Indoor Visual Comfort: A Review of Factors and Assessments

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Abstract

The importance of lighting in architectural design has evolved from influencing the structure of buildings to giving precedence to energy efficiency and, more recently, emphasizing the well-being, health, and comfort of occupants. This necessitates a fresh perspective on examining lighting and its multifaceted impact on indoor spaces. This paper conducts a systematic comprehensive review of published research to explore and identify the diverse factors that affect visual comfort indoors and the assessment methods and techniques to evaluate it.

The paper adopts a systematic literature review as a methodology and explores the relevant papers from the past 15 years in the domain of building sciences, architecture, lighting technology, and chronobiology with a focus on visual comfort and luminous environment. It also includes a few data from some older sources to provide a broader perspective on research in the field.

The findings demonstrate current knowledge on visual comfort research and should be a valuable resource for architects, engineers, and building designers seeking to create comfortable, healthy, and wellbeing-promoting environments.

It concludes that lighting research has progressed to encompass a holistic approach to indoor visual comfort, considering factors like lighting, environment, human elements, and architecture. Objective assessments now employ innovative techniques like computational simulations and HDR imagery, while subjective assessments concentrate on occupant preferences and eye-tracking methods integrating Building Management Systems (BMS) in buildings. The adoption of the Equivalent Melanopic Lux (EML) metric by ISHRAE is a positive development in India's context, but there is a need for more diverse research in various settings and populations. Significantly, more studies are required on visual comfort in educational, residential, and commercial settings, indicating the need for immediate attention to better environments.

Keywords: Indoor Visual Comfort, Luminous environment, Comfort indices, Lighting, Occupant satisfaction, Productivity.

Introduction

Visual comfort in indoor spaces, influenced by factors related to occupants, lighting, and the built environment (Al Horr et al., 2016), significantly impacts occupants' subjective reactions to the quantity and quality of light in different spaces (Fakhari, Vahabi, and Fayaz, 2021). Particularly in formal learning environments like classrooms, libraries, and laboratories. There is a strong correlation between Indoor Environment Quality, academic performance, and student satisfaction (Ramprasad and Subbaiyan, 2017). Moreover, lighting affects the overall room atmosphere and aesthetic perception (Mandala, 2019; Moscoso and Matusiak, 2018).

The concept of the "luminous environment," encompassing both natural and artificial light sources, contributes to the ambiance and functionality of indoor spaces (Kralikova and Wessely, 2016). Optimizing the luminous environment through strategic building design, configuration, and control systems considering occupant preferences can significantly impact human well-being, ultimately influencing performance and productivity (Cadena et al., 2022).

Moreover, factors contributing to indoor environment quality extend beyond the luminous environment and include considerations such as thermal comfort, indoor air quality, acoustical comfort, and spatial elements like furniture layout and occupant density (Al Horr et al., 2016). These factors collectively play a crucial role in fostering occupant comfort and well-being, as illustrated in Figure 1.

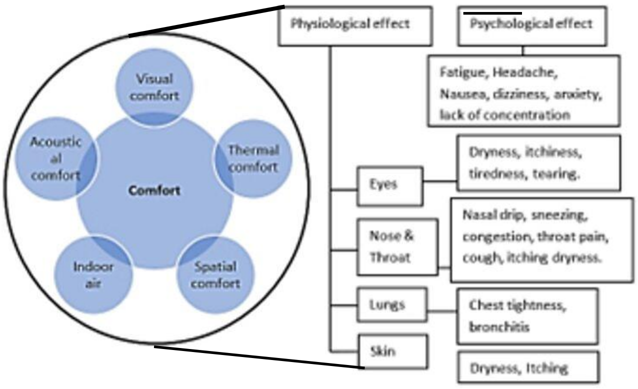

Fig. 1: Comfort Indices: Components and risks of negligence
Source: Kapoor et al., 2021

Research suggests that Thermal Comfort (TC) and Indoor Air Quality (IAQ) have the greatest influence on occupant comfort and productivity (Nelson, Nilsson, and Johnson, 1984; Andargie, Touchie, and O'Brien, 2019). Visual Comfort (VC) and lighting also play significant roles in enhancing indoor comfort (Horr et al., 2016; Chiou, Saputro, and Sari, 2020).

Visual comfort encompasses various aspects, including light composition, glare experiences (Kapoor et al., 2021), and spatial factors such as working plane height, space composition, usage, and outdoor views (Ramprasad and Subbaiyan, 2017). Both natural and artificial lighting contribute to enhancing visual comfort. Daylighting is essential during the day, offering accuracy and aesthetics, while artificial lighting remains indispensable, particularly at night. Artificial lighting can enhance the quality of spaces and create unique atmospheres, such as in historical buildings (Hakim et al., 2022).

Artificial lighting can be tailored for specific tasks, contributing to visual equity and overall comfort (Zissis and Kitsinelis, 2009) However, it is not without drawbacks, as excessive exposure to the blue light component of white LEDs can harm the human retina (Alsereidi, Alhammadi and Amer, 2022).

This paper delves into a comprehensive exploration of visual comfort within the broader context of the indoor luminous environment. It reviews published research to identify factors contributing to Indoor Visual Comfort (IVC), including those related to occupants, the environment, and the built environment while also reviewing assessment methods and techniques. The goal is to serve as a roadmap for visual comfort studies, offering readers a thorough understanding of this phenomenon.

Research Methodology and Data Collection

This paper reviews research from the past 15 years, with some older sources for context, focusing on the increasing trends in visual comfort and the luminous environment research since 2006.

