DOUBLE DYNAMIC LIGHTING BALANCING DIFFUSE AND DIRECT LIGHT

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Abstract

The **objective** of this paper is to investigate how daylight dynamics can act as a point of inspiration for developing a lighting design concept for work environments such as open space offices. Most often the dynamics of light in lighting design strategies are limited to the aspects of intensity (lx level) and colour of light (CCT). However, the natural variation of diffuse and direct light may also be of importance, since people have a general preference and a profound relation to the dynamics of daylight, given that perception and vision have evolved underneath changing sky conditions.

Based on this hypothesis, a **research approach** has been defined, investigating the relationship between the light distribution and light modelling qualities of daylight and how these qualities can be complemented by electrical lighting.

Four representative sky types have been studied to investigate the range of the light modelling qualities found in daylight. The ratio between diffuse to direct daylight has been examined through simulations and analysis of digital photographic images. Tests were then carried out exploring how the three-dimensional light modelling effects of these four daylight conditions can best be reproduced with electrical lighting sources in a lighting laboratory.

The survey suggested that the desired light modelling qualities are appearing, when the ratio between direct and diffuse light sources is above 13% and below 52% of the total amount of light. This initial finding indicates that daylight modelling qualities can be recreated in office environments with standard diffuse ceiling lighting by adding only 13% direct light on the work plane. The direct light must, however, have similar directionality as the daylight inflow through windows, to reinforce an experience of *flow of light*. The upper and lower perceptual boundaries of the diffuse to direct light ratio will be investigated further in relation to the dynamics of interior daylight illumiation patterns.

The qualities of daylight such as *light modelling* and the *flow of light* can thus be adapted into electrical lighting to develop strategies for double dynamic lighting, with the aim of creating work environments stimulating through a natural variating flow of lighting.

Keywords: *Dynamic lighting | double dynamic lighting | office lighting design | flow of light | light modelling*

Objective

The objective of this paper is to investigate how daylight dynamics can act as a point of inspiration for developing a double dynamic lighting design concept for work environments such as open space offices. The dynamics in question are the variation in light intensity, colour temperature and the distribution of light, the main focus in this study.

These dynamics are studied in relation to naturally changing sky conditions, and specifically the ratio and characteristics of two daylight components: direct warm sunlight and diffuse cold sky light. The core of the study is to illustrate how ratios of diffused and direct light can be used as variables when designing dynamic lighting to supplement and complement daylight in the interior space.

In this paper, we discuss how people inherently desire variation in light, as we are strongly predisposed by the natural dynamics of daylight. A logical consequence is to consider similar parameters for dynamics in electrical lighting for lighting design strategies. Most often the dynamic parameters of electrical light are limited to the aspects of intensity (lx level) and colour of light (CCT). However, the variation in the distribution of light is also important for light modelling qualities. Therefore, this paper investigates how a variation in diffuse and direct light can be integrated into lighting design strategies and thereby meet people's need for variation and light modelling qualities.

Background

Human perception and vision have evolved underneath the sky and in response to the dynamics of daylight. Tregenza and Wilson emphasize that the human body evolved in the diurnal cycle of light and dark and is tuned to the spectrum of the Sun´s radiation. They argue that we respond to daylight in many ways: *"our luminous environment affects our health; triggers responses in us that can be traced to requirements for safety and survival; it affects our interaction with other people; it determines the ease with which we carry out visual tasks. Crucial to all of these is that daylight is not a constant flow of light but something dynamic, varying with time and place."* [1]

We know that people have a general preference for and relation to daylight, and thus also the dynamics of daylight, as explained by Tregenza and Wilson: *"People like daylight….There has not been enough research to be certain why we have this desire for daylight. Strong but circumstantial evidence implies that changeability is crucial: the continual variation of brightness in a daylight room is literally, stimulating because our senses respond to change, not to unvarying conditions."* [1]

Today in the Western world people spend 90% of their time indoors in spaces typically designed according to quantitative standards for uniform distribution and light levels to meet standards for visual tasks. The standards are defined through experiments, where the tasks are intentionally isolated from any larger context. This approach to visual standards has therefore ignored the human preference for variation in light intensity and distribution. This study aims to expand our concept of dynamic lighting for interior office spaces, focusing on the qualities of light modelling in order to create a more stimulating light environment for the users of the space.

