A STUDY ON THE EVALUATION METHODS OF INDOOR LIGHT ENVIRONMENT FOR OCCUPANT COMFORT AND WELL-BEING

Ki Rim Kim,[1] Kyung Sun Lee [1,*] and Jaewook Lee[2]

ABSTRACT

Since the COVID-19 pandemic, awareness of the importance of the indoor environment has increased. The indoor light environment is crucial because it impacts the energy consumption of buildings and affects human health and biorhythms as people spend most of their time indoors. Previous studies have concluded that the indoor light environment is essential to human health. However, it is not sufficient to analyze and evaluate the indoor light environment related to occupants' health in the context of building design. Therefore, this study aims to review and propose an indoor light environment evaluation methodology for human well-being using quantitative and qualitative evaluations of light, health, and environment. This study presents guidelines for evaluating buildings' indoor light environment for sustainability and well-being. Additionally, it provides an overall checklist of the indoor light environment evaluation process in Conceptualization, Light Environment Identification, Questionnaire, Environment Analysis, Comparison, and Conclusion. The evaluation checklist established through the results of this study could help establish a research methodology for the indoor light environment for human well-being, and apply it to evaluate indoor light environments for residents' comfort and well-being.

KEYWORDS

Human well-being, Indoor light environment, Evaluation system, Daylight, Building design, Sustainability

1. INTRODUCTION

The value of a good quality of life is highly sought after in contemporary society. This phenomenon is expressed as the concept of wellness that comprehensively captures what people desire regarding their well-being, happiness, and health [1, 2]. In addition to this social phenomenon, an increasing interest in supporting human wellness in buildings focuses on improving the buildings' energy performance.

1. School of Architecture, Hongik University, Seoul 04066, Republic of Korea; kkl881008@gmail.com
2. Department of Future & Smart Construction Research, KICT, Goyang-Si 10223, Republic of Korea; juklee531@gmail.com
* Author to whom correspondence should be addressed; E-Mail: ksunlee01@gmail.com
Tel.: +82-10-3731-2170 (K.L.)

People spend about 90% of their daily lives in indoor spaces (i.e., buildings) [2, 5]. The environment inside a building differs from the environment outside in various aspects, such as light, sound, heat, and air [6, 7]. In particular, people's lifestyles have recently changed due to the limited face-to-face lifestyle brought about by the COVID-19 pandemic, highlighting and increasing the importance of the environment inside buildings [8, 9]. Among the characteristics of indoor environments, the light environment, especially daylight, is one of the most critical factors that affect the interior of a building in combination with the building design process [10–12].

A primary advantage of daylight is that it reduces the load on artificial lighting that depends on the heating and cooling energy in a building in conjunction with the building design [13, 14]. Recently, the advantages of qualitative and quantitative daylighting have been highlighted [12, 15]. Recent studies indicate that daylight plays a vital role in people's mental and physical health, well-being, sleep, performance, and biological systems [16]. Lee et al. [17] distinguished between offices with and without daylight and directly measured the illuminance value of the light environment exposed inside a building for 50 participants. Along with performing computer simulations, the sleep and well-being of the participants were analyzed according to differences in illuminance. It was confirmed that the sleep and well-being index of those who worked in a daylight environment was higher than those who worked in an artificial light environment. Boubekri et al. [18] distinguished between offices with and without electrochromic windows and compared the spectrum of the light environment exposed inside the building for 28 participants. This study analyzed human sleep, well-being, and cognitive function according to light level and spectrum differences. It was found that the indices of sleep, well-being, and cognitive function of people who worked in an environment where there was a great deal of blue light were better than those who worked in other environments [19]. Anderson et al. [20] defined the exposure period of daylight and its role. In particular, daylight's timing and exposure time were discussed while explaining that exposure to daylight between 06:00 and 10:00 plays an important role in human biological rhythms.

The main characteristics of daylight are light level, spectrum, timing, and duration. As a metric to measure the quality factors of daylight, a method of measuring glare and melanopic illuminance has been studied [21–23]. In addition, a wellness-related certification system has been developed and applied to various buildings [24]. However, related research is still relatively scarce, and literature in the area, an experimental plan, and a certification system have not been established.

The primary purpose of this research was to analyze which evaluation methodologies effectively improved the quality of the light environment, focusing on indoor space comfort and well-being. As part of this process, research trends were investigated based on an analysis of metrics related to daylight, an analysis of certification systems related to human health and wellness, and evaluation methodologies based on a literature review. In particular, in terms of evaluation methodologies, existing studies are organized according to the size of the experimental space, the classification of the indoor space, and the detailed classification of the wellness measurement method. Methods that can be used in future research, experimental plans, and certification systems were investigated.

2. METHODS

For the research method, a literature review and analysis focused on existing studies to propose a light environment evaluation methodology for indoor space well-being was undertaken.

This study was conducted in three main steps, which correspond to the following sections of this article:

> First, a text mining-based analysis was conducted on previous studies related to the indoor light environment. For this, keywords that mainly dealt with the indoor light environment were derived, and the current research trends were dealt with through representative papers on keyword topics. Web of Science and Scopus were used for analyzing previous studies, and VOSviewer was used for text mining analysis.
>
> Second, detailed evaluation items were analyzed based on keywords derived from previous studies. We investigated quantitative or qualitative measurement methods for each keyword, systematized these data, and explored the applicability of the evaluations through mutual comparisons.
>
> Third, a checklist for evaluating the indoor light environment was constructed by synthesizing the quantitative and qualitative evaluations for each keyword. This checklist can be used as a basis for researchers to establish a research methodology for the indoor light environment related to human well-being. In addition, it can be applied as an environmental evaluation index for the indoor light environment in architectural spaces.

3. PREVIOUS REVIEWS

In this research, previous studies were considered using a bibliographical technique to establish a light environment evaluation methodology, and the current research trends of the light environment evaluation methods were analyzed. As part of this process, previous studies were organized using VOSviewer (www.vosviewer.com). VOSviewer is a program based on text mining and is used as follows: (1) a bibliographic database is collected by working with multiple search engines, (2) author and co-occurrence data of a targeted thesis are analyzed, or keyword analysis is performed, (3) correlations of analyzed data are derived, (4) the analyzed data are clustered, and (5) the analyzed data are visualized [26].

VOSviewer is used as part of literature reviews and for viewing research trends in various fields. In this study, keyword analysis and research on extant light environment evaluation methodologies were more broadly reviewed, and recent research trends were analyzed. Based on this, the main implications of the study through clustering were derived and used as primary data for the analysis of the light environment evaluation methods.

This study utilized bibliographic information from the Web of Science and Scopus [27]. Its search engine collected 1792 studies of prior research on green buildings, wellness, and light environment (988 studies in Web of Science, 804 studies in Scopus). The main keywords that entered the studies were light, health, and building. The bibliographic information was visualized using VOSviewer, and the correlations among the data were derived; the results are shown in Figure 1 and Table 1. The size of the circles in the figure indicates the frequency of the keywords within the studies, and the distance between the circles indicates the degree of co-occurrence. Also, the color of the circle identifies the cluster type. VOSviewer performs keyword clustering by automatically analyzing correlations and co-occurrences between keywords, and in this study, four clusters were derived.

Among the four clusters, the red one means that the proportion of studies is the highest, and the proportion decreases in the order of green, blue, and yellow. The main keywords for the red cluster were *Light*, *Human*, *Building*, *Sleep*, and *Daylight*. This means that the proportion of daylight is high in studying light, and there is an increased interest in how daylight affects humans and buildings. The main keywords for the green cluster were *Health*, *Performance*, *Environment*, *Productivity*, and *Quality*. This indicates that health is essential to human behavior, efficiency, and quality of life. Finally, the keywords of the blue cluster were *Office Buildings*, *Lighting*, *Architectural Design*, *Human Health*, *Sustainability*, and the keywords of the yellow cluster were *Built Environment*, *Design*, *Quality of Life*, *Physical Activity*, and *Mental Health*, which resulted in the theme of environment. It can be seen that many studies have been conducted to analyze the effect of human health and quality of life through architectural and environmental design.

The top 20 keywords were the most repeatedly used among the studies retrieved from the Web of Science and Scopus (using the initial keywords *Light*, *Health*, and *Environment*). Through this, the trends of research could be identified.

Figuiero et al. [28] conducted individual and comprehensive studies on light, health, and the environment. From spectral and level-based lighting measurement machine development, research was conducted by researchers in various fields with a wide variety of participants. In

FIGURE 1. Scientific landscape and clustering of the publications by VOSviewer.

