VARIATION IN PHOTOPIC AND MELANOPIC LIGHTING IN SWISS OFFICES: A FIELD STUDY

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Abstract

Health requirements for lighting in buildings are becoming increasingly important in building standards. Yet, there is a lack of concrete data on the lighting conditions that prevail in our workplaces, in terms of their spectral characteristics, their seasonal variation, the influence of orientation or the chosen blind control strategy, and how they might impact occupants' well-being. The objective of this study is to start addressing this gap by offering insights into the kind of lighting environments that typical Swiss open-plan offices provide to their occupants regarding non-image forming (NIF) effects of light. Towards this end, we conducted on-site continuous measurements of spectral irradiance and photopic illuminance in two open-space offices presenting some common characteristics (e.g., WWR, artificial lighting strategy, climate) and some differences (e.g., orientation, floor to ceiling height, venetian blind control system). On average, we recorded three times more light, both photopic and melanopic, in office A compared to office B. Our hypothesis to explain such a large difference is that the blinds, which were exclusively manually controlled in office B, were kept mostly closed independently of the outside conditions. Automated blinds seem like a more suitable option to optimize daylight penetration and NIF effects of light, though it must be associated with a manual override option to avoid negatively impacting the occupant's perceived comfort.

Keywords: Non-image forming (NIF) effects; Light; Melanopic EDI, Daylight, Well-being

1. Introduction

Over the past 20 years, we became aware of the critical role played by light in synchronizing our internal clock. These so-called non-image forming (NIF) effects of light are mediated by the intrinsically photosensitive Retinal Ganglion Cells (ipRGCs) present in the mammalian eye and are most sensitive to the bluer wavelength range (Brainard et al. 2001; Berson et al. 2002). Light exposure has been shown to influence our mood, alertness, immune system and sleep quality (Lockley et al. 2006; Chellappa et al. 2011), as well as many other processes necessary for our well-being and health (Smolensky et al. 2016; Roenneberg and Merrow 2016). These NIF effects must hence be carefully taken into account when discussing the environmental quality of workplaces (Amundadottir et al. 2017). Of particular importance are the intensity, spectrum and timing of the light exposure in triggering both phase-shifting (circadian, e.g. sleep quality) and acute effects (e.g. alertness) (Webler et al. 2019).

Models able to determine what light exposure would be needed for proper circadian entrainment and alertness at the desired time are still in their early stages of development. At the same time, there is a lack of concrete data on the lighting conditions that actually prevail in our workplaces, in terms of their seasonal variation, their spectral characteristics, the influence of orientation or the chosen electric lighting strategy, and how they might impact occupants' well-being. The objective of this study is to start addressing this gap by offering insights into what lighting environments typical Swiss open-plan offices provide to their occupants regarding NIF effects of light.

The acronym "eCOMBINE" stands for energy use, COMfort, Behaviour, and INdoor Environment in office buildings. eCOMBINE is a data collection framework that aims at capturing relevant variables to describe the relationship between the indoor and outdoor environment, global environmental comfort, occupant behavior and energy use (Barthelmes et al. 2020). This framework involves, amongst many other variables, the measurement of illuminance and spectral irradiance. So far, it has been applied in two Swiss offices, which has enabled us to obtain, for the first time in a field study, information on the influence of season, orientation and the use of electric lighting on the variation of spectral irradiance and photopic illuminance indoors. This study focuses on the variations in lighting observed in these offices and over different seasons and orientations.

2. Methods

2.1. Case-study spaces

We conducted continuous measurements of spectral irradiance and photopic illuminance over several periods of two weeks in two open-plan offices (referred to as A and B) in Switzerland, which present the following characteristics:

- **Open space office A** is on the second floor of a five-story office building located in the periphery of Lausanne, Switzerland. The building was completed in 2011 and has a floor to ceiling height of 3.4 m. It has a dominant northern exposure as well as shorter East and West orientations. It is certified according to the Minergie standard (MINERGIE Building Agency 2008). Shading is provided by venetian blinds which are regulated automatically, according to solar irradiance and wind speed, but can be overridden manually. The desk lights are equipped with motion sensors and turn on automatically. Ceiling lights installed along the central staircase block are always on during working hours and cannot be individually controlled by the employees.
- **Open space office B** is on the fifth floor of a six-story office building located in the urban center of Geneva, Switzerland. The building was completed in the 80s (with tenant-specific interior renovations since completion) and has a floor to ceiling height of 2.7 m. It presents dominant exposures to South-West, South and South-East. Shading is provided by venetian blinds, which are controlled manually. The desk lights are equipped with a motion sensor and turn on automatically.

