

Flow of Light: Balancing Directionality and CCT in the Office Environment

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ABSTRACT

Human perception and vision have evolved in response to dynamic daylight, a combination of radiation from direct sunlight and diffuse skylight, which has created a flow of variations in light, in terms of direct:diffuse distribution, intensities and spectrum. This study investigates the qualities of the flow of light in an office after adding ceiling-mounted spotlights (32° tilt angle) to traditional diffuse ceiling panels. The intention is to create a flow of task light – a light-zone at each work-plane – complementing the directionality of the natural daylight inflow from the windows. An experiment was carried out in an office, in two parts. Four ratios of direct:diffuse light were tested by 30 people. Then one ratio was tested in five combinations of high, neutral and low color temperatures by 15 people in two daylight situations: overcast and clear sky. The visual light quality and perceived atmosphere of the office environment was tested through questionnaires, reaction cards and semi-structured interviews. The direct flow of light is recommended to be more than 15% of the total illuminance at the work-plane to provide the distinct visual appearance of modeling and a cozier atmosphere, which is preferable for socializing, and less than 45% to avoid glare and high contrast for visual tasks. Direct warm and diffuse cool lighting were perceived as the most natural but were not always preferred. There is an indication of slight preference for cooler ambient lighting in clear sky situations and warmer ambient lighting in overcast situations. Especially the preference in relation to sky conditions needs to be further investigated. A field study will implement these findings in a double dynamic lighting concept responding to daylight level and sky character. Strong individual preferences for combinations of color temperatures was identified, this opens up new research areas for personalized flows of light in future dynamic lighting designs.

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1. Introduction

1.1. Aim and perspective

People spend most of the daylight hours indoors, often in office spaces where daylight inflow is supplemented by electrical lighting, which is designed according to traditional guidelines for horizontal and diffuse illuminance for visual tasks. Advances in LED lighting systems and control and sensor technologies have increased the design complexity and the number of design parameters when designing lighting to meet people's needs. The potential in dynamic lighting has been recognized, and there is an increased awareness of the non-image-forming effects of light on health and well-being, investigated using objective methods (Hansen and Mathiasen 2019). Studies of people's appraisal of lighting have demonstrated that light significantly influences impression of objects'

visual appearance as well as appreciation of the atmosphere of a space (Cuttle 2015; De Kort and Smolders 2010; Stokkermans et al. 2017; Veitch and Newsham 2000; Veitch et al. 2008, 2013).

Human perception and vision have evolved in response to the natural variation of daylight. This variability is created by the combination of direct sunlight and diffuse skylight, defined by the altitude and orientation of the sun as well as the sky condition. These interactions with respective dynamics in intensities, spectrum and direction create the visual characteristics and temporal patterns recognized as the natural flow of light (Cuttle 2015; Tregenza and Wilson 2011). Lam (1977) referenced the qualities of daylight by introducing the biological needs for environmental information and stressed the perception-based approach: "Light has always been recognized as one of the most powerful form-givers available to the designer."

The aim of this study is to investigate if the perceived qualities of the flow of light, a balance of radiation from direct warm sunlight and diffuse cool skylight, can inspire a new design concept for indoor dynamic lighting. A full-scale experiment was conducted in two parts to answer the following research question:

What ratio of direct:diffuse lighting with respective correlated color temperatures can be combined to enhance the visual appearance and perceived atmosphere of an office environment, in referring to the qualities of the *flow of light*?

1.2. The flow of light

A pre-study was conducted to explore how human perception of daylight qualities can be defined as a reference for lighting design variables (Hansen and Mathiasen 2019). The two main components of daylight – direct sunlight and diffuse skylight – generate directionality as a flow of light and create shadow patterns that interact with three-dimensional objects under different sky conditions, referring to the qualities of *light modeling* (Frandsen 1989; Zaikina 2016). Balancing direct:diffuse light can create *light-zones*, which are bubbles or spheres of light in a space with the architectural potential to accelerate a perception of a space (Madsen 2007). In a spatial context, particularly associated with spaces lit by side windows, daylight creates a strong light-modeling effect and light zone, characterized as *the flow of light* (Cuttle 2015). Throughout the history of architecture, daylight has been recognized as the most important tool for visual quality, illumination hierarchy and forming spatial appearance through daylight inflow from windows (Hansen and Mathiasen 2019).

1.3. Direct and indirect light

Previous research has studied the combination of direct and indirect electrical lighting components in offices. Fleischer et al. (2001a) tested ratios of indirect and direct components related to illuminance in the work plane. They found the maximum percentage of an indirect component of 50%. In terms of room impression, 75% direct lighting is judged the most cheerful. After combining

indirect warm light with direct cool light, as compared with combining indirect cool and direct warm white light, Fleischer et al. (2001a) concluded pleasure can be maximized by combining warm white and daylight color with a large indirect component, and the least pleasing is to use a large direct component. They pointed out that adding direct light had an activating influence on office workers and stated that this makes it possible to design variable lighting situations (Fleischer 2001b). Houser et al. (2002) studied the subjective response to linear fluorescent direct/indirect lighting systems and reported that the walls and ceiling contribute to the perceived overall brightness when the work plane illuminance is held constant and that the room appears more spacious when more light was supplied indirectly. Investigating the ratio, they stated that the settings where the indirect component had a horizontal illuminance contribution of 60% or more were favored. Boyce et al. (2006) studied lighting quality in offices through two field experiments. They found that direct/indirect systems were evaluated as being more comfortable than direct-only systems as well as a further increase in comfort associated with individual control (Boyce et al. 2006). The effects of diffuse daylight in a space without a view were studied by Stokkermans et al. (2018), who found very little effect and argued that this could be due to the lack of a direct sun component. They stressed the potential of combining direct and diffuse lighting to create the atmospheric perception people often relate to day-lit spaces. De Bakker et al. (2019) studied luminance distribution preferences in relation to the time of day and subjective alertness, and they found that participants preferred varying luminance distributions. Veitch and Newsham (2000) recommended a mixture of direct and indirect ambient lighting, with approximately 40% being indirect.

A general finding in these studies is that a combination of direct and diffuse lighting is preferred over only using direct or indirect lighting in offices. Common to these studies is that they focused on direct/indirect lighting systems using uplights or ceiling panels as the indirect components and downlights as the direct component. The novelty in this project is that we add direct light with a tilt angle (32 degree) – a directionality – complementing the

directionality of the inflow of daylight from the side windows. Another new approach is that we study the ratio of this direct flow of lighting in relation to the diffuse lighting, in combination with different color temperatures and the sky conditions.

1.4. Combined directionality and CCT

The temporal and dynamic patterns of daylight's color appearance are defined by the sun's altitude and the sky conditions. Daylight can be perceived as cool, such as illumination from deep blue skylight during a cloudless day; neutral white; or even warm, during the transition hours when the sun is close to the horizon and the longer red wavelengths are less scattered than the shorter blue wavelengths are. A low correlated color temperature (CCT), perceived as warm, is defined as being between 2000 and 3000 Kelvin (K), neutral CCT is from 3000 to 5000 K and a cool color appearance is 5000 K and above (Cuttle 2015). Painters such as the Danish impressionists have explored the perceived effects of combining the use of direct sunlight and diffuse skylight, creating light-zones of warm sunlight and cool shadow patterns. Stage lighting designers have also exploited combinations of color appearance with the directionality of lighting. Stanley McCandless (1958) incorporated the "sun and sky lighting effect," where objects on stage are illuminated directionally from opposite sides with different CCTs. Kruithof (1941) defined the preferred combinations of illumination and CCTs based on their perceived qualities. Low illuminance and high CCT can be perceived as too cool and harsh, whereas higher illuminance and lower CCT can appear unnatural. This combination of directionality and CCT has shown that an impression of relaxation can come from a warm and non-uniform light distribution (Flynn 1988). Studies have also identified that the preference for electrical lighting depends on the weather type along with different intensities, distribution and colors of the daylight inflow (Fleischer 2001b).

1.5. Design experiments

Office environments are influenced by their lighting, which directly affects workplace satisfaction,

work engagement and motivation. People who appraise the lighting as good also tend to appraise the room's visual appearance and the perceived atmosphere as being more attractive. This leads to a more pleasant mood among the employees and thereby higher satisfaction with the work environment and overall engagement in their work (Veitch et al. 2008; Veitch, Stokkermans, and Newsham, 2013).

