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DAYLIGHT EXPOSURE AND CIRCADIAN EFFICIENCY IN OFFICE ROOMS EQUIPPED WITH ANIDOLIC DAYLIGHTING SYSTEMS

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ABSTRACT

Anidolic Daylighting Systems (ADS) typically reduce the daylight flux reaching an office room's window section and increase it in the rear of the room. They offer interesting possibilities for the combination of comfortable daylighting and highly energy-efficient office lighting designs. The objective of this study was to get an insight into typical ocular daylight exposures in office rooms equipped with ADS and to compare them to an artificial blue-enriched light source. Results from a recent study by Viola et al. [9] demonstrated that the use of the same light source positively influenced subjective wellbeing and sleep quality in office workers. We recorded daytime irradiance values for several weeks from April-May 2009 in an experimental office setup in our laboratory using a portable digital spectroradiometer. The artificial light sources were measured during the night. With respect to more circadian aspects of day- and artificial lighting designs we finally corrected the measured irradiances with a c(λ)-curve.

Our results showed to which extent external sky conditions influenced light exposure of office workers in an ADS-equipped office room for different sky types. The considered ADS was able to supply natural blue light irradiance levels during large parts of days with intermediate and clear skies, which were much higher than those created by our artificial lighting installation based on two blue-enriched fluorescent lamps. The same was true for weighted circadian irradiance values E_{ec}. We conclude that for the tested ADS-equipped office room, complementary artificial lighting with blue-enriched polychromatic fluorescent tubes might be useful on days with predominantly overcast skies and before 09:00 and after 16:30 on all days.

INTRODUCTION

The southern front of the Solar Energy and Building Physics Laboratory (LESO-PB), located on the campus of the Swiss Federal Institute of Technology in Lausanne (EPFL), is equipped with Anidolic Daylighting Systems (ADS) [1]. These highly efficient daylighting systems typically reduce the daylight flux reaching an office room's window section and increase it in the rear of the room. Thus, glare related problems can be largely avoided and gloomy rear areas can be brightened [2]. Preliminary results in ADS-equipped office rooms within the LESO solar experimental building showed both satisfied office occupants [3, 4] and possibilities for highly energy-efficient integrated lighting solutions [4, 5]. Besides the visual comfort in ADS-equipped office rooms, it is not well understood to which extend the change in room lighting conditions

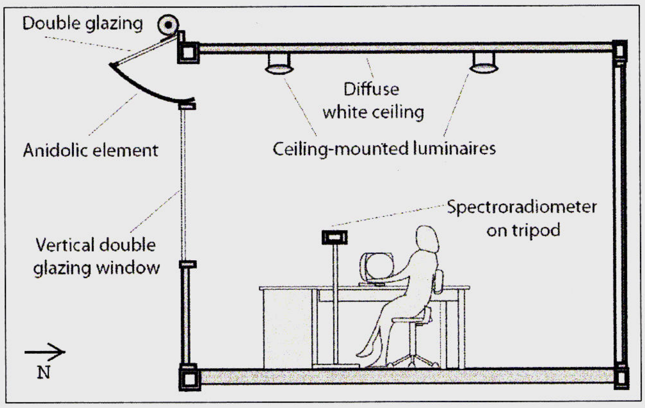


Figure 1: Overview of the experimental setup used during our measurements in spring 2009.

during daytime has an impact on the circadian rhythms and neurobehavioral performance of office occupants. Considering that many people spend a fair amount of their time inside of office rooms, this is a topic that should be taken more into consideration when designing lighting scenarios for office buildings [6, 7].

Recent research has revealed that the impact of lighting conditions on human circadian rhythms is strongly dependent not only on light intensity and timing of light exposure but also on spectral properties of the visible light. In particular, it has been shown that in humans, the circadian peak sensitivity to light as assessed by nocturnal melatonin suppression is in the blue range of visible light between 457-464 nm [8, 10].

We aimed to get an insight into typical ocular daylight exposures in ADS-equipped office rooms and to compare them to an artificial blue-enriched light source. Results from a recent study by Viola et al. demonstrated that the use of the same light source positively influenced subjective wellbeing and sleep quality in office workers [9]. As light in the blue range of the electromagnetic spectrum is most effective to influence circadian rhythms in humans, we wanted to take a closer look at the blue part of the measured ocular irradiance values, especially on its time course across a day. As a last step, we aimed to weight the measured irradiance levels with the only currently available circadian function $c(\lambda)$, which represents a circadian efficiency-curve based on data from human melatonin suppression by light [11].