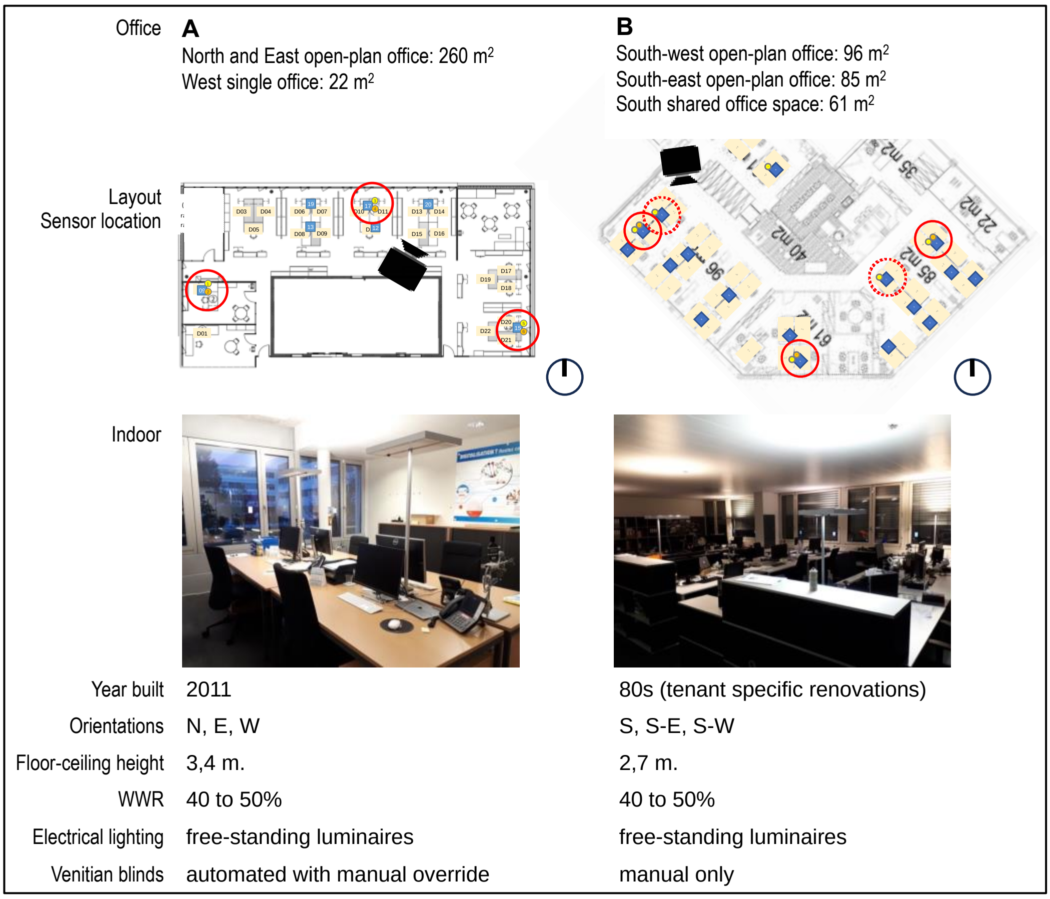

Figure 1 – Plans of the offices and photographs of the interior. The location of the sensors is indicated on the plans (blue box for the illuminance sensors and red circle for the spectral irradiance sensors). For office B, we had to change sensor location due the changes in occupants' seating position (the dotted line indicates the location of the sensors in Summer)

The window to wall ratio (WWR) is not known accurately. Based on the façade drawings for the offices considered, we estimated a WWR of 40 to 50% for both open space offices. While building A was located in a medium-density district, building B was located in a denser urban neighborhood but on a higher floor (5th floor instead of 2nd) and on a wide street; therefore, we can consider that both spaces benefited from adequate daylight on all orientations (no major obstructions). The details of each open-space and the location of sensors are provided in Figure 1.

2.2. Data collection

The spaces were studied during measurement campaigns occurring in different seasons of 2019 and 2020 (Table 1). Each campaign lasted 14 consecutive days.

Table 1 – Sample size and case-study period

	Sample size*	Fall	Winter	Summer
Office A	13 participants	28/10 - 08/11/2019	27/01 - 02/07/2020	NA
Office B	31 participants	18/11 - 29/11/2019	17/02 - 28/02/2020	17/08-28/08/2020

*Number of participants having signed the consent form at the beginning of the study.

