VNU Journal of Science: Mathematics – Physics, Vol. 40, No. 3 (2024) 23-30

VNU Journal of Science: Mathematics - Physics

Journal homepage: https://js.vnu.edu.vn/MaP

Original Article

Optimizing Classroom Lighting: Balancing Illuminance Uniformity and Glare Control with Led Technology

Duong Thi Giang*, Pham Hong Duong

Institute of Materials Science, VAST, 18 Hoang Quoc Viet, Cau Giay, Hanoi, Vietnam

Received 29 January 2024
Revised 10 June 2024; Accepted 06 August 2024

Abstract: Indoor lighting environment significantly impacts students' concentration and learning performance. Optimal lighting conditions enhance reading speed, accuracy, and comprehension abilities. In contrast, poor lighting conditions may lead to decreased concentration and increased errors in tasks. Therefore, classroom lighting is an important factor to consider in classroom design to optimize cognitive efficiency of students. Current classroom lighting solutions using LED systems have met European Norm (EN) standard in terms of illuminance and energy efficiency. However, although the issue of glare has been addressed, it has not been completely resolved. This study introduces a solution for glare-free classroom lighting that maintains uniformity while adhering to existing standards. This approach aims to create a visually comfortable learning environment, balancing effective lighting with glare reduction.

Keywords: LED, classroom lighting, illuminance, glare, uniformity.

1. Introduction

The importance of lighting in classrooms is underscored by its direct impact on students' concentration and learning efficiency. Research by Barkman et al. highlights the benefits of "focused" lighting scenarios, which involve adjusting both intensity and color spectrum [1, 2]. These adjustments have been shown to improve concentration, reading speed, and comprehension, and positively influence student behavior. Sleegers demonstrated that students' concentration increased with changes in lighting intensity (300-1,000 lx) and spectrum (color correlated temperature ranging from 3,000-12,000 K) [3]. Additionally, enhancing lighting intensity in the morning compared to standard not only increased alertness of students but also helped them sleep deeper and longer at night [4]. Qiang researched the

* Corresponding author.
E-mail address: giangdt@ims.vast.ac.vn

https//doi.org/10.25073/2588-1124/vnumap.4915

impact of LED lighting and fluorescent lighting on visual perception and found differences only in color perception and atmosphere, with no significant difference to alertness and cognition [5].

Nowadays, students primarily spend their time at schools where artificial lighting is often too weak in local intensity, disrupted over time, and deviant in spectral structure, causing many visual consequences such as an increased risk of refractive errors [6, 7], as well as physical, physiological, and psychological health deterioration [8]. According to the latest statistics, Vietnam has 5 million children suffering from refractive errors, most commonly among children aged from 6 to 15 years, accounting for 20-40% in urban areas and 10-15% in rural areas [9]. One of the causes of school myopia is due to insufficient, unreasonable lighting arrangements, and substandard light quality [10]. To protect eye vision and health, lighting must satisfy both imaging (IF) and non-imaging (NIF) functions [11], controlling all important aspects including uniform illuminance, non-glare, reasonable spectral structure, color correlated temperature, and changing intensity. The European Norm (EN) standard for classroom lighting requires a minimum illuminance of 500 lx on desks, 500 lx on the board, uniformity ≥ 0.7, and a glare rating (Unified Glare Rating – UGR) ≤ 19 [12]. Current classroom lighting solutions primarily utilize direct lighting from fixtures to the floor. In classrooms using older solutions with fluorescent lamps, the average illuminance on the desk surface reaches about 300 lx, with a uniformity of 0.7, meeting the EN standard - 2011, but not the EN standard - 2021. In newly built or renovated classrooms that use LED technology to replace fluorescent lamps, the average desk illuminance is 500 lx with a uniformity of 0.7, meeting the EN standard - 2021. However, both solutions fail to meet the glare standard, with the UGR ranging from 21-23, while the standard requires it to be less than 19.

Ye et al., (2020) demonstrated that a 90° lighting distribution angle achieves maximum uniformity and an acceptable UGR of less than 19, suitable for classrooms [13]. Yet, despite these advancements, reducing glare requires the production of larger light boxes (applicable for large LED panels).

