Impact of Visual, Thermal, and Indoor Air Quality Conditions on Students' Wellbeing and Learning Performance in a Primary School of Bolzano, Italy

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Abstract

Poor Indoor Environmental Quality *IEQ* conditions, defined by the four environmental comfort domains (thermo-hygrometric, visual, Indoor Air Quality *IAQ* and acoustic), can cause not only discomfort to building occupants, but also lack of concentration, and harmful and unhealthy status. In this work, visual, thermal and *IAQ* conditions in a primary school located in Bolzano, Italy, were analysed to assess their impact on students' learning performance. After a survey in the school, which included measurements of illuminance, luminance, optical properties of materials, air temperature and CO_2 concentration, some simulation models were developed. Through a Radiance model, daylight metrics (e.g., Daylight Factor and Daylight Autonomy) and glare metrics (e.g., Daylight Glare Index and Daylight Glare Probability) were calculated. Furthermore, the melanopic illuminance was simulated to evaluate the non-visual effects of light on children's circadian cycles. In addition to that, EnergyPlus simulations allowed an evaluation of the long-term indoor air quality and thermal comfort conditions, which were used to estimate the students' potential performance loss according to some models in the literature. Interventions on shading devices and *HVAC* system controls were suggested, in order to optimize *IEQ*, with a minimization of performance loss and energy consumption.

1. Introduction

Indoor Environmental Quality *IEQ*, defined by the combination of the four environmental comfort domains (thermo-hygrometric, visual, Indoor Air Quality *IAQ*, and acoustic), must be carefully guaranteed in places such as schools, where people spend a considerable amount of their lifetime. In fact, poor environmental conditions can lead to discomfort in the occupants, and even to poor learning and work performance (UNI EN 15251:2007, UNI EN 16798-1:2019). Furthermore, recent studies in the literature suggest taking comfort from a multi-domain point of view into account (Schweiker et al., 2020; Toftum, 2002; Torresin et al., 2018).

As regards visual comfort, several studies in the literature found this fundamental for indoor wellbeing, since it also affects psychological and psychophysical conditions, as well as circadian rhythms and people's performance (Aries et al., 2010; Cajochen et al., 2005; Khanie et al., 2016; Stevens & Rea, 2001; Webb, 2006; Zaniboni et al., 2022).

As far as the circadian rhythms are concerned, the first models of sensitivity to circadian light were defined in 2001 by Brainard et al. (2001) and Thapan et al. (2001). Later, Rea et al. (2005; 2011) proposed an empirical model of human circadian response based on the neuroanatomy and neurophysiology of the retina and on the results of psychophysical studies. In this model, the concept of Circadian Stimulus *CS*, which represents the relative effectiveness of circadian light, was introduced. According to Rea et al. (2005; 2011), a *CS* of 0.3 in the morning is suitable for the promotion of a good circadian cycle.

Figueiro et al. (2016) highlighted that, in order to stimulate the circadian rhythm, a high circadian stimulus with bright, bluish-white light must be received in the morning, while a low circadian sti-

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mulus with dim, yellowish-white light is preferable in the evening. In this way, both levels of alertness and sleep quality are improved. Nevertheless, as Figueiro et al. (2016) discovered, several aspects must be taken into careful consideration to have a correct *CS* trend during the day:

1. spectral power distribution of light sources has to be characterized, not relying exclusively on Correlated Colour Temperatures *CCTs*;
2. both vertical illuminance E_v and only horizontal illuminance E_h on the work plane have to be considered;
3. the fact that illuminance level influences *CS* more than *CCT* has to be remembered.

As regards *IAQ*, CO_2 concentration is the main parameter usually monitored. In fact, even if CO_2 is not classified as a pollutant by the World Health Organization, it can be considered a good proxy of the Indoor Air Quality (López et al., 2021). As Bakó-Biró et al. (2012) stated, large CO_2 concentrations have been proven to reduce pupils' attention and vigilance, thus negatively affecting memory and concentration.

Similar effects can be generated by thermal discomfort. Indeed, as observed by Porras-Salazar et al. (2018), thermal discomfort in classrooms can reduce the ability of students to perform typical school tasks, and has an impact on their performance scores.

Given these premises, this study aimed to discuss the impact of visual and thermal aspects and *IAQ* on students' wellbeing and learning performance. The structure of the research was two-fold. The first part focused on the visual and non-visual effects of light on learning performance of students. The second part, on the other hand, concerned thermal comfort and *IAQ*, quantifying the pupils' expected performance loss in agreement with the models by Porras-Salazar et al. (2018) and Wargocki et al. (2019).