Objective data collection

We performed photopic illuminance and spectral irradiance measurements for each building and orientation. We positioned one spectral sensor vertically and one horizontally on an occupant's desk nearby each façade, right next to an illuminance sensor (Figure 1). We tried to keep the location of the sensors stable in all case studies, but we had to slightly change the location of some sensors across the seasons for office B due to changes in occupants' location (not all occupants gave their consent to participate in the study). Measurements were taken every 5 min, and only the hours between 7am and 6pm during weekdays were considered in our analyses. For illuminance measurements, we relied on Delta Ohm HD2021 TBA photodiode sensors (accuracy: ±10% of reading (lux), limit: 20,000 lux) connected to an Onset HOBO data logger. For the spectral irradiance measurements, we used NSP32m visual sensor head from nanoLambda (10-40 nm resolution) in the range of 380-730 nm.

Occupancy was tracked at the desks through the wireless RoomZ desk sensor, which is able to detect a sitting or standing employee at the desk. We also tracked the use of electric lighting based on the power consumption of the free-standing luminaires measured using a smart plug. These luminaires include an illuminance sensor and a motion sensor. These two signals trigger their switching, which can be overridden by the occupants.

Subjective data

The eCOMBINE monitoring framework included an online point-in-time comfort survey occurring twice per day (at 10am and 3pm, Monday-Friday) during each day of the campaigns. As far as visual comfort was concerned, participants were asked to rate it on a 5-point categorical scale ("Extremely uncomfortable", "Very uncomfortable", "Uncomfortable", "Slightly uncomfortable", "Comfortable").

The subjective protocol also included point-in-time interaction questionnaires on the occupants' motivations behind their control actions, such as opening/closing blinds and windows. This survey was delivered via a mobile app displayed on phones attached next to each window of the spaces. For the motivations pertaining to blind usage, participants could choose between 12 predefined responses, including "Too dim", "Too bright", "Too cold", "Too warm", "Prevent overheating", "Glare", "Reflection (of light on the screen)", "View outside", "Save energy", "Arriving", "Leaving" and "Other" (in case their motivation was not among the predefined responses).

2.3. Data calibration

Since the measurement accuracy of the spectral irradiance sensors was unknown, we decided to process and calibrate the data collected by these sensors using the photopic illuminance measurements. Note, however, this procedure could only be applied to horizontal spectral irradiance sensors, since no vertical photopic illuminance measurements were collected. After removing the datapoints for which the sensor reported a saturated spectral irradiance (0.2% of the dataset) and further removing data outside of the 2-week measurement period and office hours (7a.m. till 6p.m.) (81% of the dataset), the remaining dataset (n=22'325) was used to derive photopic illuminances from the measured spectral irradiances. If a corresponding horizontal photopic illuminance measurement made by the Delta Ohm sensors was available, the horizontal spectral irradiance measured by the NSP32m was scaled according to Equation 1:

$$SI_{NSP32m,cal} = \frac{E_{h,DeltaOhm}}{E_{h,NSP32m}} * SI_{NSP32m,raw} \quad (1)$$

in which: $SI_{NSP32m,cal}$ is the calibrated spectral irradiance [W/m^2/nm],
$SI_{NSP32m,raw}$ is the spectral irradiance [W/m^2/nm] measured by the NSP32m,
$E_{h,DeltaOhm}$ is the horizontal photopic illuminance [lux] measured by the Delta Ohm sensor,
$E_{h,NSP32m}$ is the horizontal photopic illuminance [lux] derived from the NSP32m measurement.

Once the horizontal spectral irradiance measured by the spectral irradiance sensor was scaled, alpha-opic quantities, including the melanopic equivalent daylight illuminance (melanopic EDI) [lux] (CIE 2018), and the non-visual direct response (nvR_D) (Amundadottir 2016), used as a relative measure of alertness, were derived. Since there were no vertical photopic illuminance measurements made by the Delta Ohm sensors, and in view of the sometimes large difference in photopic illuminance between the NSP32m and Delta Ohm measurements, it was decided to disregard the vertical spectral irradiance measurements altogether.

2.4. Data analysis methods

The analyses primarily rely on descriptive statistics applied to the photopic illuminance, melanopic EDI, and nvR_D derived from the horizontal light measurements. For the assessment of the variation in photopic illuminance and melanopic EDI, we relied on the calibrated spectral irradiance sensors. We report mean and standard deviations (SD) across all the sensors per buildings and season during weekdays. Those analyses were performed with R version 4.2.2 and the packages dplyr, stringr, data.table, ggplot2, and lightdosimetry (Hartmeyer 2022). For the assessment of the survey data, we compared occupants' comfort responses to the photopic illuminance measured closest to the occupants' desks. This explains the larger amount of photopic sensors deployed in the space. Those analyses were also performed with R version 4.2.2.