Chiang et al., (2015) proposed LED panel design focused on reducing glare while maintaining high optical efficiency and illumination uniformity. It effectively manages the UGR, keeping it below 19, which is suitable for indoor environments like classrooms [14].

This study concentrates on evaluating the lighting conditions in schools and proposing non-glare lighting solutions to enhance the effectiveness of classroom lighting.

2. Methods and Materials

2.1. Current State of Classroom Lighting

The emergence of LED technology has significantly transformed the lighting industry, making LEDs the preferred choice over traditional sources like fluorescent and incandescent bulbs. This shift is notably evident in educational settings in urban areas, where LED lighting is increasingly adopted in schools.

Classrooms designed and constructed according to the standards of the School Design Research Institute under the Ministry of Education and Training have an area of 50 m² and a ceiling height of 3.2 meters, painted white (with a reflectivity of 85-90%), and walls painted yellow (reflectivity of 75-80%). The classrooms are generally illuminated by 12 LED tube lamps combined with aluminum troughs, while the blackboard is lit by 2 lamps of dedicated board lights (Figure 1).

The average illuminance on the surface of desks and on the blackboard was measured using the Konica Minolta TM-10A illuminance meter, recording values of 340 lx and 400 lx, respectively. The uniformity on the desk is about 0.85.

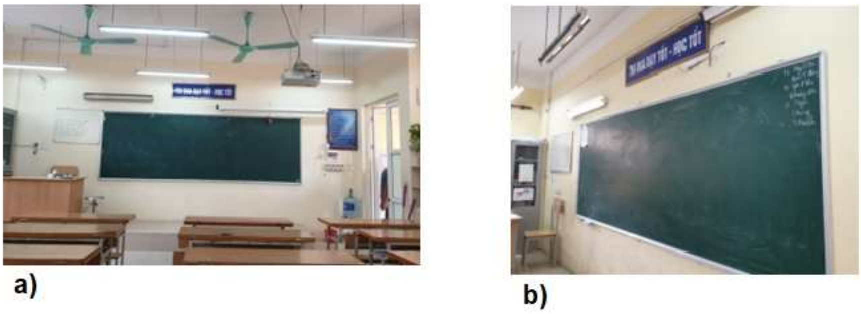

Figure 1. The image of the lighting system in classroom: general lighting (a), blackboard lighting (b).

2.2. Calculation the Angle Distribution of Lamp

In classrooms, when students look at the board, they may experience glare if there is direct light from the lamps into their eyes. Therefore, to minimize glare in classrooms, particularly when students look at the board, it's crucial to control the light distribution angle from lamps. The ideal maximum angle should be set to prevent direct light from entering students' eyes, ensuring visual comfort, and focusing on the teaching:

$$\theta_{max} = 2 \times (90^o - \alpha) \quad (1)$$

where α is the vertical field of view of the human eye looking upwards (Figure 2).

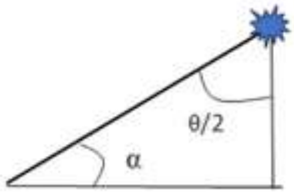

Figure 2. Calculation diagram of angle θ_{max}.

2.3. Calculation the Illuminance at Student Desks

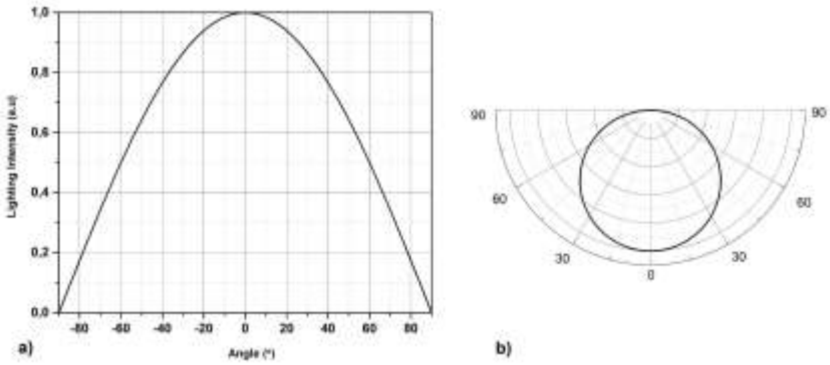

Figure 3. The lighting distribution curve of LED tube lamp: a) in Cartesian coordinates, b) in Polar coordinates.