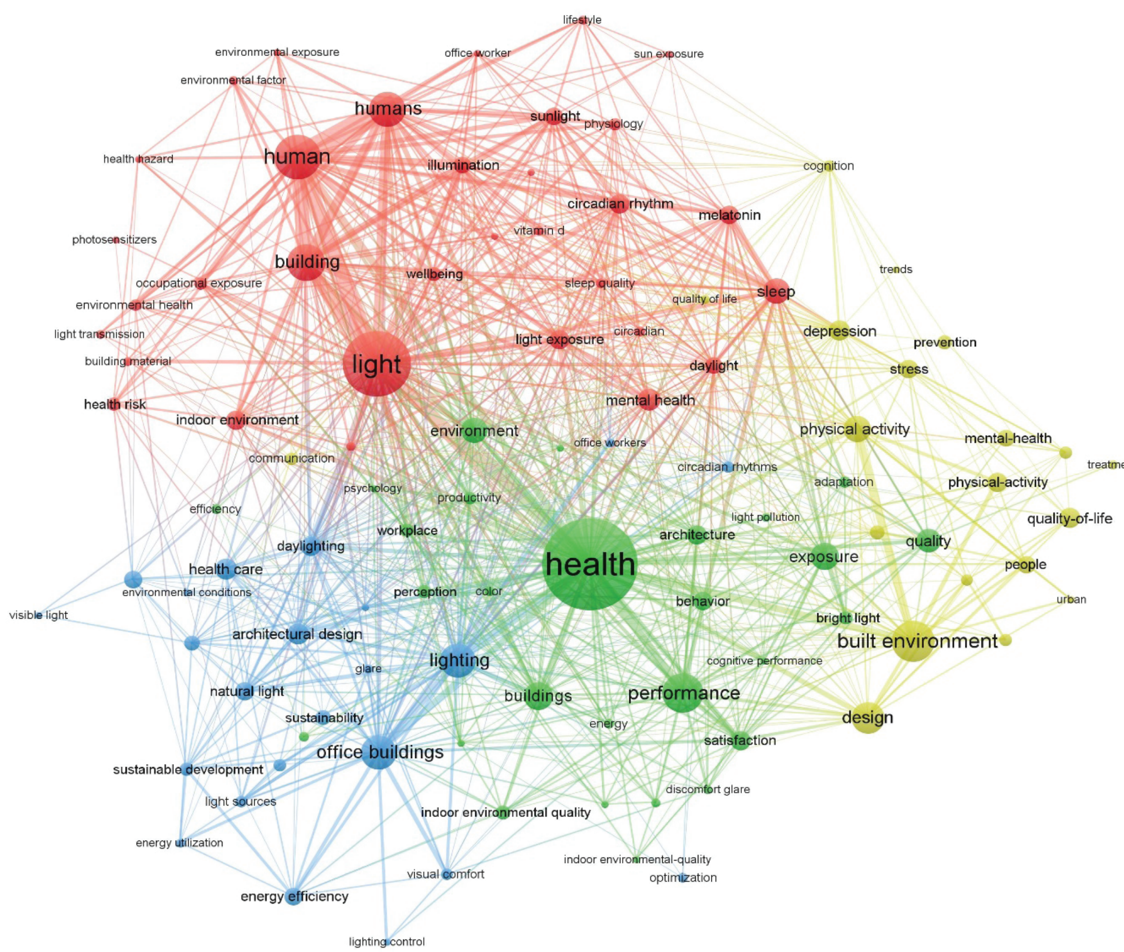


TABLE 1. Keyword clustering results.

Cluster	Topic	Main Keywords	No. of Keywords
Red	Light	Light, Human, Building, Sleep, Daylight	33
Green	Health	Health, Performance, Environment, Productivity, Quality	28
Blue	Environment (Space)	Office Buildings, Lighting, Architectural Design, Human Health, Sustainability	23
Yellow		Built Environment, Design, Quality of Life, Physical Activity, Mental Health	20

particular, she and her colleagues identified a newly described sensory pathway of light while proposing a new light-measurement strategy [29]. More recently, Figueiro et al. [30] quantified potential changes in daytime light exposure resulting from teleworking at home and examined how those changes might have affected sleep quality and overall health during the COVID-19 pandemic. The results suggest that spending one to two hours outdoors or staying in a bright room indoors may improve nighttime sleep. These results have important implications for daytime lighting in homes, offices, and schools.

3.1 Light

Boubekri et al. [31] categorized lighting characteristics into four major items: level, spectrum, timing, and duration. Based on these light characteristics, he and his colleagues studied how the lighting level and timing affected the sleep and health of office workers and elementary school students [17]. He also analyzed office workers' sleep, health, cognitive function, and economic effects according to changes in the lighting spectrum and duration [18, 32].

Dogan et al. [33] noted the importance of daylight in residential facilities that occupy a large part of the construction sector. Through the reference analysis related to this, he discovered the problem of daylight metrics that did not consider the climate in residential architecture. He suggested a climate-based daylight evaluation method to compensate for this.

Using a statistical method, Lee et al. [34] tried to combine daylighting metrics with building design elements. As a result, factors significantly influencing lighting performance during building design were derived. In addition, a statistical model that could predict the indoor lighting environment according to the building type was presented. Previous papers on daylighting analysis techniques have been developed to supplement problems based on existing analysis techniques or draft new methodologies to develop them. However, the methods and characteristics of the fundamental analysis techniques of daylighting metrics were not comprehensively arranged, and daylight performance, such as illuminance and the distribution of daylight, was concentrated. Therefore, through the current research, the primary analytic techniques of daylighting metrics are comprehensively collected, and analysis techniques for other characteristics of advanced lighting, such as glare and melanopic illuminance, as well as solar performance, are introduced.

These daylighting metrics are being used as evaluation indicators related to the light environment in various countries' sustainable certification systems. Doan et al. [35] studied the development process of the certification system by focusing on current representative eco-friendly certification systems: Leadership in Energy and Environmental Design (LEED) in the United States, Building Research Establishment Environment Assessment Method (BREEAM) in the United Kingdom, and Comprehensive Assessment System for Building Environmental Efficiency (CASBEE) in Japan. They also discussed similarities/differences and advantages/disadvantages through comparisons between the certification schemes. In addition, through project analysis, they checked whether each certification system was evaluated correctly from a sustainable perspective, such as indoor environment, energy, and materials.

Also, Potrč Obrecht et al. [36] analyzed LEED, BREEAM, and Germany's DGNB (an abbreviation for "German Sustainable Building Council" in German), which are sustainable certification systems. They focused on the health and well-being of occupants in an indoor spatial environment. It was determined that the certification systems could indirectly evaluate the health and well-being of occupants through indoor air quality, light environment, and thermal comfort. In addition, they reported that building design, management, and service were important factors. Previous papers on sustainable certification systems compared representative certification systems and had the advantage of describing each system's system structure and scoring and the critical elements on which to focus. Previous studies comprehensively covered the certification system. However, the detailed analysis and comparison of specific factors, especially standards and application methods for light environment evaluation (on which the current research focuses), were lacking. Therefore, through recent study, the light environment field of the sustainable certification system is investigated in detail, and the advantages and disadvantages are derived to suggest an improvement plan for the experimental methods of the daylight environment.

3.2 Health

To establish an indoor wellness space, one of the most critical items to understand is how people respond to light in buildings. As part of this process, it is essential to select participants for experiments and design which measures will be used to evaluate the wellness of the participants. Aries et al. [37] reviewed the effects of light with various experimental participants. Participants were classified into three occupational groups (office, school, and hospital) and analyzed health-related outcomes affected by light. In particular, the health outcomes were classified as direct (headache, seasonal affective disorder [SAD], suicide, breast cancer, and heart attack) or indirect (job burnout and physical activity), and their detailed reactions to light were investigated [1].

Similarly, Boyce et al. [38] categorized occupational groups of participants into office, school, hospital, and retail. Then reviewed people's health as it was affected by light's brightness, color, and duration. Again, the focus was on circadian rhythm, performance, and productivity in segmenting health categories. Therefore, when selecting participants, organic considerations for lighting, measure, and space should be considered.

3.3 Environment (Space)

Concentrating more on the environment, Konis [39] studied how to measure light in various ways when entering a building. In particular, he tested a novel circadian daylight metric for building design and evaluation, which broke away from an existing lighting level-oriented daylighting metric. He also field-tested how daylight affected the circadian stimulus in a health care building [38]. Edwards et al. [39] also researched how daylight affected buildings and spaces. He and his colleagues classified buildings according to their uses, such as offices, schools, retail, health care facilities, and industrial environments. Finally, they classified these various spaces by elements and reviewed how daylight affected people in each space.

4. QUANTITATIVE AND QUALITATIVE EVALUATION METHODS FOR LIGHT ENVIRONMENTS IN INDOOR SPACES

This research derived the main keywords (*Light*, *Health*, and *Environment*) for occupant comfort and well-being in an indoor light environment through bibliographical analysis (VOSviewer) and introduced previous studies related to each keyword. Based on this, quantitative and qualitative evaluation methods and indoor environment factors for light and participants were investigated and analyzed to present guidelines for the indoor light environment.

4.1 Quantitative Evaluation Methods (Light)

First, the quantitative evaluation method for the light environment is a direct measurement of the characteristics of light. For example, the characteristics of light in an indoor environment are illumination measured for light sources, the glare that affects visual perception, and melanopic lux related to health and circadian rhythm. In addition, sustainable certification systems, which are objective evaluations of the human and architectural environment, are also quantitative evaluation methods. Therefore, this study analyzed the light environment evaluation of sustainable certification systems and the direct light measurement.

4.1.1 Analysis of Measurement Techniques for Light

Various measurement techniques have been developed to assess the light environment through daylight flowing into an indoor space. Therefore, before applying a light measurement method according to a code, regulation, or guideline, it is necessary to find out about these methods. The initial daylight measurement technique presented an evaluation method that quickly and conveniently derived analytic results. As computer simulations were gradually introduced, various measures and analysis methods for light were developed, and through this, it became possible to supplement and analyze detailed light environment analysis techniques [40]. In addition, further studies have been conducted on the effects of light on circadian rhythms by non-visual effects. The methods for analyzing daylight are described below.

(1) Daylight factor (DF)

The daylight factor (DF) is the percentage (%) of indoor illuminance relative to the illuminance of all external openings and means the ratio of daylight entering a room [41]. The calculation method recommended by the International Lighting Commission is as follows [42]:

$$DF = \frac{E_i}{E_0} \times 100[\%]$$

E_i: The indoor illuminance,

E_0: The illuminance of all external openings

(2) Daylight Autonomy (DA)

The basic concept of daylight autonomy (DA) is the same as that of DF, but simulation is performed with various weather data from the relevant area [43]. In other words, compared to the existing DF, DA can effectively evaluate indoor daylight while considering the characteristics of the regional sky conditions. DA was first proposed in the Swiss Natural Lighting Code in 1989 and was based on illuminance at times throughout the entire year. It was improved and, finally, was established as a percentage of the sum of the total hours exceeding a specific illuminance value for daylight based on the working hours (08:00–18:00) throughout the year [12].