METHODS

A portable digital spectroradiometer (Specbos 1201, JETI Technische Instrumente GmbH, Jena, Germany) was fixed on a tripod at the approximate eye level of an office occupant (height 115 cm from the floor; Figure 1). The spectroradiometer was installed in one of the ADS-equipped office rooms in the LESO solar experimental building. We recorded daytime irradiance values for several weeks from April-May 2009. The device was programmed to perform a complete spectral irradiance scan between 380 and 780 nm (with resolution of 1 nm) every 5 minutes. It was connected to a PC and the measured values were continuously stored after each scan. In order to classify the weather on the recorded days, we obtained meteorological data of the same period from the local weather station (Meteosuisse, Pully, VD, Switzerland), which is located at the approximate distance of 7.7 km from the LESO building.

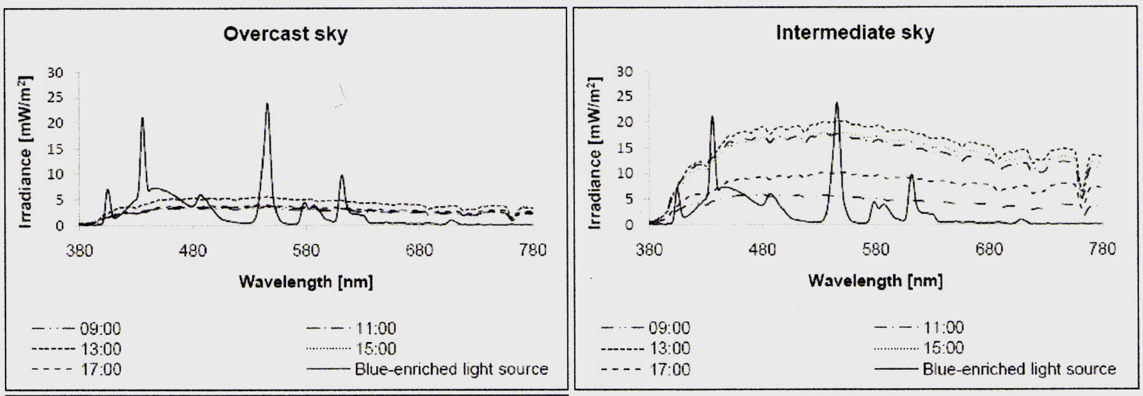
This information was used to assign one of three different sky categories to all of our recorded days: Either "overcast" (0 to 25% of sunshine / working day), or "intermediate" (25 to 75% of sunshine / working day) or "clear" (75 to 100% of sunshine / working day) sky were assigned. For the recordings of the artificial lighting, two ceiling-mounted luminaires (Tulux "Zen 3") were installed in our test office room (Figure 1). These luminaires were used to measure the ocular light exposure created by two 58 W blue-enriched polychromatic fluorescent tubes (17'000 K, Activiva active, Philips) during nighttime. The resulting horizontal illuminance on the work plane (80 cm above floor level) was 383 lx, the average vertical illuminance at eye level (i.e. the value measured through the cosine-corrected spectroradiometer lens) was 260 lx.

For the analysis of the spectral irradiance values in the blue range of the visible light, we collapsed the data obtained at 465 nm into 2h bins from 09:00 to 17:00, resulting in 4 bins averaged over the days for the same sky condition.

To obtain the c(λ)-corrected irradiance values, a weighted circadian irradiance E_{ec} was calculated from the measured spectral irradiances $E_{e\lambda}$ by using the 'circadian action function curve' (c(λ), [11]). This inverted-U shaped curve c(λ) is based on experimental findings in humans from the action spectra for light induced nocturnal melatonin suppression done by Brainard [8] and Thapan [10]. By means of this circadian action function, a weighted circadian irradiance E_{ec} can be calculated: $E_{ec} = \int E_{e\lambda}\, c(\lambda)\, d\lambda$ [11]. We used the circadian action function curve which was already implemented as selectable function in our spectroradiometer. We took into account the entire visible light spectrum between 380-780nm.