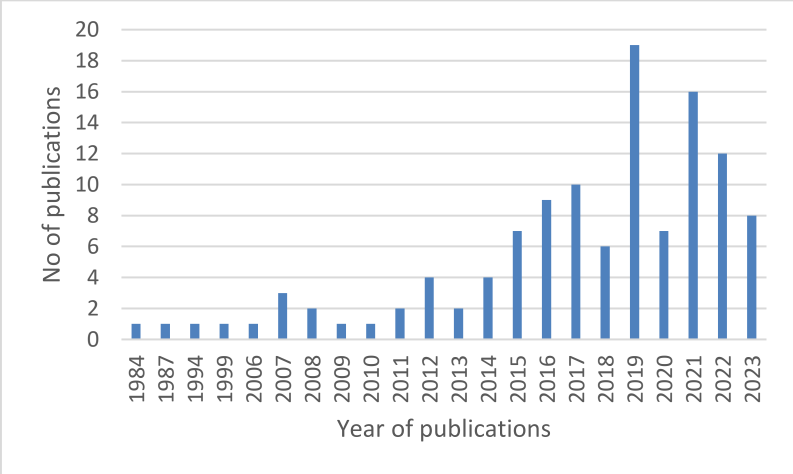

Fig. 2: Year-wise-identified articles based on their titles and abstracts.
Source: Authors, based on data collected from digital platforms

Relevant papers (refer to Fig. 2) were sourced from Science Direct, Scopus, MDPI, PubMed, and Google Scholar. During the initial screening, 150 papers were identified using keywords such as "indoor visual comfort," "luminous environment," "comfort indices," "health and wellbeing," "student productivity," "lighting," and "occupant satisfaction."

The identified papers were reviewed based on their titles and abstracts, resulting in the selection of approximately 118 papers. Subsequently, 59 papers including lighting and building codes of various countries were chosen for qualitative synthesis based on their relevance and significance after a comprehensive manual review of the full papers.

Findings and Discussion

Visual comfort research globally involves developed nations such as Canada, the UK, the USA, and some Asian and other European countries, driven by available resources, awareness, research support, and growing interest. Studies primarily focus on offices, and experiments, with limited research in education, residential, and commercial settings, as shown in Figures 3 and 4.

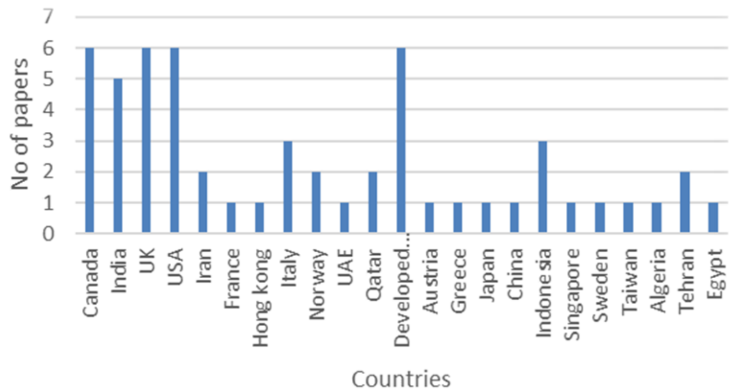

Fig. 3: Research papers across countries
Source: Authors

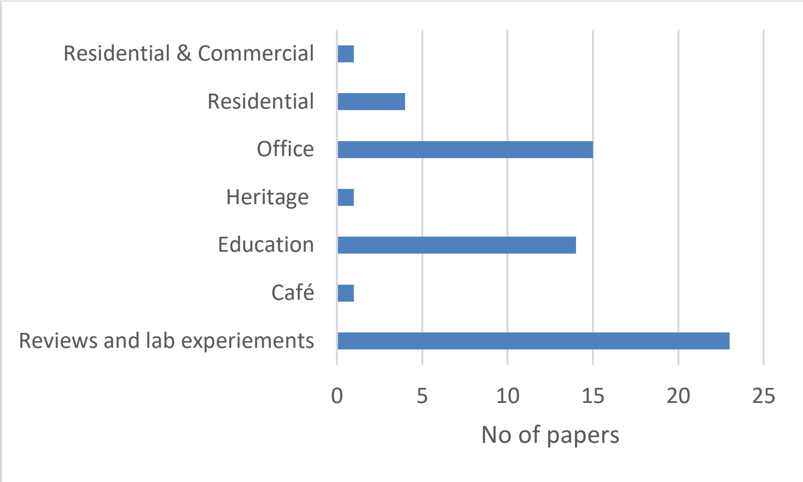

Fig. 4: Distribution of papers-building typology wise
Source: Authors

The pie chart (refer to Fig. 5) represents 59 papers, 9 delve into environmental factors,10 papers explore occupant-specific factors, 9 papers are dedicated to the built environment, 14 papers are dedicated to methods and techniques to evaluate Visual Comfort, and 5 papers pertain to lighting standards. The rest of the papers belong to at least two of the categories.

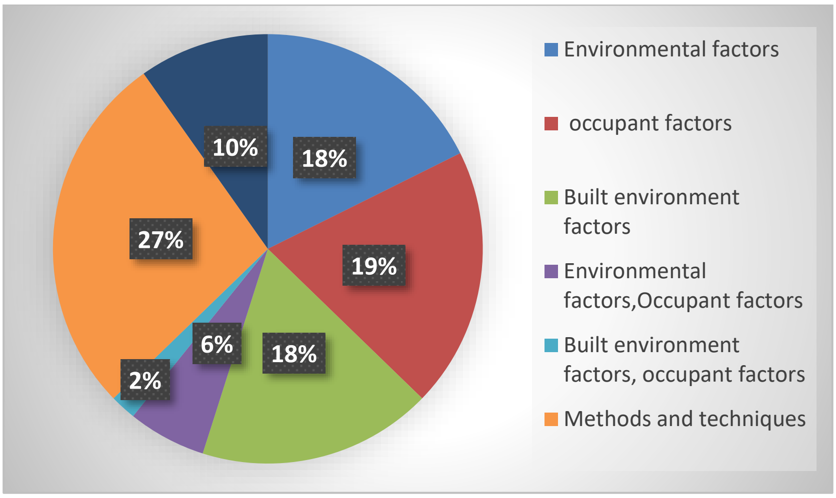

Fig. 5: Distribution of papers under classified themes
Source: Authors

In Table 1, each paper is classified based on its specific sub-topic or theme, providing reasons for its selection and assessment in this research paper.