J. Vietch et al [2] have been exploring this field of visual comfort and they argue that most offices in the industrialized world enjoy conditions that are adequate to carry out visual tasks and which do not cause extreme discomfort to their occupants. However, Vietch also suggests the possibility that lighting conditions might be further improved beyond this minimum level, to the point at which they could become positive contributors to employee performance and well-being.

According to Tregenza and Wilson [1], there is strong evidence to indicate that dynamic light has a stimulating effect on people. Technological progress by the lighting industry now enables us to design and develop lighting concepts taking these human preferences into consideration.

The importance of dynamic light to support human health and well-being has been increasingly recognized. [3] The literature review conducted by PhD fellow S. Linnebjerg, analysed how 26 different concepts within *dynamic lighting for health and well-being* have been used in different areas of research. [4] The findings demonstrated that there is a significant interest in investigating the non-visual effects on health and well-being. 77% of the concepts included research on non-visual effects, though there is most evidence for visual effects that aim at psychological health referring to the visual effect of light. The review indicates that dynamic lighting has a potential for investigating experience-orientated, perceptual qualities of light. The variable parameter, intensity of light, is used in 25 of the 26 concepts to define the dynamics of lighting and 12 of the 26 concepts also address the correlated colour temperature. But very few studies have integrated the relationship between the distribution of light and the spatial perception of electrical lighting and daylight. While daylight as the optimal light source for humans is commonly acknowledged in the 26 investigated concepts, only 31% of the projects employ daylight as an impetus for variation on different levels. Only 2 of the 26 concepts operate with a total lighting environment that equally addresses both daylighting and electrical lighting. Based on this, a research approach was defined focusing on the distribution of light and how this affects the experience of the rich variation of light qualities. The light distribution was investigated by referring to changing sky conditions and how these qualities can be defined to support and complement the daylight intake.

The questions asked in this paper are: "How can the qualities of dynamic daylight be defined and characterized?" and "How can these dynamic daylight qualities best be translated into electrical lighting design concepts?" Our hypothesis is that much of the natural variation in light and the light modelling qualities of daylight can be defined through different combinations of diffuse and direct light.

Method

In the first stage of this project, extensive literature reviews [4] were conducted to gain knowledge of the dynamics of daylight and how to implement those qualities in lighting design. Firstly, a review created an overview of the many and diverse tools and criteria used for investigating the concept of dynamic lighting technology. Secondly, a review focusing on how human needs for dynamic lighting and lighting qualities referring to diffuse and direct light, flow of light and different sky types was carried out. Based on these initial investigations, light modelling qualities in different sky conditions defined as ratios of the balance of diffuse and direct lighting were investigated through three small explorative experiments using simulations as well as light settings on objects in respectively daylight and electrical lighting.

Four sky types were investigated and characterized. The four sky types have been chosen as they, according to Tregenza, have the highest frequency of occurrence based on English weather conditions. These sky types are CIE 1, 3, 8 and 13. [1] These four sky conditions are described in detail through mathematical models of CIE sky types. These models are envisioned into relatable sky conditions with literature references to their intensity and correlated colour temperature and descriptive remarks based on the experienced light. Based on these observations and data, daylight simulations are rendered as reference for further investigations of the perception of light modelling qualities under different sky types.

