Measurements of spectral daylight variation in spaces: A case study

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Abstract. This study investigates spectral daylight quality measured in a classroom within a time span of 30-minutes under clouded sky conditions. There is a characteristic difference between vertical and horizontal measured values, where the traditional vertical measurements tend to have greater peak wavelength irradiance reduction. The findings show the importance of considering multi-directional views when considering visual and non-visual light effects. The study indicates that spectral variations and spatiality should be considered when evaluating daylight, in contrast to the static methods commonly used to evaluated the quality of daylight in buildings. The study underscores the need for simulation tools and material databases to enhance the realism of spectral simulations and ultimately contribute to a more effective approach to indoor daylight quality, prioritizing occupant well-being.

1 Introduction

Indoor environments profoundly impact human health and well-being, given that we spend a substantial portion of our lives indoors [1]. The evolving trend towards compact building designs and centralization poses challenges in meeting daylight criteria in new construction projects [2, 3]. Daylight is not merely an illuminator but a complex, spectrally dynamic light source that plays a pivotal role in regulating several human factors [4]. With the discovery of intrinsically photosensitive retinal ganglion cells [5], other non-visual effects of light have been considered, such as circadian rhythm, sleep quality and alertness impacting essential brain chemicals like melatonin and serotonin [6, 7].

Light effects on humans can be set in the three categories: visual performance, psychological light effects, and non-visual light effects. These categories are influenced by a chain of signal processing from the optical and temporal input parameters to the light users with influencing parameters to the output parameters [8]. The spectral composition of daylight significantly influences these factors and present building practice and codes do not account for the spectral composition of daylight. Glazing systems are predominantly assessed based on total light transmittance rather than spectral transmittance and light quality. Ideally, there are several other factors that should be considered such as, the spectrality of the light source, spectral transmittance into a room, spatial variation of daylight inside a room with regards to eye position and the sensitivity of the field of view, accounting for focus and depth.

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In past research, it was believed that a vertical illuminance (i.e. light that shines vertically and enters the pupil at eye level) of 2500 lux was required to suppress nocturnal melatonin in humans [9]. However, it has been found that illuminance at lower wavelength levels and in some cases less than 1 lux directly impact our melanopic response [10]. Timing of photic administration can also significantly alter both the magnitude and direction of circadian phase shifting by light [11].

The International Commission on Illumination (CIE) have developed methods to quantify the biological effect of lighting on humans using Melanopic Equivalent Daylight Illuminance (m-EDI) and Melanopic Daylight Efficacy Ratio (m-DER). m-EDI is a measure of the melanopic content of light. It's often expressed in terms of equivalent illuminance with the units of lux. m-DER is a measure of how effectively daylight stimulates the melanopsin photoreceptors compared to a reference illuminant [8]. Similar issues have been addressed in the WELL Building Standard using Equivalent Melanopic Lux (EML) for evaluating the melanopsin action spectrum. EML is weighted to the response of the retinal ganglion cells, rather than the cones, which is the case with traditional lux. It is measured by multiplying photopic illuminance (daytime eye sensitivity) by a melanopic ratio [12].

The scarcity of simulation tools that consider spectral data remains a significant hurdle in comprehensively assessing daylight quality in buildings. However, some simulation platforms have introduced light spectrality in their procedure. OWL, ALFA and Lark are lighting software which offers spectral simulations integrated in Rhinoceros 3d, utilizing Radiance and can output non-image forming effects of light [13, 14]. The software are similar and mainly differ in the way the sun and sky are represented, recently Lark v3.0 have been able to integrate more accurate and sky models [15]. All platforms have richer colour information of the context and represent physically accurate colour perceptions when compared to non-spectral standard RGB daylight simulations. It has been found that Lark outperforms ALFA in most cases [16, 17]. As simulation tools improve in quality and physical complexity, it is possible to include the influence of design parameters, choice of materials, and use of colours on the spectral quality of indoor daylight. However, this field of building physics is still in an immature state, especially when it comes to physically accurate material libraries and sky models [18].

In the contemporary evaluation of daylight in indoor environments a static daylight factor metric is often used, which is based on a single overcast sky condition and it is independent of climate, building orientation, and building use [4]. In addition, today’s approach, based on EN 17037:2018, involves measuring and simulating daylight on a horizontal plane facing upwards at 0.85 m height, not considering the reflected light on to the human eye. There is also a lack of methods and studies about the applicability of current daylight standards such as the EN 17037:2018 in specific local contexts, especially in high latitudes and cold climates [19]. These factors and methods may overlook a crucial aspect of human experience, as individuals are not static entities fixed in a single orientation or working on a flat surface such as a desktop or a working plane. Data analysis also suggest the psychological importance of surface and light colour sources on human behaviour. [20, 21]. It has also been shown that diffuse daylight only has a modest impact on the melanopic performance of a space while the direct solar component plays a dominant role [22]. Skies have significant variations for spectra across the sky dome [23].