Tube LED lamps consist of a long LED strip combined with a heat sink lamp body and a protective plate that diffuses light. The angle distribution, or light intensity distribution in space, of the LED tube lamps follows a Lambertian curve:

$$I = I_o cos\theta \quad (2)$$

Figure 3 shows the angle distribution graph of LED tube lamps in Cartesian coordinates (a) and in Polar coordinates (b). It is evident that, with the Lambertian distribution of LED lamps, the maximum peak is at angle $\theta = 0^o$, and the beam angle 120^o. Each classroom is illuminated by 12 sets of LED lamps arranged in 4 rows and 3 columns (Figure 4).

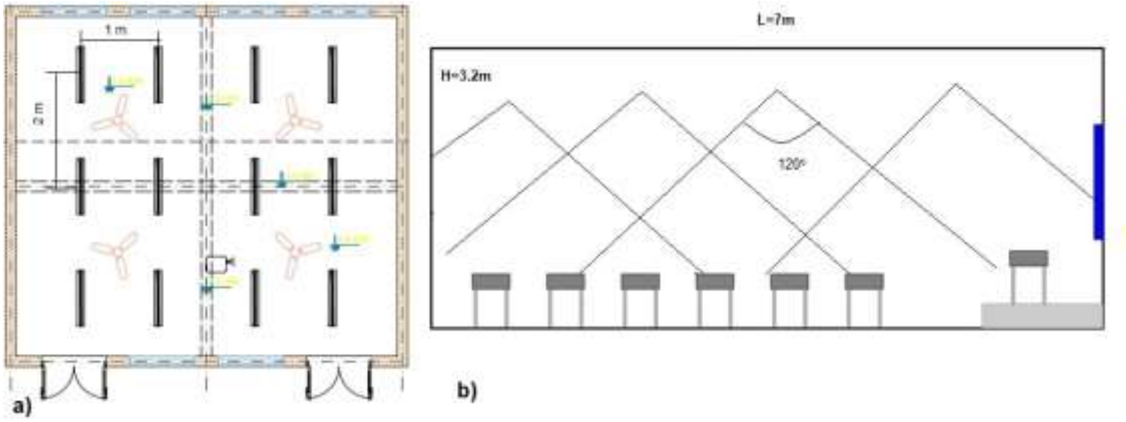

Figure 4. Lighting arrangement diagram in the classroom.

The lamps are hung 0.6 meters from the ceiling, the height of the student desks is 0.8 meters, the viewing height of the students is 1.2 meters, and the height from the students' eyes to the lamps is 1.4 meters. To evaluate the effectiveness of lighting, two factors are considered: i) Uniformity of illuminance on the surface of student desks through illuminance distribution; ii) The angular distribution of the light beam should be adjusted to minimize the light rays going directly from the lamps into the students' eyes that cause certainly glare.

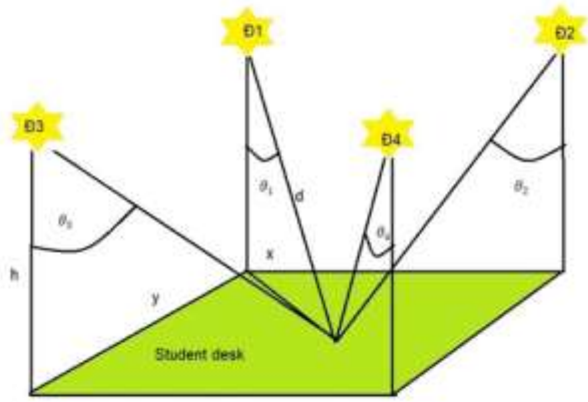

Figure 5. Calculation diagram of illuminance.