(3) Useful Daylight Illuminance (UDI)

UDI is a metric proposed by Nabil and Mardaljevic [44] in 2005, and it is a measurement method developed by supplementing DA. In the case of the existing DA, only the minimum illuminance is set, but in the case of UDI, the minimum and maximum illuminance are set. That is, UDI is expressed as a percentage of the sum of the total hours receiving illumination between 100 lux and 2,000 (or 3,000) lux during work hours throughout the year.

(4) Uniformity Ratio of Illuminance

Uniformity ratio of illuminance, or uniformity, is a measure of the evenness of the light distribution in space. The lower the uniformity, the more it psychologically affects a human's visual perception, and especially when the perceived illuminance is lower than its actual value. Uniformity is the ratio of the minimum illuminance to the average illuminance of the space and is related to the diffusivity of the light [45].

$$\text{Uniformity ratio of illuminance} = \frac{\text{The minimum illuminance}}{\text{The average illuminance}}$$

(5) Spatial Daylight Autonomy (sDA)

Spatial daylight autonomy (sDA) is a measurement method suggested by the Illuminating Engineering Society (IES). It refers to the ratio of the floor area receiving daylight over a specific illuminance (lux) during a specific working time [46]. In particular, the evaluation of the sDA was applied in LEED v4 starting in 2013 [47]. Accordingly, the evaluation criteria of LEED v4 for sDA is that the ratio of the area exceeding 300 lux of the floor area during the annual occupancy time is 50% or more.

(6) Annual Sunlight Exposure (ASE)

Annual sunlight exposure (ASE) is a measurement suggested by the IES, and it is the ratio of the area with the illumination of more than 250 hours and more than 1,000 lux per year [46]. Through ASE measurement, it is possible to indirectly understand and predict the excessive light environment of an indoor space. For example, if the ASE level is high in an office space, considering that the optimal illuminance for work is 500–700 lux, it can be assumed that light pollution occurs in this space due to excessive daylight.

(7) Glare Metrics for Daylighting (DGP, DGI, PGSV)

The evaluation and calculation formulas for glare have been developed according to the field of application and the target. In the case of disabled glare, an evaluation formula was developed mainly for vehicle drivers. In the case of unpleasant glare, an evaluation formula was designed for road, vehicle, natural, and indoor lighting. This article is primarily interested in discussions of the unpleasant glare of indoor space. Methods for evaluating an undesirable glare index for daylight entering the room include Wienold's daylight glare probability (DGP) method, Hopkinson's daylight glare index (DGI) method, and Iwata's predicted glare sensation vote (PGSV) method [48–51]. They are calculated as follows:

$$DGP = 5.87 \times 10^{-5} E_V + 9.18 \times 10^{-5} \log\left(1 + \sum_{i=1}^{n} \frac{L_{s,i}^2 \times \omega_{s,i}}{E_v^{1.87} \times P_i^2}\right) + 0.16$$

E_v: Vertical illumance at the eye (lx)
L_s: Luminance of glare source (cd/m^2)
ω_s: Solid angle of source
P: Guth position index

$$DGI = 10\log 0.478 \sum_{i=1}^{n} \frac{L_s^{1.6} \times \Omega^{0.8}}{L_b + \left(0.07\omega^{0.5} \times L_s\right)}$$

L_s: Luminance of glare source (cd/m^2)
L_b: Background luminance (cd/m^2)
Ω: Modified solid angle (sr)
ω_s: Solid angle of source

$$PGSV = 3.2\log L_w - 0.64\log\omega + (0.79\log\omega - 0.61)\log L_b - 8.2$$

L_w: Luminance of window (cd/m^2)
L_b: Background luminance (cd/m^2)
ω_s: Solid angle of source

(8) Melanopic Lux

Unlike the previous measurement methods, melanopic lux is a measure of the effect on humans of non-visual aspects of light [52]. The concentration of light stimulates the pineal gland, an endocrine organ at the back of the human brain, and melatonin is secreted through this stimulation [53, 54]. Melatonin secretion is generally low during the day and high at night; it is a neurohormone that affects sleep rhythm. In other words, this suggests that daylight in the indoor environment is closely related to the human circadian rhythm. However, there is no standardized measurement index, and melanopic lux and human circadian rhythms have been measured under various environmental light conditions, such as differing light intensity and color temperatures [39]. In addition, there is an actual measurement through a spectrometer and using simulation tools (ALFA, etc.). Also, Well Building Standard proposes a method of calculating measurements of vertical surfaces by substituting them into a specific calculation formula (EML) [29, 55].

4.1.2 Analysis of Sustainable Certification Systems for Lighting Design Criteria

With the awareness of sustainable design and related certification systems established, research has been conducted to improve a system by analyzing and comparing overall matters within a certification system [56, 57]. However, a detailed analysis of the direction and measurement methods to be pursued for specific items of the sustainable certification system is lacking.

Therefore, this study analyzed representative sustainable certification systems such as LEED, BREAM, CASBEE, DGNB, and G-SEED to improve the light environment in indoor spaces with the evaluation items related to the lighting environments and reviewed the lighting analysis techniques.

As a research method, first, each sustainable certification system's establishment period, purpose, classification system, etc., and the development direction of the certification system are examined. Then, buildings' energy performance and technology, the Well Building Standard and Living Building Challenge, which considers human life, emotions, design, society, and culture based on sustainable technologies, are examined. Finally, this study conducted a comprehensive comparison and review of the certification systems for the direction and measurement method of the light environment and found and suggested improvement points.

(1) LEED (Leadership in Energy and Environmental Design)

LEED proposes classifications and standards for the components of green buildings through quantitative measurement and evaluates the environmental performance throughout the life cycle from the overall perspective of a building. LEED has been improved to meet the changes and trends of the times and has been updated to LEED V4.1 in 2019 [58]. According to the type of building and the characteristics of the project, it classifies five different evaluation systems.

The evaluation of the light environment in LEED is divided into (1) interior lighting and (2) daylight in the indoor environmental quality category. Unlike BREEAM of the UK and DGNB of Germany, in which a right of view is included in the evaluation of the light environment, LEED provides a score through a separate item called "quality views." The required scores for business facilities and educational facilities are described in Table 2.

The first item, interior lighting, is intended to evaluate creating a good indoor environment for occupants through lighting. For this purpose, it is evaluated by the number of implementations of four details as follows: (1) glare for interior lighting through actual measurement or modeling, (2) measurement of the color reproducibility of an object through the light source, (3) area ratio with adjustable lighting brightness, and (4) measurement of the surface reflectance of ceilings and walls. The second item, daylight, aims to reduce the impact on occupants' circadian rhythms and the use of artificial light and is divided into three sub-items: (1) $sDA_{300/50\%}$ and $ASE_{1000,250}$ satisfying more than a certain area (simulation), (2) measurement method similar to UDI, a daylight analysis technique (simulation), and (3) the method is the same as in no. 2, but it is evaluated through actual measurement. The last item, quality views, aims to improve the visual environment of occupants through views. To this end, it is necessary to provide an outside view from the inside of the building above the standard area ratio, and it is acceptable to view the atrium within a specific area ratio.

(2) BREEAM (Building Research Establishment Environment Assessment Method)

BREEAM conducts a comprehensive evaluation of the impact of buildings on the environment and humans through 10 items, such as energy, health and well-being, innovation, land use, materials, transportation, and water resources [59]. This evaluation raises awareness of sustainable buildings among owners, residents, and architects. Currently, more than 70 countries are using the BREEAM system. European countries, such as the Netherlands and Spain, are developing the BREEAM system according to their local situation through National Scheme Operators (NSO). The system of BREEAM was classified into five systems according to the characteristics of the project, and it was subdivided according to the type of building.

BREEAM's evaluation of the light environment is measured in the visual comfort section, a detailed item of glare control for sunlight, right of view, indoor and outdoor lighting level, area setting, and control. The evaluation items related to the light environment and the distribution of points based on office and educational facilities are shown in Table 2.

For the first item, glare control by daylight, we check whether an appropriate strategy (such as shading) is established to identify and control the glare risk area in the indoor space. Also, it is evaluated whether these systems contribute to energy saving and proper brightness through the harmonization of lighting systems. In the case of daylighting, the second item, DF, is used to evaluate the minimum brightness conditions for daylight and how evenly the light reaches the room. The third item, the right to view, is evaluated based on whether it provides an appropriate view from the inside over a certain area (95%) of the building. Finally, the last item, indoor and outdoor lighting level, area setting, and control items, is judged according to the standards required by laws and recommendations.

(3) CASBEE (Comprehensive Assessment System for Building Environmental Efficiency)

CASBEE is an evaluation tool for comprehensive environmental performance evaluation of buildings that was developed jointly by industry, government, and academia under the support of the Japanese Ministry of Land, Infrastructure, and Transport in 2001 [60]. It was created to reduce the utilization and environmental load. CASBEE differs from other countries' sustainable certification systems in that it divides grades by level rather than using a point system and evaluates the grades of each relevant item comprehensively. The evaluation means provided by CASBEE are classified into four items according to the scale of the project. The criteria for application targets are subdivided according to the purpose.

CASBEE's evaluation of the light environment is covered in the indoor environment of the environmental quality item of buildings. The light environment is evaluated according to four criteria: sunlight, glare prevention, illuminance level, and lighting control. The evaluation items related to the light environment and the standard levels for offices and educational facilities are presented in Table 2.