Table 1: List of the papers with author and their themes
Source: Authors

Author	Theme
Nelson, Nilsson and Johnson, 1984	Environmental factors
Galasiu and Veitch, 2006	Occupant factors
Mills, Tomkins and Schlangen, 2007	Built environment factors
Stevens et al., 2007	Environmental factors, Occupant factors
Araji, Boubekri and Chalfoun, 2007	Built environment factors, Occupant factors
Veitch et al., 2008	Built environment factors

Galasiu and Reinhart, 2008	Methods and techniques
Mohamed Boubekri, 2008	Environmental factors
Fotios and Cheal, 2009	Built environment factors
Zissis and Kitsinelis, 2009	Methods and techniques
Siu-Yu Lau, Gou and Li, 2010	Occupant factors
Cantin and Dubois, 2011	Methods and techniques
Bellia, Spada and Pedace, 2013	Methods and techniques
Van Den Wymelenberg, 2014	Environmental factors, Methods, and techniques
Carlucci et al., 2015	Methods and techniques
Kent et al., 2015	Environmental factors, Occupant factors
Hafiz, 2015	Methods and techniques
Kim and Mansfield, 2016	Environmental factors
Al Horr et al., 2016	Occupant factors
Horr et al., 2016	Indoor environment quality
Kralikova and Wessely, 2016	Environmental factors, Methods, and techniques
Giarma, Tsikaloudaki and Aravantinos, 2017	Methods and techniques
Kent et al., 2017	Environmental factors, Occupant factors
Ramprasad and Subbaiyan, 2017	Built environment factors
Inanici and Hashemloo, 2017	Environmental factors, Methods, and techniques
Moscoso and Matusiak, 2018	Environmental factors
Imaizumi, Koyama and Tanno, 2018	Methods and techniques
Zhang, 2019	Occupant factors, Methods, and techniques
Andargie, Touchie, and O'Brien, 2019	Occupant factors
Mandala, 2019	Environmental factors
Song, Ying; Mao, Fubing; Liu, Qing, 2019	Methods and techniques
Bournas, Dubois and Laike, 2020	Built environment factors
(Brembilla et al., 2019	Methods and techniques
Acosta et al., 2019	Methods and techniques
Spitschan, 2019	Occupant factors
Gulati, Ritu; Sehgal Vandana; Qamruddin, Juwairia; Raushan, Arshi S.,2019	Built environment factors
Day et al., 2020	Occupant factors, Methods, and techniques
Pierson et al., 2022	Occupant factors
Chiou, Saputro and Sari, 2020	Methods and techniques
Fakhari, Vahabi and Fayaz, 2021	Environmental factors
Dimara, Krinidis and Tzovaras, 2021	Methods and techniques
Kapoor et al., 2021	Indoor environment quality
Mathew, Kurian, and Augustine, 2022	Occupant factors, Methods, and techniques
Brown et al., 2022	Occupant factors
Achsani, Wonorahardjo and Triyadi, 2022	Environmental factors
Cadena et al., 2022	Methods and techniques
Hakim et al., 2022	Occupant factors
British standard	Light and Lighting standards for Indoor spaces
British standard	Light and Lighting specifications
Indian Standard	Building code
Indian Standard	Energy efficiency code
Indian Standard	Lighting and Building code
RAIS et al., 2020	Environmental factors
Ahmed D., Abdelkader M. and Nessim A., 2023	Environmental factors
Izmir Tunahan, Altamirano and Unwin Teji, 2021	Occupant factors
Houser et al., 2021	Occupant factors
Zomorodian, Korsavi and Tahsildoost, 2016	Built environment factors
Ho et al., 2008	Built environment factors
Makaremi et al., 2017	Built environment factors

Defining Visual Comfort

Visual comfort is a multifaceted concept closely associated with daylighting yet defining it accurately, has been a challenge due to varying expert perspectives. A survey by Galasiu and Reinhart (2008) found that professionals prioritize the architectural definition of daylighting, emphasizing the interplay of natural light and building form for a stimulating, healthy, and productive interior environment. Van Den Wymelenberg (2014) emphasizes the importance of balancing energy efficiency with other priorities, like human health and a visually pleasing environment.

Visual discomfort, the counterpart of visual comfort, encompasses perception distortions, physiological symptoms, and viewing discomfort, significantly affecting the academic environment (Imaizumi, Koyama, and Tanno, 2018). The British and other standards define visual comfort as a subjective state of well-being influenced by the luminous environment (European standard, 2018), while other perspectives suggest it's a subjective reaction to lighting conditions in a specific space at a given time (Dolnikova and Katunsky, 2019). An alternative view defines visual comfort as a state of mind expressing satisfaction with the visual environment (Song, Mao, and Liu, 2019), emphasizing its subjective nature, and challenging the establishment of universally applicable metric for prediction (Van Den Wymelenberg 2014) (Cadena et al., 2022). These varied definitions navigate the factors influencing visual comfort.

Factors Affecting Visual Comfort

Environmental factors

Environmental factors play a pivotal role in influencing the visual comfort experienced within indoor spaces. Understanding these factors is vital for designing spaces that enhance well-being and productivity. Several research studies shed light on the intricate relationship between environmental factors and visual comfort. Studies considered for this category are summarized in Table 2.

Table 2: Summary of papers on environmental factors
Source: Authors

Author	Title	Issue discussed	Findings
(Nelson, Nilsson, and Johnson, 1984)	Interaction of temperature, illuminance, and apparent time on sedentary work fatigue	Environment factors and performance	Optimal illuminance for performance -100 lux found to be satisfactory for sedentary work
(Stevens et al., 2007)	Meeting report: The role of environmental lighting and circadian disruption in cancer and other diseases	Artificial lighting & circadian rhythms	Melatonin disruption and cancer risk associated with non-lit spaces
(Mohamed Boubekri, 2008)	Daylighting, Architecture, and Health Building Design Strategies	Daylight and health in the built environment	Significance of sunlight access and public health
(Van Den Wymelenberg, 2014)	Visual comfort, discomfort glare, and occupant fenestration control: Developing a research agenda	Discomfort glare in building design	Predicting occupant comfort and enhancing energy efficiency & glare control
(Kent et al., 2015)	Discomfort glare and time of day	Examining diurnal variations in glare sensation	Time-dependent glare perception and future research directions
(Kim and Mansfield, 2016)	A cross-cultural study on perceived lighting quality and occupants' well-being between UK and South Korea	Perceived lighting quality in cafés and well-being	Influencing factors: environmental control, daylight access, cultural diversity, brightness

