Daylighting provision and visual comfort in unilaterally and bilaterally illuminated classrooms

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Abstract. Children between the ages of 6 and 14 spend much of their day in school classrooms, where they are exposed to only a fraction of the daylight quantities typical for natural outdoor conditions. This paper examines unilaterally and bilaterally illuminated classrooms in terms of quantitative and qualitative requirements for daylighting in classrooms during both winter and summer. The results of measurements and simulations pointed out the advantages of bilaterally illuminated classrooms when compared to unilaterally illuminated ones. In winter, the windows placed on two opposite walls provide a significantly higher uniformity of daylight. In summer, in addition to the improved uniformity, this window arrangement offers higher variability in shading strategies, resulting in greater availability of daylight and better visual comfort. These factors can potentially prevent or limit the development of myopia.

1. Introduction
Children between the ages of 6 and 14 spend much of their time at school. During the morning and a large part of the afternoon they stay in school classrooms, where they are exposed to only a fraction of the daylight quantities typical for natural outdoor conditions, which is not optimal because of the positive effects of daylight on the human body that has been confirmed by many studies [1,2]. Daylight mediates visual perception, which influences cognitive, motor, and task performance [3]. In addition to mediating visual perception, light affects physiology on several levels. Several studies have shown that adequate access to daylight promotes circadian synchronization, improves quality and length of sleep, alleviates seasonal depression, improves cognition, and supports overall well-being [4, 5].

Scientific interest emerged recently concerning the potential link between a lack of daylight in the school classrooms and the development of myopia due to the fast-increasing number of myopic children of school age. The progression of myopia has been correlated with spending time at school and associated with daylight, or to be more specific, the lack of it. According to the World Health Organization, there were 1.4 billion people suffering from myopia in the world in 2000, with a predicted rise to 4.8 billion people by 2050 [6]. Myopia was estimated as the most common cause of distance
vision impairment and the second most common cause of blindness worldwide in 2010. It represents an economic burden of $202 billion a year [6].

The possible causes of myopia have been identified as a combination of factors, mainly time spent outside and near work [7, 8]. Children who spend more time outdoors are less likely to become myopic or progress to permanent myopia. Time spent outdoors has a beneficial effect on normal refractive development in children, and lack of time spent outdoors can cause a higher prevalence of myopia. Studies performed in 2020 [9] reveal that COVID-19 induces lifestyle changes, as well as a steep increase in myopia prevalence in 6 to 8 years old children. This is a strong sign that reduced exposure to daylight and sunlight, in this case caused by limited outdoor activities due to the pandemic, is linked to the increase of myopiogenesis. Recent studies also show that the onset and progression of myopia are higher in younger children [10]. Therefore, quality of lighting environment for school-age children should be taken into consideration.

The amount of daylight penetrating into the classroom is strongly influenced by the classroom design, its orientation to the solar path, and especially the position and size of the windows. Although the orientation to the east of classrooms has been preferred in the past, this design strategy carries the risk of reducing visual comfort by causing a glare from the direct solar radiation and this risk is more significant due to the increasing use of electronic devices in teaching. Solar rays fall at a low angle during the morning and can cause disturbing reflections and glare, especially for students sitting near the windows. Under these conditions it is difficult to create sufficient contrast on the monitor / projection screen to ensure the readability of the displayed information. To prevent such visual discomfort, blinds are often used during summer days. As in all larger rooms, the level of lighting is mostly optimal in the window area, but deteriorates as the distance from the windows increases, and the workplaces deeper in the room are often poorly lit. In the case of unilateral daylighting with windows oriented to the sun, the use of blinds makes the availability of daylight in these areas even worse.

Bilaterally daylit rooms, in comparison, provide a better distribution of light in the classroom (no dark corners) and allow customization of the shadings based on the actual position of the sun, while the other side provides sufficient daylight. This allows high visual comfort [11] and may limit the risk of fast increase of visual impairment.

From an architectural perspective, schools with bilaterally illuminated classrooms are more space consuming. The pavilion building concept shaping the building in form of “H” allows classrooms to be connected to the central corridor in the middle of the floor plan. This building concept allows the use of a maximum of about three floors, as the construction of taller buildings leads to excessive shading of classrooms on the lowest floors. In contrast, unilaterally illuminated classrooms allow for greater variability in the choice of building concept. The question arises, whether the higher demands on the school layout solution are justified by the achieved better quality of the indoor environment in the classrooms.