This study evaluates visual appearance and perceived atmosphere. The visual appearance is described with the term *flow of light* and is defined by the following light qualities: a *directionality* of the electrical lighting referring to the daylight inflow; an uneven spatial light distribution establishing an *illumination hierarchy* and *light-zones*; and *light modeling* of objects, which creates distinct shadows and highlights and thus enhances the three-dimensionality of objects on the work plane. The perceived atmosphere is defined as the subjective experience and affect of being in the space, relating to psychological well-being and motivation, such as the space being motivating, personal, natural, cozy and stimulating.

A full-scale design experiment with two parts was set up to investigate visual appearance and perceived atmosphere in different light settings and in relation to the character of daylight inflow. In part 1, four ratios of direct:diffuse lighting with no daylight inflow were investigated in an office environment. In part 2, based on the findings of part 1, new test parameters for color temperature and sky conditions were investigated. In the design experiment, static light settings combining diffuse and direct and respective CCTs were tested under two sky conditions to validate different combinations of CCTs as parameters for dynamic light settings complementing the natural light.

2. Method

2.1. Participants

The test participants in parts 1 and 2 were all employees of Aalborg University Copenhagen, including professors, PhD fellows, research assistants and administrative staff. None of the participants worked in the lighting field.

Thirty individuals participated in part 1, consisting of 13 males and 17 females. Twelve participants were aged 20–29 years, seven were aged 30–39 years, five were aged 40–49 years, three were aged 50–59 years and three were aged 60 years old or above. Sixteen of the 30 participants were Danish, and the rest had been residing in Denmark for more than five years.

In part 2, 15 participants took part in the experiment twice, consisting of seven males and eight females. One participant was aged 19–29 years, two were aged 30–39 years, five were aged 40–49 years and seven were aged 50–59 years. Thirteen of the test persons were Danish, and two were foreign but had resided in Denmark for more than 10 years.

The reason for having only 15 test participants in part 2 was the choice of conducting 30 tests, using the same group twice, once with the overcast and once with the clear sky condition, to be able to make a comparative study. The age of the test groups was heterogeneous, preventing us from focusing on one age group. Age can be an influential factor when evaluating lighting; however, participants from the same workplace, with similar office lighting, established a standard reference for work-environment lighting within the group.

The data collected from the participants consisted of questionnaires in parts 1 and 2 as well as interviews in part 2. In both parts, general good ethical conduct guidelines were followed, and the participants were provided with information about the study's purpose, procedures and confidentiality (Bjørner 2015). The participants were asked about their age, gender, nationality and usage of visual aids.

2.2. Test room

The test room was established as a laboratory office space. The room had southwest-facing windows and was located on the third floor of the Copenhagen campus of Aalborg University. No buildings were blocking the daylight inflow. The mean daylight factor was 2%, as calculated by Diva for Rhino (Solemna 2019) with a 3D model of the space. The room dimensions were 4.4 by 5 meters, with a height of 2.6 meters; see the floorplan in Fig. 1. The walls were freshly painted white to

establish a neutral space and eliminate visual focus points. The two windows were configured with a glass area of 80 cm by 107 cm, equal to 7.7% of the floor area. Reflectance was estimated with a Hagner EC1 Luxmeter measuring illuminance 15 cm distance from the surface, firstly toward the surface (reflected light) and thereafter pointed away from it (surface incoming light). The measurements were calculated, resulting in an absolute diffuse reflectance of 77% for the walls and 18% for the tables. The space was furnished with four gray working desks and blue chairs facing the middle of the space, and objects such as fruit, cups and magazines were placed on the desks to mimic an office environment.

In part 1, both window openings were blinded, establishing a space with no daylight inflow. In part 2, the window openings were uncovered, and daylight inflow was a parameter in the experiment.

2.3. Lighting and control system

The test room was equipped with two types of luminaires. Four traditional 60 × 60 cm ceiling panels were used, specifically Fagerhult Multilume Flat Delta tunable white luminaires (2700–6500 K), with a maximum luminous flux output of 3537 lm. These were placed with an even distribution corresponding to the widely used general lighting system for offices. Secondly, four tunable white spotlights (2700–6500 K), were used, specifically Zumtobel's Arcos 3 luminaires, with a beam angle of 36° and a maximum luminous flux output of 751 lm. One spotlight was placed at each table with a 32° tilt angle to create a flow of light with a directionality corresponding with the daylight inflow from the side windows. The tilt angle is the measured angle ranging from 0 to 90 degrees between the vertical and horizontal plane. The ceiling panels served as tunable white diffuse light sources, and the spotlights were tunable white directional light sources.

The spotlights were customized by adding an extended shading of 20 cm to minimize the glare from the work plane, as these fixtures were used in a new, unusual context for task lighting. All of the luminaires were installed on a track-based Digital Addressable Lighting Interface (DALI) system.

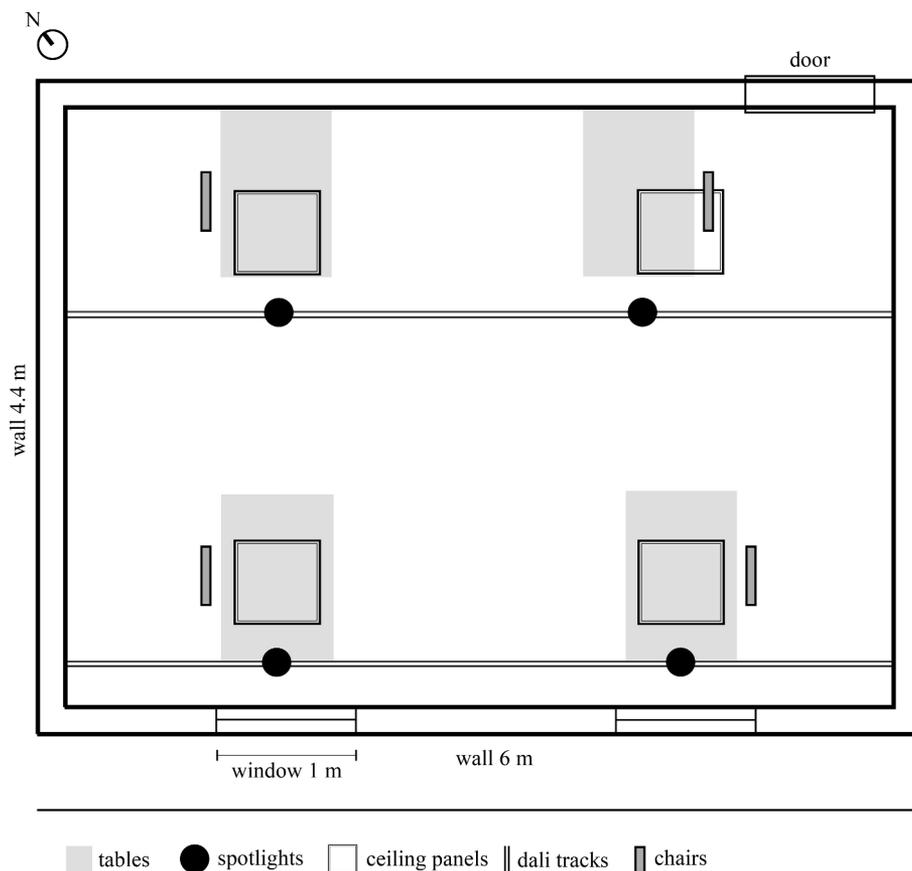


Fig. 1. Laboratory office space floorplan and fixture placements.

The DALI control system comprised a charge-coupled device (CCD) central control unit providing three separate DALI lines and a single local memory communication system (LM-Bus line). This control unit ran Zumtobel's Litecom lighting-management system (LMS). Litecom LMS utilizes the building automation and control network (BACnet) communication protocol; its architecture is representational stated transfer (REST-based), allowing hypertext transfer Protocol (HTTP) requests to and from the CCD.

2.4. Procedure

In part 1, the test participants evaluated the light settings four persons at a time, seated at the four tables, as illustrated in Fig. 1. All participants were facing the middle of the room, toward each other. The four light settings were consecutively presented to each of the participant groups, in random order to eliminate sequence effects. The illuminance conditions on the participants' tables

were identical, and with no daylight intake from the covered window openings, the effect of participants' seating was discarded.

In part 2, the test participants individually evaluated five lighting settings twice, with daylight inflow under overcast and clear sky conditions. All of the participants were seated at the same desk and had full control over switching between the five lighting settings.