(Kralikova and Wessely, 2016)	Lighting Quality, Productivity, and Human Health	Evaluation of lighting on productivity and well being	Differing views on illuminance thresholds and method refinement
(Kent et al., 2017)	Temporal effects on glare response from daylight	Temporal variables and individual differences in glare perception	Factors affecting sky conditions, time of day, prior light exposure, fatigue, hunger, caffeine intake, and mood
(Moscoso and Matusiak, 2018)	Aesthetic perception of a small office with different daylighting systems	Assessing aesthetics with different daylight systems and sky conditions	Lower daylight levels are perceived as more aesthetically pleasing
(Mandala, 2019)	Lighting Quality in the Architectural Design Studio (Case Study: Architecture Design Studio at Universitas Katolik Parahyangan, Bandung, Indonesia)	Assessment of studio lighting and student creativity and productivity	Influencing factors: lighting techniques, illumination levels, light colors, room reflection factors, and daylighting contribution.
(Fakhari, Vahabi and Fayaz, 2021)	A study on the factors simultaneously affecting visual comfort in classrooms: A structural equation modeling approach	Variables affecting visual comfort and their interrelationship	Influencing factors: light levels and lighting, thermal conditions, glare satisfaction, view satisfaction, distance to window
(Achsani, Wonorahardjo and Triyadi, 2022)	Visual Environment for Learning in the Digital Era: A Review	The impact of technology on the visual learning environment in the digital era.	Daylight-LED enhances the visual and non-visual performance
(RAIS et al., 2020)	Optimum window position in the building façade for high day-light performance: an empirical study in hot and dry climate	Window placement in hot &dry climate	Optimal windowsill height for hot, dry climate: 1.4 meters.
(Ahmed D., Abdelkader M. and Nessim A., 2023)	Effect of Adaptive Facades on Daylight -An Analytical Study in Hot Arid Climate	Sunscreen configuration for illuminance balance in hot arid climate.	Wavy façade found to be efficient in glare simulation

Mohamed Boubekri (2008) underscores the vital role of daylight in architectural designs, impacting human health and productivity. In climates ranging from hot and sunny to cold and dark, the balance of daylight becomes critical. Stevens et al. (2007) unveil the far-reaching effects of environmental lighting patterns on circadian rhythms and the hormone Melatonin, emphasizing the need for well-lit spaces for overall health. Nelson, Nilsson, and Johnson (1984) challenge established lighting norms by examining the influence of factors such as ambient temperature, illuminance, and time of day on productivity, acknowledging the role of seasonal variations. Kralikova and Wessely (2016) provide a comprehensive approach to assessing the impact of lighting on productivity and well-being, advocating for the refinement of assessment methods that consider climate and seasonal variations. Building on this, Kim and Mansfield (2016) reveal how perceived lighting quality can affect mood and overall health, particularly in brighter environments and non-daylit areas.

Achsani, Wonorahardjo, and Triyadi (2022) underscore the integration of daylight-LED lighting and technology in the digital learning environment, highlighting the evolving nature of lighting in educational settings. Furthering the discussion, Van Den Wymelenberg (2014) addresses discomfort glare metrics and their role in enhancing energy efficiency by reducing discomfort. Kent et al. (2015) stress the significance of considering temporal variations in discomfort glare to gain a comprehensive understanding of glare issues. Mandala (2019) presents a case study illustrating the significant influence of lighting quality on room quality, considering factors such as lighting techniques, illumination levels, light colors, and daylighting contributions. This research exemplifies the intricate relationship between lighting and indoor comfort. RAIS et al. (2020) explore optimal window positioning in hot and dry climates, highlighting the need for climate-specific solutions. Their findings emphasize the profound effects of sky conditions on the quantity and quality of natural light entering a building. For example, a clear sky enables abundant daylight, resulting in a bright and lively indoor space, while a cloudy sky produces softer, diffuse light, reducing glare and providing more even illumination. Ahmed D., Abdelkader M., and Nessim A. (2023) showcase the efficiency of wavy facades in managing illuminance levels and glare in hot and arid climates. Fakhari, Vahabi, and Fayaz (2021) identify variables that significantly affect students' visual comfort in classrooms, including factors such as lighting, view satisfaction, and thermal conditions, underscoring the importance of adaptable educational environments. Kent et al. (2017) expand on the temporal effects on glare responses from daylight, emphasizing the significance of considering temporal variables in glare assessments.

To conclude, Moscoso and Matusiak (2018) discuss the aesthetic perception of indoor spaces concerning daylighting systems and sky conditions. They suggest that lower daylight levels can enhance aesthetics, emphasizing the importance of aesthetics in architectural design alongside visual comfort. These provide valuable insights into the intricate interplay of environmental factors, climate, sky conditions, daylight, and seasonal variations, highlighting their profound impact on visual comfort, health, and well-being indoors.

Occupant factors

Visual comfort within indoor spaces is influenced by various occupant parameters that encompass both visual and non-visual aspects of lighting. These parameters contribute to the overall perception of luminous environments and play a pivotal role in creating a comfortable indoor atmosphere. Studies considered for this category are summarized in Table 3.

Table 3: Summary of papers on occupant factors
Source: Authors

Author	Title	Issue discussed	Findings
Galasiu and Veitch, 2006	Occupant preferences and satisfaction with the luminous environment and control systems in daylit offices: a literature review	Daylighting preferences, glare tolerance, window preferences, and controls	Preference for daylight with larger windows, adaption to glare with integrated controls
Stevens et al., 2007	Meeting report: The role of environmental lighting and circadian disruption in cancer and other diseases	Review of artificial lighting effects on circadian rhythms and implications for human well-being	Light disrupts circadian rhythms, affects melatonin, and health
Araji, Boubekri and Chalfoun, 2007	An Examination of Visual Comfort in Transitional Spaces	Analyzing architecture design impact on visual comfort in transitioning from indoor to outdoor spaces	Deep overhangs and moderate brightness ratio to reduce fatigue