The first item, daylight, was evaluated by dividing it by the average DF range and the number of types of solar installations (light shelves, light ducts, optical fibers, etc.) installed on the exterior wall. The second item, glare prevention, is evaluated according to the type of daylight control device (eaves, curtains, blinds, etc.) and a combination method for windows exposed to excessive glare. The third item, illuminance level, is evaluated according to the range of indoor illuminance values through daylight. Finally, the last item, lighting control, provides a level according to the scale and method of adjusting the brightness of artificial lighting installed in the room.

(4) DGNB (Abbreviation for "German Sustainable Building Council" in German)

Since the 1990s, building sustainable certification systems such as LEED and BREEAM have been initiated, and the need to prepare sustainable evaluation standards for buildings has gradually become an issue. In 2008, the first certification system in Germany for new offices was implemented. Unlike LEED and BREEAM, which evaluate sustainability and energy efficiency, DGNB applied the concept of sustainable buildings used by the International Organization for Standardization (ISO) [61]. This means that it is necessary to consider and analyze the economy, environment, and society while satisfying the technology and functional performance of the building. The classification system of the DGNB is primarily divided into new construction and renovation, and evaluation is carried out by subdividing it further according to the use of the building.

In the DGNB method, the evaluation items related to light environment are located in visual comfort, which is a detailed item of health/comfort and user satisfaction among social, cultural, and functional levels. Regarding the light environment, the ratio of the area where daylight can be used indoors, the external view in the room, glare, artificial lighting, and the degree of color expression of objects through lighting are evaluated. The evaluation items related to the light environment and the distribution of points based on office and educational facilities are presented in Table 2.

The first item, daylight, is evaluated by the average DF range for 50% of the exclusive area. The second item, exposure to daylight in the workspace, is measured through simulation or actual measurement. The third item, the external view from the inside, is evaluated according to the viewable area. The fourth item is scored according to the installation of a specific system for preventing glare. The fifth item is the evaluation of artificial lighting, and it is evaluated in two sub-items based on the lighting standard and implementation strategy to avoid excessive artificial lighting. Finally, the last item evaluates the color expression level of objects in all areas for daylight in the color rendering index (CRI) range.

(5) G-SEED (Green Standard for Energy and Environmental Design)

G-SEED is Korea's green building certification system that has been in operation since 2002 [62]. Initially, only two categories of office buildings and residential complexes were subject to certification, and the system was expanded to more facilities in 2005.

The evaluation in G-SEED on the light environment includes a layout plan to secure the proper sunlight rights for land use and transportation items, lighting energy saving for energy and environmental pollution items, adoption of a comfortable indoor environment control method for indoor environment items, direct sunlight control, and the installation of awnings for reducing glare. In addition, when a building applies for the best or excellent grade, an additional evaluation is made on securing daylight performance in the indoor environment of innovative design items. Therefore, depending on the building, the need for evaluation of each item is different, as shown in Table 2.

In the case of the first item, the layout plan for securing the proper daylight, the evaluation is performed through the degree of the maximum elevation angle of the building. The second item, lighting energy saving, examines the average lighting density and whether daylight is used by installing a daylight sensor. The third item, the comfortable indoor environment control method, is evaluated according to the number of types that can be directly adjusted among temperature, ventilation, air volume, and lighting to improve efficiency and create a comfortable environment in the workspace. The fourth item, shading installation for direct sunlight control and glare reduction, depends on the ratio of shade application in general areas. Finally, the last item, securing daylighting performance, is evaluated according to the average DF range. To receive the highest score, it must be equal to or higher than a certain level of uniformity.

(6) WELL Building Standard

The WELL Building Standard (WELL), established in 2007, puts the health of residents as the top priority in terms of space design, construction, and operation. It is designed to create a better environment through buildings. It is a health-building certification system with a purpose. After WELL V1 was unveiled at the International WELL Building Institute (IWBI) in 2014, it was updated to V2 in 2018 [63]. The WELL aims to improve residents' health, mood, sleep

TABLE 2. Evaluation of the light environment in LEED, BREEAM, CASBEE, DGNB & G-SEED.

Evaluation of the light environment in LEED			
Category		Contents	Points
Indoor Environmental Quality	Interior Lighting	Glare control	1–2
		Color rendering	
		Lighting control	
		Surface reflectivity	
	Daylight	sDA, ASE	1–3
		Illuminance calculations	
	Quality Views	View to the outdoor natural or urban environment	1

Evaluation of the light environment in BREEAM			
Category		Contents	Points
Health and Well-being	Visual Comfort	Control of glare from sunlight	1
		Daylighting	2
		View out	1
		Internal and external lighting levels, zoning, control	1

Evaluation of the light environment in CASBEE			
Category		Contents	Levels
Environmental Quality of the Building	Indoor Environment—Lighting & Illumination	Daylight	1–5
		Anti-glare measures	1–5
		Illuminance level	1–5
		Lighting controllability	1–5

Evaluation of the light environment in DGNB				
Category		Contents		Points
Sociocultural and Functional Quality	Health, comfort, and User Friendliness—Visual Comfort	Availability of daylight for the entire building		10–18
		Availability of daylight at the permanent workstation		8–16
		Visual contact with the outside		8–16
		Absence of glare in daylight		8–16
		Artificial lighting	Following DIN EN 12464-1	16
			Number of over-fulfillment features	3–10
		Daylight color rendering		4–8
		Exposure to daylight		—

Evaluation of the light environment in G-SEED					
Category	Office	School	Contents		Points
Land-Use and Transportation		•	Site planning for solar rights		0.4–1.0
Energy and Environmental Pollution	•	•	Saving lighting energy		1.6–4.0
Indoor Environment	•		Indoor environment control system		1.6–2.0
		•	Shading installation		0.8–2.0
Innovative Design (Additional)		•	Indoor environment	Daylighting performance	0.4–1.0

pattern, productivity, etc. in the spatial environment by reflecting research and knowledge in various fields, such as medicine and business administration, as well as the field of architecture. In particular, it focuses on the sustainability of buildings for human well-being by operating a re-certification program that conducts a post-verification of whether the environment of the building is maintained three years after the completion of the certification.

The WELL evaluates buildings through a 100-item checklist based on 10 Concepts that affect human health and well-being in the built environment (Table 3). The Well Building Standard's evaluation items related to the light environment are subdivided into nine items. Based on the light exposure and visual lighting design, which are prerequisites for the lighting environment, points are given for circadian, glare, daylight, visual balance, and artificial lighting quality and control. The evaluation items and points related to the light environment are shown in Table 3.

The first item, circadian lighting design, checks whether biorhythms and psychological health are maintained through light stimulation. For this purpose, whether or not the standard equivalent melanopic lux (EML) is maintained for four hours at a 45cm height of the workspace is measured. The second item, electric light glare control, is a strategy to prevent glare caused by artificial lighting. It is evaluated based on various glare-related indicators, including the unified glare rating (UGR). The third item, daylight design strategies, considers whether it is possible to control the inflow of light and shade. The fourth item, daylight simulation, estimates whether daylight is sufficiently introduced into the room by the floor area ratio that satisfies the average sDA300 for 50% of the space through simulation. The fifth item, visual balance, aims to create a light environment for visual comfort and is achieved if some of the

TABLE 3. 10 Concepts & Evaluation of the light environment in the WELL.

Concepts of the WELL				
Air	Thermal Comfort	Nourishment	Mozvement	Mind
Water	Sound	Light	Materials	Community
Evaluation of the light environment in the WELL				
Category	**Contents**			**Points**
Light	Pre-condition	Light Exposure		—
		Visual Lighting Design		—
	Circadian Lighting Design			3
	Electric Light Glare Control			2
	Daylight Design Strategies			4
	Daylight Simulation			2
	Visual Balance			1
	Electric Light Quality			3
	Occupant Lighting Control			3

various items are satisfied. The sixth item, electric light quality, evaluates objects' color expression and flicker through artificial lighting. The last item, occupant lighting control, aims to realize a personalized lighting environment space by controlling lighting, and the control and area of the lighting system are evaluated.

(7) Living Building Challenge

The Living Building Challenge (LBC), announced in 2007, evaluates the ecological future through eco-friendly systems, planning, and design of buildings, focusing on humanistic factors, such as social fairness, rich culture, and human health [64]. To this end, the highest level of environmental standards was defined to consider the role of buildings in the ecosystem, and it has been improved and upgraded with LBC v4.0 in 2019. In addition, projects are selected every year. As of 2020, 117 projects have been listed to encourage architects to understand materials and systems through the standards and examples to make environmentally sound choices when designing. The LBC, like the WELL, involves the completion of a post-evaluation of the health of the occupants after certification. The evaluation should be performed at least once during the period of use of 6 to 12 months. The LBC classifies building projects into four types (new building, existing building, interior, and landscape/infrastructure) and evaluates them through seven criteria and 20 checklists, as shown in Table 4.

In the LBC, the light environment does not have a specific classification. Instead, in the health and happiness category, the indoor environment, air quality, and view are evaluated for the health of the occupants in an integrated way, as shown in Table 4.