2.5. Questionnaire

Scales with bipolar semantic differentials were used in part 1 to quantify the different lighting settings' visual appearance and perceived atmosphere. Other studies have also explored and positively evaluated semantic differential scaling (Flynn et al. 1973; Johansson et al. 2014; Stokkermans et al. 2018; Tiller and Rea 1992; Veitch et al. 2008). Six questions were used to evaluate visual appearance (1–6): including perceived brightness, evenness, shadow distinction,

light modeling, visual comfort and glare. The perceived atmosphere was addressed with three questions (7–9) evaluating naturalness, coziness and dullness; see Table 1. The questionnaire also included a question about which tasks the participants would imagine carrying out under the different lighting settings, e.g. writing on paper, reading text on paper, computer work, meetings and socializing.

2.6. Reaction cards

Reaction cards were used in both parts 1 and 2 for evaluating the different lighting settings. This method was adapted and modified for this study to collect qualitative data, including feedback on the lighting settings, evaluating subjective responses to both the visual appearance and perceived atmosphere. The cards had secondary functions in part 2: as an impetus for semi-structured interviews, to provide vocabulary and to restrain the abstraction of light.

This method originated from the Product Reaction Cards Desirability Toolkit, developed by the Microsoft Corporation in 2002 (Benedek and Miner 2002). The original version comprised 118 cards with descriptive words or phrases. Previously, this method has been used for studies relevant to the computer gaming industry to assess player engagement during gameplay (Schønau-Fog and Bjørner 2012) and in an architectural context to evaluate a library's esthetic and emotional appraisals. In this latter study, the authors used 76 cards, divided into positive and negative categories.

In the current study, six original cards were chosen with relevance to the lighting-design field:

boring, comfortable, dull, motivating, stimulating and personal. Vogels (2008) used a similar approach to reveal the affective impact of lighting regarding perception, by categorizing atmosphere into the four dimensions of coziness, liveliness, tenseness and detachment. From the 38 atmosphere terms used by Vogels (2008), nine were found relevant for this study: *detached, cozy, depressed, formal, pleasant, tense, lively, uncomfortable and relaxed.*

In addition to the 15 chosen reaction cards from previous studies, another 15 cards suitable for this context of lighting assessment in an office environment were added. The reaction cards chosen in this study had two categories: *visual appearance*, with a focus on visual comfort enabling work to be carried out in a pleasant lighting environment, and *perceived atmosphere*, as experienced in relation to physiological well-being and motivation. Both categories included 15 cards, which could be interpreted positively and/or negatively; see Table 2.

2.7. Interviews

In Part 2, the chosen reaction cards were used as the impetus for semi-structured interviews to elaborate and clarify interpretations of the words. The interviews were recorded and transcribed with Otter (Otter.ai 2019), an AI-powered live transcription software, and they were then reviewed and automatic transcription faults were corrected in NVivo 12 (QSR International 2018). The interview transcripts, with systematically defined nodes and themes for each paragraph based on the reaction cards and daylight conditions, were used for a quantitative content analysis based on the most referenced nodes,

Table 1. Overview of the questionnaire with the nine questions and the semantic opposites on each side of the analogue scales.

Questionnaire statements	Differentials	Differentials
1. The current lighting makes the space appear:	Bright	Dim
2. The current lighting distribution appears:	Even	Uneven
3. The current lighting causes:	Vague shadows	Distinct shadows
4. The current lighting enhances the shape of the objects (light modeling):	Not at all	Very well
5. The current lighting is:	Uncomfortable	Comfortable
6. When looking in the space, I perceive:	No glare	Glare
7. The current lighting appears:	Unnatural	Natural
8. The current lighting appears:	Formal	Cozy
9. The current lighting appears:	Interesting	Dull
10. Which tasks would you imagine carrying out under the current lighting?		

Reading (from paper) Writing (on paper) Computer work Meetings Socializing.

Table 2. Reaction cards categorized in relation to visual appearance and perceived atmosphere.

<i>Visual appearance:</i>	<i>Perceived atmosphere:</i>
Comfortable	Cozy
Sufficient	Motivating
Task-focused	Personal
Pleasant	Intimate
Natural	Formal
Contrasting	Stimulating
Dim	Relaxed
Bright	Lively
Glary	Detached
Uncomfortable	Boring
Insufficient	Lifeless
Disturbing	Depressing
Unpleasant	Clinical
Unnatural	Demotivating
Tense	Dull

including both positive and negative statements. Each quote was referenced by the test participant who stated it. Finally, a simple positive/negative conclusion was made, based on the amount of test participants who had either positive or negative opinions about a lighting setting.

3. Part 1

3.1. Research question

In Part 1, the first objective of the research question is investigated: to define the ratio of direct:diffuse lighting that can enhance the visual appearance and perceived atmosphere in an office, referring to the qualities of *the flow of light*.

3.2. Setup

In the laboratory office space without daylight inflow and view, four light settings were defined by a ratio of direct:diffuse illuminance contribution, all meeting 500 lx at the task area (DS/EN 12464-1 DK NA 2015). The lumen outputs of the light sources were adjusted using the Litecom interface to meet the direct:diffuse ratio, and the total illuminance of 500 lx on the task area was measured with a Hagner EC1 Luxmeter. Figure 2 illustrates each setting and its corresponding direct-to-diffuse ratio. Figure 3 illustrates the conceptual idea of direct and diffuse lighting sources composed for the luminous environment. The photographs presented in Fig. 4 illustrate differences in the brightness of the walls and how the character of the space changes in the respective light settings. The light levels were solely measured on the task area the four tables and unfortunately not on the walls. Since the ratios have an essential impact on the appearance of the space it would have been informative to have measured the illumination of the wall. A light ratio of 0:100, meaning 0% of light from the spot and 100% of the light on the table is from the panel. This ratio had the brightest space appearance, with no distinct shadow patterns on the table. In contrast, the 45:55 light ratio, 45% of the light on the task area provided from the spot and 55% from the panel. This ratio created a darker space appearance as well as more distinct shadow patterns, creating a more

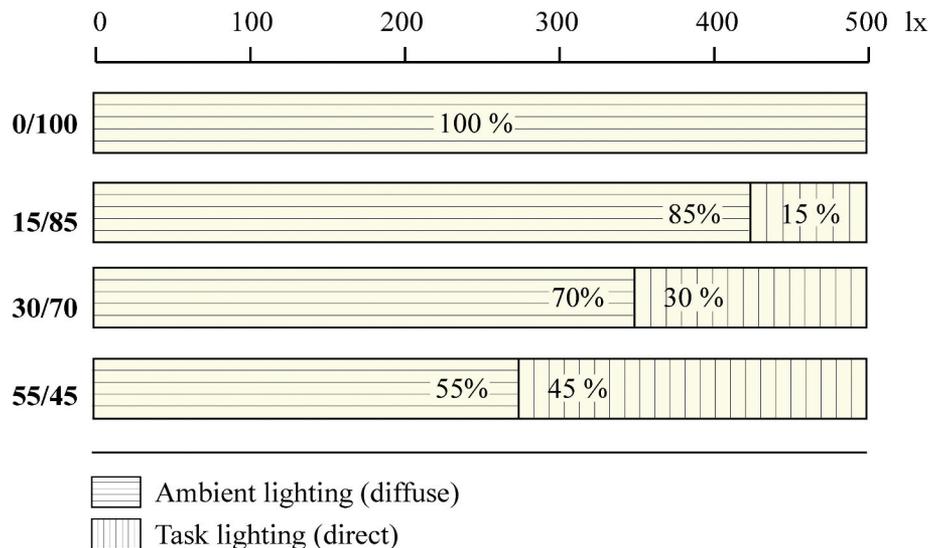


Fig. 2. Part 1, the four light settings with different ratios of direct:diffuse components, all meeting 500 lx on the task area.

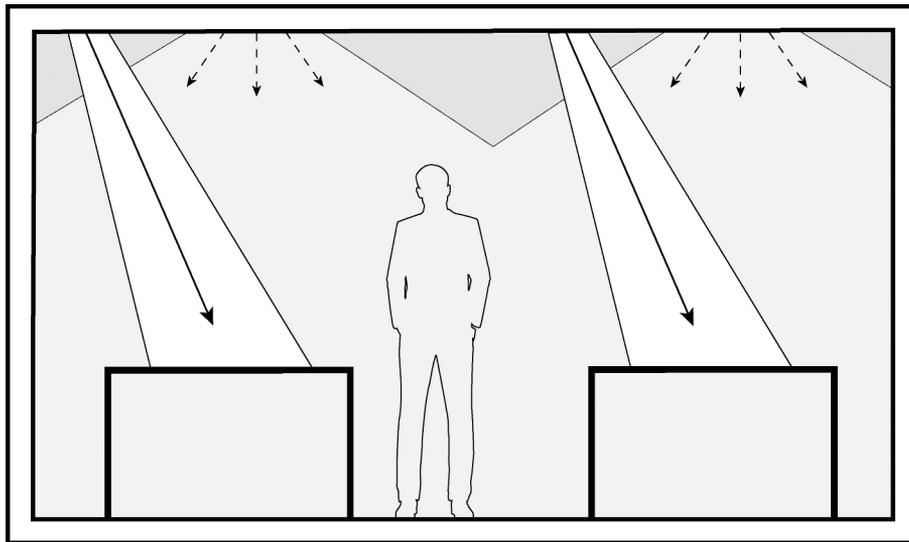


Fig. 3. Section of the laboratory office space illustrating the direct:diffuse lighting concept in test 1.