Siu-Yu Lau, Gou and Li, 2010	Users' Perceptions of domestic windows in Hong Kong: Challenging daylighting-based design regulations	User perceptions and window acceptance in a residential setting	Socio-cultural factors impact the design of windows
Kent et al., 2015	Discomfort glare and time of day	To investigate whether the sensation of glare varies with the time of day.	Tolerance rises with the day and time-of-day
Al Horr et al., 2016	Occupant productivity and office indoor environment quality: A review of the literature	Review of IEQ and spatial factors in an office environment	IEQ, lighting, mood, & holistic design
Kent et al., 2017	Temporal effects on glare response from daylight	To examine temporal variables & glare perception	Time-dependent factors in glare perception: Impacts of time of the day and individual characteristics
Zhang, 2019	The effect of library indoor environments on occupant satisfaction and performance in Chinese universities using SEMs	To examine the indoor environment occupant satisfaction productivity in university libraries	IEQ enhances satisfaction and performance: nonprofit buildings as ideal research targets
Andargie, Touchie, and O'Brien, 2019	A review of factors affecting occupant comfort in multi-unit residential buildings	Analysis of comfort factors and assessment approaches and methods	MURB comfort: thermal conditions and IEQ, unexplored factors. study interrelationships. multi-factor framework
Spitschan, 2019	Differences in rod sensitivity due to photic history?	Conversation about a scientific study on how the eyes of people with migraines react to different levels of light.	Migraines increase light sensitivity over time. light adaptation and sensitivity are different
Day et al., 2020	A review of select human-building interfaces and their relationship to human behavior, energy use, and occupant comfort	Review of building interfaces in various settings	Usability challenges, disconnect, standardization, behavior modeling, energy-comfort balance, cultural diversity, and interface research.
Pierson et al., 2022	Is there a difference in how people from different socio-environmental contexts perceive discomfort due to glare from daylight?	Comparing glare evaluations in different contexts	Socio-environmental factors contribute to varied glare sensation
Mathew, Kurian, and Augustine, 2022	Optimizing Daylight Glare and Circadian Entrainment in a Daylight-Artificial Light Integrated Scheme	Methodology to assess the impact of daylight and artificial light on circadian stimulus	Light Optimization, Genetic Algorithm, Predictors: EV, CCT, Seating Impact on CS, Morning EV < 1250 Lux, Day EV < 1500 Lux to Avoid Glare.
Brown et al., 2022	Recommendations for daytime, evening, and nighttime indoor light exposure to best support physiology, sleep, and wakefulness in healthy adults	Nonvisual effects of light sleep, hormones, performance.	Recommended Light Exposure: Daytime: 250 lux Nighttime: 10 lux Midnight: 1 lux Applicable for Healthy Adults (Ages 18-55) Without Visual Conflict, Based on Optimum EDI.
Hakim et al., 2022	The Effect of Nighttime Lighting on the Open Spaces with Heritage Values: The South Square of Yogyakarta Palace	Examining nighttime lighting's cultural impact	Nighttime lighting enhances cultural significance

Izmir Tunahan, Altamirano and Unwin Teji, 2021	Conceptual Framework of Cultural Background in the Lit Environment	Cultural background impact	Cultural factors in daylight perception ethnicity, physiology, locale, history more research needed
Houser et al., 2021	Human-centric lighting: Myth, magic, or metaphor?	Evolution of lighting design towards human-centric or integrative lighting	Need for standard metrics. light's impact on health short & long-term design

Socio-cultural factors, such as geography and cultural backgrounds, significantly influence how individuals perceive indoor luminous environments. Variations in light sensitivity among different populations are attributed to factors like ethnicity, eye physiology, living conditions, and cultural behavior patterns. For instance, Asians exhibit lower light sensitivity than North Americans, who, in turn, exhibit lower sensitivity than Europeans (Pierson et al., 2022).

Individual ethnicity, eye physiology, living conditions, and cultural behavior patterns contribute to the variability in light sensitivity among populations, highlighting the importance of understanding these cultural nuances for tailored lighting designs (Izmir Tunahan, Altamirano, and Unwin Teji, 2021). Social and behavioral dynamics also influence the perception of the built environment, as seen in a study in Hong Kong, where factors like dining habits and privacy played a significant role (Siu-Yu Lau, Gou, and Li, 2010).

Various personal factors, including age, corrected vision, time of day, mood, well-being, and previous exposure to luminous environments, impact an individual's sensitivity to light and visual comfort. For instance, elderly individuals may require lighting designs with deep overhangs and moderate brightness ratios to prevent visual shock when transitioning between bright and darker environments due to age-related changes in eye physiology (Fig 4) (Araji, Boubekri, and Chalfoun, 2007; Kent et al., 2017).

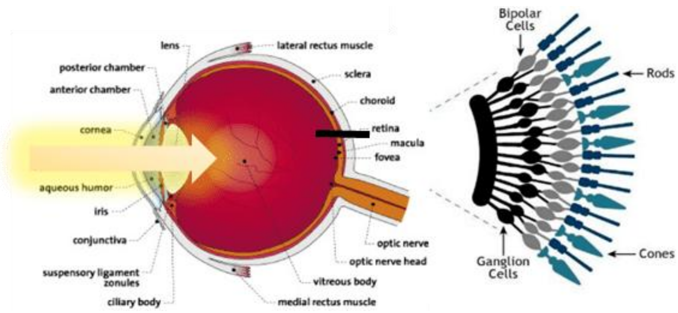

Fig. 4: Anatomy of the human eye and cross-section of the retina,
Source: https://www.neovisioneyecenters.com

Various factors influence an individual's perception of glare and discomfort, including the use of spectacles or contact lenses, as noted by Kent et al. (2015). Additionally, an individual's prior exposure to different lighting conditions can affect their sensitivity to the current luminous environment. For example, previous exposure to low light can alter rod sensitivity and light adaptation duration, impacting how they perceive subsequent lighting conditions (Spitschan et al., 2019).

Lighting goes beyond visual comfort, impacting circadian rhythms, alertness, and physiological responses. Daylight is especially vital for occupant well-being, and indoor lighting design should account for non-visual effects, like circadian rhythms and hormonal regulation (Mathew, Kurian, and Augustine, 2022). Disruptions in the contrast between day and night in indoor environments can affect melatonin and cortisol levels, potentially increasing the risk of chronic diseases (Stevens et al., 2007; Brown et al., 2022).