2. Aim of the study

This study investigates the effect of window arrangement on daylighting in primary school classrooms. In winter conditions, when the access to direct sunlight in the Czech Republic is limited due to the cloud cover during 65% of the time [12], we compare the daylighting provision in the classrooms, its quantity and spatial distribution under the overcast sky condition. In summer, clouds cover reduces to less than 40% of the time. More direct sunlight and higher general outdoor illuminance are available over longer daylight hours. It results in a higher daylighting provision, but also increases the risk of glare. Therefore, in summer we assess the visual comfort and the impact of shading strategies with simulation under the CIE clear sky model.

We assume that in winter the bilaterally illuminated classroom will show significantly more equal daylight distribution across the room and fewer zones with very low daylight provision compared to unilaterally illuminated classrooms. Furthermore, we assume that bilaterally illuminated classrooms will
show lower glare risks and better visual comfort in summer, thanks to the more alternatives in the positioning of shading elements.

3. Design of the study
Classrooms from two elementary schools in the Czech Republic were selected. Both schools were built around 1980 in pavilion-shape style. Jan Palach Elementary School, located in Kutná Hora, has standard unilaterally illuminated classrooms. The classrooms of Rakovský Elementary School, located in Prague, are bilaterally illuminated. Both schools provide facilities for primary school pupils in the age 6 to 15 years.

One classroom was chosen in each of the schools, so that the mean daylight factor (DF) was comparable between the two rooms, see Table 1 for details. The size of the rooms is similar, but the variation in windows arrangement (unilateral/bilateral daylighting) implies a difference in glass to floor ratio. In order to compare rooms with similar mean DF, rooms were chosen on different floors, so the shading from surrounding buildings balances the difference in the size of the windows. Also, the orientation towards cardinal directions differs. Windows of unilaterally illuminated classroom face towards the east, windows of bilaterally illuminated classroom face towards the north and the south. The different windows arrangement is also associated with different needs and alternatives of using shading elements for glare protection.

| classroom          | unilateral daylighting | bilateral daylighting |
|--------------------|------------------------|-----------------------|
| classroom location  | third floor            | first floor           |
| room dimensions (length x width x height) | 7.3×8.8×3.3 m | 7.7×9.2×3.0 m |
| window to floor ratio | 16.4 %                | 22.6 %               |
| orientation of windows | east                   | north, south     |
| sha (fraction of visible sky in the view) | 80-100 % of view (surrounding buildings) | 20-40 % of view (own building - pavilions) |
| number of pupils in classroom | 30                    | 28                   |
| blackboard type    | chalk blackboard       | chalk blackboard     |
| dominant type of teaching | frontal               | frontal              |

Conditions during both winter and summer seasons were examined in both classrooms. To assess the lighting condition during the time of limited daylight availability, the actual daylighting provision has been measured with luxmeter calibrated set GOSSEN MAVOLUX 5032C and Luminance Distribution Analyzer LDA LumiDISP under the winter overcast sky condition. Data were compared between the two types of classrooms. Light reflection factors were determined and used to create a virtual model in software Building Design [13]. Daylight factor (DF) was calculated in the same software [13]. The requirements follow the legislation of EU for location in Czech Republic [14]. Minimal standard for daylighting in the classrooms is declared at Table A.1 [14] as target daylight factor (DT) of 2.0 and minimum target daylight factor (DTM) of 0.7, corresponding to target illuminance level $E_T$ 300 lx and minimum target illuminance $E_{TM} 100$ lx, respectively. To reach median level of daylighting, DT and DTM increase to 3.4 and 2.0 representing 500 lx and 300 lx.

In the time of excessive daylight and direct sunlight, visual comfort and risk of glare needs to be evaluated using advanced methods [15]. Under the CIE clear sky, calculation of Spatial Daylight Autonomy (SDA) and Annual Sunlight Exposure (ASE) were used to assess the potential risk of glare and heat gains in both classrooms. The calculation was performed in LightStanza software [16].
For more detailed analyses of glare and effect of shadings with external mobile venetian horizontal blinds, Daylight Glare Probability assessment (DGP) was performed in the LightStanza software. DGP model calculates the percentage of people probably disturbed by glare, with possible categories of glare: imperceptible, perceptible, disturbing, or intolerable [17]. Under the CIE clear sky condition two shading setups were evaluated – with no blinds and with blinds in horizontal position, so the maximal view out is possible. In unilaterally illuminated classroom, the blinds were used on all windows (east façade). In bilaterally illuminated classroom, blinds were used only at the sunlit side, i.e., the south facing windows were covered with blinds while the north façade, where there is no risk of glare causing direct solar radiation, was left without shading.