3. Results

3.1. Variations in melanopic EDI

Impact of electric lighting

The smart plugs enabled us to track when electric lighting was on. Electric light was commonly used during daytime leading to a concurrent usage of daylighting and electric lighting. When electric lighting is switched on, we observed that the ratio of melanopic EDI to photopic illuminance is always below 1, suggesting that electric lighting is optimized for photopic vision (Figure 2). Compared to the electric lighting system installed, daylight presents a substantially higher share of short-wavelength blue light, making it more effective to trigger NIF effects.

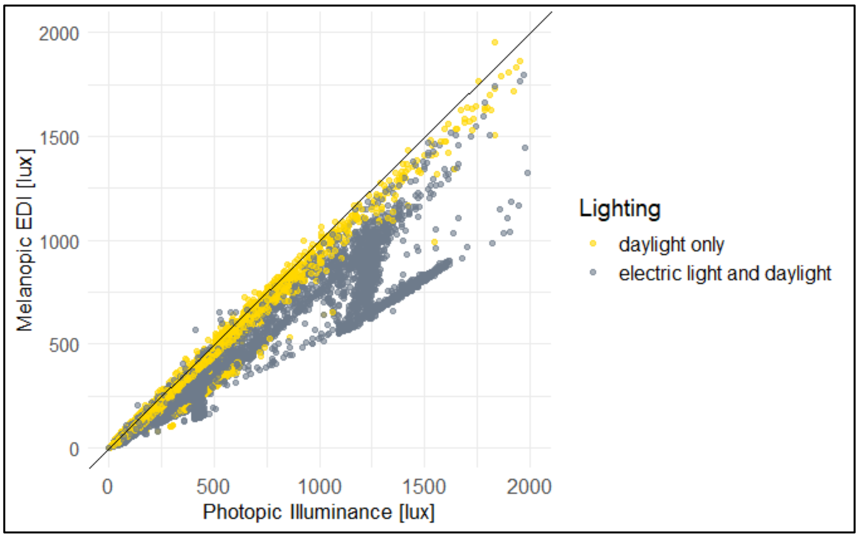

Figure 2 – Impact of electric lighting on the relationship between melanopic EDI and photopic illuminance

Impact of building design and seasons

In office B, the average desk-level photopic illuminance was substantially below the recommended 500 lux (EN12464-1:2021) in the Fall and Winter, and of 517 lux in Summer, while the melanopic EDI was below 200 lux in the Fall and Winter, and of 466 lux in Summer (see Table 2 and Figure 3). By contrast, the average desk-level photopic illuminance and melanopic EDI in office A were about three times higher in Fall and Winter. These values are all reflecting horizontal measures. For melanopic EDI, it would be valuable to also report on the vertical values (considering occupant eye position and direction at 1.20 height) and compare it to the recommended value of 250 melanopic lux (WELL 2020; Brown et al. 2022). As this data was not available in our study, we report this threshold with a dotted line in Figure 4.

Our hypothesis for the observed discrepancy in illuminance and melanopic EDI levels between the two buildings is a lack of usage of the manually operable blinds in office B. These blinds remained closed or partially closed for long periods of time, even when light levels were low and when the shading was not required for glare protection or overheating. The usage of automated blinds (with manual override) in office A could be a more suitable option to optimize daylight penetration and NIF effects of light. This hypothesis is reinforced by a slightly lower ceiling height for office B.

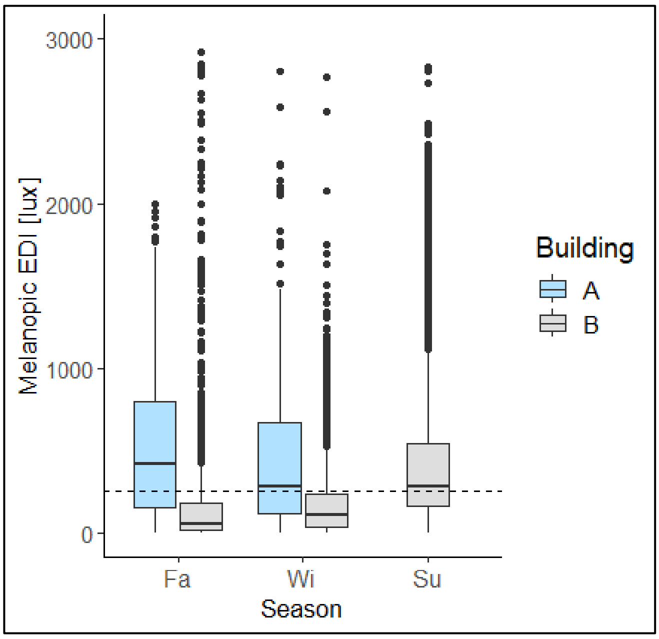

Figure 3 – Desk-level melanopic EDI by building and season. The dotted line indicates 250 lux (reference for vertical measures).