Figure 5 is a diagram for calculating illuminance and light distribution angle of the light beam emitted from the four lamps, where h is the height from the lamp to the student desk; θ is the angle between the direction of the light ray and the perpendicular direction to the student desk surface; d is the distance from the lamp to the calculation point. The illuminance on the student desk is calculated as:

$$E = \frac{I(\theta)cos\theta}{d^2} = \frac{I(\theta)\cos^3\theta}{h^2} \quad (3)$$

With the arrangement of 12 lamps for a 50 m² classroom divided into 3 rows and 4 columns as in Fig. 3, to simplify the calculation of illuminance on student desks, it is assumed that only 4 adjacent lamps illuminate the same area. The illuminance value on the student desk will be equal to the sum of the illuminance from 4 nearby lamps, calculated as:

$$E = E_1 + E_2 + E_3 + E_4$$
$$= \frac{1}{h^2}(I(\theta_1) * \cos^3\theta_1 + I(\theta_2) * cos^3\theta_2 + I(\theta_3) * \cos^3\theta_3 + I(\theta_4) * cos^3\theta_4) \quad (4)$$

Thus, the illuminance on student desks depends on the angular intensity distribution of the lamps used and the location of the survey point. The goal of this work is to find the appropriate angle distribution of the lamps so that the illuminance on student desks is uniform at all locations.

3. Results and Discussion

3.1. Calculation the Angle Distribution of Lamp

The normal human eye has a peripheral vision of 50° upwards and 60° downwards [15]. When students look at the board, the vertical field of view, α is 50°. To ensure that there are no direct light rays from the lamps into students' eyes, the maximum angle of light distribution should be θ_{max} = 80°.

The used LED lamps have a Lambertian distribution and an angle of θ = 120° will cause glare when students look at the board. Therefore, to address this glare issue, it's necessary to narrow the light beam so that θ ≤ 80°. The light distribution function will then follow a Gaussian distribution with a standard deviation corresponding to the angle of distribution θ.

$$I = \frac{I_0}{e^{\frac{1}{2}(\frac{\theta-\theta_0}{\omega})^2}} \quad (5)$$

where ω is the standard deviation or the half-width at half-maximum of the peak; θ_o is the center position of the peak, θ_o = 0°.

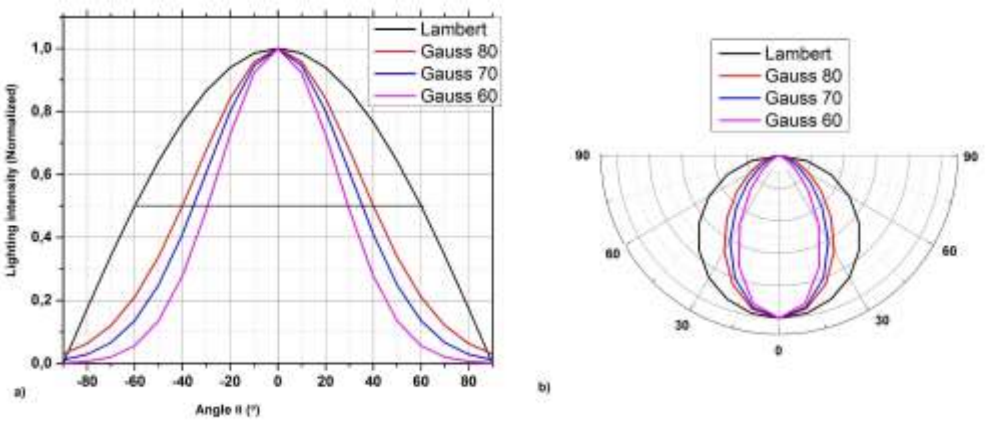

Figure 6. Comparison of angular distribution of Lambertian LED lamps and narrow-angle LED lamps: a) in Cartesian coordinates, b) in Polar coordinates.

Figure 6 illustrates the angular distribution of LED tube lamps (Lambertian) and the new narrow-angle LED lamps (Gaussian) on angular coordinates (a) and polar coordinates (b). With the central position θ_o at 0°, the half-width of the distribution peak is reduced (ω = from 80° to 70°, 60°), narrowing the light intensity distribution. However, as the angle of light distribution narrows, the illuminance distribution on the student desks becomes uneven as some areas are not well-lit. Therefore, when designing classroom lighting, a balance must be struck between reducing glare through the angle of light distribution and ensuring uniform illuminance on student desks.