4. Results
The results of measurements and simulations pointed out the advantages of bilaterally illuminated classrooms when compared to unilaterally illuminated classrooms.

In winter, daylight factor (DF) was measured and calculated under the CIE Overcast sky. The mean DF in the two classrooms was comparable, it reached 2.8 in the unilaterally illuminated and 3.0 in the bilaterally illuminated classroom. Median values differ more considerably, 1.9 vs. 2.5, which represents the difference of 90 lx (30% increase) in the median illuminance. Further, illuminances lower than 200 lx (DF 1.4) are present in 28 % of the classroom with unilateral daylight, while such low illuminance does not exist in the bilateral daylight. For details see Table 2 and Figure 1.

| Table 2. Daylighting – winter, overcast sky |
|---------------------------------------------|
| Mean DF [-] | Median DF [-] | Percentage of floor area reaching E<sub>T</sub> |
| Eh [lx] | Eh [lx] | 500 lx | 300 lx | 200 lx | 100 lx |
| unilateral | 2.8 | 1.9 | 32% | 48% | 72% | 100% |
| 414 | 283 |
| bilateral | 3.0 | 2.5 | 28% | 67% | 100% | 100% |
| 451 | 373 |

DF = daylight factor; Eh = calculated daylight provision (illuminance on horizontal plane), E<sub>T</sub> = target illuminance

In summer we apply the CIE Clear sky model. The workspaces in both classrooms receive enough daylight during standard school operating hours (8 a.m. to 2 p.m.). The target values of spatial daylight...
autonomy ($SDA_{300,50}$) are reached on 100% of the floor area of both classrooms. That means that in summer, the daylighting is satisfactory in both types of classrooms. Direct solar radiation in summer can be visually disturbing and causes a risk of glare. According to calculation in LightStanza, annual sunlight exposure (ASE, > 1000 lux / 250 h) significantly differs between the classrooms. In the unilaterally illuminated classroom, ASE occurs at 46% of the floor area, while in the bilaterally illuminated classroom ASE reaches only 11% of the floor area (data not presented).

To address the risk of glare in more detail, two shading strategies were simulated for DGP analysis, see Figure 2. Without the use of binds, the probability of intolerable glare reached 100% in unilaterally and 66% in bilaterally daylight classroom. If the external blinds are used in a horizontal position, the probability of intolerable glare decreases to 78% and 0% in the two classrooms, respectively. (To further reduce the risk of glare and provide a glare-free environment also in the unilaterally illuminated classroom, Venetian blinds would have to be tilted 40 degrees from the horizontal, and this arrangement would disrupt the view and excessively block the access of daylight.)

5. Conclusion
Results of the measurements and simulations confirmed that in the bilaterally illuminated classrooms the daylight is better distributed, the median daylighting provision is significantly higher and areas with low daylighting level are eliminated. More importantly, the placement of windows in opposite walls offers greater flexibility in the positioning of shading elements according to the actual needs. It allows protection from the glare caused by direct solar radiation (and also related overheating), without excessively blocking the view out or restricting the access not only to sunlight but also to diffused daylight unlike the case of unilaterally illuminated classrooms.

Schools equipped with bilaterally illuminated classrooms have higher requirements for the size of the plot. Hence, this design principle is rarely used. However, as our data suggest, sufficient daylight can be achieved in a bilaterally lit classroom, even if a significant part of the view is blocked by obstacles such as near standing buildings. This implies the possibility to create denser building structures and thus achieve higher land use.

The role of daylight in classrooms as prevention of myopia had already been studied in the 20th century. Later, the belief that new powerful electric light sources could be a full-fledged substitute for daylight, along with misinterpreted scientific knowledge [18], made the topic to be considered irrelevant. Nowadays we are observing children myopia increasing at nearly an epidemic pace. It is time to reopen this question. Our findings suggest that there are architectural design strategies that could be beneficial for protecting healthy pupils' eyesight.

This study is clearly limited by the fact that the objective findings are not correlated with data on subjective evaluation of visual comfort in the monitored classrooms. Due to the long-term closure of
schools during the ongoing pandemic, children were not present at school and it was not possible to secure such data. This data will be collected during the follow-up research.

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