Table 2 – Mean and standard deviation in desk-level photopic illuminance and melanopic EDI by building and season

		Fall		**Winter**		**Summer**	
		Phot. Ill. [lux]	**mel-EDI [lux]**	**Phot. Ill. [lux]**	**mel-EDI [lux]**	**Phot. Ill. [lux]**	**mel-EDI [lux]**
Office A	**mean** (SD)	**704** (495)	**531** (384)	**637** (599)	**440** (442)	/	/
Office B	**mean** (SD)	**228** (732)	**182** (688)	**215** (326)	**169** (268)	**517** (549)	**466** (516)

Impact of orientation

Comparing East and West orientations for office A, and South-East and South-West for office B, we observed, as expected, that the East/South-East orientation offers higher indoor light levels in the morning on average, while the West/South-West orientation will in the afternoon (Figure 4). Since for circadian entrainment, exposure to bright light is recommended especially in the morning, an Eastern orientation should be preferred when choice is given.

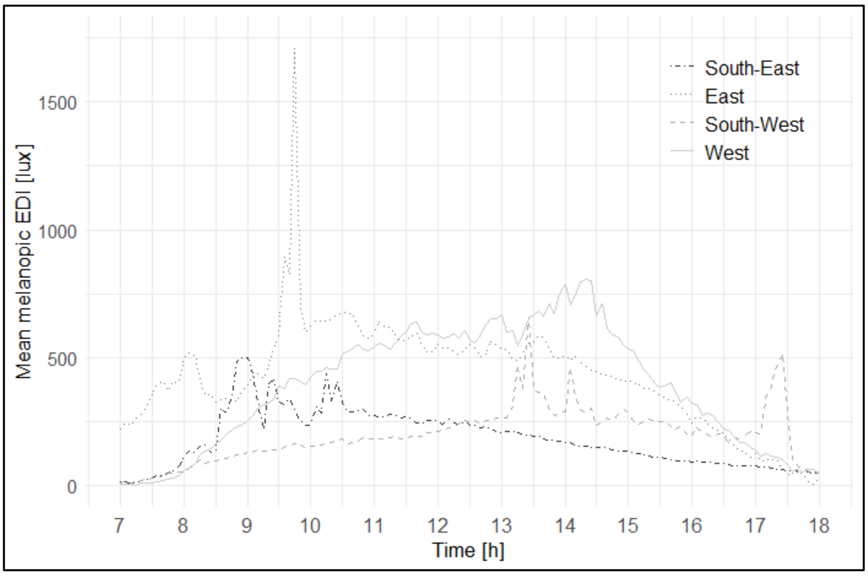

Figure 4 – Evolution of the mean melanopic EDI over the course of one day for Eastern and Western orientation (Office A: East and West, Office B: South-East and South-West)

We generally measured higher melanopic EDI along the dominant North and South facades respectively for buildings A and B compared to the less prevalent orientations in each building (Figure 5). For office A, this can be explained by the fact that the North orientation is less prone to the use of shading devices (less discomfort/unwanted solar gains) and thus daylight levels will tend to stay higher along this facade. For office B, the South office appeared to be substantially less used than the side orientations, with the shading devices left up for longer time periods as a result.

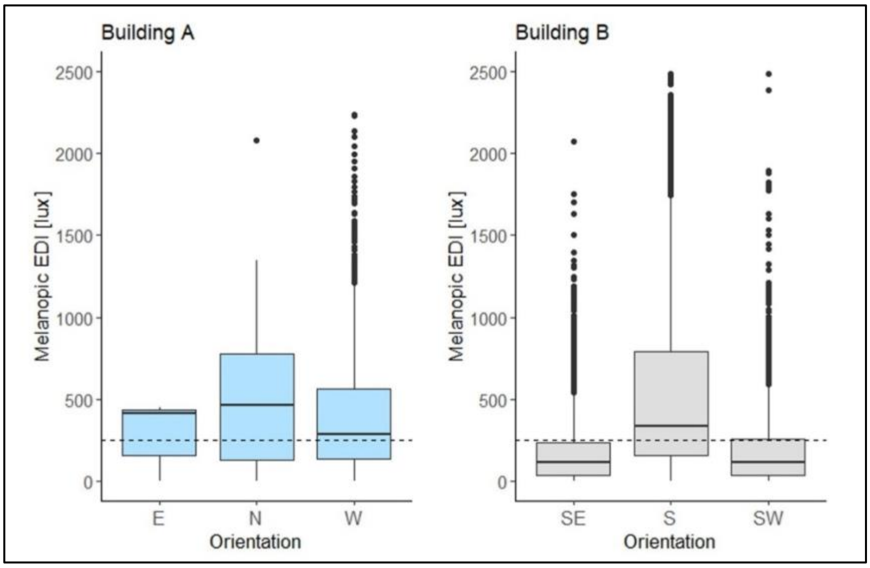

Figure 5 – Boxplot showing the desk- level melanopic EDI by building and orientation. The dotted line indicates 250 lux (reference for vertical measures).