Fig. 4. Photo registrations of the light modeling of objects on the table and the light distribution in the office space for the four light settings, from left to right: 0:100, 15:85, 30:70 and 55:45.

apparent three-dimensional light modeling of objects on the table. See Fig. 4 and the shadow of the white mug as an example. No additional luminance measurements were conducted. In future studies, elaborated measurement plans, surface colors and reflections could be addressed parallel to the subjective visual appearance registrations.

3.3. Results of part 1

3.3.1. Questionnaire

To answer the research question, the following hypothesis was used for the quantitative analysis of the questionnaire: The participants will be able to identify differences in the lighting between the

light settings for the 30:70 ratio and above with the 0:100 ratio.

Shapiro-Wilk normality tests were applied for each of the nine questions (see the table in Appendix 1) and passed, with statistical significance above .05. The used scales represented a linear analogue space, in which the participants found semantic opposites on each of the two sides of the scale and marked their selection in between. Lighting settings with directional lighting ratios if 15:85, 30:70 and 45:55 were compared with the 0:100 ratio, the baseline setting with no directional lighting.

The results (see the table in Appendix 1) demonstrate that the participants clearly perceived

illumination evenness in the space throughout the settings, followed by a decline as the ratio of direct to diffuse increased. On average, the perceived evenness (0 for most uneven, 10 for most even) for the 0:100 ratio up to the 45:55 ratio was $M = 7.38$, $M = 6.41$, $M = 5.96$ and $M = 4.19$. Paired t-tests of the 15:85, 30:70 and 45:55 ratios with the baseline ratio of 0:100 returned $t(29) = 2.01$ for the 15:85 ratio, $t(29) = 2.89$ for the 30:70 ratio and $t(29) = 6.94$ for the 45:55 ratio, with 2-tailed significance between $p = .05$ and $p = .01$ and effect size above $r = 0.30$.

The perceived brightness also clearly decreased as the direct-to-diffuse ratio increased. The mean values from the 0:100 ratio to the 15:85, 30:70 and 45:55 ratios for perceived brightness (0 for extremely dim, 10 for extremely bright) were $M = 7.94$, $M = 6.34$, $M = 6.01$ and $M = 4.15$. The paired t-test for this dimension between the 0:100 lighting setting and setting with the 30:70 and 45:55 ratios resulted in $t(29) = 4.81$, $t(29) = 4.9$ and $t(29) = 12.44$, respectively. The perceived brightness had the strongest effect size throughout the light settings, with $p = .01$. Importantly, the 45:55 ratio had the highest effect size of brightness ($r = 0.92$) in comparison with the baseline. When comparing this with the effect size from the 30:70 ratio to the 0:100 ratio, with $r = 0.67$, we can assume that the participants tended to agree that the brightness was exaggerated from the direct:diffuse ratios of 30:70 to 45:55.

When the directional lighting from the spotlight increased from the 0:100 ratio toward the 45:55 ratio, the coziness question also increased and was highest at the 45:55 ratio. The average scores for each (0 being perceived as the most formal and 10 being perceived as the coziest) from the 0:100 ratio to 45:55 ratio were $M = 3.07$, $M = 3.95$, $M = 3.81$ and $M = 5.41$. At baseline, the settings ratios of 15:85 and 30:70 averagely were below 5 (closest to formal), while the 45:55 ratio was the only setting scoring above 5, toward cozy.

Regarding the questions of natural versus unnatural and dull versus interesting, variance increased throughout the settings, with lower effect sizes and significance, making the results inconclusive. This could be due to the laboratory test conditions, with no daylight or view.

The participants also perceived shadow distinctions, which increased as the ratio increased. For

the ratios 0:100 to 45:55 (ranging from 0 for vague shadows to 10 for distinct shadows), the mean scores were $M = 4.41$, $M = 5.06$, $M = 5.50$ and $M = 6.41$. In particular, the 45:55 and 30:70 ratios had effect sizes larger than medium, $r > 0.30$ and $p < .05$.

For the light-modeling question, no clear tendency was noted as the ratio increased, and the mean values for all four settings were located relatively close to 5.90 on the scale (ranging from 0 for unclear light modeling to 10 for clear light modeling). This could have been caused by a lack of understanding of the phrase *light modeling*; see question 4 in [Table 1](#).

Perceived glare results increased as the ratio increased, with the highest again being at the 45:55 ratio. The average glare values, for each setting from the 0:100 ratio to the 45:55 ratio, were $M = 5.61$, $M = 6.03$, $M = 6.69$ and $M = 6.90$ respectively. For the 30:70 and 45:55 light settings, the significance was $p < .01$, and the effect size of the t-test was between 0.4 and 0.5.

In light settings with 15:85, 30:70 and 45:55 ratios regarding perceived comfort, no strong tendencies were noted, and the significance and effect sizes were not aligned.

The questions rating visual appearance, such as perceived brightness and evenness, had the strongest effects and produced consistent and significant results, while questions rating perceived atmosphere such as coziness as well as visual appearance such as shadow distinction and glare had medium to strong effects. The aforementioned five questions contributed to confirming the hypothesis that the participants would be able to identify differences between the 30:70 and 45:55 settings. The scale questions rating visual comfort, dullness and naturalness did not yield results to contribute to the hypothesis. The reason could have been that the testing environment resembled a situation closer to a lab environment, with blocked windows and minimal furnishings; thus, asking participants to rate a space's naturalness or dullness may have been problematic.

3.3.2. Tasks

The participants were asked to choose which tasks they would imagine carrying out under the different light settings. The differences between the

settings with direct lighting and with no direct lighting were analyzed; see Fig. 5. We employed spider plots to visually compare the light settings. The most notable increase was in socializing, which tended to increase as the ratio increased. On the other hand, writing and reading tasks displayed clear decreases as the ratio increased. The additional directional lighting tended to cover more tasks, although further work is needed to confirm this assumption with certainty.

3.3.3. Reaction cards

The number of reaction cards chosen for the four lighting settings varied between 144 and 148 cards, due to the participants' inconsistency in choosing five cards per person per setting. Amongst the 10 most frequently chosen reaction cards, five were categorized as visual appearance and five were categorized as perceived atmosphere (see Table 3). The results of the visual appearance cards show that the space appeared brightest with 100% diffuse lighting and dimmest with the 45:55 ratio of direct:diffuse lighting. The diffuse light settings were also characterized as most *task-focused* (43%) with diffuse lighting only. The lighting was found to be *pleasant* in all settings, besides the 0:100 setting. The most

chosen perceived atmosphere cards were *formal*, which 53% of the participants chose; followed by *clinical* (43%) and *unnatural* (43%). All of these were chosen the most for the lighting setting with a direct:diffuse ratio of 0:100.

3.4. Part 1: Summary

In part 1, the ratio of direct: diffuse lighting was investigated to enhance the visual appearance and perceived atmosphere in an office, regarding the qualities of the flow of light. The questionnaire results showed that visual appearance scales such as *perceived brightness* and *evenness* were identified as having the strongest effects and produced consistent and significant results, with significance between $p = .01$ and $p = .05$ and effect size above $r = 0.30$; see Table 1 in appendix 1. Questions addressing perceived atmosphere such as *coziness* and visual appearance such as *shadow distinction* and *glare* were recognized with medium to strong effects. Five out of seven questions contributed to confirming the hypothesis that the participants could identify differences in the lighting when comparing the settings for a 30:70 ratio and above with the baseline. The data indicate that



Fig. 5. Choice of tasks for the 15:85, 30:70 and 45:55 settings compared to the 0:100 setting.

Table 3. Overview of the top 10 reaction cards chosen in part 1's testing.