4.1.3 Comprehensive Analysis of Measurement Techniques and Sustainable Certification Systems for Light Environment

So far, daylighting metrics and light environment evaluation criteria in seven sustainable certification systems for five countries have been investigated. First, the light environment evaluation criteria of the sustainable certification systems were summarized; the commonalities, differences, and peculiarities were analyzed. In addition, we examined how daylighting metrics are applied in these evaluation criteria and explored how the current study can contribute to the light environment evaluation method in a future certification system and green smart light evaluation method. As shown in Table 5, the light environment evaluation standards are organized, and daylighting metrics, indoor artificial lighting, and glare are common in the six sustainable certification systems. In contrast, in the case of the right of the view, the color expression of objects, and circadian lighting, there are differences in each certification system. When analyzing daylight in the light environment evaluation of the certification system, most certification systems use DF, a static metric, as the main analysis technique, as shown in Table 6. In the case of LEED, the dynamic daylight metrics of sDA, ASE, and UDI are used, and WELL is based on the sDA. In the case of using dynamic daylighting metrics, it was determined that a more accurate evaluation could be made on the solar performance that directly affects the occupants through the evaluation of the specific working hours. However, in the case of glare, although three analysis methods (DGP, DGI, PGSV) have been introduced, it is not applied in most sustainable certification systems. Glare is considered difficult to evaluate because recognizing glare differs from person to person. Therefore, most sustainable certification systems focus only on the technical effects of light, and there is a lack of interest in how the light environment affects human behavior, health, and emotions. However, the analysis technique for melanopic illuminance that can measure a health effect is only applied in WELL. Therefore, through this

TABLE 4. Criteria and checklists & Evaluation of the light environment in the LBC.

Criteria and checklists of the LBC	
Criterion	**Checklist**
Place	Ecology of Place
	Urban Agriculture
	Habitat Exchange
	Human-Scaled Living
Water	Responsible Water Use
	Net Positive Water
Energy	Energy + Carbon Reduction
	Net Positive Carbon
Health + Happiness	Healthy Interior Environment
	Healthy Interior Performance
	Access to Nature
Materials	Responsible Materials
	Red List
	Responsible Sourcing
	Living Economy Sourcing
	Net Positive Waste
Equity	Universal Access
	Inclusion
Beauty	Beauty + Biophilia
	Inspiration + Education

Evaluation of the light environment in the LBC			
Category		**Contents**	**Points**
Health + Happiness	Healthy Interior Environment	Provide views outside and daylight for 75% of regularly occupied spaces	—
	Healthy Interior Performance	Provide access to views and daylight from 95% of regularly occupied spaces and opportunities for those occupants in the remaining 5% of regularly occupied spaces to move to compliant spaces for a portion of their day.	—
	Access to Nature	Complete a post-occupancy evaluation that addresses the health benefits of the project, including the benefits of daylight, fresh air, and access to nature, at least once within six to 12 months of occupancy.	—

TABLE 5. Light environment evaluation criteria in sustainable certification systems.

Sustainable Certification System	Year	Light Environment Evaluation Criteria						
		Daylighting	Indoor Artificial Lighting		Glare	View	Color Rendering	Circadian Lighting
LEED (US)	1993	sDA / ASE / UDI	Control	Brightness Level	Candela / UGR	Viewable area	CRI / CFI*	—
			Reflection	Reflectivity (Ceiling, Wall)				
BREEAM (UK)	1990	DF / Uniformity ratio / DA	Compliance with code and requirements		Anti-glare strategy	Viewable area	—	—
CASBEE (Japan)	2001	DF	Illuminance	Lux	Shade type and combination	—	—	—
		Number of daylight device types	Control	Brightness control area and method				
DGNB (Germany)	2007	Entire building / DF	Compliance with code		Protection system and classification	Viewability	CRI	—
		Workspace / DA	Balance	Lux / CCT* / Adjustment				
G-SEED (Korea)	2002	DF / Uniformity Ratio	Energy Saving	Lighting density	Shade installation ratio	—	—	—
				Daylight sensor installation				
			Control	Individual adjustment				
WELL (US)	2007	sDA / Distance between glazing and individual unit	Illuminance	Compliance with requirements	Light emission / Candela / UGR / Shade control	—	CRI	EML
				Footcandle (fc)				
			Balance	Luminance ratio / Uniformity Ratio / CCT*				
			Control	Brightness adjustment method and area				
			Flicker	Compliance with Requirements				
LBC (US)	2007	Area and Accessibility of Daylight	—		—	Viewable area	—	—

*CCT : Correlated Color Index
CFI : Color Fidelity Index

TABLE 6. Application of daylighting metrics in sustainable certification systems.

Sustainable Certification System Daylighting Metric		LEED	BREEAM	CASBEE	DGNB	G-SEED	WELL
DF			●	●	●	●	
DA			●		●		
UDI		●					
Uniformity Ratio			●			●	●
sDA		●					●
ASE			●				
Glare	DGP						
	DGI						
	PGSV						
Melanopic Lux							●

* For LBC, detailed metrics for daylighting are unknown

research, analysis techniques and surveys for glare and melanopic illuminance were cross-verified to complement the quantitative measurement method in the light environment of the existing sustainable certification systems. Also, a qualitative method to evaluate the health and psychology of occupants was also added.

4.2 Qualitative Evaluation Methods (Health)

The qualitative evaluation method for the light environment is a questionnaire for occupants. The effects of natural and artificial light on sleep, health (physical and mental), and performance have been described in many previous studies. In medical science, these factors are generally evaluated using questionnaires. Therefore, the questionnaires covering sleep, health, and performance are summarized in Table 7. Through this indirect measurement method, the occupant's health can be inferred. It can also be used as an indicator to analyze the correlation between light factors, occupants' comfort, and well-being to establish guidelines for the indoor light environment.

4.2.1 Sleep

The following well-established and validated sleep questionnaires can be used to obtain subjective sleep data. Participants can complete the Berlin Questionnaire (Berlin), the Pittsburgh Sleep Quality Index (PSQI), the Horne-Ostberg Self-Evaluation Questionnaire (HO), the Munich Chronotype Questionnaire (MCTQ), the Functional Outcomes of Sleep Questionnaire (FOS-Q), the PROMIS Sleep-Related Impairment Item Bank and the PROMIS Sleep Disturbance Item Bank (PROMIS). We summarize the key features of each questionnaire below.

TABLE 7. Outcome measures for health.

Category	Procedures	Outcome Measures
Sleep	Subjective Questionnaires	Berlin
		PSQI
		HO
		MCQT
		FOS-Q
		PROMIS
Health And Well-being	General Health	SF-36
	Mental Health	STAI
		PSS
		CES-D
		PANAS
	Exercise	IPAQ
Performance	Cognitive function	SMS
	Activity	PVT

(1) Berlin Questionnaire (Berlin)

These questions are designed to identify adult respondents likely to have sleep apnea. The questionnaire asks about snoring behavior, wake-time sleepiness or fatigue, and the presence of obesity or hypertension [65].

(2) Pittsburgh Sleep Quality Index (PSQI)

This self-rated 21-item questionnaire assesses individual sleep habits (bedtime, morning rising time, sleep-onset latency, and nighttime sleep duration), insomnia, and hypnotic use over a 1-month time interval [66]. The PSQI has been widely applied in various clinical settings and epidemiological studies in many countries because of its satisfactory psychometric properties.

(3) Horne-Ostberg Self-Evaluation Questionnaire (HO)

These questions are designed to identify the subjective evening or morning inclinations of the respondent [67].

(4) Munich Chronotype Questionnaire (MCTQ)

Munich Chronotype Questionnaire (MCTQ). These questions identify chronotype-related sleep/wake behaviors based on work versus free days [68].

(5) Functional Outcomes of Sleep Questionnaire (FOS-Q)

The purpose of this questionnaire is to determine if there is generally difficulty carrying out certain activities due to being too sleepy or tired [69].

(6) PROMIS

The PROMIS Sleep-Related Impairment Item Bank. This instrument assesses perceptions of alertness, sleepiness, and tiredness during usual waking hours and the perceived functional impairments during wakefulness associated with sleep problems or impaired alertness. The Sleep-Related Impairment Item Bank measures waking alertness, sleepiness, and function within the context of overall sleep-wake function but does not directly assess cognitive, affective, or performance impairments [70].

The PROMIS Sleep Disturbance Item Bank. This instrument assesses perceptions of sleep quality, sleep depth, and restoration associated with sleep; perceived difficulties and concerns with getting to sleep or staying asleep; and perceptions of the adequacy of and satisfaction with sleep. The PROMIS Sleep Disturbance Scale does not include symptoms of specific sleep disorders nor provides subjective estimates of sleep quantities (e.g., the total amount of sleep, time to fall asleep, or amount of wakefulness during sleep) [71].

4.2.3 Health and Well-being—General Health

A health questionnaire can be used to gather generalized health status and history information from a respondent. A demographics form can be used to document a respondent's demographics and ethnicity, as defined by the National Institute of Health [72, 73].

(1) Short Form 36 (SF-36)

This questionnaire measures health-related quality of life with 36 items related to the physical and psychosocial domains of health influenced by a respondent's experiences, beliefs, and perceptions of health. The SF-36 survey is a well-validated health status questionnaire that measures an individual's physical functioning, bodily pain, and perception of the ability to perform physical, social, and emotional role functions [74].

4.2.4 Health and Well-being—Mental Health

The following questionnaires can be used for a qualitative assessment of participants' mood, anxiety, and stress.

(1) State-Trait Anxiety Inventory (STAI)

State-Trait Anxiety Inventory (STAI). This questionnaire is used to determine anxiety [75]. The State-Trait Anxiety Inventory Form Y (STAI-Y) is a well-validated instrument for measuring anxiety in adult respondents. The STAI differentiates between the temporary condition of state anxiety and the more general and long-standing quality of trait anxiety. The STAI has 40 questions with a range of four possible responses for each.

(2) Perceived Stress Scale (PSS)

This scale is used to determine levels of stress [75]. The PSS measures a global perception of stress during the previous month. It also has the virtues of being widely used, general in nature, brief, and able to assess stress response on a continuum from relatively mild to severe.