RESULTS

We recorded 18 complete working days (i.e. from 09:00 to 17:00) between March and April 2009. By means of the previously explained classification method, we obtained two days with a mainly overcast sky, nine days with intermediate skies and seven days with mainly clear skies. For visual illustration of the time course across the visible light spectrum between 380 and 780 nm, we plotted the irradiance levels at five different times of day for each sky condition (Figure 2). Plots correspond to averaged values of the corresponding days at 09:00, 11:00, 13:00, 15:00 and 17:00. The spectral irradiances obtained under artificial lighting are equally plotted on each graph for comparative reasons.



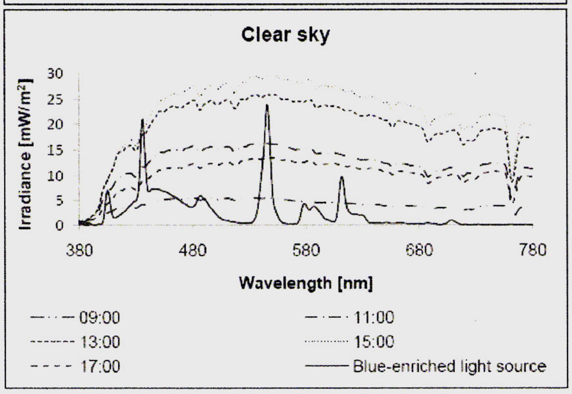


Figure 2: Irradiances at eye level in the visible range of the electromagnetic spectrum for overcast, intermediate and clear skies are shown every 2 hours from 09:00-17:00 h. In addition, the spectrum of the blue-enriched light source is plotted.

In order to investigate the blue range of visible light, the averaged irradiances values at 465 nm are plotted in four time bins across the working day for the three sky types separate (Figure 3). For comparative reasons, the resulting blue light at 465 nm obtained under artificial lighting at nighttime is also shown. A Mann Whitney U-test revealed significant differences between the clear and the overcast sky during all times ($p<0.05$) except for the morning hours (09:00-11:00). There was no significant difference between days with intermediate and clear skies. On overcast days, blue light irradiance at 465 nm was lower in the later afternoon when compared to the intermediate sky condition. The time course on days with clear and intermediate skies exhibited higher values between 11:00 and 15:00 than in the morning or later afternoon ($p<0.05$;

Friedmann-Anova). For the overcast sky there was no significant change in the irradiance level across the day.

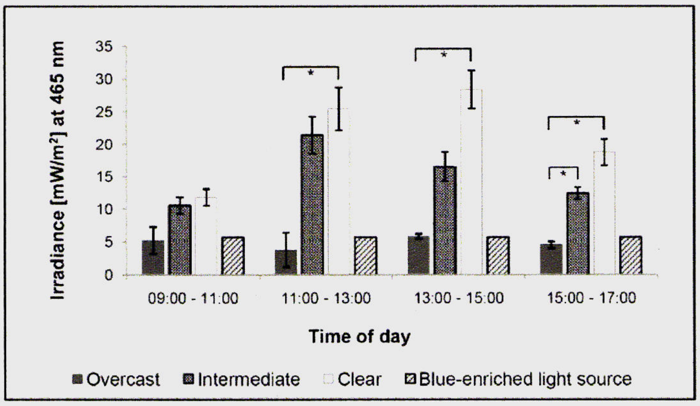


*Figure 3: Daylight irradiances (mW/m2) at 465nm for three sky types between 09:00 and 17:00. *=p<0.05; ± SE, expressed in 2h bins. The irradiance of the artificial blue-enriched light source at 465nm (during night time) is also shown.*

The c(λ)-corrected irradiances (E_{ec}) for overcast, intermediate and clear sky conditions are shown in Figure 4. The c(λ)-corrected irradiance we obtained from the artificial blue-enriched light source was 0.5032 W/m^2 in our specific setting and is indicated in Figure 4 as a vertical line.