3.2. Calculation the Illuminance at Student Desks

The illuminance on student desks using LED lamps with Lambertian distribution is calculated as:

$$E = \frac{I_0}{h^2}(cos^4\theta_1 + cos^4\theta_2 + cos^4\theta_3 + cos^4\theta_4) \quad (6)$$

The illuminance on student desks using narrow-angle LED lamps is calculated as:

$$E = \frac{I_o}{h^2}\left(\frac{cos^3\theta_1}{\exp(\frac{\theta_1^2}{2\omega^2})} + \frac{cos^3\theta_2}{\exp(\frac{\theta_2^2}{2\omega^2})} + \frac{cos^3\theta_3}{\exp(\frac{\theta_3^2}{2\omega^2})} + \frac{cos^3\theta_4}{\exp(\frac{\theta_4^2}{2\omega^2})}\right) \quad (7)$$

where:

$\theta_1 = arctan\left(\frac{\sqrt{x^2+y^2}}{h}\right)$; $\theta_2 = arctan\left(\frac{\sqrt{(l_1-x)^2+y^2}}{h}\right)$;

$\theta_3 = arctan\left(\frac{\sqrt{x^2+(l_2-y)^2}}{h}\right)$; $\theta_4 = arctan\left(\frac{\sqrt{(l_1-x)^2+(l_2-y)^2}}{h}\right)$

with l_1, l_2 being the fixed distances between two adjacent lights in rows and columns (Figure 4). In the surveyed classroom, l_1 = 1 m; l_2 = 2 m; h = 1.4 m.

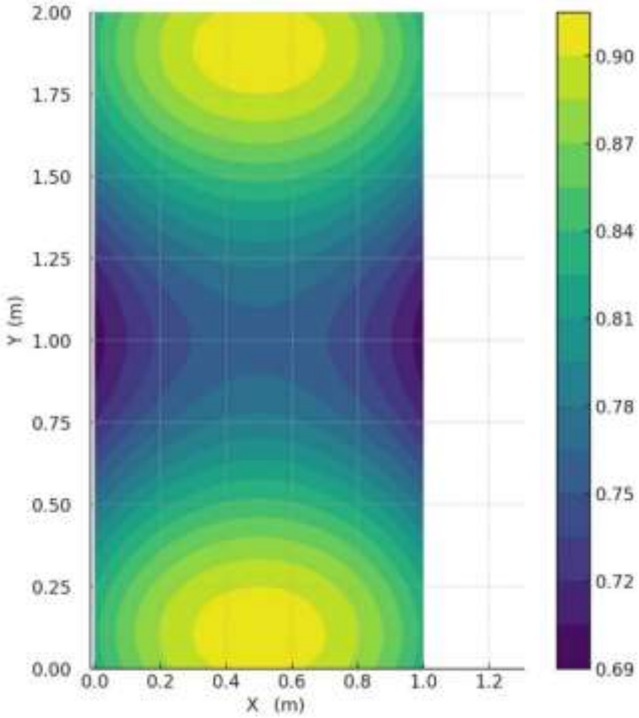

Figure 7. Graph of calculated illuminance distribution on student desks using LED tube lamps with Lambertian distribution.

Figure 7 shows the illuminance distribution graph in the area between four adjacent hanging lamps. The graph reveals that with the Lambertian distribution of LED tube lamps, the illuminance on student desks reaches 0.85, exceeding the uniformity standard for classroom lighting.

Similarly, the illuminance distribution on student desks is calculated using formula (7) for narrow-angle LED lamps with angles of 80°, 70°, and 60° (Figure 8).

