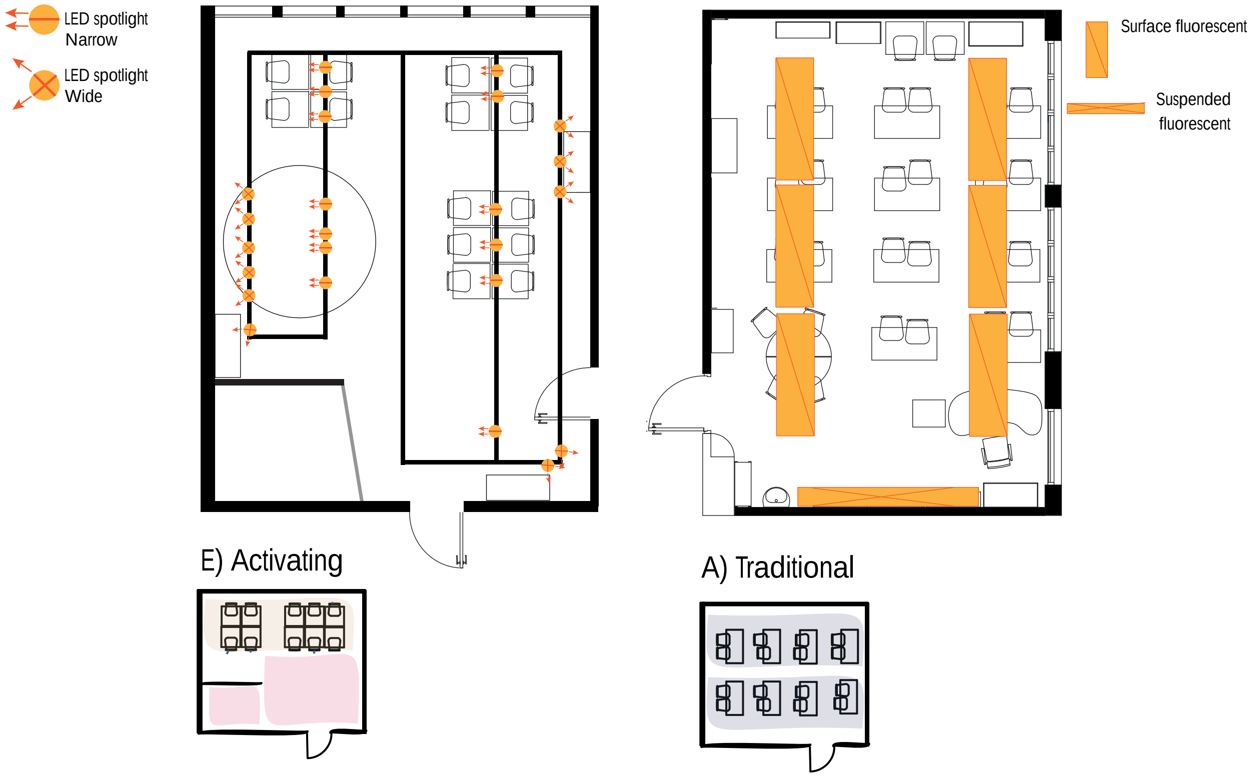
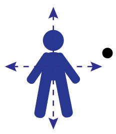
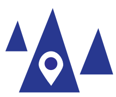


Figure 135 Comparison of RCPs and floorplan topologies

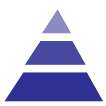
The light source topology and layout contribute to the socio-spatial assembly. The traditional teacher-centred pedagogical topologies can be seen as supported by the fluorescent tubes fixed in straight lines and the lack of illumination hierarchy. We now have a new philosophy of teaching, as should be seen in furnishing, architecture, and lighting layout.



- The fixed grid of fluorescent tubes and the uniform light create a lack of variation in orientation – adaptability, on the other hand, supports a variation of both gaze direction and of the ways in which the lines of movement happen.



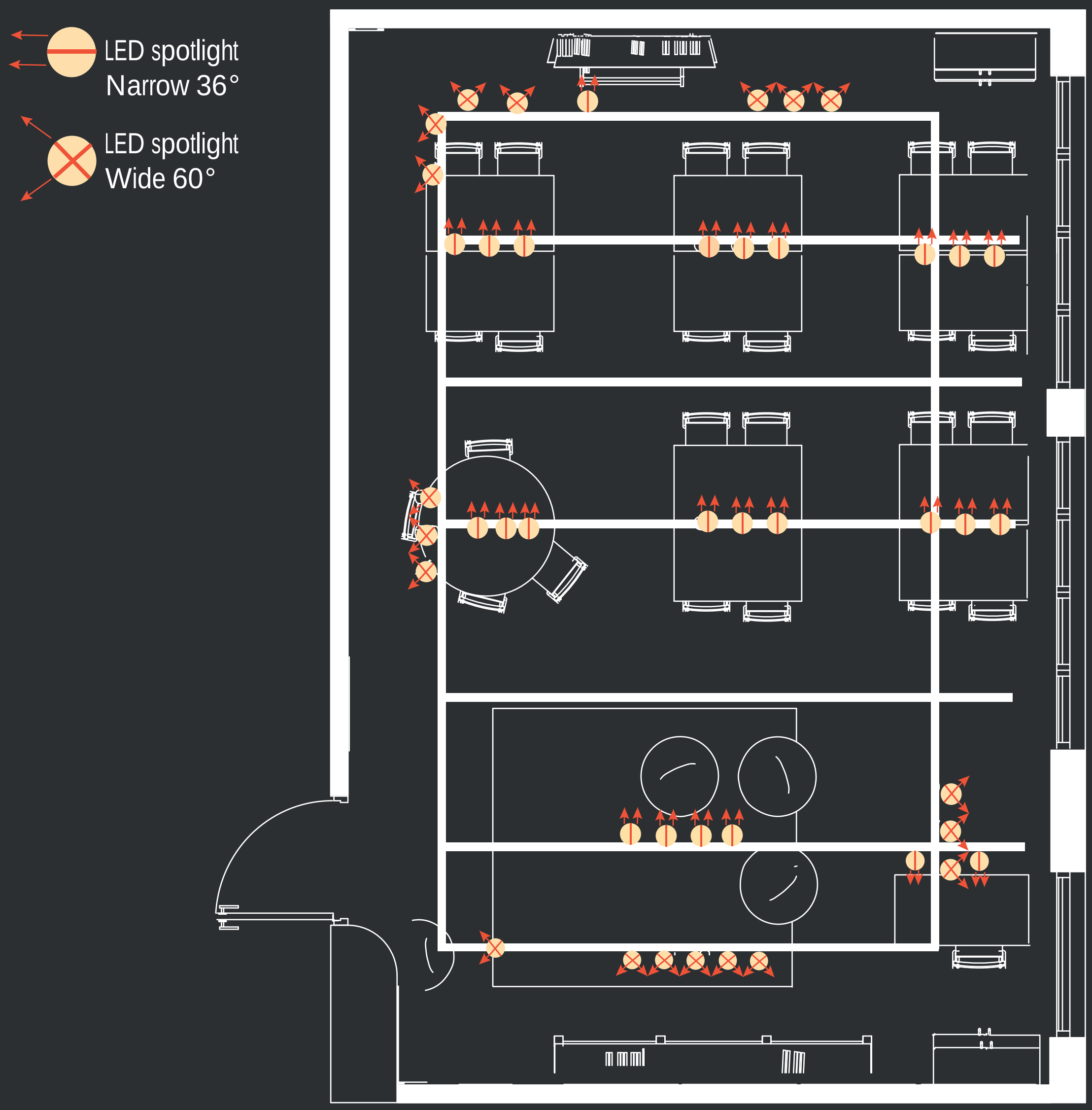
- The different sensations of scale can support different pedagogical activities. Landmarks can be accentuated with a focal glow to support the spatial recall.