Direct:diffuse ratio	0:100	15:85	30:70	45:55
<i>Total reaction cards</i>	148	144	147	148
Visual appearance cards				
<i>Bright</i>	18 (60%)	15 (50%)	11 (36%)	3 (10%)
<i>Task-focused</i>	13 (43%)	12 (40%)	7 (23%)	6 (20%)
<i>Sufficient</i>	6 (20%)	10 (33%)	7 (23%)	5 (17%)
<i>Pleasant</i>	0	7 (23%)	7 (23%)	9 (30%)
<i>Dim</i>	0	4 (13%)	4 (13%)	14 (47%)
Perceived atmosphere cards				
<i>Formal</i>	16 (53%)	11(37%)	9 (30%)	6 (20%)
<i>Clinical</i>	13 (43%)	9 (30%)	12 (40%)	4 (13%)
<i>Unnatural</i>	13 (43%)	7 (23%)	10 (33%)	8 (27%)
<i>Boring</i>	4 (13%)	9 (30%)	5 (17%)	6 (20%)
<i>Lifeless</i>	6 (20%)	7 (23%)	8 (27%)	8 (27%)

increasing the direct lighting ratio also increases the distinction of coziness and shadow, positively contributing to light modeling of shadows on objects and to the perceived atmosphere. However, an increase in glare was detected, which could negatively impact visual comfort for carrying out work tasks.

The question regarding tasks supports this finding. The data revealed that an increase in direct lighting increased socializing as a possible activity in addition to the other four activities (writing, reading, computer work and meetings). Indicators showed that uneven lighting distribution creating *light-zones* best facilitated socializing, although further study on this is needed. Moreover, the data show a tendency for increased directional lighting supports a large spread of tasks; see Fig. 5.

The reaction cards seemed to complement the questionnaire data and contribute to studying the perceived atmosphere. The reaction cards *bright*, *dim*, *formal* and *task-focused* displayed clearer tendencies than the cards chosen for the 0:100 ratio. This setting, with diffuse lighting only, was evaluated as the brightest and the most formal, unnatural and clinical. Less clear tendencies were identified with the cards *sufficient* and *pleasant*, as they were chosen slightly more frequently as the direct lighting ratio increased, while *unnatural* and *clinical* were the highest for the lower ratios.

Based on these findings, one can conclude that adding directional lighting to a traditional diffuse ceiling lighting in an office environment can enhance the visual appearance of objects as well as the perceived atmosphere. However, this must

be balanced to avoid to high contrasts. More evidence is needed to define the qualities of the perceived atmosphere and to be able to evaluate the long-term effects of lighting, which are not addressed in this study.

4. Part 2

Part 2 addresses the second objective of the research question. Which correlated color temperatures can be combined with a direct:diffuse ratio to enhance the visual appearance and perceived atmosphere in an office environment, referring to the qualities of the flow of light?

4.1. Setup

In this part of the experiment, different CCTs of direct:diffuse electrical lighting components were investigated in relation to two contrasting daylight conditions: overcast and clear sky. The daylight inflow in the space was addressed as an equal component contributing to the space's luminous condition. These two sky conditions reference the CIE3 and CIE13 sky types (Tregenza and Wilson 2011), which were investigated in relation to light-modeling qualities (Hansen and Mathiasen 2019).

The electrical lighting components, the directional spotlights and the diffuse ceiling panels were programmed with a fixed ratio of 40:60 on the task area, based on the findings from part 1. The light settings were designed to meet the 500 lx level on the task area (defined as an area in the middle of the long side of table and at 1/3 of width of the table) and a minimum of 300 lx in the

immediate surroundings (measured at the edges of the table). These were defined according to lighting for work places in European Standard EN 12464-1. A minimum daylight intake of 50 lx was defined and measured on the task area of the table, located furthest from the door and windows, see Fig. 1. The lumen outputs were controlled by measuring the illuminance with a Hagner EC1 Luxmeter, as done previously, in the first part of the experiment. The CCT values were defined as high, perceived as cool (C) (5800 K), medium, perceived as neutral (N) (4200 K) and low, perceived as warm (W) (3300 K). Five light settings were composed (see Figs. 6 and 7) and programmed using the Litecom interface to address the chosen intensities and color temperatures. The room specifications, including the surface reflectance values, can be found in section 2.2.

The tests were carried out on six days, between 23 April and 9 May 2019 between 9 a.m. and 12 p.m., eliminating the possibility of direct sunlight entering the southwest-facing windows. Three of the days were with overcast, and three days had clear sky conditions.

Eighteen daylight measurements of light intensity with a Hagner EC1 Luxmeter and of color temperature with an AsenseTek Lighting Passport (ALP-01) were carried out during four out of the six testing days. Half of the measurements were under overcast conditions, and the other half were under clear sky conditions. The measurements were taken at the task area of the participant's table (see Fig. 1), located by the wall, furthest from the door.

On average, the daylight values were 176 lx and 6310 K during clear sky conditions. The lowest illuminance was 112 lx, and the maximum was 278 lx. The CCT values ranged between 5825 K and 6965 K. The average values under overcast days were 156 lx and 6143 K. The lowest illuminance was 40 lx, and the maximum was 253 lx. The CCT values were between 5819 K and 6618 K (see Table 4 for reference). The modest contrast in variations of lux levels and CCT across the sky-types, measured in this experiment, should be considered when validating the sky-type variable. In future studies, daylight CCT is proposed to be measured in several areas of the room and on different surfaces to achieve higher accuracy.

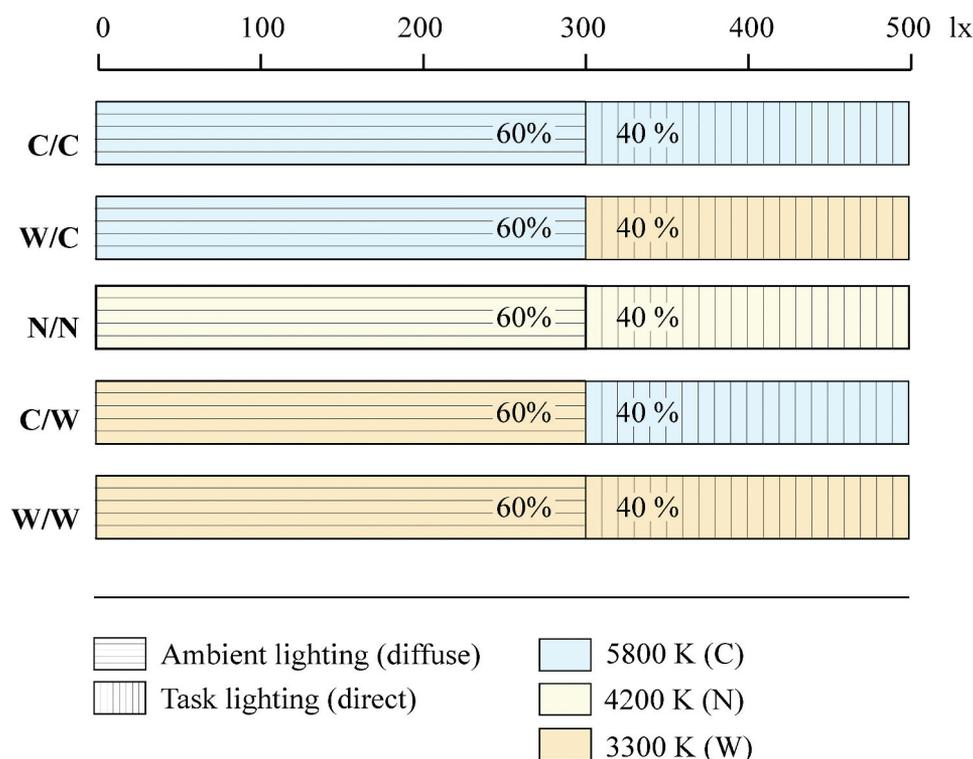


Fig. 6. Light settings in part 2 and their combined high, neutral and low CCTs in terms of direct:diffuse lighting components.