To investigate how the light modelling is perceived in a space with one side window opening, a visual study in a 1:1 day lit office space was carried out. Photography was used for comparing the appearance of the objects and the light modelling ability under different sky conditions, referring to three CIE sky types. Photos were taken of the view and sky conditions parallel to photos aligned of three spherical objects placed on a horizontal plane 0.85 m above the floor and with a 0.5 m distance from the window opening. Photos were taken with a Canon EOS 70D camera on HDR mode. The office space was established at Aalborg University, Copenhagen Campus. The dimensions of the space were similar to a small office, with a length of 4m, width of 3m and height of 2,6m. The window opening with a surface of 1,5m^2 was facing southwest. The walls of the space were freshly painted white and the floor was covered with grey textile, establishing a neutral space.

To investigate how light modelling established through daylight can be reproduced by electrical lighting, a small experiment was carried out in the lighting lab at Aalborg University in Copenhagen. The tests were conducted with a large-scale diffuse light source in the celling, 2x2 m tuneable and dimmable light. In addition to the diffuse light source, a single iGuzzini Palco spotlight fixture, ø 142 mm and with a 48-degree optic was mounted on a celling light track and used as direct light source. The laboratory tests were documented through digital photographic images. The three light settings in the experiment refer to the light modelling seen from the three sky types: CIE sky type 3, 8 and 13. The CIE 1 sky type was excluded, as the aim was to achieve one distinct directionality of light with reference to the window opening.

Dynamic daylight is a combination of sunlight and skylight

"Daylight can be divided into the two components, sunlight and skylight. Sunlight is light received at the Earth's surface, directly from the sun. Sunlight produces strong, sharp-edged shadows. Skylight is light from the sun received at the Earth's surface after scattering in the atmosphere. It is scattered light that gives the sky its blue appearance. Skylight produces only weak, diffuse shadows. The balance between sunlight and skylight is determined by the nature of the atmosphere and the distance with the light passes through it." [5]

The variation of the sky according to the relation between sunlight, skylight, cloud cover and light intensity has also been studied in the Ph.D. thesis by N. Mathiasen: *Nordic Light – and its impact on the design of apertures in Nordic architecture.* In the simulations below, Mathiasen illustrates how the cloud coverage affects the intensity of light defined by the two components: skylight and sunlight. The study demonstrates that the magnitude of light intensity does not vary drastically whether the clouds cover the whole sky or not, though the character of the light can differ drastically from a clear blue sky, characterized by sharp-edged shadows to an overcast sky with diffuse and soft shadows, modelling the surroundings in two completely different visual appearances. [6]

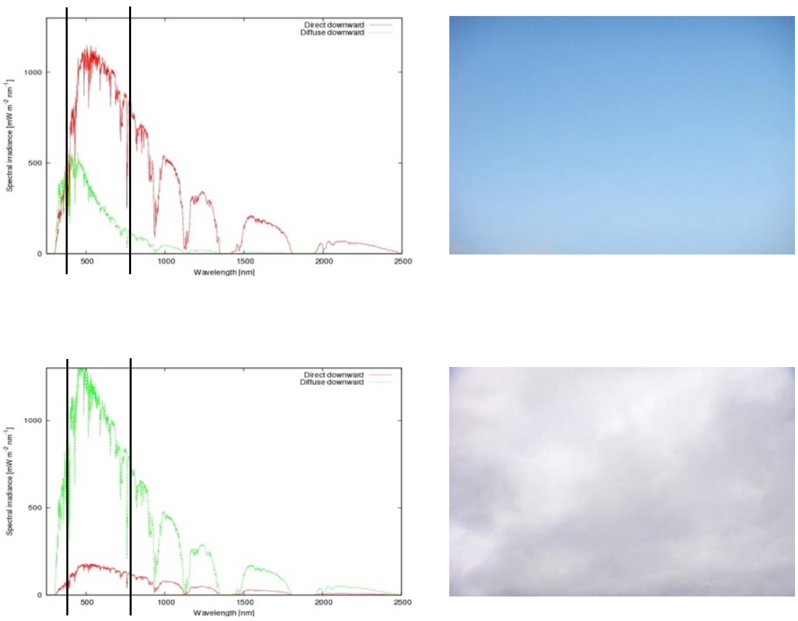

Figure 1. Simulations and photographic representation of a clear blue sky and an overcast sky. The graphs show spectral irradiance on the vertical axis and on the horizontal axis the wavelength of direct downward (red) and diffuse downward (green) and how the cloud cover affects these parameters. The simulations are made for Copenhagen 65˚N and a cloud cover that is neither very thick nor very thin. Illustrations from the publication "Nordic Light – and its impact on the design of apertures in Nordic architecture" [6]

These different qualities of daylight modelling are further investigated in the following section, where combinations of diffuse and direct light are investigated.