- The illumination hierarchy is the cornerstone of the change: the traditional standard solution lacks illumination hierarchy, and the activating adaptable solution gives options using the illumination hierarchy.

- The spatial rhythm between shadow and light is a part of supporting spatial understanding.

4.4.1. Conclusionary design light source topology



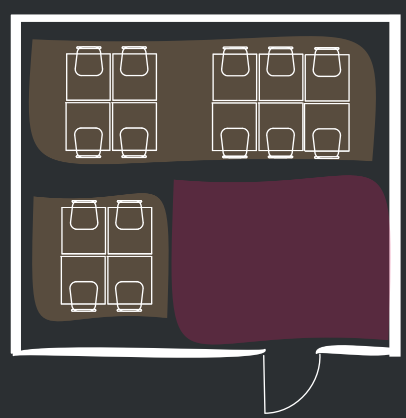
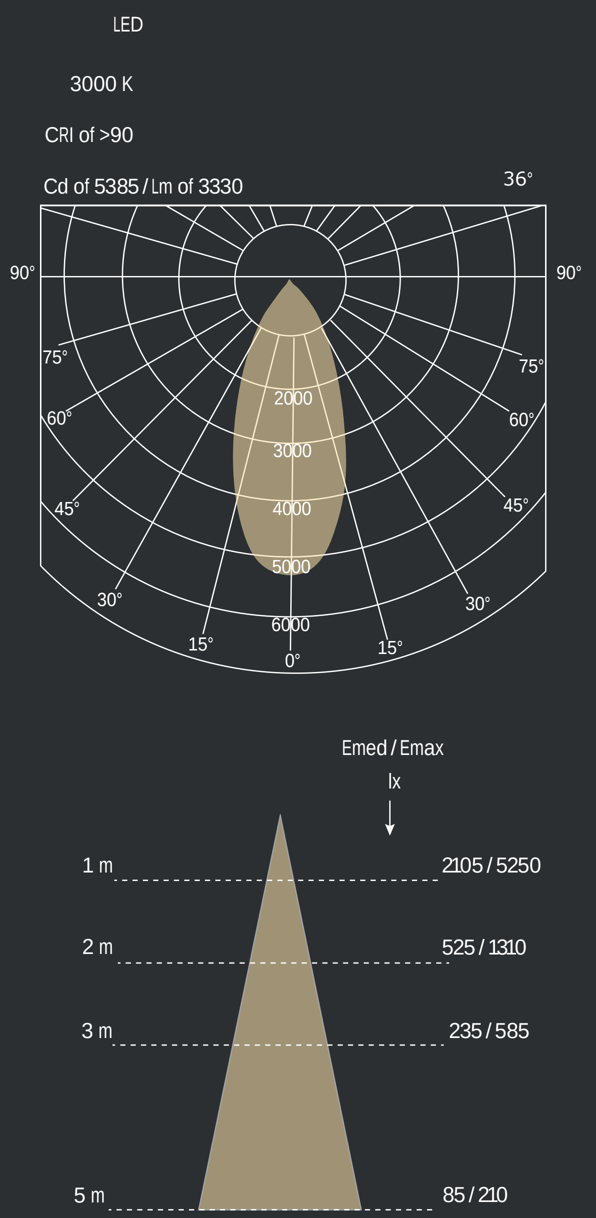
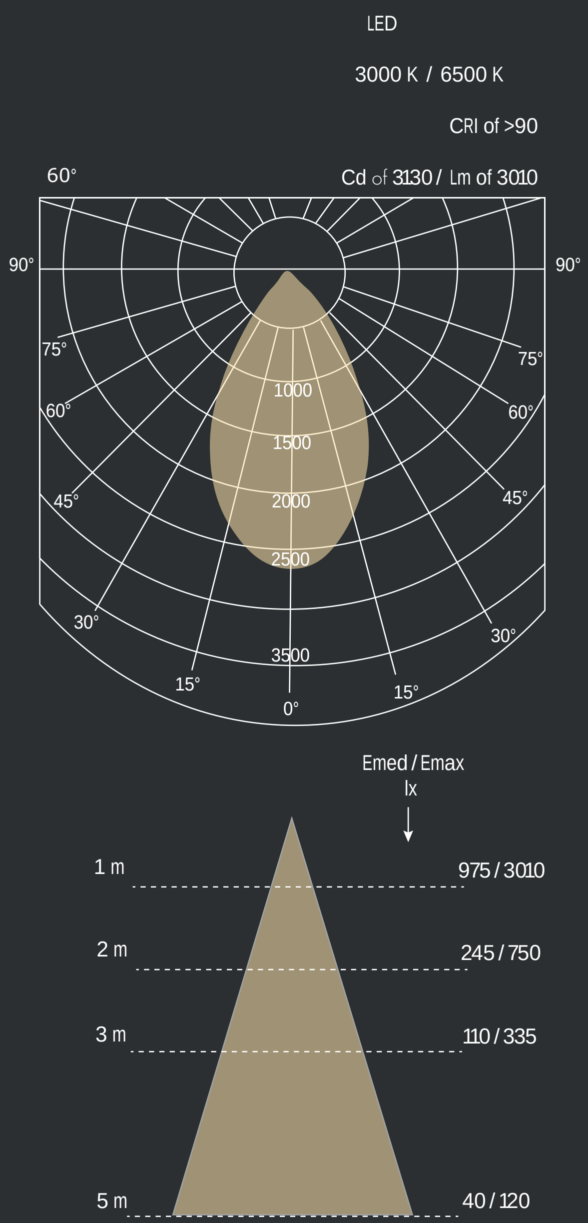