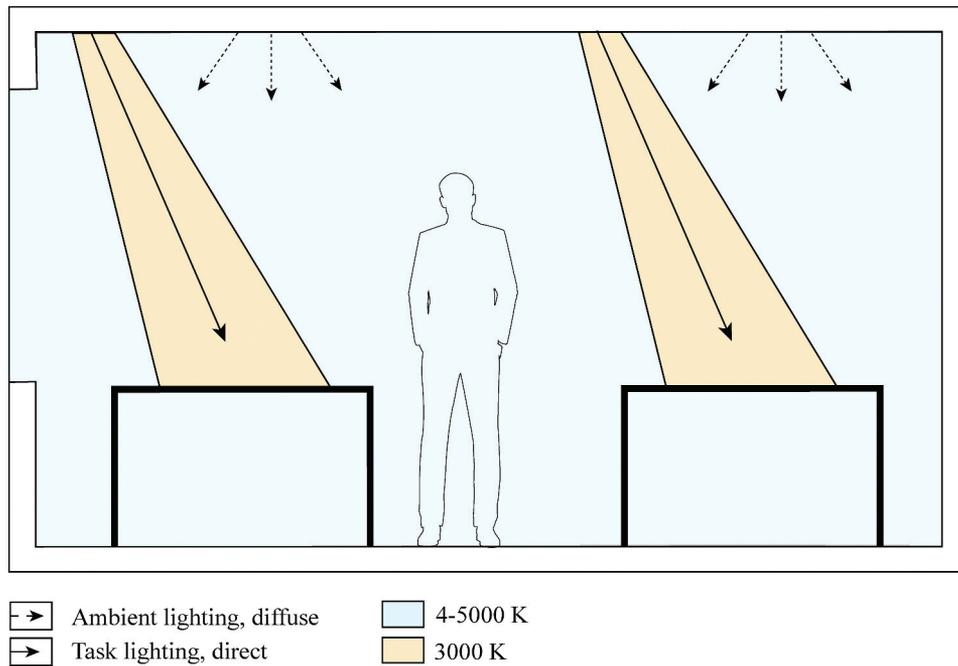


Fig. 7. Section of the laboratory office space, illustrating the W:C light setting.

Despite the nearly identical values for clear and overcast sky the view to the sky and daylight reflected from surrounding buildings can be argued to have an impact on the perceived atmosphere in the space and thereby influence the choice of electrical lighting settings. The sky conditions were photographed by the participant's desk one minute prior to every test, to document the daylight conditions and to ensure the accuracy of sky-types. When overcast nor clear sky could be detected, the test was not carried out. Daylight is dynamic by nature, and the variations in the data represent that even in short time periods, the sun's position and the thickness and spread of the cloud coverage can affect the intensity and color of the perceived light in indoor spaces. Although general patterns remained, overcast sky conditions had lower intensity and CCTs, while clear sky

conditions had higher intensity and CCTs. Each of the 15 participants conducted one individual test under overcast conditions and one test in clear sky conditions, 30 tests in total.

The photographs represent how the light distribution in the space and the light modeling of objects can be perceived. The variation in tunable white was the most visible factor, with cooler variations on the wall surfaces under the C:C and W:C light settings and warmer tones in the C:W and W:W settings. On the other hand, the warmer tones to the objects were detected under the W:C, C:W and W:W lighting settings. These registrations were aimed at providing an overall expression of the space's luminous conditions; however, the subjective experience is best presented when one is present in the space. [Figure 8](#)

Table 4. CCT output values for the direct and diffuse lighting components and measured combined values at the table, with and without daylight. In the W:C light setting, interreflections (such as from the blue office chairs) contributed to the high CCT value.

Light settings	Direct	Diffuse	Combined (no daylight)	Clear sky (7023 K)	Overcast (5966 K)
C:C	5800 K	5800 K	5894 K	6066 K	5916 K
W:C	3300 K	5800 K	4800 K	4927 K	4796 K
N:N	4200 K	4200 K	4240 K	4593 K	4451 K
C:W	5800 K	3300 K	4131 K	4496 K	4309 K
W:W	3300 K	3300 K	3345 K	3719 K	3559 K



Fig. 8. Photo registrations, on an overcast day, of the light modeling of objects on the table and the light distribution in the office space for the five settings in part 2. From left to right: C:C, W:C, N:N, C:W and W:W.

4.2. Results of part 2

4.2.1. Preferences

The results of the most favored light settings demonstrated a large variation in preferences (see Table 5). Specifically, 80% of the participants did not choose the same first preference within the two daylight conditions, which could indicate that daylight's characteristics affect the preference for a color temperature of electrical lighting.

Under **overcast** conditions, the most favored setting was N:N (27%), followed by W:W (23%), W:C (20%) and C:W (20%). The C:C setting (10%) was the least preferred. The preferences for light settings in the overcast condition did not provide sufficiently clear data on the most favored setting. However, the C:C light setting was ranked lower than the others were and can be excluded from being the most favored. Under the **clear sky** conditions, the most favored settings were C:W (30%) and N:N (23%), followed by W:C (20%) and W:W (20%). The C:C setting (7%) was also the lowest ranked in this daylight condition.

It can be concluded that the C:C setting was the least favored light setting under both daylight conditions. The variation in preferences for the other four light setting provided indications but no clear conclusions.

4.2.2. Reaction cards

Identical reaction cards to those used in part 1 were applied to this part of the experiment. The participants were asked to choose up to three cards out of 30 that best described the light settings. The frequencies of the cards being selected were used to evaluate the perceived atmosphere and visual appearance.

The reaction cards chosen for the **clear sky** conditions (see Table 6) illustrate how the visual appearance cards *natural* and *unnatural* are related to the settings. To describe the C:W setting 40% of the participants chose the card *natural*, while 33% of the participants described both C:C and W:C as *unnatural*. This supports the approach of using direct, warm task light and cool, ambient light when referring to natural daylight elements, whereas the opposite – cool direct and warm ambient light – is perceived as unnatural.

The perceived atmosphere cards demonstrated the warm light setting, W:W, to be *coziest* by 47% and most *relaxed* by 40% of the participants, followed by the C:W setting providing warm ambient lighting, while the cool lighting, C:C, was experienced as *clinical* by 60% of the participants.

Under **overcast** sky conditions, the C:C setting was ranked highly in terms of negative cards in both visual appearance and perceived atmosphere. The visual appearance cards revealed that the N:N

Table 5. Preferences (first and second choice combined) for the different light settings under the overcast and clear sky conditions.

Light settings	C:C	W:C	N:N	C:W	W:W
Direct:diffuse CCTs	5800:5800 K	3300:5800 K	4200:4200 K	5800:3300 K	3300:3300 K
Clear sky	2 (7%)	6 (20%)	7 (23%)	9 (30%)	6 (20%)
Overcast	3 (10%)	6 (20%)	8 (27%)	6 (20%)	7 (23%)

Table 6. Overview of the top 10 reaction cards chosen in part 2 under clear sky conditions.

Light settings	C:C	W:C	N:N	C:W	W:W
Direct:diffuse CCTs	5800:5800 K	3300:5800 K	4200:4200 K	5800:3300 K	3300:3300 K
Total reaction cards	45	45	45	45	45
Visual appearance cards					
<i>Pleasant</i>	2 (13%)	3 (20%)	3 (20%)	3 (20%)	4 (27%)
<i>Comfortable</i>	2 (13%)	2 (13%)	2 (13%)	3 (20%)	3 (20%)
<i>Natural</i>	1 (7%)	6 (40%)	3 (20%)	2 (13%)	0
<i>Bright</i>	1 (7%)	2 (13%)	1 (7%)	3 (20%)	3 (20%)
<i>Unnatural</i>	5 (33%)	2 (13%)	1 (7%)	5 (33%)	4 (27%)
<i>Unpleasant</i>	4 (27%)	2 (13%)	4 (27%)	3 (20%)	2 (13%)
<i>Uncomfortable</i>	4 (27%)	0	2 (13%)	1 (7%)	1 (7%)
Perceived atmosphere cards					
<i>Cozy</i>	0	2 (13%)	3 (20%)	2 (13%)	7 (47%)
<i>Relaxed</i>	1 (7%)	2 (13%)	0	3 (20%)	6 (40%)
<i>Clinical</i>	9 (60%)	4 (27%)	2 (13%)	3 (20%)	0

setting, with neutral ambient and task lighting (4000 K), was the highest ranked for three cards: *pleasant* (53%), *comfortable* (47%) and *natural* (33%). The W:W setting was ranked highest as *relaxed*, by 27% of the participants.

One can conclude that different combinations of color temperatures can enhance a space's visual appearance and perceived atmosphere in response to the luminous conditions, such as by creating a more appealing work environment described as natural, comfortable and pleasant. The W:C setting in clear-sky conditions was rated as the most *natural*, whereas the N:N setting was the most *natural* and *pleasant* of the overcast conditions.

4.2.3. Interviews

In the content analysis of the interviews concerning the settings under **clear sky** conditions, the W:C setting with cool ambient lighting and warm task lighting showed the highest score, with 67% of the opinions being positive; see Table 7. This setting was followed by the W:W (60%) and N:N (35%) settings.