Diffuse and direct light balancing light modelling

The ratio between the intensity of direct and diffuse light is essential for how we experience and perceive our surroundings. Studies on perception and understanding of our visual environment has been a central part of the investigations.

V. Zaikina refers to the ratio of diffuse and direct light as *light modelling*, an important part of the lighting quality concept: "It determines not only the capability of the eye to detect any objects in a space but also its ability to discriminate contours, shapes and details, the most important visual characteristics of any object." [7]

Within the same field of interest, S. Frandsen describes the diffuse and direct light through an experiment of lighting up three different spheres: *"In parallel light the shadows are so sharp and so dense that the spheres almost lose their form….In very diffuse light the lack of shadows means lack of three-dimensional form. The spheres do not appear spherical and the texture is missing."* [8]

Similar statements are presented by C. Cuttle, when he defines the directional properties of a light source that generates shading patterns through interactions with three-dimensional objects. Cuttle states that this aspect of lighting is particularly associated with spaces lit by side windows. In this case, daylight creates a strong effect, which is characterized as *the flow of light.* [9] This flow of light is referring to the directionality of the light from a window, which traditionally is recognized as an important element when creating the visual environment and spatial appearance.

These references all emphasise light distribution and its qualities in a three-dimensional context, the light modelling qualities. They all point out the importance of combining the direct and diffuse light. When combining daylight and electrical light, the electrical lighting may potentially supplement the flow of light and light modelling qualities.

The optimal balance, in order to create a good light modelling of an object, is described in S*cale of Shadows* by Sophus Frandsen [8]. These optimal modelling qualities are defined in relation to the visual environment and the ability to see objects through a combination of direct and diffuse light where the shadow pattern is of particular importance for the definition of these qualities. The character of the shadow is established through the combination of direct and diffuse light, consequently the balance between the direct and the diffuse light, is crucial. Frandsen suggests that the diffuse light is combined with directional light where the angle of the directionality of the beam of light is between 11,5° - 40°.

The following initial experiments were made to investigate these light modelling effects within different combinations of direct and diffuse light modelling quality referring to the Scale of Shadow. The investigations were firstly made as simulations and photos within different daylight conditions and secondly reproduced with electrical light sources.

The dynamics of direct and diffuse light referring to different sky types

Daylight is dynamic by its nature. The International Commission on Illumination has defined 15 sky types, based on the variation of meteorological and climatic conditions. The first CIE standard overcast sky was defined in 1955, describing the luminance distribution of daylight in the sky and was subsequently followed by other more detailed definitions. [1]

In the matrix below, the four sky types are characterized by a definition of the sky types, a reference image, a specification of the characteristics of the light and its' dynamics, colour temperature, contrast, intensity and directionality.