Figure 136 Proposal for RCP and light source topology in Case I





Programmable with KNX / DALI Can be moved on a

track Rotatable 360°

Tiltable 90°

Figure 137 Light source topology, technical data

7.4.2 *Conclusionary concept*

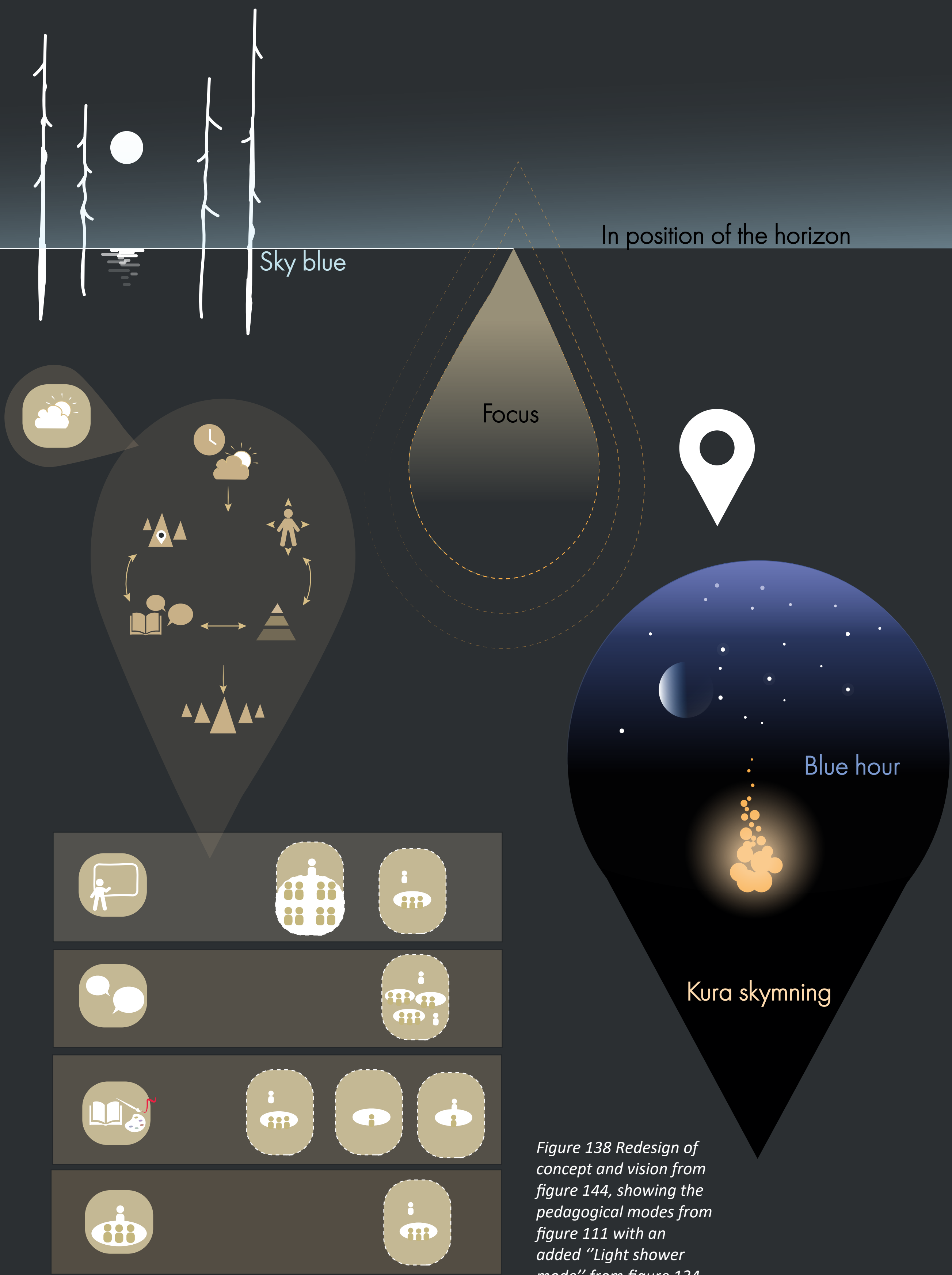


Figure 138 Redesign of concept and vision from figure 144, showing the pedagogical modes from figure 111 with an added ''Light shower mode'' from figure 134

	Presentation	Discussion	Focus	Gathering	Light shower
Whiteboard	90%	80%	10%	20%	90%
Desks	70%	30%	90%	10%	90%
Walls	20%	90%	10%	10%	90%
Carpet	10%	10%	90%	90%	90%
Bookshelf	20%	90%	90%	20%	90%