In lighting design, it's crucial to consider occupant parameters related to both visual and non-visual aspects, such as visual acuity and factors like circadian rhythms, alertness, body temperature, heart rate, and other physiological and psychological responses, as highlighted by Brown et al. (2022). Achieving a balance among these parameters and understanding the complex interplay between cultural, personal, and non-visual factors are essential for optimizing indoor lighting (Houser et al., 2021).

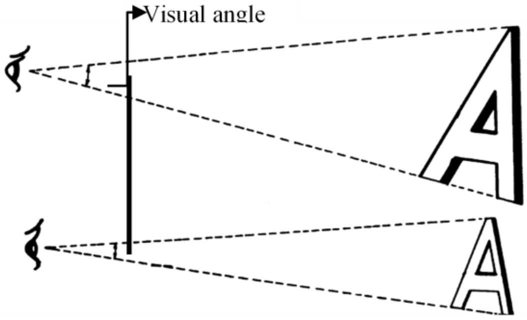

Fig. 5: Visual Acuity
Source:SP 41, 1987

Visual acuity refers to the eye's ability to distinguish fine details, expressed as the reciprocal of the visual angle, and is improved by higher levels of illumination. The visual angle, which depends on the size and distance of an object, is crucial for seeing, and larger angles make objects more visible.Recently developed, the international WELL standard, sets minimum lighting requirements based on melanopsin's spectral response in humans, using the Equivalent Malanopic Lux (EML) concept to determine equivalent lux levels for optimal circadian stimulus. However, the efficacy of compliant lighting solutions is untested, as threshold values of EML corresponding to optimal illuminance have changed over time. **(**Houser et al., 2021)

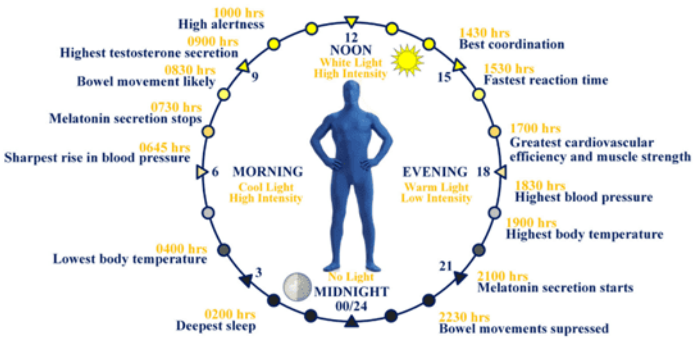

Fig. 6: Natural daylight and healthy human circadian rhythms.
Source:(Kapoor et al., 2021)

Factors associated with Built Environment

The built environment plays a significant role in influencing visual comfort, subsequently affecting the well-being and performance of its occupants. Numerous studies shed light on various aspects of the built environment that contribute to visual comfort summarized in Table 4.

Table 4: Summary of papers on built environment factors
Source: Author

Author	Title	Issue discussed	Findings
Mills, Tomkins and Schlangen, 2007	The effect of high correlated color temperature office lighting on employee wellbeing and work performance	Impact of high-color temperature lighting	High-color temperature lighting improves concentration, alertness, and reduces fatigue in call center employees. Further research is needed.
Araji, Boubekri and Chalfoun, 2007	An Examination of Visual Comfort in Transitional Spaces	Impact of architectural design on user comfort during indoor-to-outdoor transitions with a focus on visual comfort	Deep overhangs and moderate brightness ratio to reduce fatigue
Veitch et al., 2008	Lighting appraisal, well-being, and performance in open-plan offices: A linked mechanisms approach	Impact of lighting conditions on well-being and task performance in office setting	Higher-quality office lighting enhances attractiveness, mood, and well-being. direct-indirect lighting with control is favored, but more research is required.
Ho et al., 2008	Optimal sun-shading design for enhanced daylight illumination of subtropical classrooms	Assess window sunshades for cost reduction.	Sun-shading specifics: Height of the floor: +240 cm, width and length of the shading device: 40 cm, energy use reduced by ~70% (Winter & Summer Solstices).
Fotios and Cheal, 2009	Obstacle detection: A pilot study investigating the effects of lamp type, illuminance, and age	Obstacle detection under different lamp types and illuminance levels	Obstacle detection is influenced by lamp type, illuminance levels, and observer age. Implications for lighting conditions in pedestrian environments.
Zomorodian, Korsavi and Tahsildoost, 2016	The effect of window configuration on daylight performance in classrooms: A field and simulation study	Daylighting and its effects on students' health, learning, and visual performance of the students	Recommendation: south-side windows with light shelves and north-side roof monitor for balanced daylight. future studies should consider all aspects, combining subjective and objective data.
Ramprasad and Subbaiyan, 2017	Perceived indoor environmental quality of classrooms and outcomes: a study of a higher education institution in India	To identify the factors influencing Perceived Indoor Environmental Quality (PIEQ)	The study identified six specific IEQ factors that had an impact on PIEQ: Adaptive opportunities Furniture, Daylight Acoustics, Indoor Air Quality (IAQ), Thermal aspects
Makaremi et al., 2017	Quantifying the effects of interior surface reflectance on indoor lighting	To analyze surface reflectance impact on lighting and energy use.	Lighter materials boost reflectance and enhance indoor lighting
Gulati, Ritu; Sehgal, Vandana; Qamruddin, Juwairia; Raushan, Arshi S.,2019	Architectural Spaces as Socio-Cultural Connectors: Lessons from the Vernacular Houses of Lucknow, India	Socio-Cultural Aspects in Narha, India	Elements promoting social connection: Chabutra, Balcony, Jharokha (Windows), Courtyard, Verandah, Terraces. Windows provide Views and fosters social interaction.