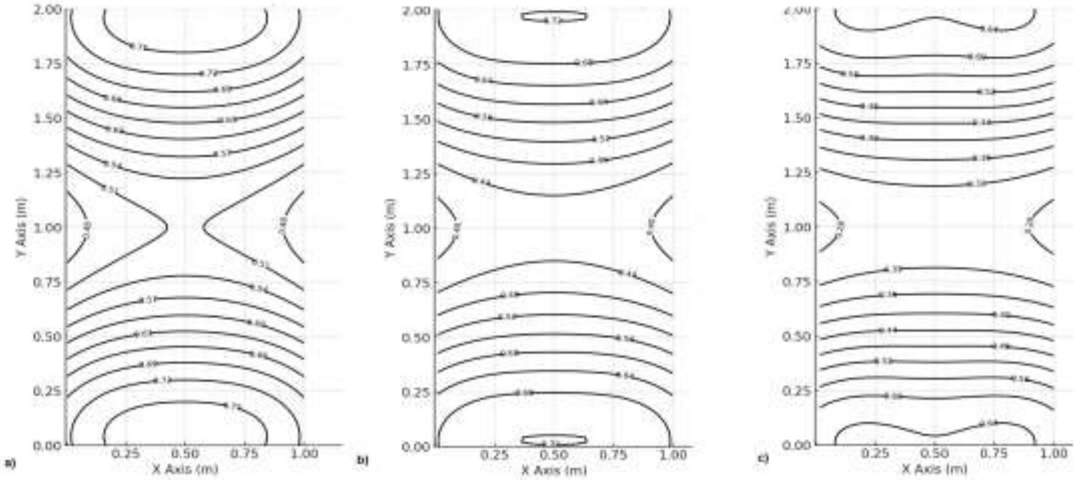

Figure 8. Graph of illuminance distribution on student desks using narrow-angle LED lamps ω = 80° (a), ω = 70° (b), ω = 60° (c)

The calculation results show that as the angle of light distribution narrows, the uniformity decreases. Specifically, with an angle of ω = 80°, the uniformity is 0.74, with ω = 70°, it is 0.69, and with ω = 60°, the uniformity drops to 0.58.

Table 1. Summary of calculated results with varied light sources.

N_o	Light sources	Angle distribution	Average illuminance	Uniformity	EN Standard
1	LED tube lamps with Lambertian distribution	120°	0.82 I_o	0.85	0.7
2	Narrow-angle lamps with Gauss 1 distribution	80°	0.63 I_o	0.74	0.7
3	Narrow-angle lamps with Gauss 2 distribution	70°	0.56 I_o	0.69	0.7
4	Narrow-angle lamps with Gauss 3 distribution	60°	0.46 I_o	0.58	0.7

Table 1 is a summary of the calculated results for illuminance and uniformity when changing the lighting intensity distribution of the light sources. It shows that, the conventional Lambertian distribution provides the highest uniformity but causes glare for students when looking at the board. Conversely, with lamps narrowed to an angle of < 70°, which does not cause glare when looking at the board, the illuminance distribution on the desks falls below 0.7, failing to meet the lighting standards. Therefore, with the same power consumption as the lamps but with different lighting distribution, the results of illuminance and its distribution on student desks also vary. To balance both factors - avoiding glare and ensuring uniform illuminance - the solution of narrowing the light distribution angle to around 70 - 80° meets the lighting standards according to EN standard.

4. Conclusion

This research presents an innovative method for calculating the illuminance distribution on student desks in standard classrooms, effectively integrating considerations for human peripheral vision. Our findings reveal that using narrow beam angle lamps, specifically between 70° and 80°, strikes an optimal balance between achieving uniform illuminance and controlling glare.

Lamps with beam angles larger than 80° ensure uniformity across the desk surfaces but introduce significant glare, while those with angles smaller than 70° effectively minimize glare at the cost of reducing illuminance uniformity.

By optimizing beam angles, we propose a practical approach that adheres to lighting standards and supports a conducive learning atmosphere.

Acknowledgement

This research was supported by a public grant from the Ministry of Science and Technology of Vietnam (MOST) under the project ĐTĐLCN.17/23.

Conflicts of interest

The authors declare no conflict of interest in this research.