(3) Center for Epidemiologic Studies Depression Scale (CES-D)

This scale is used to determine mood. The CES-D is a 20-item instrument developed by the National Institute of Mental Health (NIMH) to detect major or clinical depression in adolescent and adult respondents [76]. The CES-D has four separate factors: depressive affect, somatic symptoms, positive affect, and interpersonal relations. The questions are easy to answer and cover most areas included in the diagnostic criteria for depression. It has been used in urban and rural populations and cross-cultural studies of depression. Studies using the CES-D indicate excellent internal consistency, acceptable test-retest stability, and construct validity. The CES-D takes approximately 10 minutes to complete and is effectively used in various mental health settings.

(4) Positive and Negative Affect Schedule (PANAS)
This assessment comprises two mood scales, one that measures positive affect and another that measures negative affect [77]. The PANAS is used as a psychometric scale for relations between positive and negative affect scales.

4.2.5 Health and Well-being—Exercise

(1) International Physical Activity Questionnaire (IPAQ)
This questionnaire is used to obtain internationally comparable data on health-related physical activity and has been extensively tested for reliability and validity across 12 countries (and 14 sites) in 2000 [78].

4.2.6 Performance

(1) Strategic Management Simulation (SMS)
This assessment provides scores on nine cognitive domains based on validated, computer-based simulation software [80]. The SMS assessment offers a blended approach using real-world scenarios, which ultimately leads to stronger correlations with other indicators of job performance, such as salary at age, the number of employees supervised, and the number of promotions [81].

(2) Psychomotor Vigilance Task (PVT)
The assessment is a sustained attention task that measures a participant's reaction time to a visual stimulus [79]. The participant is given a hand-held or computer device and is asked to press a button as soon as a light appears. The light turns on randomly every few seconds over a 5-–10-minute interval. Reaction time measures can be calculated, as well as a count of how many times the button was not pressed when the light was on, which indicates lapses in attention.

4.3 Indoor Light Environmental Factors for Occupant Comfort and Well-being (Environment)
People spend a great deal of time inside buildings. In particular, since the start of the COVID-19 pandemic, more people have been working from home, and accordingly, interest in the light environment of indoor spaces has grown. The amount of light required may vary depending on the nature of the space. Especially the amount of daylight in a room varies depending on the type of building and the space design. In addition, the occupancy time according to the purpose and behavior of the occupants in the space is different, and the time exposed to the light environment is affected. Therefore, the appropriate illuminance and exposure time, considering the building use and the occupants' behaviors, were analyzed to present guidelines for the indoor light environment.

4.3.1 Indoor Illuminance by Space Type
The Illuminating Engineering Society of North America (IESNA) suggests minimum light levels for different indoor spaces. As shown in Table 8, the illuminance according to various spaces is

TABLE 8. *IESNA Lighting Handbook* guidelines. [82]

Room Type	Light Level (LUX)	IECC 2021 Lighting Power Density (Watts per m^2)
Cafeteria–Eating	200–300	4.31
Classroom–General	300–500	7.64
Conference Room	300–500	10.44
Corridor–General	50–100	4.41
Corridor–Hospital	50–100	7.64
Dormitory–Living Quarters	200–300	5.38
Exhibit Space (Museum)	300–500	3.34
Gymnasium–Exercise / Workout	200–300	9.69
Gymnasium–Sports / Games	300–500	9.15
Kitchen / Food Prep	300–750	11.73
Laboratory (Classroom)	500–750	11.95
Laboratory (Professional)	750–1,200	14.32
Library–Stacks	200–500	12.70
Library–Reading / Studying	300–500	10.33
Loading Dock	100–300	9.47
Lobby–Office/General	200–300	9.04
Locker Room	100–300	5.60
Lounge / Breakroom	100–300	6.35
Mechanical / Electrical Room	200–500	4.63
Office–Open	300–500	6.57
Office–Private / Closed	300–500	7.97
Parking–Interior	50–100	1.61
Restroom / Toilet	100–300	6.78
Retail Sales	200–500	11.30
Stairway	50–100	5.27
Storage Room–General	50–200	4.09
Workshop	300–750	13.56

presented. A hallway requiring relatively low light is 50 lux; the illuminance of a general office is 300 lux, and it shows over 1000 lux in a particular space requiring concentration. Also, comparing the lighting power density (LPD) values of the International Energy Conservation Code (IECC) provided in the same table shows a similar trend to that shown by the light level. This indicates that the occupants' behavior and the purpose of the spaces affected the values of light level and LPD.

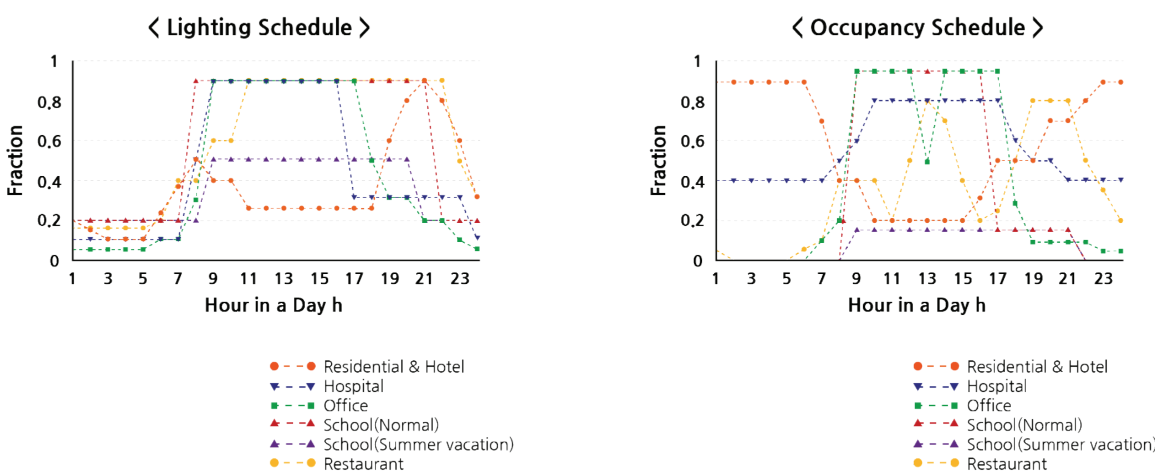
4.3.2 Exposure to the Light Environment of Occupants According to Building Use

Finally, Figure 2 shows the internal occupant schedules of the five reference buildings. Because each building has different functions, the internal gain schedules are also different. The schedules that start inside the buildings of hospitals, offices, and schools (generally) are similar, indicating that the schedules peak between 10:00 and 17:00. The restaurant's occupancy schedule consists of two peaks: 12:00–14:00 and 19:00–21:00. However, the hotel's occupancy schedule is different from the other four building types. Its peak was from 23:00 to 06:00 the following day. Lighting schedules for hospitals, offices, schools, and restaurants are similar, peaking during the day from 09:00 to 17:00. The hotel's lighting schedule reaches a small peak between 08:00 and 10:00 and a prominent peak at around 21:00. The opposite is the case for residential buildings. In residential buildings, the peak of occupancy is from 21:00 to 07:00 the following morning, and the occupancy rate is low from 07:00 to 19:00 when daylight is essential. Therefore, the occupants' schedules may vary depending on the purpose of the building. This schedule diversity is closely related to the artificial lighting schedule and exposure to daylight. In particular, for hospital staff that spends most of the day inside a building and for students living inside a building at a time when daylight is maximized, it is necessary to provide customized lighting-related design and experiment with conditions according to the type of occupants.

5. GUIDELINES OF RECOMMENDED PRACTICES FOR INDOOR LIGHT ENVIRONMENT EVALUATION

This study derived major keywords (*Light*, *Health*, and *Environment*) related to the light environment through a bibliography analysis of previous reviews. For the first keyword, *Light*, a

FIGURE 2. Lighting and occupancy schedule of the five buildings.



more objective measurement method was considered by analyzing measurement techniques for light and evaluation criteria in sustainable certification systems. For the second keyword, *Health*, it was found that the occupant's physical and psychological health could be assessed using a qualitative evaluation method like a survey. For the last keyword, *Environment*, the space was subdivided according to its function to identify the appropriate illumination, lighting schedule, and the occupant's use time for each space. Based on this, research guidelines for establishing an indoor light environment evaluation considering humans and the environment are proposed. The overall process of the guideline and the main checklist in each process is organized as shown in Table 9. The guidelines proposed in this study are based on five phases: *Conceptualization*, *Light Environment Identification*, *Questionnaire*, *Environment Analysis*, *Comparison*, and *Conclusion*.

The first phase is to establish a concept for evaluating the light environment. The most important part of this process is to set the target space and conduct a literature review. Through this, it is possible to grasp the unique characteristics of the space and new investigation contents that have not been covered in previous studies.

The second phase is light environment identification. For this, actual measurement and simulation using 3D modeling are recommended. In the case of actual measurement, illuminance and luminance meters can be used to identify the illuminance and areas at risk for glare in the space. In the simulation case, illuminance can be identified through sDA and ASE, and glare through DGP. This is because sDA, unlike DF, is a dynamic measurement method that considers the local climate and working hours. In addition, ASE can identify excessive inflow of daylight, which can indirectly determine the occurrence of glare. Although various evaluation methods exist for glare, most are used as evaluation indicators for indoor artificial lighting. For indoor artificial lighting, UGR is used, and for large-area light sources such as daylight, DGP is used. Additionally, it is recommended to conduct actual measurements using a spectrometer and simulation tools (ALFA, etc.) for melanopic lux, which has recently been found to affect the human circadian rhythm, so additional analysis is necessary.