3.2. Variations in non-visual direct response

Impact of building design, orientation and seasons

Based on the recommended 4.2 threshold on the unitless nvR_D scale for vertical measurements (Amundadottir et al. 2017), we can compare office A to office B in terms of their potential to meet appropriate light levels for occupants' non-visual direct responses (e.g., alertness). Again, this comparison is made using the horizontal spectral irradiance proxy we have available in this study.

The analysis shows that office A performs better than office B in that regard, with higher nvR_D values reached for all orientations. Office B (also measured in the Summer) seems to suffer from a strong dependency on orientation when it comes to expected non-visual direct responses to light. More significant differences in light-induced alertness levels would thus be expected in office B between occupants depending on orientation. Since the desks were oriented perpendicularly to the facades in both offices, these results would need to be confirmed with additional measurements conducted vertically at the eye of the building occupants.

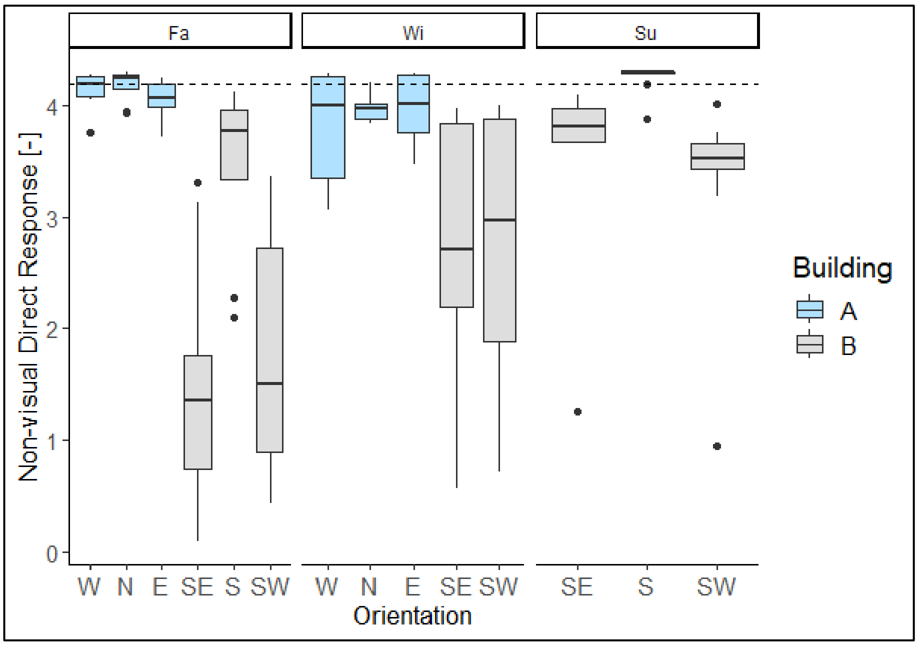

Figure 6 – Cumulative non-visual direct response (nvR$_D$) between 9 and 14h by season, building and orientation for horizontally-mounted sensors. The dotted line indicates the reference value of 4.2 for vertical measures.

3.3. Subjective results

Visual comfort

While the recorded photopic illuminance levels were higher in office A, with a greater frequency of occurrence above the standard threshold (> 500 lux, EN12464-1:2021), we found that occupants reported more visual discomfort than in office B. Looking at the details of occupants' votes organized by bins of illuminance values and by building (Figure 7), there were not many instances of very low/very high illuminance levels for which subjective data was collected in office A. In building A, the occupants had automated blinds with manual override, while in building B, the blinds were only manually controlled. The occupants of building B were thus "more in control" of their conditions, which could explain the slightly higher reported comfort levels (Galasiu and Veitch 2006; Day et al. 2019) even if the illuminance levels were actually way lower than any recommendation. The control allows the occupants to adapt the conditions to their personal preferences while typically bringing along a sense of forgiveness when the conditions are not ideal (Leaman and Bordass 1999).