Bournas, Dubois and Laike, 2020	Perceived daylight conditions in multi-family apartment blocks – Instrument validation and correlation with room geometry	Opinions vs. Daylight Measurements	Observer-Based Environmental Assessment (OBEA) Reliability, Window Size, and Brightness

Several elements in the built environment significantly contribute to achieving visual comfort. These include the arrangement of openings (Zomorodian, Korsavi, and Tahsildoost, 2016), interior space configuration (Bournas, Dubois, and Laike, 2020), shading device implementation (Ho et al., 2008) (Araji, Boubekri, and Chalfoun, 2007), outdoor views (Gulati et al., 2019), spatial composition, surface color, and texture (Makaremi et al., 2017), furniture selection (Ramprasad and Subbaiyan, 2017), and artificial lighting choice (Fotios and Cheal, 2009) (Veitch et al., 2008). For example, classroom studies have shown that factors like window configuration, window-to-wall ratio, the use of roof monitors, light shelves, and clerestory windows significantly impact daylight intensity, uniformity, and outdoor views, enhancing occupants' connection to nature and their surroundings (Zomorodian et al., 2016). Traditional Indian houses with features like "jharokhas" facilitate interaction between interior and exterior spaces, providing areas for occupants to enjoy pleasant weather conditions & outdoor views (Gulati et al., 2019).

Shading devices, including dual-layer sun-shadings and deep overhangs, can effectively reduce glare, improve light uniformity, regulate temperature, enhance energy efficiency, and increase overall comfort and aesthetics (Ho et al., 2008) (Araji, Boubekri, Chalfoun, 2007). In the context of interior spaces, room geometry, glass area, and surface textures significantly affect perceived brightness, as demonstrated by Bournas, Dubois, and Laike (2020) and Makaremi et al. (2017). These studies indicate that surface reflectance (Table 2) and material choices can enhance visual comfort and energy efficiency. However, it's essential to consider discomfort glare limitations, such as selecting luminaires with a specified Unified Glare Rating (UGR<19), when choosing surface materials for specific spaces.

Table 5: Desirable reflectance of room surfaces: ratio of luminous flux reflected by a body (with or without diffusion) to the flux it receives.
Source: Author

Reflectance	Ceiling	walls	floors	furniture	Standards
Surface	0.7-0.9	0.5-0.8	0.2-0.4	0.2-0.7	EN12464-1(European standard, 2011)
	0.7-0.8	0.5-0.6	0.15-0.30	-	(SP 41, 1987)
color	Dark colors: 0.1, Middle tints: 0.3 Light colors: 0.5, White and very light colors: 0.7				NBC 2016(NBC, 2016)

In addition. Mills, Tomkins, and Schlangen (2007) found that a highly correlated color temperature of artificial light, specifically at 17000 K, was associated with reduced fatigue and daytime sleepiness, improved concentration, alertness, and work performance. Also, research by Fotios and Cheal (2009) revealed that the type of lighting, specifically the use of metal halide lamps (CDM), significantly influenced obstacle detection ability, with CDM lamps performing optimally at higher illuminance levels. Notably, Veitch et al. (2008) emphasized the importance of using direct-indirect lighting with control as the preferred lighting configuration in indoor spaces. Moreover, the use of flexible furniture that can be adjusted to different teaching modes has been found to significantly contribute to creating conducive learning spaces and enhancing student satisfaction (Ramprasad and Subbaiyan, 2017).

In the pursuit of visual comfort, the built environment's various elements, including spatial design, views, furnishings, and lighting, significantly influence visual comfort, well-being, and performance. Understanding these factors is essential for designing spaces that meet user needs and preferences, promoting a high-quality indoor environment that optimizes energy efficiency, comfort, well-being, and performance.

Methods and Techniques to Evaluate Visual Comfort

There are various methods, tools, and techniques are available to evaluate indoor visual comfort globally. Studies considered for this category are summarized in Table 6.

Table 6: Summary of papers on methods and techniques to evaluate Visual Comfort
Source: Authors

Author	Title	Issue Discussed	Findings
Galasiu and Reinhart, 2008	Current daylighting design practice: A survey	Review of tools and standards for daylight design	Standardize daylight performance assessment efficiency, glare control, DF, and outdoor views.
Zissis and Kitsinelis, 2009	State of art on the science and technology of electrical light sources: From the past to the future	Evolution, challenges, and future: Artificial light technology	The emergence of Organic LED requires interdisciplinary expertise
Cantin and Dubois, 2011	Daylighting metrics based on illuminance, distribution, glare, and directivity	Evaluation of daylight quality in office spaces	Application of visual protection devices to minimize glare
Bellia, Spada and Pedace, 2013	Lit environments quality: A software for the analysis of luminance maps obtained with the HDR imaging technique	Impact of luminance and brightness on visual comfort and energy efficiency	Brightness, equivalent luminance, and glare: essential for comfort and perception in lighting design. Videographic techniques are recommended.
Van Den Wymelenberg, 2014	Visual comfort, discomfort glare, and occupant fenestration control: Developing a research agenda	Analysis of discomfort glare metrics in building design	Current measurements and simulation techniques- for occupant acceptance, minimizing discomfort glare, and energy efficiency.
Carlucci et al., 2015	A review of indices for assessing visual comfort with a view to their use in optimization processes to support building integrated design	Review of visual comfort indices and metrics	Indices for evaluating visual comfort- Useful Daylight Illuminance (UDI), Daylight Glare Probability (DGP), and other glare metrics. Standardization of glare assessment, and long-term glare measurements.
Hafiz, 2015	Daylighting, Space, and Architecture: A Literature Review	Review of Visual comfort analysis methods	Luminance and illuminance-based metrics with associated thresholds.
Kralikova and Wessely, 2016	Lighting Quality, Productivity, and Human Health	Effect of lighting on productivity and well being	Mixed views on illuminance threshold for better productivity assessment Methods with a holistic approach