2. Case Study

This study features a primary school located in Bolzano, Italy. The building, opened in 2014, has a simple and linear architectural form, with a fully glazed atrium on a central square, a place of meeting and social gathering for the neighborhood community. The structure is organized into two sectors connected by a central element.

Fifteen classrooms, each with an area of about 50 m², are on the first and second floors. Classrooms are illuminated by large windows equipped with internal light curtains, and with ceiling tube LED lamps. This analysis focused on three classrooms, north, south and east-oriented.

Fig. 1 – Internal northern classroom view

3. Photopic and Melanopic Analysis

3.1 Survey and Building Model

During the survey, performed on October 23rd, 2019, the following information was collected:

- every surface's color, with reflected luminous fluxes, incident luminous fluxes, reflectance, and chromatic coordinate (Yxy), obtained by means of a portable spectrophotometer;
- illuminance values on students' task area, measured with a luxmeter;
- luminance and luminance maps considering students' typical viewpoints, measured with a spot luminance meter and a calibrated digital camera.

These data were used as inputs for the development of Radiance models.

3.2 Photopic Simulation Model

The Radiance models were developed using Rhinoceros and Grasshopper, with the Ladybug and Honeybee plugins. Urban and natural contexts were imported using Blender. A 2019 actual meteorological year was employed first to compare the simulated results with the measurements, and then for annual simulations.

The following analyses were performed:

a) *Image-based point-in-time simulations to detect glare risks for students and teacher and validate the model against measured data*.
The pupils are supposed to change frequently their view, looking at the desk or at the teacher alternatively. Thus, the selected visual task area was not limited to the desk, but also included the frontal view. Furthermore, the teacher's view of the classroom was included as well. 15 comparisons between simulated Daylight Glare Probability *DGP* values and those calculated from the luminance maps collected with the calibrated digital camera were carried out.

b) *Calculation of daylight metrics:* assessment of the *Daylight Factor DF*, with CIE overcast sky, and of *dynamic daylight metrics*, such as Daylight Autonomy *DA*, continuous Daylight Autonomy *cDA*, Useful Daylight Illuminance *UDI*, and spatial Daylight Autonomy *sDA*. In both cases, a 210-point squared grid (0.5 m x 0.5 m x 0.7 m) on the task area of seated students was used, in agreement with the EN 12464-1.

c) *Annual calculation of eDGP*, in particular, considering students looking at the window.

d) *Annual shading and lighting switch profiles*, suggesting, respectively, if venetian blinds need to be adopted or not and whether lights need to be turned on during the year and at which intensity level.

3.2.1 Results

The following figures show some of the results obtained through the simulations described in Section 3.2. Fig. 2 and Fig. 3 show a comparison between the *DGP* calculated from a *HDR* camera luminance map and the simulated one in the eastern classroom. As can be noticed, both gave a value of 0.20, demonstrating the accuracy of the developed Radiance model.

Table 1 shows the Daylight Factors for the three classrooms considered. Except for the south-oriented classroom, it can be noticed that DF is larger than 4 %, in agreement with the current requirements set by Italian law for these types of buildings.

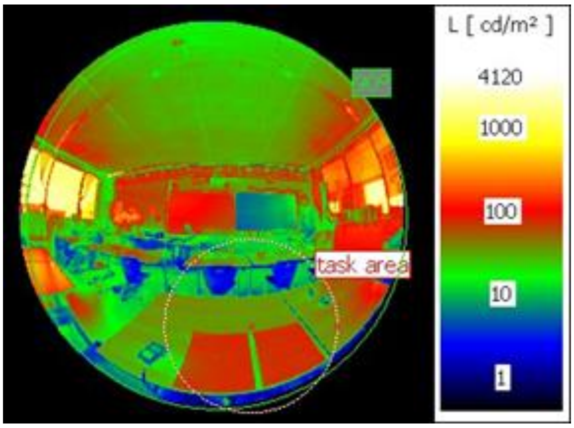

Fig. 2 – Eastern classroom – measured luminance map and student's view DGP = 0.20

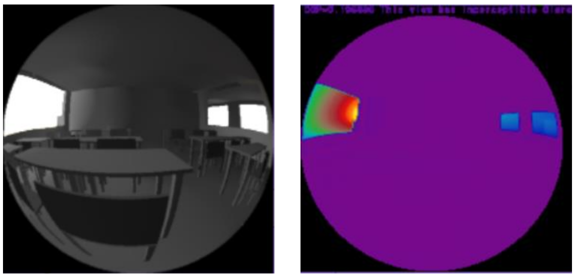

Fig. 3 – Eastern classroom – simulated luminance map and student's view *DGP* = 0.20

Table 1 – Daylight factor

	Northern classroom	Southern classroom	Eastern classroom
$DF_{average}$	4.4 %	3.2 %	4.2 %

Figs. 4-6 show the values of *DA*, *cDA* and *UDI* for the east-oriented classrooms. As can be noticed, the portion of the room closer to the windows shows a large value of *DA* and *cDA*; however, the natural illuminance can be excessive, as can be observed considering the *UDI* shown in Fig. 6.