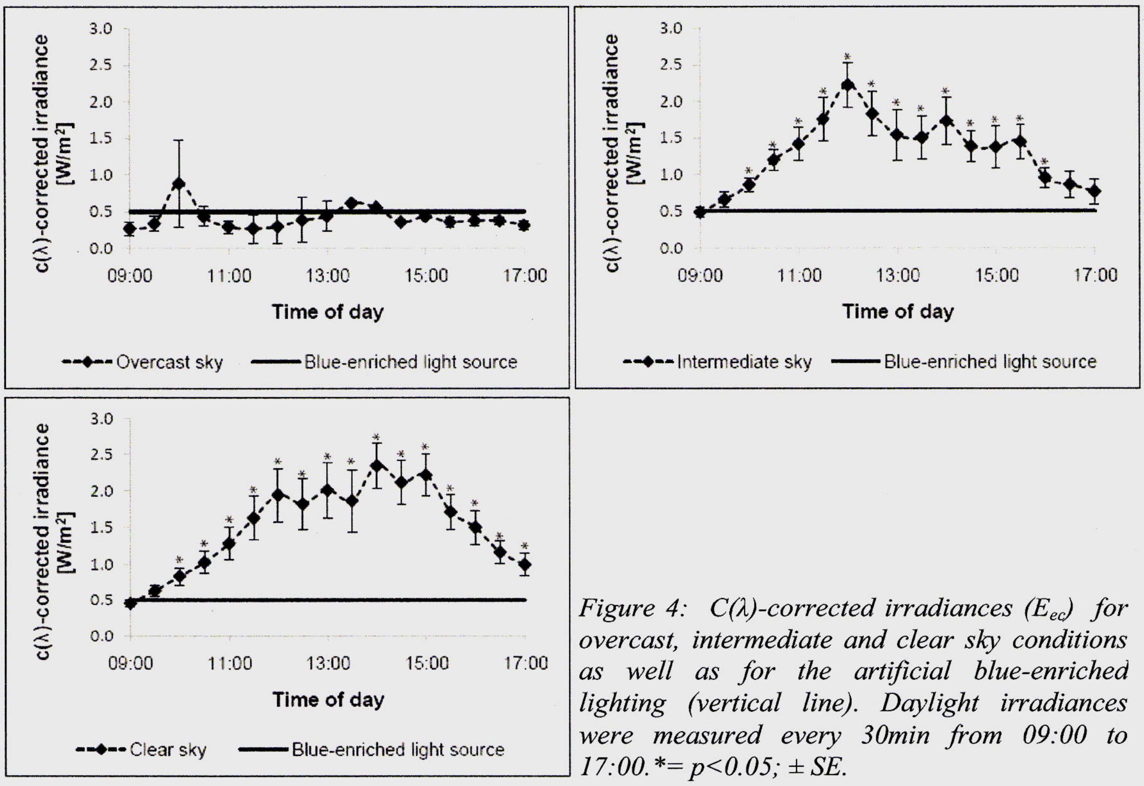


*Figure 4: C(λ)-corrected irradiances (E_{ec}) for overcast, intermediate and clear sky conditions as well as for the artificial blue-enriched lighting (vertical line). Daylight irradiances were measured every 30min from 09:00 to 17:00. *= p<0.05; ± SE.*

For intermediate and clear days, the c(λ)-corrected irradiance levels were significantly higher during large parts of the working day than the artificial lighting ($p<0.05$; t-test), except in the morning hours before 10:00 and in the afternoon after 16:00. However, for overcast sky conditions, the c(λ)-corrected irradiance levels are close to those with artificial lighting conditions ($p>0.1$). When we compared the different sky conditions, we found significantly higher c(λ)-corrected irradiances on clear days, between 14:00 and 16:30 in the afternoon than during overcast days and slightly higher between 11:00 and 13:00 ($p<0.1$). Irradiances on clear days were also higher at 16:00 compared to intermediate sky conditions ($p<0.05$). On overcast mornings between 10:30 and 12:00 the c(λ)-corrected irradiance levels were slightly lower than those with intermediate sky conditions between 10:30 and 12:00 ($p\leq0.05$).

DISCUSSION

As expected, we found significant differences of daylight irradiances between the three sky types (Figure 2-4). Our results also showed the variability of irradiances and the spectral composition across working hours between 09:00 and 17:00. Irradiance values for overcast skies are in general much lower than those of intermediate and clear skies, especially between 11:00 and 15:00. Yet higher irradiance values are obtained on clear days, especially between 13:00 and 15:00. The same effects are visible in Figure 3 where we analyzed only the spectral irradiance at 465 nm.