One participant described the W:C setting as follows: “The light in the ceiling is similar to the light that comes in from the windows: bright and contrasting, because of the light in the ceiling and the light from the windows ... The light on the table is softer ... The light in the ceiling is like a

reflection of the light from the windows” [TP231]. Another participant stated, “I think this is the setting where I most forget that the light is turned on. It's sort of in the background, and I sort of forget about it ... I'm a bit light sensitive, and this is the one I think felt most natural to me” [TP219]. A few participants expressed the feeling of a light-zone in this setting: “Natural and task-focused, because I see that there is an island of light here – that is a warmer color.”

In contrast, the least favored setting was C:C under clear sky conditions, which was described as follows: “I think it's a little too white and too cold. It's something you would expect in an unnatural environment ... It's something clinical that doesn't have anything to do with the natural light outside. You could find this kind of lighting in a room without windows, like in a hospital” [TP215].

In the content analysis of the interviews concerning the settings in **overcast** sky conditions, the most favored setting was N:N with neutral ambient and task lighting, followed by W:C with cool ambient and warm task lighting. The N:N setting was described as follows: “It's bright and comfortable. It's definitely my favorite. The lighting makes it brighter in here, but in a natural way, I think. And comfortable, in a way that it's just nice to be in here” [TP235]. On the contrary, the W:W

Table 7. Content analysis results of positive opinions in relation to the different lighting settings.

Lighting settings	C:C	W:C	N:N	C:W	W:W
Direct:diffuse CCTs	5800:5800 K	3300:5800 K	4200:4200 K	5800:3300 K	3300:3300 K
Clear sky	26,6%	67%	53%	33%	60%
Overcast	20%	73%	80%	60%	60%

setting was described as follows: “It’s very warm for me, this kind of yellow-orange. It’s nice, but I don’t think it’s natural. It’s very relaxing, but not for working” [TP235].

Content analysis proved to be a valuable method of evaluating the perceived atmosphere and qualities of the light settings (see Table 7). The interviews referring to the selected reaction cards allowed the test participants to express their experience of the combinations of CCT in the lighting settings, as reflected in their subjective evaluations of being in the space in relation to the daylight inflow and a natural atmosphere. The researcher coded and evaluated the statements as positive or negative. The results of the content analysis in Table 8 enable one to compare lighting settings and sky conditions, and to form some evidence for the most suitable combinations. The data suggest excluding the C:C lighting settings for both daylight conditions and the C:W setting under clear sky conditions.

4.3. Part 2: Summary

In part 2, the CCTs were combined with a direct:diffuse ratio in clear and overcast sky conditions, to study an office environment’s visual appearance and perceived atmosphere. The analyses revealed that the C:C light setting with the cool ambient and cool task lighting was the lowest performing lighting setting under both overcast and clear sky conditions, in all three types of analyses. The four other lighting settings are proposed to be applied in future research, where the accuracy of sky-type documentation and CCT measurements can

confirm the results of this study. It can be deducted, that there are indications of varying preference and need for various CCT combinations, dependent on the character of the daylight inflow in a space, however the following results are to be addressed as indications.

The analyses suggested following findings under **clear sky** conditions: The preference for light settings did not indicate valid findings, as the choice of settings was diverse. The clearest findings from the reaction cards were for the C:C, W:C and W:W settings. The C:C setting was characterized with negative reaction cards such as *unnatural* (33%), *uncomfortable* (27%), *unpleasant* (27%) and the perceived atmosphere card *clinical* (60%). The W:W setting was ranked highest for *relaxed*. For the W:C setting, combining warm task light and cold ambient light, 40% of the participants described it as *natural*, while 33% of the participants described both the C:C and C:W settings as *unnatural*.

The content analyses of the interviews demonstrated that the W:C setting, with cool ambient and warm task lighting, was the highest ranked, with 67% positive opinions. According the reaction cards, the W:W setting was found to be *cozy* (47%) and *relaxed* (40%) in terms of the choices of reaction cards, and participants called it unsuitable for an office environment. Based on these findings, one can conclude that the W:C and N:N settings are implied to create the most *pleasant* and *natural* electrical lighting design, with daylight inflow under clear sky conditions.

The analyses suggested the following findings under **overcast** sky conditions. The differences in the preference results were too small to be significant. In the selection of reaction cards, the N:N

Table 8. Overview of the top 10 reaction cards chosen in part 2 under overcast conditions.

Light settings	C:C	W:C	N:N	C:W	W:W
Direct:diffuse CCTs	5800:5800 K	3300:5800 K	4200:4200 K	5800:3300 K	3300:3300 K
Total reaction cards	45	45	45	45	45
Visual appearance cards					
Comfortable	0	6 (40%)	7 (47%)	4 (27%)	5 (33%)
Pleasant	0	5 (33%)	8 (53%)	3 (20%)	4 (27%)
Natural	2 (13%)	4 (27%)	5 (33%)	2 (13%)	1 (7%)
Sufficient	2 (13%)	4 (27%)	3 (20%)	4 (27%)	1 (7%)
Bright	0	5 (33%)	5 (33%)	2 (13%)	0
Unnatural	2 (13%)	1 (7%)	1 (7%)	2 (13%)	6 (40%)
Unpleasant	6 (40%)	1 (7%)	1 (7%)	2 (13%)	0
Uncomfortable	5 (33%)	1 (7%)	1 (7%)	0	2 (13%)
Perceived atmosphere cards					
Clinical	7 (47%)	2 (13%)	1 (7%)	2 (13%)	0
Relaxed	1 (7%)	1 (7%)	3 (20%)	2 (13%)	4 (27%)

setting received the highest number of selected positive visual appearance cards, such as *comfortable* (47%), *pleasant* (58%), *natural* (33%) and *bright* (33%). In addition, in the content analysis of the interviews, the N:N setting was the highest ranked, with 80% of the participants having positive opinions about this setting. This was supported by their card choices, characterizing the N:N setting the highest for the cards *pleasant* (53%) and *comfortable* (47%). It is implied that the N:N setting was found to be the most pleasing. Based on these findings, it is suggested that the N:N setting can create the most pleasant and natural electrical lighting design, with daylight inflow under overcast sky condition.

In lighting research today, where daylight inflow is addressed as different sky-types, paired and evaluated in relation to different electrical lighting settings is a narrow subject with modest research in the field. The findings in this paper are addressed as indications. However, a large-scale research study in office environment, over a year, carried out in mid 90s in the Netherlands, shows similar tendencies, demonstrating results of variations of color temperature preference with an average of 6000 K under clear sky and 5300 K under overcast sky (Begemann et al. 1997).

5. Conclusion

The aim of this study was to investigate if the qualities of the flow of light, i.e. a balance of radiation from direct warm sunlight and from diffuse cool skylight, can inspire the future development of a new indoor dynamic lighting design concept. A full-scale experiment was conducted in two parts to answer the following question: What ratio of direct to diffuse lighting with respective correlated color temperatures can be combined to enhance an office environment's visual appearance and perceived atmosphere, in reference to the qualities of the flow of light?

Four direct spotlights, one for each table, with a 36° beam angle and a 32° tilt angle, resembling the directionality of daylight inflow, were added to the diffuse ceiling panels, and an experiment was conducted in an office environment. Firstly, different ratios of direct to diffuse light were tested to investigate the perceived qualities of the flow of

light. An increased ratio of direct lighting decreased the perceived brightness and evenness of the lighting with high significance and effect size, contributing to confirming the hypothesis that the participants would identify differences in diffuse:direct lighting in comparison to only diffuse lighting. The settings with 30% and 45% direct light created increased preference for socializing, indicating correlations with different lighting settings and tasks. Discomfort from glare, however, increased alongside decreasing preferences for visual tasks, such as reading and writing, particularly when 45% of the lighting was direct.

The atmosphere was perceived as *unnatural* and *clinical* by 43% of the participants for diffuse lighting only, in comparison to 13% and 27% for the 45% direct lighting setting. Similar trends existed among the visual appearance terms *bright*, *formal* and *task-focused*.

These data, from a modest test group, show detectable patterns that could be used for implementation of future tests. Based on the findings in part 1, directional lighting is recommended to be more than 15% of the total light to create light-zones at work planes and to contribute to light modeling of objects. This study also implies that having less than 45% of lighting be directional is recommended to avoid discomfort from glare for visual tasks. These results correspond with Fleischer et al. (2001a) defining 50:50 as the maximum ratio for direct light, Houser et al. (2002) stating that 40:60 is favored and recommending approximately 40:60, despite that these results are based on direct vertical light.