Table 2 summarizes the dynamic daylight metrics for all three classrooms. The eastern classroom shows the highest values of *DA*, *cDA* and *sDA*, while the south-oriented one is characterized by the minimum ones. This is due to the exposure, the effects of reflectance of nearby buildings and the absence of high obstacles.

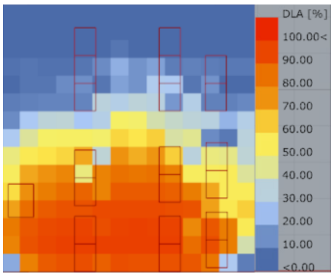

Fig. 4 – Eastern classroom – *DA*

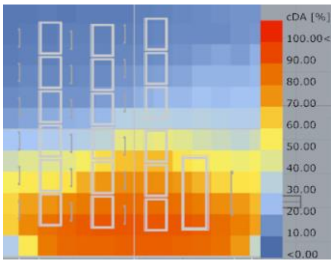

Fig. 5 – Eastern classroom – *cDA*

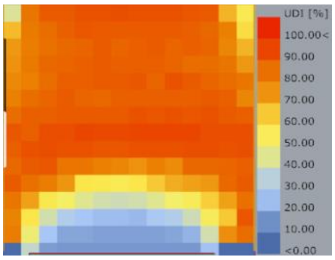

Fig. 6 – Eastern classroom – *UDI*

Table 2 – Dynamic daylight metrics

	Northern classroom	Southern classroom	Eastern classroom
$DA_{average}$	30.9 %	20.9 %	40.1 %
$cDA_{average}$	60.3 %	40.1 %	63.8 %
$UDI_{average100\text{-}2000lx}$	85.0 %	47.9 %	70.8 %
sDA	31.6 %	22.6 %	40.9 %

Finally, Figs. 7-9 represent the annual distribution of *eDGP* calculated for the view of a student in the centre of the room, recommended usage of shading devices and light switch for the eastern classroom. As can be noticed, the risk of glare is frequently encountered, in particular, during autumn and spring. Therefore, the presence of shadings is here recommended. The same applies to the south-oriented classroom.

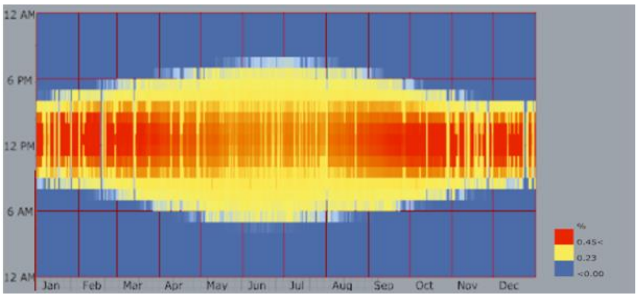

Fig. 7 – Eastern classroom annual DGP

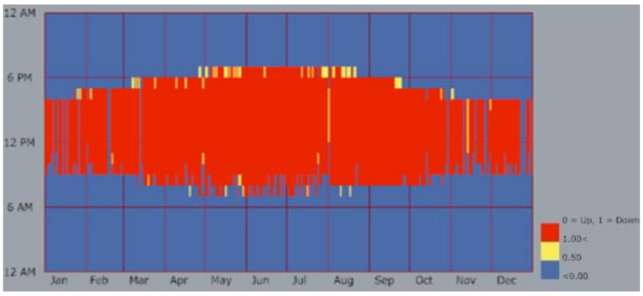

Fig. 8 – Eastern classroom annual shadings device

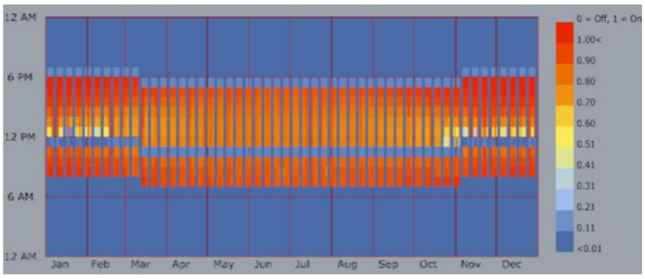

Fig. 9 – Eastern classroom annual lighting switch

3.3 Melanopic Simulation Model

The melanopic illuminance was computed using Lark, a Grasshopper plugin released by Inanici et al. (2015). In order to perform a simplified monthly calculation, a representative day for each month was considered, in accordance with Klein (1976). For the sake of comparison, the analysis was performed using both a CIE clear sky and a climate-based sky.