2 Method

This study examines spatial variations of spectral composition of daylight inside a classroom. The data is obtained by measurements in a real in-use classroom using a spectrometer, camera and irradiance sensors. The measurements were conducted 15th of November 2023 between 11.25 to 11.55 AM. The room used in the present paper is located in Ås, Norway (59.67 N;
10.78 W) and a technical layout is illustrated in Fig. 1. The dimensions of the classroom are; length: 12 m, width: 10 m and a height 3.8 m. The classroom is a side-lit space with 2 large apertures (1.2 x 4.9 m) in the facade, facing towards North, situated on the second floor. Shading devices and electrical light where not activated during the monitoring, and the building is without significant roof overhang. The room is used for various educational activities, including face to face teaching classes and practical sessions.

![Fig. 1. A horizontal section of the classroom, showing position of and labelling placement of measurement.](image)

2.1 Spectral measurements

A UPRtek MK350S Premium spectrometer was used for spectral measurements. 5 measurements with an interval of 10 seconds were conducted for each measurement position and direction. Vertical measurements were conducted at work plane height 0.85 m (Position 0, 1a and 2a in Fig. 1) and horizontal measurements was conducted at seated eye height 1.2 m (Position 1b-e and 2b-e in Fig. 1). Measurements were taken 2 m (Position 1) and 6 m (Position 2) from the aperture. Outdoor measurements were also conducted before and after the indoor measurements. Automatic integration time was used based on light level ranging from 1.4 to 480ms. Dark calibration was performed before measurements and when moving from outside and inside.

2.2 Visual measurements

Compact digital camera Olympus Tough TG-5 with a 4.5-18.0 mm lens was also used. This was placed above and oriented in the same direction as spectrometer. The sensitivity was set to ISO 250 and the white balance to “Sun”-setting. The focusing mode was set to manual, and the focus checked/adjusted for sharpness once the camera was in position. One picture was taken for each location and direction, matching the spectral measurements.

2.3 Sky conditions

Radiation was measured during the measurements at Ås weather station 785 m south from the test site with a sampling period at 10 minutes intervals.
3 Results

The measurements were conducted over a 30-minute period. The outdoor sky conditions consisted of an overcast sky and underwent slight changes during the measurement period, with lux values decreasing from 8590 lux (0a) to 6790 lux (0b). The spectral values remained consistent up to a wavelength of 450 and then exhibited a noticeable separation, as illustrated in Fig. 2a, average values is further used in this study. A photograph is highlighting the difference between the two sky conditions is presented in Fig. 2b and Fig. 2c.

![Figure 2a](image1)

![Figure 2b](image2)

![Figure 2c](image3)

**Fig. 2.** Spectral sky conditions before and after the conducted measurements (a). Photo taken of the sky before (b) and after (c) the conducted measurements separated in time by 30 minutes.

Monitored radiation from the weather station also showed a slight decrease in solar radiation during the 30-minute measurement period. The development in irradiance is shown in Fig. 3, which illustrates the changes in solar radiation levels corresponding to the timeline of the measurements.

![Figure 3](image4)

**Fig. 3.** Changes in irradiance during the measurement period between 11:20 AM to 12:00 PM., measured at weather station 785 meters from the test-site.
View directions of the position 1 and 2 are illustrated in Table 1. Each row corresponds to a specific direction, and each column represents a different position. The descriptions provide an overview of what can be observed from each position in various directions, offering insights into the spatial perspectives associated with the study locations.

**Table 1.** Photos of view from position and directions.

<table>
<thead>
<tr>
<th>Direction</th>
<th>Position 1</th>
<th>Position 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vertical</td>
<td><img src="image" alt="Vertical" /></td>
<td><img src="image" alt="Vertical" /></td>
</tr>
<tr>
<td>Window</td>
<td><img src="image" alt="Window" /></td>
<td><img src="image" alt="Window" /></td>
</tr>
<tr>
<td>Whiteboard</td>
<td><img src="image" alt="Whiteboard" /></td>
<td><img src="image" alt="Whiteboard" /></td>
</tr>
<tr>
<td>Door</td>
<td><img src="image" alt="Door" /></td>
<td><img src="image" alt="Door" /></td>
</tr>
<tr>
<td>Wall</td>
<td><img src="image" alt="Wall" /></td>
<td><img src="image" alt="Wall" /></td>
</tr>
</tbody>
</table>