References

[1] C. Barkmann, N. Wessolowski, M. S. Markwort, Applicability and Efficacy of Variable Light in Schools, Physiology & Behavior, Vol. 105, No. 3, 2012, pp. 621-627, https://doi.org/10.1016/J.PHYSBEH.2011.09.020.
[2] N. Wessolowski, H. Koenig, M. S. Markwort, C. Barkmann, The Effect of Variable Light on the Fidgetiness and Social Behavior of Pupils in School, Journal of Environmental Psychology, Vol. 39, 2014, pp. 101-108, https://doi.org/10.1016/J.JENVP.2014.05.001.
[3] P. Sleegers, N. Moolenaar, M. Galetzka, A. Pruyn, B. Sarroukh, B. Zande, Lighting Affects Students' Concentration Positively: Findings from three Dutch Studies, Lighting Research & Technology, Vol. 45, No. 2, 2013, pp. 159-175, https://doi.org/10.1177/1477153512446099.
[4] J. Xu, M. Liu, L. Li, Z. Xia, Effects of Environmental Lighting on Students' Sleep, Alertness and Mood: A Field Study in a Chinese Boarding School, Lighting Research & Technology, Vol. 56, No. 2, 2024, pp. 185-206, https://doi.org/10.1177/14771535231165263.
[5] Q. Liu, Z. Huang, Z. Li, M. R. Pointer, G. Zhang, Z. Liu, H. Gong, Z. Hou, A Field Study of the Impact of Indoor Lighting on Visual Perception and Cognitive Performance in Classroom, Applied Sciences, Vol. 10, No. 21, 2020, pp. 7436, https://doi.org/10.3390/APP10217436.
[6] B. A. Holden, T. R. Fricke, D. A. Wilson, M. Jong, K. S. Naidoo, P. Sankaridurg, T. Y. Wong, T. J. Naduvilath, S. Resnikoff, Global Prevalence of Myopia and High Myopia and Temporal Trends from 2000 through 2050, Ophthalmology, Vol. 123, 2016, pp. 1036-1042, https://doi.org/10.1016/j.ophtha.2016.01.006.
[7] S. Vitale, R. D. Sperduto, F. L. Ferris, Increased Prevalence of Myopia in the United States Between 1991-1972 and 1999-2004, Arch Ophtalmol. Vol. 127, No. 12, 2009, pp. 1632-1639, https://doi.org/10.1001/archophthalmol.2009.303.
[8] R. J. Lucas, S. N. Peirson, D. M. Berson, T. M. Brown, H. M. Cooper, et al., Measuring and Using Light in the Melanopsin Age, Trends Neurosci. Vol. 37, No. 1, 2014, pp. 1-9, https://doi.org/10.1016/j.tins.2013.10.004.
[9] Hanoi Eye Hospital 2, Current Status of Myopia in Vietnam, Statistics Data in 2023, https://mathanoi2.vn/kien-thuc/thuc-trang-can-thi-o-viet-nam.html, 2022 (accessed on: Janurary 14th, 2024) (in Vietnamese).
[10] X. You, L. Wang, H. Tan, X. He, X. Qu, H. Shi, J. Zhu, H. Zou, Near Work Related Behaviors and Myopic Shifts in Primary School Students, PLOS ONE, 2016, pp. 0154671, https://doi.org/10.1371%2Fjournal.pone.0154671.
[11] P. Khademagha, M. B. C. Aries, A. L. P. Rosemann, E. J. Loenen, Implementing Non-Image-Forming Effects of Light in the Built Environment: A Review on What We Need, Building and Environment, Vol. 108, 2016, pp. 263-272, https://doi.org/10.1016/j.buildenv.2016.08.035.
[12] Standard EN 12464-1:2021, Light and Lighting-Lighting of Workplaces-Part 1: Indoor Work, BSI Standards Publication, 2021, pp. 69-73.
[13] Z. T. Ye, M. J. Ruan, H. C. Kuo, CSP–LEDs Combined with Light Guide Without Reflective Matrix for Antiglare Design, IEEE Access. Vol. 8, 2020, pp. 156718–156726, https://doi.org/10.1109/ACCESS.2020.3019314.
[14] C. W. Chiang, Y. K. Hsu, J. W. Pan, Design and Demonstration of High Efficiency Anti-Glare LED Luminaires for Indoor Lighting, Opt. Express, Vol. 23, 2015, pp. A15-A26, https://doi.org/10.1364/OE.23.000A15.
[15] H. K. Walker, W. D. Hall, J. W. Hurst, Clinical Methods: The History, Physical, and Laboratory Examinations, Butterworths, Boston, 1990.