Within this computation, the light stimulus was evaluated vertically (e.g., in the direction of gaze) by means of six virtual sensors placed across a regularly spaced analysis grid of nine points, at a height of 1.2 m (seated person eye level). All the simulations were set with the same hourly time intervals during the occupational period, i.e., from 8 am to 4 pm.

After the calculation of Rea's melanopic illuminance, the three classrooms were analyzed, verifying if a *CS* value of 0.3 was achievable for at least 1 h in the early part of the day.

3.3.1 Results

In all three classrooms, melanopic illuminance was unevenly distributed and quite low. This was particularly true for the positions far away from windows and during winter months, as shown in Fig. 10 and Fig. 11 for the eastern classroom. This condition risks not allowing a shift in the biological clock of the occupants. Results from annual calculations indicated that roughly 1/2 of the area in the northern classroom, 1/2 of the area in the southern classroom, and 1/3 of the area in the eastern classroom did not benefit from melanopic illuminance all year long.

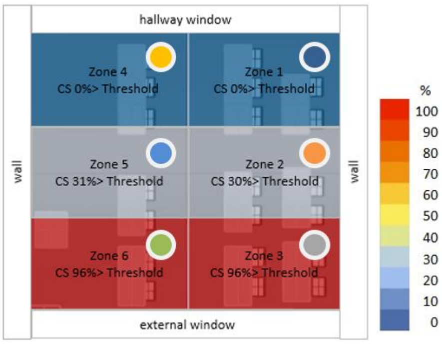

Fig. 10 – Eastern classroom sensor position and percentage of threshold exceedance over the year

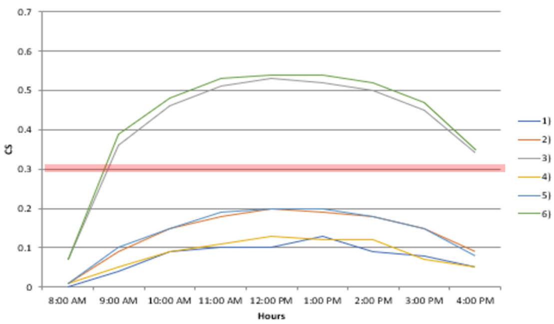

Fig. 11 – Eastern classroom *CS* trend on January 17th

4. CO_2 and Thermal Analysis

4.1 Survey and Building Model

A monitoring campaign was performed in one of the three classrooms, specifically the southern one, measuring air temperatures and CO_2 concentrations from November to December 2019, with a 10-minute time step.

An EnergyPlus model was developed using a 2019 actual meteorological year and including the surrounding urban context. The thermophysical properties of the building envelope (material thermal conductivity, thickness, density and specific heat capacity) were taken from the technical report and the CasaClima building energy certificate. As regards the glazing system, double glazed low-e windows were modeled with WINDOW by the Lawrence Berkeley National Laboratory (LBNL), considering a window gap of 0.016 m, with a mixture of 90 % argon and 10 % air.

Internal gains were estimated considering the 9 luminaires of 166 W each installed, the presence of 100-W electric equipment (laptop and beamer), and occupants (ASHRAE Handbook of Fundamentals), with a metabolic rate of 1.2 met (as suggested in EN ISO 7730 for sedentary activities), clothing of 1 clo, and in agreement with the school official occupancy schedules. An overall CO_2 generation rate of 0.00002 m^3/s was set, and a reference of 400 ppm CO_2 concentration.

Infiltration and ventilation rates were set according to Table 3. Specifically, typical opening schedules of windows were simulated according to the information given by school teachers. Similarly, the control of the shading devices was set in agreement with the typical behavior communicated by school teachers, also considering lowering the shadings when the direct radiation incident on the window is larger than 150 W.

The model calibration was performed manually, varying the infiltration rate, the carbon dioxide generation and the optic properties of obstacles and internal shadings.

4.2 Simulated Configurations and Outputs

The EnergyPlus simulations were computed with four different controls for the HVAC systems:

- *Standard*: simulation of the heating period with heating setpoint of 20 °C and natural ventilation;
- *VAR1*: simulation of the same *Standard* configuration with an additional cooling system with a cooling setpoint of 26 °C;
- *VAR2*: simulation of the same *Standard* configuration with the addition of a Mechanical Ventilation System *MVS* supplying 5 h^{-1} (i.e., 11 l/s/person during hours of occupation);
- *VAR3*: the combination of *VAR1* + *VAR2*.