- Whiteboard group
- Desk group
- Wall group
- Carpet group
- Bookshelf group

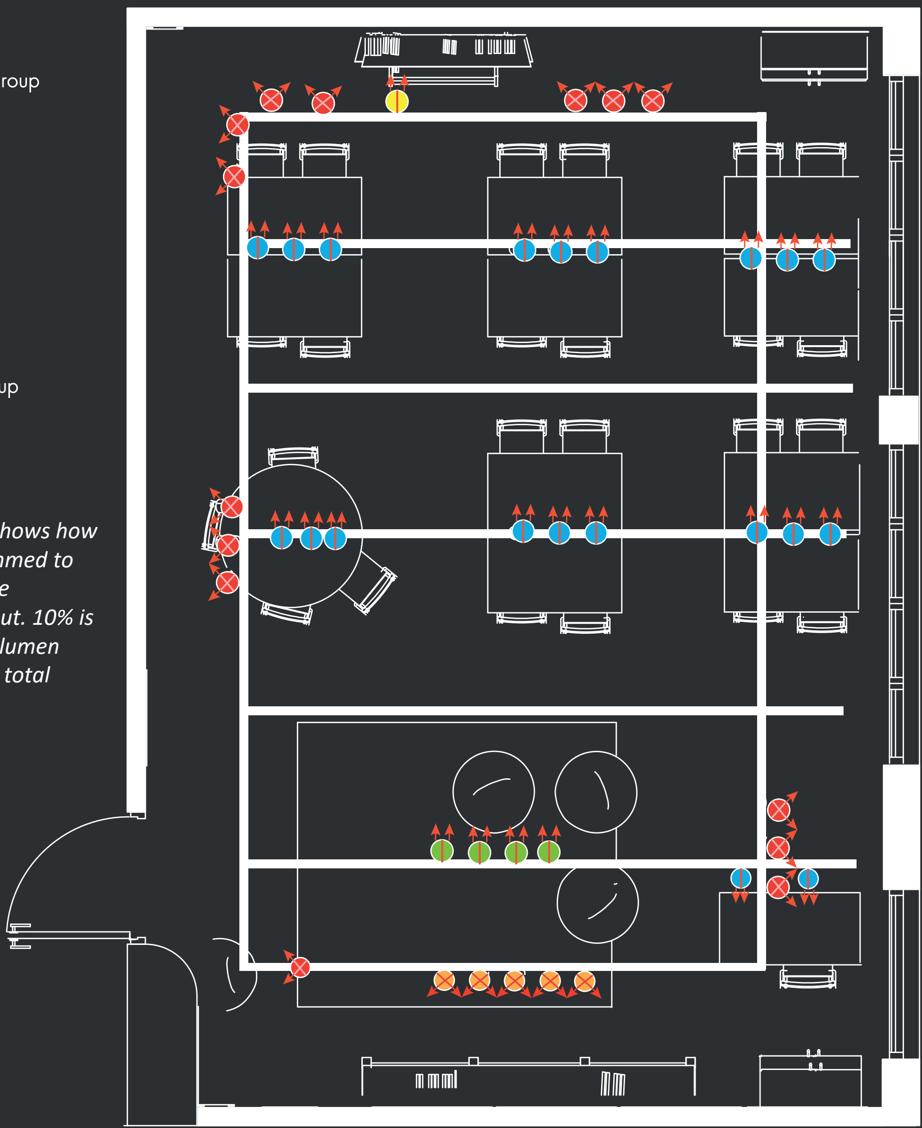


Figure 139 The figure shows how the modes are programmed to dim a percentage of the luminaire's lumen output. 10% is 10% of the luminaire's lumen output, and 100% is its total capacity

7.4.3. Conclusionary design visualisations

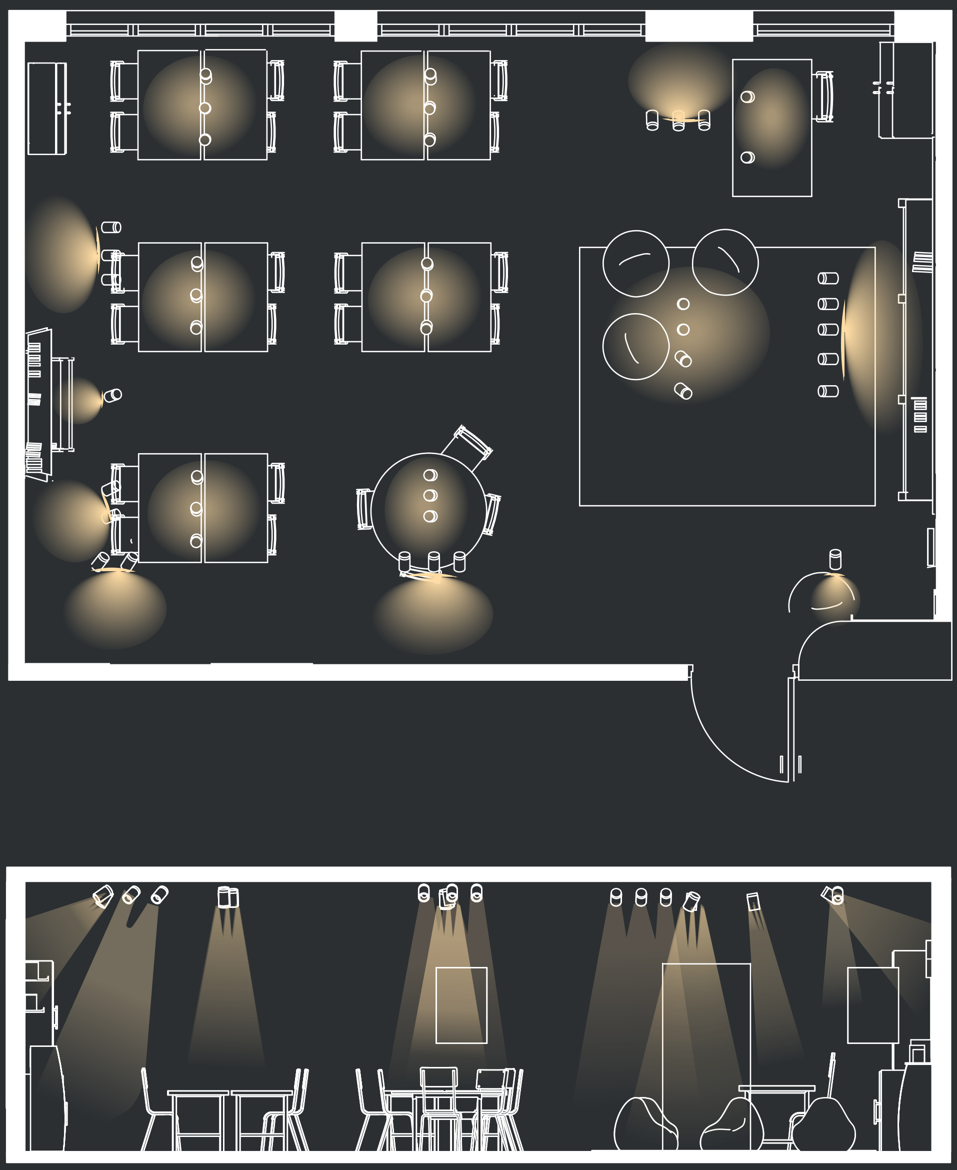


Figure 140 Floorplan and section visualisations of spatial light distribution

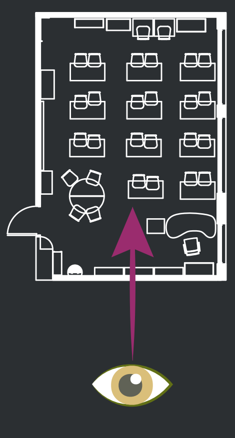


Figure 141 Visualisation with and without "Light shower mode"