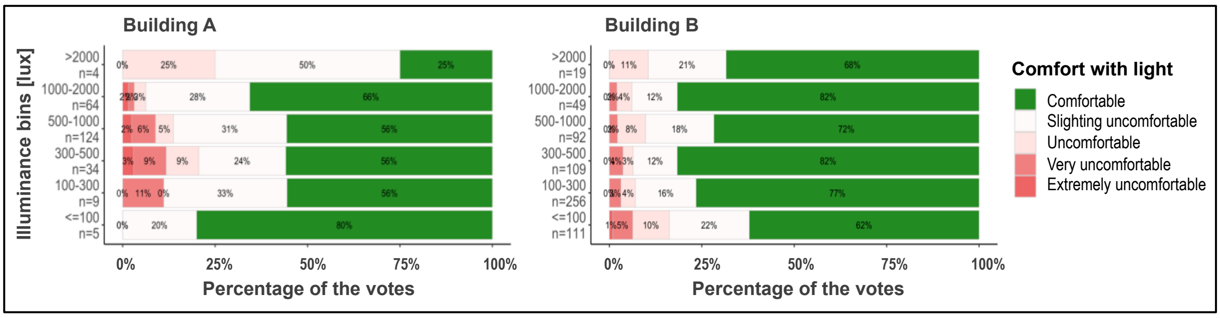

Figure 7 – Occupants' subjective responses to comfort with lighting conditions arranged by illuminance bins [lux]. The sample size of each bin is indicated on the graphs

Motivations behind actions

Table 3 shows the number of blind actions reported by the occupants for each campaign. Considering the few occurrences of blind actions in building A, we merged the data of buildings A and B in Figure 8. For the blind opening actions, the motivation is primarily the lack of light (too dim) that takes precedence. The view comes next, yet far behind. For the blind closing actions, discomfort due to glare, an excessive brightness, and reflections dominate the responses and can explain occupants' dissatisfaction in supposedly comfortable photopic illuminance ranges (300-2000 lux).

Table 3 – Number of actions to open / close the blinds reported by the occupants for each building and each season

	Building A		Building B		
	Fall	**Winter**	**Fall**	**Winter**	**Summer**
closing	*6*	*5*	*31*	*45*	*8*
opening	*4*	*6*	*36*	*36*	*12*
Total	**10**	**11**	**67**	**81**	**20**

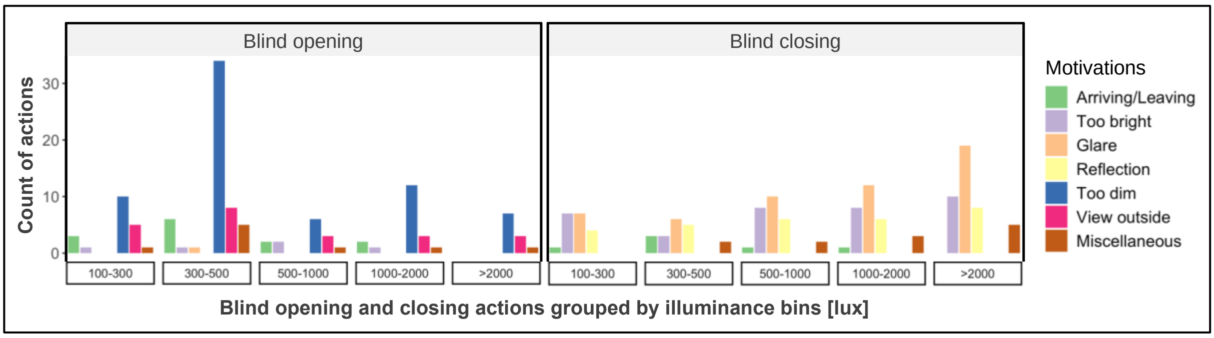

Figure 8 – Count and motivations regarding blind opening/closing actions, classified by illuminance bins [lux]

4. Discussion and limitations

The eCombine protocol was originally designed for multimodal comfort and to evaluate the impact of a space's occupants actions (e.g., window or blind opening behavior) on building energy consumption. While the framework involves the measurement of spectral irradiance, it does not question occupants on alertness nor other NIF responses to light. The surveys in place are focused on occupant comfort, satisfaction and actions to reach comfort. Additional questionnaires could be considered to complement the framework and allow a deeper assessment of the NIF effects of light.

The eCombine protocol also included vertical measurements of spectral irradiance, which is the recommended approach to assess the NIF effects of light. Yet, unlike our horizontal measurements, these vertical measurements were not complemented by illuminance levels. While analyzing the data from our horizontal sensors, we noticed some discrepancies between the illuminance levels derived from the spectral sensors and the ones retrieved directly from our illuminance meters. Since our illuminance sensors were calibrated, we decided to recalibrate the data from the spectral sensors, so that the illuminance matches the one from our reference illuminance sensors. This recalibration was not consistent across the sensors (some required a higher correction factor than others), which led us to leave aside the data collected for the vertical sensors and to carry our analysis on the basis of horizontal sensors only. Using horizontal spectral irradiance does not allow us to derive conclusive statements on the NIF effects of light for our case-study, as the reference remains the vertical measurement. We remained descriptive in our analyses and primarily compared the two buildings in light of requirements that would apply to vertical measures.