In the second part of the experiment, low, neutral and high CCTs for respective direct versus diffuse lighting settings were tested under clear sky with no direct sunlight and overcast sky conditions. The results of the analyses regarding the sky and daylight conditions are proposed to be confirmed in future research, with higher accuracy of documentation of the CCT measurements in the space in relation to sky-types. However, the results of the experiment indicate the potentials of combining CCT's, through the following indications:

The light setting with cool ambient diffuse and cool directional lighting had the lowest results in both sky conditions. Under the clear sky

conditions, the warm directional lighting and cool diffuse ambient lighting (W:C) setting was perceived as the most *natural*. The same setting was also ranked highest in the content analysis of the interviews in terms of positive opinions. On the contrary, for the opposite setting, with cool directional and warm ambient lighting (C:W), the card *unnatural* (33%) was frequently most chosen, although it remained the most preferred setting under overcast conditions. This illustrates that even though warm directional and cool ambient lighting was perceived as natural, other CCT combinations were also preferred in the test context, acknowledging a need for future research about individual needs and preferences. One can conclude that there is a tendency to prefer cool and neutral ambient lighting and warm task lighting under clear sky conditions.

Under the overcast sky conditions, the neutral direct and neutral ambient lighting setting was ranked highest across the analyses, but with too low variance to make this valid. The content analysis revealed the largest amount of positive opinions (80%) for the N:N setting. In terms of reaction cards, the N:N setting was also ranked highest for the cards *pleasant* (53% of the participants) and *comfortable* (47%). One can conclude that the N:N light setting was found to be the most suitable for future studies on office lighting with daylight inflow from overcast sky conditions. Additionally, a tendency exists toward warm directional task and neutral diffuse ambient lighting being preferred under clear sky conditions.

Furthermore, regarding the perceived qualities of the flow of light, a balance of radiation from direct warm sunlight and diffuse cool skylight can inspire new design concepts for indoor dynamic lighting. The results indicate that adding directional lighting that complements the daylight inflow, composed of different color temperatures and ratios, can affect and enhance a space's visual appearance and perceived atmosphere. Thereby, dynamic lighting as a tool can contribute to a more natural, pleasant and motivating work environment. The experiments demonstrated the potential for using direct warm sunlight and diffuse cool skylight as an inspiration for future

dynamic lighting by responding to the character of daylight and bringing the qualities of natural light into the office environment.

Based on the findings from this specific test environment, the following **design recommendations** are defined:

- The direct flow of light on the task plane with an app. 30° tilt angle should be above the ratio of 15:85 and less than 45:55.
- Combine respective CCTs of the direct flow of task light and the ambient diffuse light responding on different sky conditions. There are indications, that warm (app. 3300 K) direct light and cool (app. 5800 K) diffuse light are perceived as the most natural conditions and are preferred under clear sky conditions and that neutral (app. 4200 K) diffuse ambient and direct task light are preferred under overcast sky condition.

6. Discussion

The design recommendations must be understood as a concept referring to this specific setup. The direct-to-diffuse light ratio will always be context specific since factors such as reflectance from horizontal and vertical surfaces will contribute to the perception of overall brightness (Houser et al. 2002). The tilt angle of the directional lighting has been separately evaluated, and no negative effects were registered in this study. The recommendations were applied as the basis of the design criteria for the second part of the experiment.

The use of the reaction cards to study the perceived atmosphere was most successful, when combined with semi-structured interviews and content analysis as done in part 2, stressing the difficulty for the test-takers to rank their preferences for different lighting settings with little variations in data. In contrast, the interview format enabled the participants to elaborate on how the objects and the space appeared and how they experienced the atmosphere. For future research on the perceived atmosphere, the use of reaction cards can be improved by defining fewer words with more distinctive opposite definitions.

7. Future work

This study reveals strong individual preferences for lighting, especially as demonstrated in Part 2, when comparing the different combinations of the color temperatures. Future research could expand the potential of applying the qualities of the flow of light in a personalized light-zone by providing individual control over the task lighting, while the ambient lighting would respond to the quantity and character of the daylight inflow.

Based on the findings from this study, an experimental field study will be designed for future testing of the direct-to-diffuse lighting setting ratio with different CCTs, responding to two parameters: changes in daylight level and the two sky conditions: clear and overcast. The double dynamic lighting concept has been tested over four months, during the fall and winter of 2019. The aim was to investigate if the design recommendations and criteria identified through this experiment can be implemented in dynamic lighting contexts and influence work motivation and engagement for future creative work environments.

Finally, by developing this complementary response to daylight conditions and individual needs, the double dynamic lighting concept has an important potential for optimizing energy use for electrical lighting in future offices and other buildings.

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Appendix 1

Table A1. Questionnaire results, showing each mean value (M), standard deviation (SD), standard error (SE), t-value (t), effect size (ES (r)) and p-value (p) for significance.

	Scenario 1.1			Scenario 1.2						Scenario 1.3						Scenario 1.4					
	M	SD	SE	M	SD	SE	t	ES (r)	(p)	M	SD	SE	t	ES (r)	(p)	M	SD	SE	t	ES (r)	(p)
Dim - Bright	7.94	1.10	0.20	6.34	1.85	0.34	4.81	0.67	p<0.01	6.01	1.85	0.34	4.91	0.67	p<0.01	4.15	1.66	0.31	12.44	0.92	p<0.01
Uneven - Even	7.38	1.86	0.34	6.41	2.15	0.40	2.01	0.35	p<0.05	5.96	1.91	0.35	2.89	0.47	p<0.01	4.19	1.89	0.35	6.94	0.79	p<0.01
Vague shadows - Distinct shadows	4.41	2.10	0.39	5.06	1.79	0.33	-1.27	0.23	p>0.10	5.50	1.99	0.37	-1.94	0.34	p<0.05	6.41	1.92	0.36	-3.89	0.59	p<0.01
Not at all - Very well	6.03	2.17	0.40	5.82	1.82	0.34	0.44	0.08	p>0.10	5.76	1.91	0.35	0.51	0.09	p>0.10	5.79	2.16	0.40	0.43	0.08	p>0.10
Uncomfortable - Comfortable	5.32	2.10	0.39	5.98	1.99	0.37	-1.31	0.27	p>0.10	5.70	2.13	0.40	-0.76	0.14	p>0.10	6.28	1.77	0.33	-1.57	0.28	p>0.10
No glare - Glare	5.62	1.92	0.36	6.07	1.53	0.28	-1.03	0.19	p>0.10	6.69	1.78	0.33	-2.61	0.44	p<0.01	6.90	1.77	0.33	-2.74	0.45	p<0.01
Unnatural - Natural	4.86	2.27	0.42	4.90	2.04	0.38	-0.07	0.01	p>0.10	5.00	2.11	0.39	-0.28	0.05	p>0.10	5.19	2.10	0.39	-0.60	0.11	p>0.10
Formal - Cosy	3.07	2.10	0.39	3.95	1.60	0.29	-2.04	0.35	p<0.05	3.81	2.27	0.42	-1.41	0.25	p>0.10	5.41	1.54	0.29	-4.93	0.68	p<0.01
Dull - Interesting	4.50	2.21	0.41	5.17	1.59	0.29	-1.81	0.32	p>0.10	5.03	2.25	0.42	-1.01	0.18	p>0.10	5.43	1.67	0.31	-1.69	0.30	p>0.10

Table A2. Overview of questions, divided into three categories: visual comfort, perceived atmosphere and work engagement. All months are showing dynamic and static periods with mean values and standard deviations.

Month	September		October		November		December												
	Static	Dynamic	Static	Dynamic	Static	Dynamic	Static	Dynamic	Control										
Week nr.	36-37		38-39		42-43		40-41		45-46		47-48		51-52		49-50		49-50		
Mean / Standard Deviation	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD	
Visual Comfort																			
1.1 During this week, the lightning has been good for carrying out my work tasks.																			
1.2 During this week, I have experienced discomfort caused by the electrical lighting.																			
1.3 During this week, I have experienced discomfort caused by daylight.																			
Perceived atmosphere																			
2.1 During this week, the electrical lighting in the space has had a positive impact on the work atmosphere.																			
2.2 During this week, the combination of daylight and electrical lighting has felt natural for me.																			
2.3 During this week, the electrical lighting has been stimulating for my work.																			
2.4 During this week, I have been feeling comfortable being in the room.																			
Work engagement																			
3.1 During this week, my work performance has been good.																			
3.2 During this week, I have been feeling motivated to work.																			
3.3 During this week, I have produced some novelty/innovative ideas.																			
3.4 During this week, I have been feeling concentrated on my work.																			
3.5 During this week, I have had a good workflow.																			
3.6 During this week, I have been willing to take risks in my work tasks.																			