Figure 142 Visualisation of discussion and focus mode

The two prominent landmarks are the bookshelf and the carpet. The bookshelf and carpet are constantly illuminated at 20% of the lumen output to maintain continuity and spatial identity.
The carpet stands out in colour-contrast and illumination contrast; this gives it strong landmark quality.
Both are illuminated with 36° spotlights.

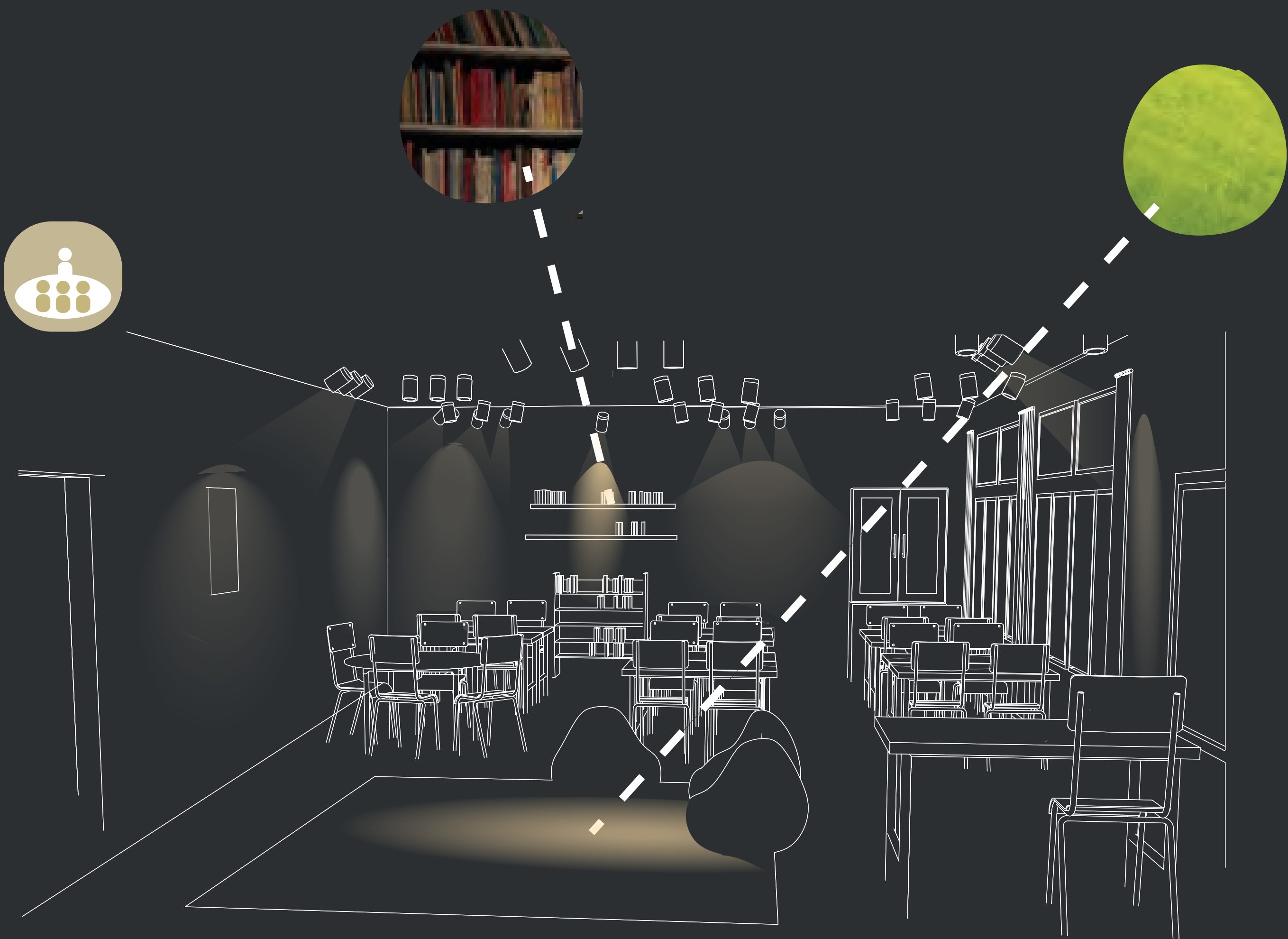
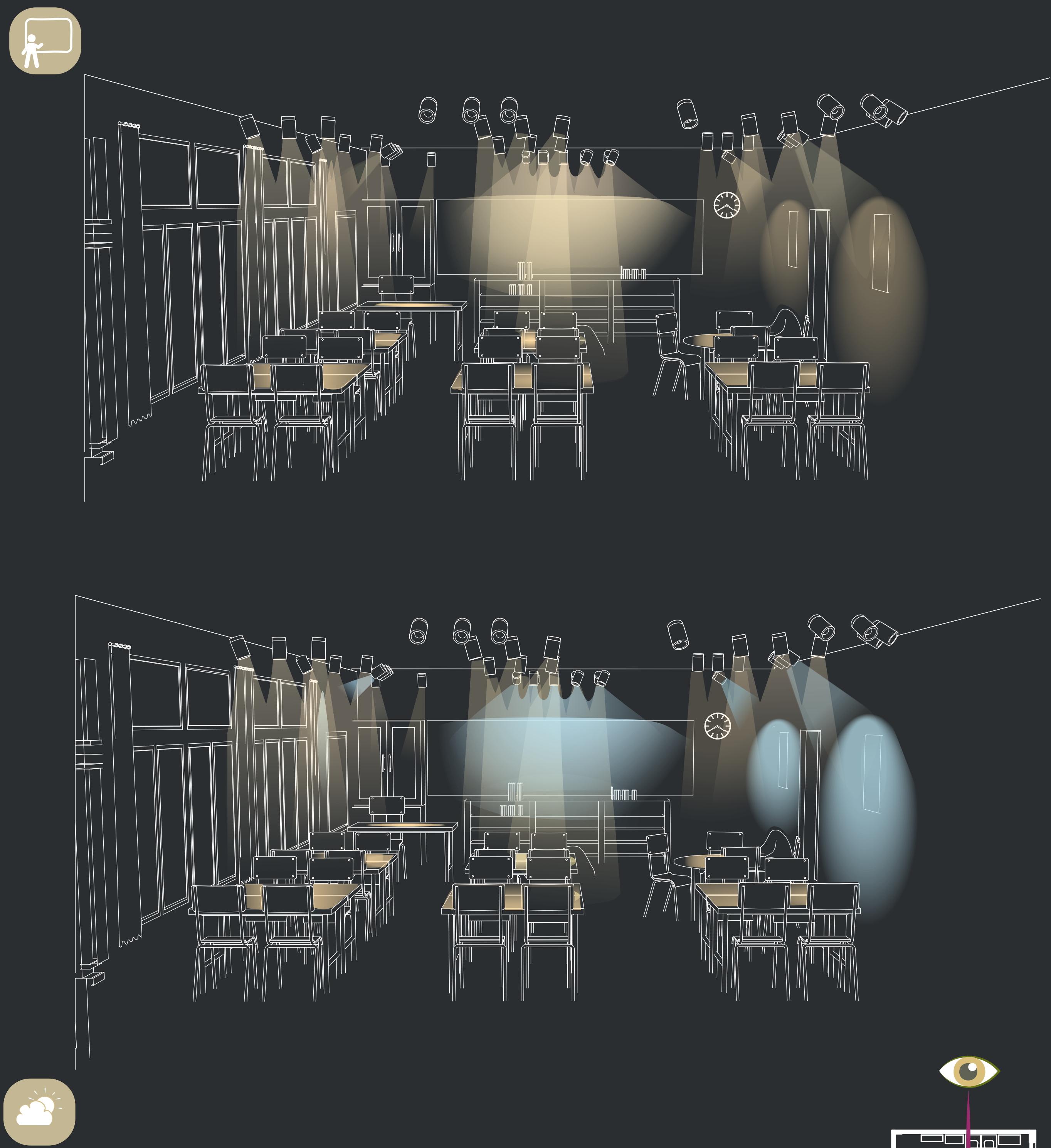