**3.1 Comparison of illuminance measurements**

The comparison of Lux values across different positions and directions reveals notable variations in the lighting conditions within the studied indoor environments. As shown in Fig. 4, Lux values are documented for various points of interest, including horizontal surfaces (1a and 2a), windows (1b and 2b), towards whiteboard (1c and 2c), door (1d and 2d), and wall (1e and 2e). Position 1 generally exhibits higher illuminance values than Position 2, as it is closer to the aperture and receiving more direct and indirect daylight. Illuminance values in position 2 have more uniform lighting distribution than position 1. Position 1b towards the aperture receives the highest illuminance values of 720 lux. Position 2d is receiving the lowest illuminance values of 27 lux. Compared to the outdoor conditions the vertical positions 1a and 2a receive 4.2 % and 0.6 % fraction of the average outdoor sky condition (before and after) respectively.
By averaging the horizontal illuminance (b, c, d, and e) and comparing them to the vertical illuminance (a), we observe a strong correspondence between the two sets of values, see Fig. 5. Notably, the vertical illuminance decrease more rapidly as one moves further into the room compared to the horizontal illuminance. Vertical illuminance is reduced from 315 to 46 lux (86 % reduction) and average horizontal illuminance is reduced from 293 to 53 lux (82 % reduction). In comparison to the fraction of the outdoor sky conditions the average horizontal fraction is 3.9 % and 0.7 %. This trend suggests a spatial variation varies based on viewpoint and measured directions, emphasizing the importance of considering both vertical and horizontal illuminance for a comprehensive understanding of lighting dynamics within the indoor environment.

3.2 Comparison of spectral measurements

The comparison of spectral values across various positions and view directions show nuances in the composition of light within the examined indoor space. Fig. 6 illustrates the variations in the spectral composition for position 1 closest to the aperture. All measurements having the same peak at wavelength 495 nm. Measurement 1b towards the window yielding the highest illuminance having a peak irradiance of 11.6 mW/m². Measurement 1d receiving the lowest illuminance with a lower intensity of 0.9 mW/m². It can be observed that view direction a, c and e having a rather uniform distribution ranging from 1.4 to 5.0 mW/m².
Fig. 6. Spectral composition for position 1 compared to the outdoor sky conditions (dotted line).

Fig. 7 illustrates the variations in the spectral composition for position 2. Notably, the peak irradiance within this position exhibits a more dynamic range, fluctuating between wavelength 495 and 545 nm. Two peaks can be observed at direction 2d and 2e, this likely stems from the electrical lighting in the hallway, as the frequencies correspond to those of electrical light sources there. This introduce a disturbance to the measurements, as can be seen in Table 1. Measurement 2b towards the window yielding the highest illuminance having a peak irradiance of 1.5 mW/m². Measurement 2d receiving the lowest illuminance with a lower peak irradiance intensity of 0.4 mW/m². It can be observed that view direction a, c and e have almost identical wavelength pattern ranging from 0.3 - 0.7 mW/m².

Fig. 7. Spectral composition for position 2 compared to the outdoor sky conditions (dotted line).

All datapoints are normalized to peak irradiance and gathered in Fig. 8 and Fig. 9. Ranging from start at 380 nm between 0.00 and 0.40 to peak between 460 to 550 nm and ending at 780 nm between 0.45 to 0.70.
Fig. 8. Comparison of all normalized measurements for position 1 and sky.

By averaging horizontal illuminance and comparing it to the vertical illuminance similarly to the illuminance reduction from Fig. 5, it can also be observed that the vertical reduction of irradiance from position 1 to position 2 is greater than for the average horizontal directions. Fig. 10 and Fig. 11 illustrates this shift in irradiance, we can also see that the spectral measurements is similar in shape in position 1. The greatest irradiance difference between vertical and average horizontal directions is 0.44 mW/m² (8.6 % reduction) at wavelength 483 nm for position 1 and 0.12 mW/m²(16.5 % reduction) at wavelength 485 nm in position 2.
The irradiance difference ($\Delta$) between position 1 and 2 is shown in Fig. 12. If we compare directions, it can be observed that greatest difference in irradiance occurs between wavelength 420 and 670 nm, with peak at around 492 nm. This indicates that the main spectral reduction is around the melanopic action spectrum. The greatest difference occurs for the window direction (b) with a peak irradiance difference of 10.1 mW/m² (13 % reduction) at wavelength 496 nm. This also corresponds with previous observations with illuminance. The window direction (b) has the greatest overall reduction, see Fig. 4. Vertical direction (a) has a difference of 4.5 mW/m² (13 % reduction) also at wavelength 496 nm. Door direction (d) has the greatest percentage difference of 51 % (0.5 mW/m²) at wavelength...
495 nm. It should be noted that the outdoor sky conditions changed slightly during the measurement period and the reduction for position 2 could be overestimated.