Sky type	CIE Standard type 1 Overcast Sky Steep luminance gradation towards zenith, azimuthal uniformity	CIE sky type 3 Overcast, moderately graded with azimuthal uniformity	CIE sky type 8 Partly cloudy sky, no gradation towards zenith, distinct solar corona	CIE Standard type 13 Clear Sky, polluted atmosphere
Reference image				
Characteristic light	Reasonable intensity diffuse light soft scattered light. Ambient comfortable lighting	Lower intensity levels diffuse Light soft scattered light Uniform or even dull with lack of visual interest.	Cooler colors, and more diffuse daylight	Warmer colours. with high Contrast and intensity. Sharp edges on patterns interior reflected light from objects outside
Dynamics	Static subtle to slow and gradual changes	Almost none	dynamic patterns with change in intensity levels, color temperatures, and directionality resulting from moving clouds	Sunlight patches, strong dynamic patterns of filtered light ex. Through trees or from water
Color temperature	(6000–7000K)			Sun component (3000–5000 K) blue diffuse sky component (12000–18000K).
Contrast	Low	low	mixed	Glare due to high contrast
Intensity	1000 – 5,000 lux	1,000 - 2,000 lux varying in absolute brightness somewhat from sunrise to sunset	10,000 - 30,000 lux	30,000 - 130,000 lux
Directionality	Multiple directions reflected light	Uniform to none	Mixed and changeable directionality	Strong directionality

Figure 2. Characteristics of the four sky types.

To illustrate the light modelling qualities in relation to the changing sky condition, the four sky types were used as a reference to create daylight simulation of a sphere and its shadow pattern.

Sky type	CIE Standard type 1 Overcast Sky Steep luminance gradation towards zenith, azimuthal uniformity	CIE sky type 3 Overcast, moderately graded with azimuthal uniformity	CIE sky type 8 Partly cloudy sky, no gradation towards zenith, distinct solar corona	CIE Standard type 13 Clear Sky, polluted atmosphere
Lighting type	**Diffuse / diffuse** Balance between two or more diffuse sources.	**Totally diffuse** One or more fully synchronized sources.	**Direct / diffuse combinations** Multiple sources.	**Direct** Single primary directional source.
Reference image				
Characteristic light modelling / Shadow type	Attractive semi-soft lighting. Good definition of volume and detail both in shadows and for materials.	Soft light creates little form and volume lack of shadows and contrast makes the material details and qualities difficult to see.	Precise light. The correct balance allows definition without the loss of detail in the shadows and material detail.	Hard defined/dense shadows. Objects are less voluminous, material detail qualities are enhanced.
Dynamics	Static subtle to slow and gradual changes.	Almost none.	Dynamic patterns with noticeable change in intensity levels, colour temperatures, and directionality.	Strong directional bias which ideally would follow sun path although not necessarily a sunlight pattern.
Contrast	Low	Low	Mixed	Glare due to high contrast
Intensity	1000 – 5,000 lux	1,000 - 2,000 lux Varying in absolute brightness somewhat from sunrise to sunset.	10,000 - 30,000 lux	30,000 - 130,000 lux
Directionality	Multiple directions reflected light	Uniform to none	Mixed and changeable directionality	Strong directionality

Figure 3. Light modelling shadow pattern referring to the four different sky types are here reproduced and illustrated through renderings.

These different light settings on a sphere, combining direct and diffuse light sources, demonstrate how a balanced combination of diffuse and direct light influence the light modelling. Moreover, the character of light affects how we perceive an object. This highlights the importance of investigating a good balance between diffuse and direct light. It demonstrates how the shadow patterns of three-dimensional objects strongly influence how the visual perception process enables us to recognise object attributes, such as lightness, texture and form. Exactly the aspects Cuttle defines as the flow of light. [9]

From the renderings of the sphere, we can visually assess the directional and diffuse light condition of the CIE8 sky type to be closest to the best light modelling of an object. This lighting condition is characterized by creating a clear directionality of light, a shadow pattern, which is precise but not too hard and though creates an emphasis on the three-dimensionality and texture of the object, without overexposure of light.

Light modelling qualities and the directionality of daylight in a room

Figure 4. Different sky conditions, from the top and down referring to the daylight inflow with respectively CIE sky types 13, 3 and 8 and to the right photo illustrating how the different daylight situations affect light modelling qualities of the spheres. Photo: Mihkel Pajuste.