Figure 143 Visualisation of gathering mode and landmarks



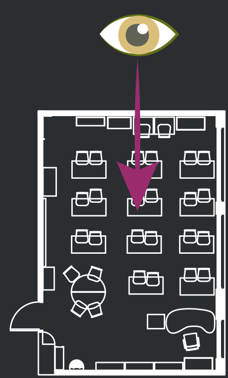


Figure 144 Visualisation of presentation mode and the "Light shower mode"

7.5.Conclusionary design calculations and conclusions on standards

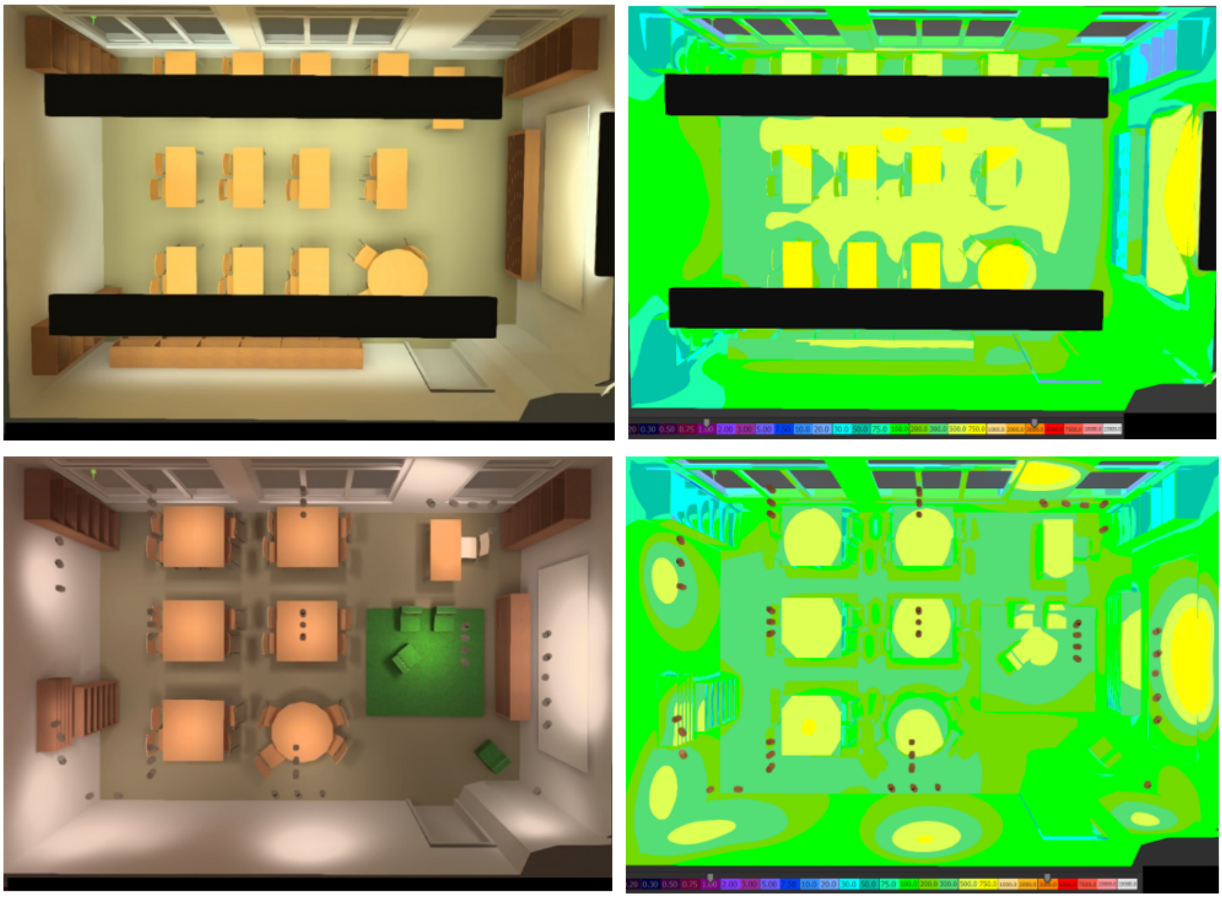


Figure 145 Comparison of lx levels before and in the proposed design illustrated with false colour. The designed scenario shows 90% of the lumen output