Table 3 – Natural and mechanical ventilation in the different configurations

	Standard	VAR1	VAR2	VAR3
Infiltration (Always present)	0.05 h^{-1}	0.05 h^{-1}	0.05 h^{-1}	0.05 h^{-1}
Tilt open (Occupancy period)	0.1 h^{-1}	0.1 h^{-1}	-	-
Windows completely open (Lunch break, after lessons)	5 h^{-1}	5 h^{-1}	-	-
MVS (Occupancy period)	-	-	5 h^{-1}	5 h^{-1}

Simulated CO_2 concentrations and Fanger PMVs were correlated to pupils' performance loss according to the model developed by Porras-Salazar et al. (2018) and Wargocki et al. (2019). Diverse learning activities were considered, including typical schoolwork tasks, such as arithmetical calculations, reading and comprehension exercises, psychological tests measuring cognitive skills and the abilities needed to perform schoolwork (i.e., tests measuring concentration, memory and response time, results of aptitude and national tests examining progress in learning, results of midterm and final exams and end-of-year grades). Short-term sick leave rates were evaluated as well.

4.2.1 Results

As may be observed in Fig. 12, if no mechanical ventilation is used (as in the *Standard* and *VAR1* configurations), the level of CO_2 concentration exceeds those recommended in EN 16798-1:2019 for school environments (i.e., category I). As reported in Table 4, this issue led to important losses, especially in "*speed and reaction time*" and "*national and aptitude tests and exams*" scores.

On the whole, simulations revealed that the main performance loss of pupils in all the four configurations is due to thermal discomfort, up to 20 %. This result is consistent with Sarbu et al. (2015), who reported that occupants are more sensitive to temperature variations than to CO_2 concentration variations.

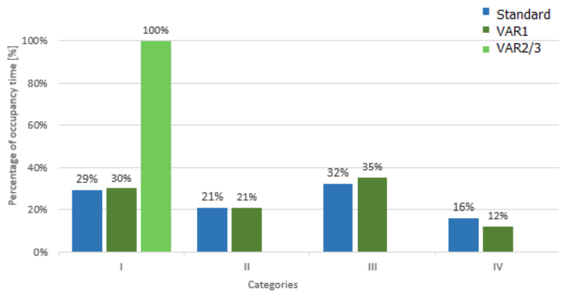

Fig.12 – Share of occupied time in the different *IAQ* categories in accordance with EN 16798-1:2019

Table 4 – Different configurations and maximum performance losses

max % performance losses	Standard	VAR1	VAR2	VAR3
Speed or reaction time	12 %	12 %	0 %	0 %
Accuracy	2 %	2 %	0 %	0 %
National and aptitude tests and exams	16 %	16 %	0 %	0 %
Daily attendance	4 %	4 %	0 %	0 %
Thermal discomfort	22 %	21 %	16 %	16 %

5. Discussion and Conclusion

This study uses experimental monitoring and dynamic simulation to assess *IEQ* in three classrooms of a case study school in Bolzano, evaluating the impact on students' wellbeing and learning performance.

In the first part of the study, related to the visual and non-visual analysis of classroom lighting conditions, several issues were identified. In fact, not all environments were well illuminated by daylight (due to the building configuration and to the presence of nearby buildings and mountains), and the risk of glare occurred all year round in east and south-oriented classrooms. For this reason, it was found advisable to adopt shading devices and dimmed daylight systems controlled by a photosensor in order to solve issues of glare and lack of daylight. Also, timed control artificial lighting, compensating for the lack of daylight, could be beneficial. These recommendations can be considered to be in agreement with what has been suggested in other works in the literature (e.g., Akashi et al., 2013; Choi et al., 2020).

As regards the non-visual effects of light, it was found that in all three classrooms, melanopic illuminance was unevenly distributed and quite low, especially for the east-oriented classroom, with the risk of not allowing a proper shift in the biological clock of the occupants.

The second part of the study revealed that the main performance loss (from 16 % to 22 %) of the pupils is due to thermal discomfort. In this respect, a potential measure could be the adoption of a local thermostat for controlling the room temperature, avoiding typical problems of overheating in winter months, with positive effects on the energy consumption and pupil performance.

Furthermore, mechanical ventilation was found necessary to ensure good *IAQ* conditions for students. In this framework, an integrated control of the *HVAC* system could be helpful to further improve both environmental quality and energy performance.

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