![Irradiance difference (∆) between position 1 and 2 for each direction (a-e).](image)

**Fig. 12.** Irradiance difference (Δ) between position 1 and 2 for each direction (a-e).

4 Discussion

The measurements conducted in this study provide insights into the spectral composition of daylight in an indoor environment. As illustrated in Fig. 6 and Fig. 7, variations in the spectral composition are evident, with distinct peak observed in different positions and view directions. Notably, the peak wavelength in position 1 remains consistent at 495 nm, whereas position 2 exhibits a larger range of fluctuating between 495 and 545 nm. These variations are attributed to factors such as spatial positioning and view directions. The observed reductions in spectral irradiance between wavelengths of 420 and 700 nm, with a peak at approximately 492 nm, are particularly significant in the context of circadian rhythm regulation. This range aligns closely with the melanopic action spectrum, emphasizing the potential influence of daylight spectral composition on the biological effects of light. Fig. 10 and Fig. 11 highlights a peak irradiance reduction at 496 nm in the vertical direction (a) and average horizontal direction (b-e) for both positions, suggesting a consistent impact on melanopic response.

The evaluation of daylight in indoor environments has traditionally relied on metrics like daylight factor, often based on a single overcast sky condition and measured on a horizontal surface. However, as demonstrated in this study, such metrics may overlook crucial aspects of human experience, especially in dynamic real-world scenarios. Static and vertical directed daylight measurements do not consider factors such as building orientation and user perspective. Although the measurements of average illuminance in the horizontal direction are similar to the vertical direction, the individual horizontal directions have a wide range of irradiance values compared to the single vertical direction. This spatial variance is important to evaluate when designing and regulating building projects.

Considering the viewer's perspective, measuring the horizontal light direction into the eye height, is imperative to get more comprehensive understanding of the melanopic effect of daylight in an indoor space. Daylight, as experienced by occupants, should be evaluated not only in its intensity but also in its spectral composition as perceived from eye height and in multiple directions. This shift in measurement perspective acknowledges the dynamic nature of human engagement with the built environment, ensuring that the impact of daylight on
occupant well-being is accurately assessed in diverse spatial scenarios. By incorporating eye-level measurements in various directions, we can enhance our ability to design spaces that prioritize the spectral quality of daylight, thus contributing to a more nuanced and occupant-centric approach to building physics.

The field of building physics, particularly in assessing daylight quality, faces challenges due to the scarcity of simulation tools and material databases that consider spectral data. The paper acknowledges the positive trajectory of tools such as Lark and ALFA, noting that improvements in quality and physical complexity enable a more holistic consideration of factors influencing spectral quality. Studies have shown the importance in outdoor sky models and the significance impact of the direct sun component on the melanopic effect. It is therefore important to get a better understanding of the spectral composition of the outdoor environment and how it can be more realistically incorporated in simulation software. Even if Lark has shown better results in overcast sky situations, ALFA is more accurate in clear sky conditions, which might make it a better fit for evaluating melanopic effect in buildings. While simulation tools are evolving, the challenge lies in developing comprehensive libraries that accurately represent the spectral behaviour of materials. This is crucial for simulations to provide realistic and reliable outcomes, especially in scenarios where material properties significantly influence spectral conditions.

Despite the recognized impact of the direct sun component on the melanopic effect in buildings, the prevailing practice in building performance evaluation continues to rely on the simplified daylight factor with an overcast sky. While daylight factor consists of 1 data point (overcast sky and one sensor direction) and climate based 8760 data points (annual and one direction) a spectral based method with multiple view directions can generate 14.1 million data points in comparison (annual, 4 views and 401 wavelengths). This can obviously be simplified in ways like utilizing metrics such as Equivalent Melanopic Lux (EML) but is still factors that must be considered while integrating such comprehensive databases and metrics in our tools and software. Fig. 13 illustrates different scenarios going from daylight factor (a), climate based (b) to spectral based (c) with room sensors using room centre (d), grid of sensors on the horizontal plane (e) to grid of view directions in the vertical plane (f).

Fig. 13. Illustration of data generation between different metrics (a-c) and room sensors (d-f).
In navigating the complexities of spectral daylight considerations, it underscores the pivotal crossroads between human-centric design, simulation methodologies, and the evolving landscape of building physics. As we navigate this field and delve deeper into a holistic understanding of daylight quality, a paradigm shift within daylight metrics seems necessary.

5 Conclusion

This case study addresses the spectral composition of daylight within a room. As buildings trend towards compact designs, meeting daylight criteria becomes a complex challenge. Daylight, far beyond its role as an illuminator, significantly influences psychological and non-visual factors crucial to human health. The integration of spectral considerations into methodologies, bringing spatiality of view into play and thereby a more precise user-centric focus, can lead to more effective daylight design.

The study highlights limitations in traditional evaluation metrics, advocating for a nuanced approach that considers spatial variations. Spectral measurements reveal great variations between vertical and horizontal directions, emphasizing their substantial impact on humans and circadian rhythm regulation. Navigating these complexities underscores the need for paradigm shifts in our approach to indoor daylight quality, necessitating a revision of traditional daylight metrics for a more occupant-centric design.

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