Both of the solutions comply with the 5:3:1 recommendation. Nevertheless, the immediate surrounding of the desks in the middle of the standard solution has 500 lx, and the lx levels on the desks exceed 500 lx.[11] The standard classroom has a uniformity of 0.5 in uniformity and is close to the standard of 0.6. Moreover, the designed scenario has a uniformity of 0.2 and is not close to the uniformity standard.[2] The average is 500 lx in the designed scenario and 700 lx in the standard scenario.

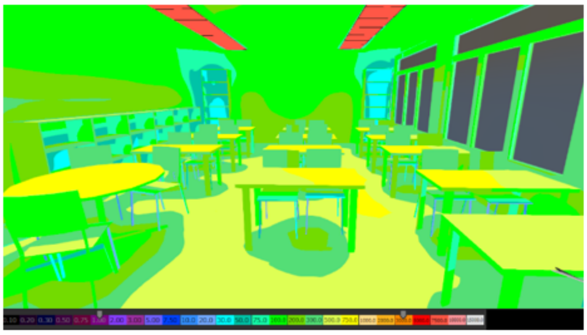


Figure 146 Lx levels in the classroom before the design illustrated in false colour

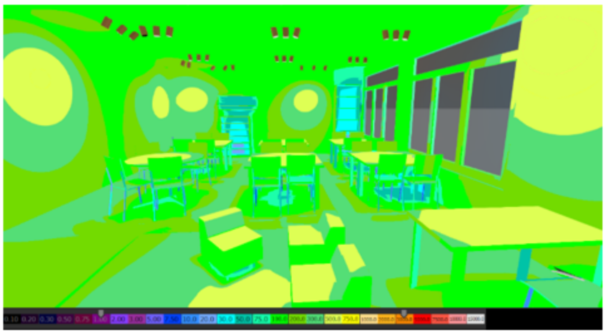


Figure 147 Lx levels in the design proposal illustrated in false colour with 90% of the lumen output

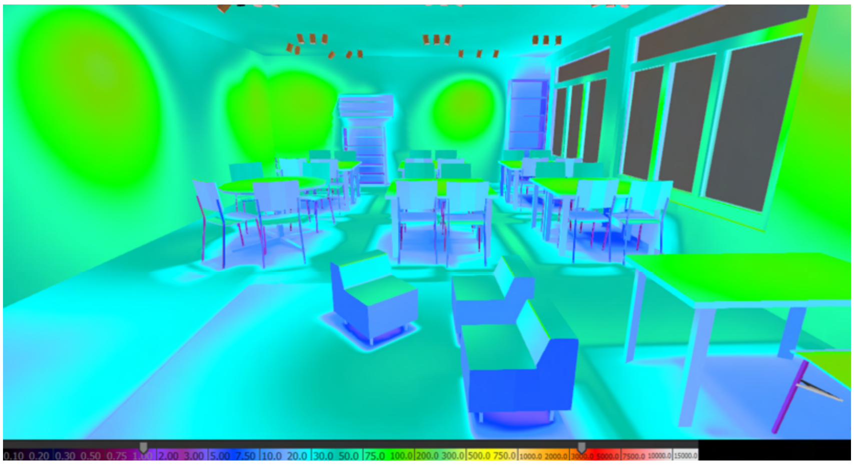


Figure 148 Cd/m^2 with 90% of the lumen output in false colour

The matte white walls have a cd/m^2 of 50-200, while the oak-coloured desks have about 75-150 cd/m^2 in the designed scenario; this is a change from the past beam distribution with about 30 cd/m^2 on the walls, see *figure 62.* The carpet's matte fabric has 10-20 cd/m^2 (see carpet in *figures 149-149*). The lumen output was decreased to 90% due to the cause of 100% lumen output creating excessively concentrated light pools at the walls when spotlights were directed in groups of three.

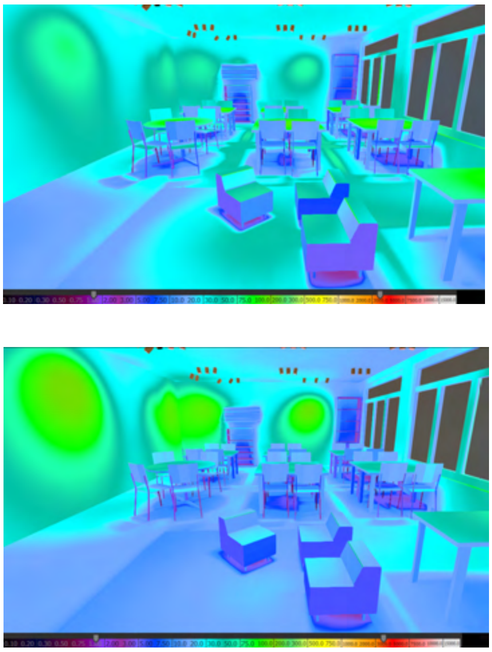
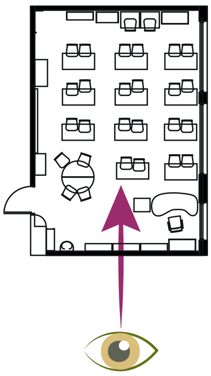


Figure 149 Cd/m^2 in the two modes; discussion and focus illustrated in false colour



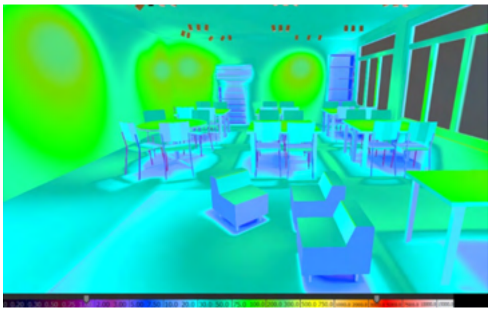


Figure 150 100% of the lumen output and intense centres of the pools of 300 cd/m^2 in false colours

8. Discussion

The light levels in the standard classroom exceed the recommended 5:3:1, having 500 lx on the floor, which is equivalent to the lx level recommended at the horizontal task plane. The light levels on the floor are unmotivated; however, the standard does not have a maximum level, only a minimum level, so it still complies with standards. The 5:3:1 recommendation considers how a space is perceived and the horizontal task plane performance [11], while the uniformity standard SIS SS-EN 12464-1 only regards the uniformity and light levels.[2] There should be a standard for maximum light levels to avoid over-illuminating floors and irrelevant classroom surfaces.
Implemented skillfully, this would support both criteria for sustainable, energy-conscious design as well as visual perception and comfort.