The spheres lit by three different sky types coming from a window opening results in shadow patterns which appear similar. Whether the sky is clear blue or cloudy, the light in flow from the window will create a soft shadow pattern on the spheres, though with a clear directionality of the light coming from the window opening. This demonstrates, that even without the direct sunlight in the space, the interior daylight illumiation has a distinct directionality. This directionality shows that the diffuse daylight produces a flow of light. A flow which has a direction related to the position of the window opening.

This points towards a potential for supporting the flow of the daylight from the window opening and the light modelling qualities from directional electrical lighting. This could be achieved by a light source creating a direct light with the same directionality as the daylight from the window and thereby support the flow of light as well as creating a more distinct light modelling and shadow pattern.

This leads to the question: How much direct light do we need to create these light modelling qualities? The following and last experiment therefore investigated the ratio between diffuse and direct lighting.

Light modelling qualities and ratios of diffuse and direct light

Firstly, a diffuse light setting was installed, with a reference to CIE standard sky type 3, an overcast daylight situation. This setting created diffuse and subtle shadows around the object. This lighting condition can often be referred to as the common office lighting, where uniform electric lighting is illuminating the space and objects on a working plane.

The second experiment refers to CIE sky type 8, a mix of clear blue sky and clouds. A low level of direct light from the spotlight is added to the diffuse general electrical light and thereby creating a well-balanced light with the mix of diffuse and direct light. The lighting condition is perceived as good and supportive for experiencing both space and objects. The qualities of the light is similar to the qualities described in relation to the Scale of Shadow [8].

And thirdly, the experiment referring to CIE sky type 13, a clear blue sky with sun, was carried out by increasing the intensity of the spotlight. This scenario is perceived to have too high contrast to create visually stimulating light modelling. To quantify the impact of the light modelling, data concerning the contrast values were auto-generated from the HDR photo by using the HDRScope program, developed at the University of Washington Seattle. [11] This tool enabled us to measure and compare the three light settings with approximate ratios of direct and diffuse light. The result of the study of the ratios illustrates that the directionality of the light within CIE Sky type 3 is 0%, CIE sky type 8 is 13%, and CIE sky type 13 is 52%.

This indicated that the direct light must be within 13-52% of the total lighting to create a sufficient and well-perceived light modelling. It is especially worth noting that 13% was perceived to be enough to create the desired light modelling condition. In figure 5 the photographs illustrate the different combination of diffuse and direct light where the photo in the middle refers to CIE sky type 8. And the contrast measurements' matrix in Table 1 shows a contrast value component to be 13% in the same light setting, referring to CIE 8 (diffuse/ direct 1).

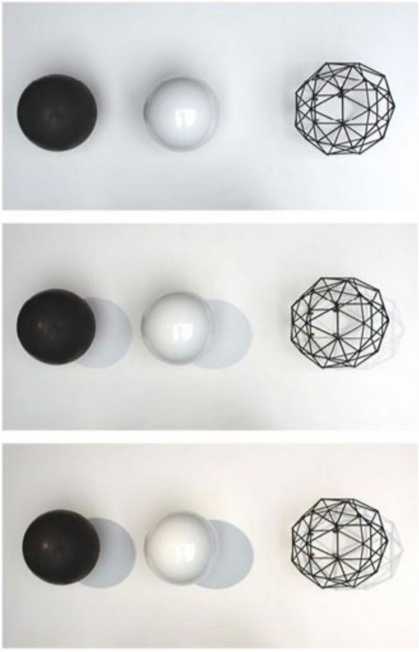

Figure 5. Light modelling experiments with different ratio of diffuse and direct light. From the top and down the electrical light setting referring to sky type 3, 8 and 13. Photo: Michael Cleary and Mihkel Pajuste.

	Diffuse	Diffuse/direct 1	Diffuse/direct 2
Minimum:	1.07	1.28	1.65
Maximum:	0.97	1.10	1.51
Mean:	0.97	1.13	1.52
Median:	0.97	1.11	1.51
Standard Deviation	0.79	0.34	0.87
Contrast	0.02	0.13	0.52

Table 1. Contrast measurements with HDRscope of fig. 5 images of electrical lighting made with reference to sky types CIE 3 (diffuse), CIE 8 (diffuse/direct 1) and CIE 13 (diffuse/direct 2). The qualitative balanced light modelling has direct lighting in a range of 13-52%.