These initial findings visualize the fact that the daylight exposures of occupants in those ADS-equipped office rooms are increasing when the weather outside is improving (i.e. the sky is clear). In other words, the occupants can benefit from nice weather, even while working inside. One could of course argue that glare might occur and visual comfort might decrease when ocular irradiances increase. However, we can assume from this and earlier work that good visual comfort was generally achieved during our experiments [1-4]. The occupants usually "ease" temporarily occurring glare by using the installed window blinds. Glare typically occurs on clear days when there is a high risk of direct sunlight reaching the office. Furthermore, such situations typically occur in the mornings and afternoons when sun elevations are comparably low.

As a matter of fact, the irradiance differences that are apparent in Figure 2 and 4 between 11:00, 13:00 and 15:00 are more important under clear sky conditions than under intermediate sky conditions. Those differences could be the result of closed window blinds on the mornings of clear days. Interestingly, around 09:00 the irradiance levels are similar under all three sky conditions. If our objective would be to add artificial light on overcast days in order to make the ocular irradiances comparable to those occurring on clear days, this would be most easily achievable in the early mornings. Furthermore, the graphs for intermediate and clear skies in Figure 2 visualize the fundamental differences between artificial fluorescent light and daylight: Whilst the fluorescent light spectrum is mainly composed of several distinct peaks (centered on the emitting wavelengths of the applied fluorescence substances) the daylight spectrum is much more continuous and complete: virtually no wavelengths are "missing".

The comparably low spectral irradiance in the blue range achieved under the artificial blue-enriched light source (Figure 3) might seem surprising at first sight. This can partly be explained by the fact that the "blue peak" of the artificial lamp is at approximately at 436 nm (Figure 2), which had of course no influence on the irradiance levels at 465 nm.

After their experiments in a UK office building, Viola et al. concluded that the lighting situation created by the newly installed blue enriched lighting design was sufficient to improve alertness, performance and mood as well as subjective sleep quality in office workers. The average horizontal work plane illuminance during their experiments was found to be 310 lx. The lighting design in our test office room led to an average work plane illuminance of 383 lx. Thus, the two lighting designs are comparable. Whether we might find the same positive effects in our office occupants in terms of alertness, performance, mood and sleep quality, needs to be tested. We may assume that any other light source which performs at least as well as the two blue-enriched light sources in terms of weighted circadian irradiance E_{ec} could also induce those positive effects. Therefore, on working days with intermediate and clear skies, no additional blue-enriched artificial light would be needed in our ADS-equipped office rooms during very large parts of the working day: daylight almost always creates sufficiently high E_{ec} levels (Figure 4). However, the plots in Figure 4 suggest that additional artificial lighting with blue-enriched polychromatic fluorescent tubes such as "Activiva active" might be useful on overcast days and even before 09:00 on days with intermediate and clear skies, in order to improve the building occupants' wellbeing, alertness, performance and mood.

CONCLUSION

Our results showed to which extent external sky conditions influenced light exposure of office workers in an ADS-equipped office room for different sky types. We also found that the considered ADS was able to supply natural blue light irradiance levels during large parts of days with intermediate and clear skies, which were much higher than those created by our artificial lighting installation based on two blue-enriched fluorescent lamps. The same is true for weighted circadian irradiance values E_{ec}. It seems admissible to assume that, within this tested ADS-equipped office room at the LESO solar experimental building, complementary artificial lighting with blue-enriched polychromatic fluorescent tubes might are useful on days with predominantly overcast skies and before 09:00 and after 16:30 on all days. Our results suggest that in all other cases, the available daylight is sufficient during this time of year.

Finally, the use of the circadian action function $c(\lambda)$ has of course several limitations because it does, for example, not account for the length of light exposure and is based on nocturnal melatonin suppression only.

Further research will reveal whether daylight and ADS are sufficient to obtain the described positive effects [9] without artificial lighting and to also investigate objective variables. In particular, we need to quantify how much artificial lighting is required to complement insufficient natural light conditions, especially in the blue range of visible light, in order to optimize circadian biological and behavioral functions of office workers and other populations.

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