Nevertheless, there is little to no consideration for flexible modes for other activities than working on the horizontal task plane. As shown in this thesis, there is a need for adaptability and flexibility in standards for classroom illumination. Having up to 200 cd/m^2 in pools at the walls, as in the conclusionary design, may not be optimal when operating on the horizontal task plane. However, it supports other essential purposes, henceforth, the need for flexibility.

Uniformly illuminated classrooms can reach the WELL standards [1] with high light levels. Nonetheless, lower light levels are needed when illuminating vertically (preferably with a sky blue component) since the eye receives circadian stimulus most effectively from the horizon position (vertically) and less from the horizontal plane.[9]

The grid of fluorescent tubes can be seen as a part of the socio-spatial assembly reinforcing the teacher-centred pedagogical topologies. The floor is spatially dominant due to the intense illumination, which covers a big part of the pupil's field of view. An adaptable light solution that makes the relational and interpersonal visible is relevant—using phenomenology to investigate orientational lines and their social implications proved to be useful when approaching the matter. The findings in this thesis suggest that the vertically organised lighting solution supports an upward orientation of the gaze while the standard solution instead supports a downward gaze.

Findings regarding the seven factors show that diffuse vertical light pools created a sensation of spaciousness, and direct horizontal light pools, with less ambience, led to a sensation of intimate closedness. However, the landmark theory needs to be further investigated, with emphasis on how it supports spatial recall in pedagogical activities and the perceived scale's role concerning spatial recall.

8.1. Further improvements and suggestions based on simulation and experience

During Case II experiments, a problem occurred with the vertical light pools becoming visually distracting and too dominating. The problem was solved by reducing the lumen output from 100% to 90%. In the Dialux simulation, the calculations showed an excessively high cd/m^2 when directing the luminaries with 100% of the lumen output in groups of three at an area of approximately one to two square meters.

The fusion Optix photographs showed similar indications. Moreover, the illumination hierarchy analysis showed that the beams appeared to be like focal glow instead of ambient luminescence when that concentrated. Aspects illuminated with a focal glow are elements of importance, while the vertical organisation is meant to provide a vertical orientation. Nevertheless, if an important spatial aspect is situated on the wall, it can be illuminated with a focal glow. However, if all of the walls are illuminated with a focal glow, all of them will attract focus.

In order to create balanced light pools for ambient luminescence using spotlights, the spotlights need to be dimmed or put at a further distance; optionally, the walls could have another colour, the spotlights a broader beam, or they could be directed at a bigger area.

The shadows around the desks are sharp and would need a less direct beam to create softer pools with less eyestrain risk. There is a risk of glare when using spotlights. Glare risks must be controlled using proper accessories such as honeycombs and glare shields suited for the fixtures; there should be caution when placing the luminaires to avoid potential risks of glare.

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List of figures

Appendix

1. **The seven factors survey forms**

Form 1

Evaluate your space based on V/P seven factors

LOCATION	NAME
DATE & TIME	WEATHER CONDITIONS

V/P Theory: The Seven visual-perceptive FACTORS that describe light in space

	FACTORS	Describe with your own words
1	Level of light:	
2	Spatial distribution of Light:	
3	Shadows:	
4	Reflections:	
5	Glare:	
6	Colour of light:	
7	Colour of surfaces:	

Form 2

1 Level of light:	dark	☐	☐	☐	☐	☐	bright
	poor	☐	☐	☐	☐	☐	good
2 Spatial distribution of Light:	uniform	☐	☐	☐	☐	☐	varied
	poor	☐	☐	☐	☐	☐	good
3 Shadows:	sharp	☐	☐	☐	☐	☐	diffuse
	poor	☐	☐	☐	☐	☐	good
4 Reflections:	soft	☐	☐	☐	☐	☐	clear
	poor	☐	☐	☐	☐	☐	good
5 Glare:	tolerable	☐	☐	☐	☐	☐	disturbing
	poor	☐	☐	☐	☐	☐	good
6 Colour of light:	cold	☐	☐	☐	☐	☐	warm
	poor	☐	☐	☐	☐	☐	good
7 Colour of surfaces:	natural	☐	☐	☐	☐	☐	distorted
	poor	☐	☐	☐	☐	☐	good

Form 3

confining	☐☐☐☐☐☐	expanding
dim	☐☐☐☐☐☐	bright
uncomfortable	☐☐☐☐☐☐	comfortable
unsafe	☐☐☐☐☐☐	safe
desaturated	☐☐☐☐☐☐	saturated
foreboding	☐☐☐☐☐☐	inviting
calming/relaxing/soothing	☐☐☐☐☐☐	exciting/energizing/ alerting
dull	☐☐☐☐☐☐	vibrant
bland/plain	☐☐☐☐☐☐	vivid/intense
cool	☐☐☐☐☐☐	warm
pale	☐☐☐☐☐☐	rich
unsettling	☐☐☐☐☐☐	pleasing
flat	☐☐☐☐☐☐	textured
heavy	☐☐☐☐☐☐	light
subtle	☐☐☐☐☐☐	bold
homogenous	☐☐☐☐☐☐	varigated
flickery	☐☐☐☐☐☐	steady

Form 4

intimate	**dim**	**tense**	**playful**
stimulating	**cosy**	**boring**	**public**
happy	**sleepy**	**closed**	**constricting**
expansive	**relaxed**	**bright**	**generous**
dull	**warm**	**expansive**	**tight**
fun	**intense**	**vivid**	**private**
narrow	**cold**	**depressing**	**spacious**
serious	**open**	**formal**	**serene**

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