The third phase is a questionnaire on the occupants' health. To evaluate the health of occupants using the space, this study categorized the topic (sleep, health and well-being, and performance) and introduced surveys suitable for each topic in Chapter 4.2. Among them, the researcher should select an appropriate questionnaire related to the light environment and the subject they want to investigate. In this process, it is effective to establish the total number of survey subjects and the questionnaire participation criteria, such as current health status and working period.

The fourth phase is the environment analysis. Based on the appropriate illumination range proposed by IESNA according to the purpose of the space, it is determined whether the architectural design elements (building orientation, windows, shades, etc.) affecting the inflow and distribution of daylight in the target space and the environmental factors (furniture arrangement, occupancy schedule, etc.) affecting the behavior of the occupants using the space are appropriate.

The fifth phase is comparison and conclusion. Based on the light environment identification in the space, the evaluation of the occupants' health and the space environment is compared and analyzed. For this intercomparison, data analysis is conducted using various statistical models and techniques. Through this analysis, it is possible to effectively determine whether the current light environment is appropriately created in relation to human and architectural elements or where limitations occur in developing an appropriate light environment.

TABLE 9. Guideline for indoor light environment evaluation related to occupant comfort and well-being.

Phase		Recommended Practices	Checklist
I	Conceptualization	Target space selection	• Characteristics of the space
		Literature review	• New investigation contents
II	Light Environment Identification	Actual measurement	• Use illuminance and luminance meters • Melanopic Lux (use spectrometer): optional
		Simulation using 3D modeling	• Illuminance: Mean Illuminance, sDA, ASE • Glare (Daylight): DGP • Glare (Indoor Artificial Light): UGR • Melanopic Lux (ALFA, etc.): optional
III	Questionnaire	Sleep	• Selection of questionnaires according to research topics • Establish the number of subjects and criteria for participation in the survey
		Health and Well-being	
		Performance	
IV	Environment Analysis	Architectural Design Elements	• Orientation of the Building, Window, Shade, etc.
		Environmental Factors	• Furniture arrangement, Occupancy schedule, etc.
V	Comparison and Conclusion	Intercomparison of Questionnaire and Environment Analysis based on Light Environment Identification	

According to these guidelines, it is important that the light environment evaluation follow a set schedule to minimize variability. This is because the amount and direction of daylight entering an indoor space changes over time and season.

6. CONCLUSION

This paper reviews the evaluation methods for lighting that affect people in the indoor space of green buildings. Primary keywords such as *Light*, *Health*, and *Environment* were derived by completing literature research and comparing the assessment methods for every keyword to present a more optimized evaluation method.

First, it was found that the evaluation methods for the lighting environment have mainly been based on measurement techniques (DF, DA, UDI, ASE, etc.) for illuminance through investigations of sustainable certification systems. However, the evaluation of glare and melanopic lux, which are indirect effects of light, was found to be insufficient. Regarding glare, methods that can reduce excessive light inflow (such as shading) were evaluated, while the evaluation of melanopic lux existed only in WELL certification (EML).

Second, the effect of light on human health has been confirmed in previous literature. The investigation method mainly involves surveys related to health, well-being, performance, and sleep, and the survey indicators for each item were introduced in section 4.2 of this study. Therefore, this study can subdivide the investigation into physical and psychological responses of humans to the lighting environment and select appropriate surveys accordingly.

Third, people spend a significant amount of time in buildings and are greatly affected by the lighting environment. In particular, daylight affects the human circadian rhythm, and it is necessary to consider it in terms of the spatial environment. Section 4.3 of this study introduces appropriate illuminance levels based on the purpose of the space, lighting schedule, and occupancy schedule related to human behavior. Through this, the study discusses the importance of architectural and environmental factors in regulating the inflow and distribution of light, as well as the behavior of occupants.

Finally, this study presents and combines quantitative and qualitative evaluation data on light, health, and environment to provide guidelines for the indoor lighting environment of buildings that promote human well-being. These guidelines are established through *Conceptualization*, *Light Environment Identification*, *Questionnaire*, *Environment Analysis*, *Comparison*, and *Conclusion*. This study establishes a research methodology for evaluating the indoor lighting environment while considering the comfort and well-being of occupants. It also provides a detailed checklist for each phase.

As a further study, we will select occupants in offices and investigate the physical and psychological effects of the indoor light environment on them by applying the guidelines. Furthermore, we aim to demonstrate the relationship between the quantitative and qualitative results and analyze the importance of a detailed checklist.

Acknowledgments

This work is supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIT) (No. NRF-2021R1A2C2011849)

REFERENCES

1. Beute, F. and Y.A. de Kort, Salutogenic effects of the environment: Review of health protective effects of nature and daylight. *Applied psychology: Health and well-being*, 2014. **6**(1): p. 67–95.
2. Boubekri, M., *Daylighting, architecture and health: building design strategies*. 2008: Routledge.
3. Ellis, E.V., et al. Auto-tuning daylight with LEDs: sustainable lighting for health and well-being. in *ARCC conference repository*. 2013.
4. Leslie, R., Capturing the daylight dividend in buildings: why and how? *Building and environment*, 2003. **38**(2): p. 381–385.
5. Boubekri, M., *Daylighting design*. 2014: Birkhäuser.
6. Seyedolhosseini, A., et al., Daylight adaptive smart indoor lighting control method using artificial neural networks. *Journal of Building Engineering*, 2020. **29**: p. 101141.
7. Baker, N. and K. Steemers, *Daylight design of buildings: a handbook for architects and engineers*. 2014: Routledge.
8. Zarrabi, M., S.-A. Yazdanfar, and S.-B. Hosseini, COVID-19 and healthy home preferences: The case of apartment residents in Tehran. *Journal of Building Engineering*, 2021. **35**: p. 102021.
9. Li, C. and H. Tang, Study on ventilation rates and assessment of infection risks of COVID-19 in an outpatient building. *Journal of Building Engineering*, 2021: p. 103090.

10. Boyce, P., C. Hunter, and O. Howlett, *The benefits of daylight through windows*. Troy, New York: Rensselaer Polytechnic Institute, 2003.
11. Tregenza, P.R. and I. Waters, Daylight coefficients. *Lighting Research & Technology*, 1983. **15**(2): p. 65–71.
12. Reinhart, C.F., J. Mardaljevic, and Z. Rogers, Dynamic daylight performance metrics for sustainable building design. *Leukos*, 2006. **3**(1): p. 7–31.
13. Yi, Y.K., et al., Multi-objective optimization (MOO) of a skylight roof system for structure integrity, daylight, and material cost. *Journal of Building Engineering*, 2021. **34**: p. 102056.
14. Cheong, K.H., et al., A simulation-aided approach in improving thermal-visual comfort and power efficiency in buildings. *Journal of Building Engineering*, 2020. **27**: p. 100936.
15. Mardaljevic, J., L. Heschong, and E. Lee, Daylight metrics and energy savings. *Lighting Research & Technology*, 2009. **41**(3): p. 261–283.
16. Brainard, J., et al., Health implications of disrupted circadian rhythms and the potential for daylight as therapy. *Anesthesiology*, 2015. **122**(5): p. 1170–1175.
17. Lee, J. and M. Boubekri, Impact of daylight exposure on health, well-being and sleep of office workers based on actigraphy, surveys, and computer simulation. *Journal of Green Building*, 2020. **15**(4): p. 19–42.
18. Boubekri, M., et al., The impact of optimized daylight and views on the sleep duration and cognitive performance of office workers. *International Journal of Environmental Research and Public Health*, 2020. **17**(9): p. 3219.
19. Rea, M.S., M.G. Figueiro, and J.D. Bullough, Circadian photobiology: an emerging framework for lighting practice and research. *Lighting Research & Technology*, 2002. **34**(3): p. 177–187.
20. Andersen, M., J. Mardaljevic, and S.W. Lockley, A framework for predicting the non-visual effects of daylight–Part I: photobiology-based model. *Lighting Research & Technology*, 2012. **44**(1): p. 37–53.
21. Wienold, J. Dynamic daylight glare evaluation. in *Proceedings of Building Simulation*. 2009.
22. Konstantzos, I., A. Tzempelikos, and Y.-C. Chan, Experimental and simulation analysis of daylight glare probability in offices with dynamic window shades. *Building and Environment*, 2015. **87**: p. 244–254.
23. Kolberg, E., et al., Insufficient melanopic equivalent daylight illuminance in nursing home dementia units across seasons and gaze directions. *Lighting Research & Technology*, 2021: p. 1477153521994539.
24. Bellia, L., et al., Matching CIE illuminants to measured spectral power distributions: A method to evaluate non-visual potential of daylight in two European cities. *Solar Energy*, 2020. **208**: p. 830–858.
25. Van Eck, N.J. and L. Waltman, Software survey: VOSviewer, a computer program for bibliometric mapping. *Scientometrics*, 2010. **84**(2): p. 523–538.
26. Van Eck, N.J. and L. Waltman, *VOSviewer manual.* Leiden: Univeristeit Leiden, 2013. **1**(1): p. 1–53.
27. Mongeon, P. and A. Paul-Hus, The journal coverage of Web of Science and Scopus: a comparative analysis. *Scientometrics*, 2016. **106**(1): p. 213–228.
28. Figueiro, M., et al., Comparisons of three practical field devices used to measure personal light exposures and activity levels. *Lighting Research & Technology*, 2013. **45**(4): p. 421–434.
29. Lucas, R.J., et al., Measuring and using light in the melanopsin age. *Trends in Neurosciences*, 2014. **37**(1): p. 1–9.
30. Figueiro, M., C. Jarboe, and L. Sahin, The sleep maths: A strong correlation between more daytime light and better nighttime sleep. *Lighting Research & Technology*, 2021. **53**(5): p. 423–435.
31. Boubekri, M., et al., Impact of windows and daylight exposure on overall health and sleep quality of office workers: a case-control pilot study. *Journal of Clinical Sleep Medicine*, 2014. **10**(6): p. 603–611.
32. MacNaughton, P., et al., Economic implications of access to daylight and views in office buildings from improved productivity. *Journal of Applied Social Psychology*, 2021.
33. Dogan, T. and Y.C. Park, A critical review of daylighting metrics for residential architecture and a new metric for cold and temperate climates. *Lighting Research & Technology*, 2019. **51**(2): p. 206–230.
34. Lee, J., M. Boubekri, and F. Liang, Impact of building design parameters on daylighting metrics using an analysis, prediction, and optimization approach based on statistical learning technique. *Sustainability*, 2019. **11**(5): p. 1474.
35. Doan, D.T., et al., A critical comparison of green building rating systems. *Building and Environment*, 2017. **123**: p. 243–260.
36. Potrč Obrecht, T., et al., Comparison of health and well-being aspects in building certification schemes. *Sustainability*, 2019. **11**(9): p. 2616.