With its Southern exposure, office B would potentially be more conducive to higher light levels; yet we observed higher photopic and melanopic illuminations in office A. While a difference in ceiling height may have benefited building A (which shows a slightly higher ceiling height than building B), our main hypothesis to explain this difference is that the blinds are kept closed for a longer time in office B. This hypothesis would be in line with earlier literature on occupant behavior, which suggests that occupants do not change the blind position daily and most likely activate it when direct sunlight reaches the work area (as it creates glare and thermal discomfort), but seldom changes the setting for view or daylight

(Rubin et al. 1978; Rea 1984). The same studies also highlighted that the occupants' preference for a certain blind configuration is mostly based on perceptions formed over long periods of time ranging from weeks to months. In their review study, O'Brien and al. reported that most office occupants do not operate their shades more than weekly or monthly and they do so based on long-term solar radiation intensity and solar geometry trends rather than reacting to short-term events (O'Brien et al. 2013). The preference and high tolerance for low light level was observed in several papers based on artificial lighting control (Newsham et al. 1995, 2002; Moore et al. 2002; Reinhart 2004) where the majority of users were satisfied with the quantity of light on their workstations while a large numbers of them were working in illuminances significantly below recommended levels (Moore et al. 2002). Moore et al. noted the potential for energy savings in the case of personal control, as this can lead to reduced lighting power without adversely affecting occupant perceived lighting quality and visual comfort. Yet this observation brings up another type of conflict, as it also concerns the health of the occupants. Our study leads us to conclude that automated blinds with manual override appeared as a more suitable option to optimize daylight penetration and NIF effects of light, even though it can negatively impact occupant comfort and energy savings.

Reflecting on orientations, we generally measured higher melanopic EDI along the dominant North and South facades respectively for buildings A and B compared to the less prevalent orientations in each building. While the southern office seemed to be relatively less used (in office B), the northern orientation (in office A) was less conducive to the use of shading devices. Comparing East and West, we noted as expected that the Eastern facades had a higher peak in melanopic EDI in the morning. As such, and following this assessment, the Eastern and Northern orientations seemed the most adequate for circadian entertainment. Finally, as compared to daylighting, the installed electric lighting systems in this field study were optimized for photopic vision. The contribution of natural lighting is therefore a game changer when it comes to NIF effects of light.

Finally, as this was a field study, there were a few common obstacles to an ideal data collection. We were not able to influence the layout of the space nor displace the items of the employees on their desk. As a consequence, we could not position our sensors at the same distance of the free-standing luminaires. Consequently, the measurements collected may not correspond exactly to the average for each desk. Due to changes in the offices' staff, we had to change the location of a few sensors between the seasons. Then, because of the COVID-19 pandemic, the Spring campaign was cancelled and the Summer campaign could only be conducted in office B, but with a reduced occupancy rate. These challenges limited our assessment to 3 seasons and 5 campaigns in total instead of 4 seasons and 8 campaigns.

5. Conclusion

We conducted on-site continuous measurements of spectral irradiance and photopic illuminance in two offices in Switzerland. The offices showed a similar window-to-wall ratio but differences in orientations, ceiling height and in exterior blind management, which we identified as the key contributors for the differences in measured photopic illuminance, melanopic EDI and non-visual direct response (alertness). Our study conducted over 3 seasons (autumn, winter and summer) revealed that, on average, office A benefited from three times more light, both photopic and melanopic, than office B. We explain this difference by the control of the blinds, which were exclusively manually controlled in office B and presumably remained closed most of the time, regardless of outside conditions. Thus, automated blinds appear to be a more appropriate option for optimizing daylight penetration and the NIF effects of light, although they must be combined with a manual control option to avoid having a negative impact on occupant-perceived comfort. The solution adopted in building A thus appears to be a good compromise.

To our knowledge, this is the first field-study involving continuous measurements of spectral irradiance in offices. Unfortunately, we were unable to use our vertical measurements as a basis. The results still show a great level of consistency with regard to the large difference in mel-EDI and nvR_D between the two buildings. For future studies, we recommend proper sensor calibration and a placement of these sensors to replicate the light intake from the eye. The hypothesis formulated concerning the impact of blind control on NIF effects may also form the basis of future studies.

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