Future work

The literature study as well as the conducted experiments described in this paper indicate a preference for a balanced light modelling combining direct and diffuse light. These findings lead to the hypothesis that dynamic light can be defined through the ratio of direct and diffuse lighting responding to different sky conditions, thereby creating a better visual appearance and a stronger relation to the outside. The daylight qualities defined as the ratio between direct sunlight and diffuse skylight are found stimulating and even vital for human beings. This forms the basis of future investigations of how diffuse and direct daylight and electrical lighting can supplement and complement each other to create visual stimulating environments.

Future lab tests will aim at defining the upper and lower boundaries for a ratio of direct and diffuse light sources and how these can respond to different daylight conditions in order to create a well-lit office space with a connection to the outside. In a controlled light lab, the boundaries for ratio between a warm direct spotlight on a work plane and cold diffuse ceiling lighting panels will be studied with reference to the two daylight components: skylight and sunlight. It will be investigated which range of ratios is preferred, referring to the perception of light modelling.

This will be followed by surveys on when and how the electrical lighting can supplement and complement the daylight intake. The initial scenario for testing both the ratio of direct warm and diffuse cold light in relation to different sky types could be described through a new concept of *double dynamic lighting*. And finally, the new double dynamic lighting scenario will be implemented in an office environment as an intelligent lighting system responding to daylight conditions. A LM-TLM outdoor sky sensor, placed on the rooftop will track the direct and diffuse daylight. The effect of the double dynamic lighting will be tested on people working in an office environment over a longer period of time to test the impact of the dynamic lighting over days, weeks, months and seasons. The results will be analysed and translated into a design guideline for a double dynamic lighting concept.

Conclusion

Most often the dynamics of light in lighting design strategies are limited to the aspects of intensity (lx level) and colour of light (CCT). However, inspired by daylight, more variation of diffuse and direct light is found to be of importance, since people have a general preference for and a profound relation to the dynamics of daylight, as human perception and vision have evolved underneath the changing sky conditions.

To study these qualities, the ratio of direct and diffuse light referring to CIE Standard sky types was investigated with the emphasis on light modelling and flow of light. The qualities of the light distribution of the different sky types were reconstructed in lab experiments with diffuse general lighting and direct light sources observed on the work plane. This study illustrated that the light modelling qualities were appearing, when the ratio between direct and diffuse light sources was above 13% and below 52%. This initial finding indicated that the light modelling qualities we are aiming at can be achieved in office environments with standard diffuse ceiling lighting by adding direct light on the work plane. The direct light must have the same directionality as the daylight coming from the side window. This illustrates a potential for complementing the daylight intake with electrical direct light, creating a flow of light and a more distinct light modelling.

The qualities of daylight described as *light modelling* and *the flow of light* can hereby be adapted into electrical lighting strategies, to generate a more stimulating work environments by complimenting the perception of interior space through the dynamics of natural lighting condition. In further investigations, this can be explored by defining upper and lower boundaries of ratios between diffuse and direct electrical light sources responding to the qualities of daylight as both the ratio of diffuse and direct daylight as well as the intensities and colour temperatures. Through that the electrical lighting design can establish a connection to the outside and at the same time create a better visual environment referring to the qualities of natural light.

Acknowledgements

The luminaire manufacturer Zumtobel, Fagerhult and iGuzzini and the component manufacturer Tridonic have teamed up with Aalborg University to take up the challenge of investigating how double dynamic lighting can meet human needs for a more natural indoor work environment. The literature review and initial tests presented in this paper could not have been carried out without the support from the partners. Thank you, Michael Clary for setting up these initial tests supported from Mihkel Pajuste and thank you Lisa Heschong for your valuable input.

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