37. Aries, M.B., M.P. Aarts, and J. van Hoof, Daylight and health: A review of the evidence and consequences for the built environment. *Lighting Research & Technology*, 2015. **47**(1): p. 6–27.
38. Boyce, P.R., The impact of light in buildings on human health. *Indoor and Built Environment*, 2010. **19**(1): p. 8–20.
39. Konis, K., A novel circadian daylight metric for building design and evaluation. *Building and Environment*, 2017. **113**: p. 22–38.
40. Yi, Y.K., Building facade multi-objective optimization for daylight and aesthetical perception. *Building and Environment*, 2019. **156**: p. 178–190.
41. Ibarra, D. and C.F. Reinhart. Daylight factor simulations–how close do simulation beginners' really'get. in *Building Simulation*. 2009.
42. Boubekri, M. and J. Lee, A comparison of four daylighting metrics in assessing the daylighting performance of three shading systems. *Journal of Green Building*, 2017. **12**(3): p. 39–53.
43. Reinhart, C.F. and D.A. Weissman, The daylit area–Correlating architectural student assessments with current and emerging daylight availability metrics. *Building and Environment*, 2012. **50**: p. 155–164.
44. Nabil, A. and J. Mardaljevic, Useful daylight illuminances: A replacement for daylight factors. *Energy and Buildings*, 2006. **38**(7): p. 905–913.
45. Nocera, F., et al., Daylight performance of classrooms in a mediterranean school heritage building. *Sustainability*, 2018. **10**(10): p. 3705.
46. LM, I., *Approved method: IES spatial Daylight autonomy (sDA) and annual sunlight exposure (ASE)*. Illuminating Engineering Society. https://www. ies. org/product/ies-spatial-daylight-autonomy-sda-and-annual-sunlight-exposure-ase, 2013.
47. Mardaljevic, J. Examples of climate-based daylight modelling. in *CIBSE National Conference*. 2006. Citeseer.
48. Wienold, J. and J. Christoffersen, Evaluation methods and development of a new glare prediction model for daylight environments with the use of CCD cameras. *Energy and Buildings*, 2006. **38**(7): p. 743–757.
49. Iwata, T. and M. Tokura, Examination of the limitations of predicted glare sensation vote (PGSV) as a glare index for a large source: Towards a comprehensive development of discomfort glare evaluation. *International Journal of Lighting Research and Technology*, 1998. **30**(2): p. 81–88.
50. Wienold, J., et al., Cross-validation and robustness of daylight glare metrics. *Lighting Research & Technology*, 2019. **51**(7): p. 983–1013.
51. Chaloeytoy, K., M. Ichinose, and S.-C. Chien, Determination of the Simplified Daylight Glare Probability (DGPs) Criteria for Daylit Office Spaces in Thailand. *Buildings*, 2020. **10**(10): p. 180.
52. Brown, T.M., Melanopic illuminance defines the magnitude of human circadian light responses under a wide range of conditions. *Journal of Pineal Research*, 2020. **69**(1): p. e12655.
53. Arendt, J., *Melatonin and the mammalian pineal gland*. 1994: Springer Science & Business Media.
54. Stehle, J.H., et al., A survey of molecular details in the human pineal gland in the light of phylogeny, structure, function and chronobiological diseases. *Journal of Pineal Research*, 2011. **51**(1): p. 17–43.
55. Enezi, J.a., et al., A "melanopic" spectral efficiency function predicts the sensitivity of melanopsin photoreceptors to polychromatic lights. *Journal of Biological Rhythms*, 2011. **26**(4): p. 314–323.
56. Faqih, F. and T. Zayed, A comparative review of building component rating systems. *Journal of Building Engineering*, 2021. **33**: p. 101588.
57. Awadh, O., Sustainability and green building rating systems: LEED, BREEAM, GSAS and Estidama critical analysis. *Journal of Building Engineering*, 2017. **11**: p. 25–29.
58. Elkhapery, B., P. Kianmehr, and R. Doczy, Benefits of retrofitting school buildings in accordance to LEED v4. *Journal of Building Engineering*, 2021. **33**: p. 101798.
59. Mardaljevic, J., J. Christoffersen, and P. Raynham. A proposal for a European standard for daylight in buildings. in *Proc. Int. Conf. Lux Europa*. 2013.
60. Murakami, S., et al., Development of a comprehensive city assessment tool: CASBEE-City. *Building Research & Information*, 2011. **39**(3): p. 195–210.
61. Eberl, S. DGNB vs. LEED: A comparative analysis. in *Conference on Central Europe towards Sustainable Building*. 2010.
62. Roh, S., S. Tae, and S. Shin, Development of building materials embodied greenhouse gases assessment criteria and system (BEGAS) in the newly revised Korea Green Building Certification System (G-SEED). *Renewable and Sustainable Energy Reviews*, 2014. **35**: p. 410–421.

63. Park, J. and T.R. Rider. Facilitating the WELL Building Standard through Wellness Programs in the Workplace. in *ARCC Conference Repository*. 2018.
64. Hellmuth, D.F., et al., Biology and Building—The Living Learning Center at Washington University's Tyson Research Center: A Journey on the Path to the Living Building Challenge. *Journal of Green Building*, 2009. **4**(4): p. 55–83.
65. Netzer, N.C., et al., Using the Berlin Questionnaire to identify patients at risk for the sleep apnea syndrome. *Annals of Internal Medicine*, 1999. **131**(7): p. 485–491.
66. Buysse, D.J., et al., The Pittsburgh Sleep Quality Index: a new instrument for psychiatric practice and research. *Psychiatry Research*, 1989. **28**(2): p. 193–213.
67. Vernet, C. and I. Arnulf, Idiopathic hypersomnia with and without long sleep time: a controlled series of 75 patients. *Sleep*, 2009. **32**(6): p. 753–759.
68. Zavada, A., et al., Comparison of the Munich Chronotype Questionnaire with the Horne-Östberg's morningness-eveningness score. *Chronobiology International*, 2005. **22**(2): p. 267–278.
69. Billings, M.E., et al., Psychometric performance and responsiveness of the functional outcomes of sleep questionnaire and sleep apnea quality of life index in a randomized trial: the HomePAP study. *Sleep*, 2014. **37**(12): p. 2017–2024.
70. Yu, L., et al., Development of short forms from the PROMIS™ sleep disturbance and sleep-related impairment item banks. *Behavioral Sleep Medicine*, 2012. **10**(1): p. 6–24.
71. Hanish, A.E., D.C. Lin-Dyken, and J.C. Han, PROMIS sleep disturbance and sleep-related impairment in adolescents: examining psychometrics using self-report and actigraphy. *Nursing Research*, 2017. **66**(3): p. 246.
72. DHS, M., *Demographic and health surveys.* Calverton: Measure DHS, 2013.
73. Mihrshahi, S., et al., Determinants of infant and young child feeding practices in Bangladesh: secondary data analysis of Demographic and Health Survey 2004. *Food and Nutrition Bulletin*, 2010. **31**(2): p. 295–313.
74. Jenkinson, C., A. Coulter, and L. Wright, Short form 36 (SF36) health survey questionnaire: normative data for adults of working age. *British Medical Journal*, 1993. **306**(6890): p. 1437–1440.
75. Al-Sanea, S.A., M. Zedan, and S.A. Al-Ajlan, Adjustment factors for the ASHRAE clear-sky model based on solar-radiation measurements in Riyadh. *Applied Energy*, 2004. **79**(2): p. 215–237.
76. Radloff, L.S., The use of the Center for Epidemiologic Studies Depression Scale in adolescents and young adults. *Journal of Youth and Adolescence*, 1991. **20**(2): p. 149–166.
77. Watson, D. and L.A. Clark, *The PANAS-X: Manual for the positive and negative affect schedule-expanded form.* 1999.
78. Craig, C.L., et al., International physical activity questionnaire: 12-country reliability and validity. *Medicine & Science in Sports & Exercise*, 2003. **35**(8): p. 1381–1395.
79. Drummond, S.P., et al., The neural basis of the psychomotor vigilance task. *Sleep*, 2005. **28**(9): p. 1059–1068.
80. Loon, M., J. Evans, and C. Kerridge, Learning with a strategic management simulation game: A case study. *The International Journal of Management Education*, 2015. **13**(3): p. 227–236.
81. Streufert, S., R. Pogash, and M. Piasecki, Simulation-based assessment of managerial competence: reliability and validity. *Personnel Psychology*, 1988. **41**(3): p. 537–557.
82. Wotton, E., The IESNA Lighting Handbook and office lighting. *Lighting*, 2000. **14**.