Giarma, Tsikaloudaki and Aravantinos, 2017	Daylighting and Visual Comfort in Buildings' Environmental Performance Assessment Tools: A Critical Review	Evaluation of visual comfort in green building tools	Green building tools (CASBEE, SB Tool, LEED, BREEAM) to assess visual comfort.
Inanici and Hashemloo, 2017	An investigation of the daylighting simulation techniques and sky modeling practices for occupant-centric evaluations	To compare different sky models and simulation techniques.	Measurement-based sky models and annual simulations -for luminance measurements
Imaizumi, Koyama and Tanno, 2018	Development of the Japanese version of the Visual Discomfort Scale	To create and validate the Japanese version of the Visual Discomfort Scale to measure visual discomfort.	Simple and unidimensional method to measure visual discomfort – beneficial to evaluate migraine headaches and associated reasons as well.
Zhang, 2019	The effect of library indoor environments on occupant satisfaction and performance in Chinese universities using SEMs	Indoor environment occupant satisfaction productivity	IEQ impacts occupant satisfaction and performance. Nonprofit buildings should be targeted for interdisciplinary research.
Song, Ying Mao, Fubing Liu, Qing,2019	Human Comfort in Indoor Environment: A Review on Assessment Criteria, Data Collection and Data Analysis Methods	Comfort assessment criteria, data collection methods, and data analysis techniques	The use of sensor technology and machine learning was found to be effective
Brembilla et al., 2019	Evaluation of climate-based daylighting techniques for complex fenestration and shading systems	Exploration of annual daylight performance metrics -CBDM	Daylighting simulation techniques and their suitability for shading devices annual daylight metrics: variation ±20%. ASE metric:47 %, depending on the simulation method
Acosta et al., 2019	Daylighting design for healthy environments: Analysis of educational spaces for optimal circadian stimulus	Circadian Stimulus (CS) and electric lighting	Pale blue environments, cool LED lamps (CCT of 6500 K), and high reflectance surfaces: optimum CS
Day et al., 2020	A review of select human-building interfaces and their relationship to human behavior, energy use, and occupant comfort	Review of issues related to building interfaces in various settings	Interface design and challenges-efficient use, Buyer-User Discrepancy, Standardization gap, Behavior modeling challenges, other interface design challenges
Chiou, Saputro and Sari, 2020	Visual comfort in modern university classrooms	Classroom Lighting Effects on Student Well-being, Work Surfaces, Scenarios	Visual comfort priority: luminance distribution, key factors, task-specific lighting, HDRI mapping
Dimara, Krinidis and Tzovaras, 2021	Comfit: A Novel Indoor Comfort Inference Tool	Introducing COMFIT: an innovative tool for residential and office comfort assessment	Only luminance data was used for evaluation and found that this VC metric was found to be accurate.
Mathew, Kurian, and Augustine, 2022	Optimizing Daylight Glare and Circadian Entrainment in a Daylight-Artificial Light Integrated Scheme	Methodology to assess the Impact of daylight and artificial light on circadian stimulus	Optimizing multi-objective genetic algorithm for glare estimation: key predictors - cs, Ev, and seating position.

Cadena et al., 2022	Current Trajectories and New Challenges for Visual Comfort Assessment in Building Design and Operation: A Critical Review	Methods to consider individual occupant characteristics	Occupant Assessment: Glare Source, Eye-Plane, View Quality. Innovative BMS Eye Tracking for Non-Intrusive Monitoring and Efficient Simulations

In the multifaceted realm of visual comfort, the interplay of factors such as brightness, light distribution, shadows, reflections, glare, and color quality significantly influences the perception of luminous environments, underscoring the need for comprehensive assessments (Carlucci et al., 2015). Despite this complexity, visual comfort assessments often focus on quantifiable parameters. Metrics like luminous intensity (I), illuminance (E), and luminance (L) are commonly employed (Fig.7) to gauge lighting quality and quantity, offering essential insights into luminous environments (SP 41, 1987; European standard, 2011).

Luminous intensity (I) quantifies light emitted within specific solid angles, usually measured in steradians, while illuminance (E) assesses light falling on a square meter, quantified in lux (SP 41, 1987). These metrics are vital for ensuring visual acuity and comfort in various settings. For example, illuminance values are integral to daylight factor assessments, which determine indoor-to-outdoor light availability ratios, while luminance values are crucial for evaluating indoor glare (Day et al., 2020; Mathew, Kurian, and Augustine, 2022).

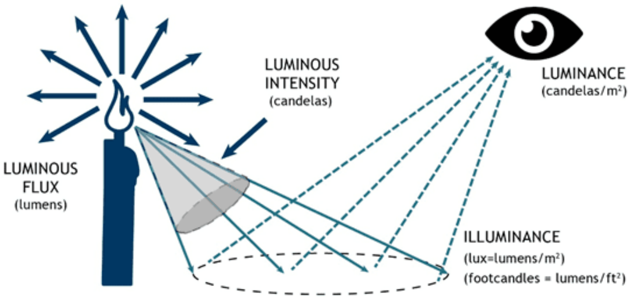

Fig 7: Interrelation and difference among light-measuring terms
Source: https://www.luminus.com

Adjusting vertical illuminance levels has been shown to have a significant impact on visual comfort, task performance, and physiological responses (Zhang, 2019). Maintaining illumination standards, as outlined in Table 1, and managing illuminance ratios between spaces can enhance comfort and prevent visual fatigue. For instance, the British Standard (EN) 12464-1:2011 recommends minimum lighting levels to create visually comfortable environments (Cadena et al., 2022).

Table 7: Minimum recommended illuminance levels for task areas based on various codes and standards in classrooms and lecture rooms on desks.
Source: Author

Parameter	Range	Codes/ratings systems
Horizontal work surface	300 lux	SP41,1987
	100-300-500 lux	EN12464-1
	200-300-500 lux	NBC,2016, IES
Vertical work surface (Green, white, and blackboards)	200-300 lux	SP41,1987
	500 lux	EN12464-1, NBC 2016, IES

Luminance metrics, equally important, measure perceived surface and object brightness, enhancing lighting quality (Inanici and Hashemloo, 2017). Researchers have employed these metrics to assess light quality, predict occupant satisfaction, and recommend optimal light levels (Van Den Wymelenberg, 2014). High Dynamic Range (HDR) imaging

(Bellia, Spada, and Pedace, 2013), recognized for its ability to replicate real-world lighting conditions, is increasingly used to collect luminance data more accurately than generic CIE skies (Inanici and Hashemloo, 2017).

As the field of visual comfort evolves, a holistic approach to lighting quality is emerging, incorporating aspects such as color perception, correlated color temperature (CCT), and Color Rendering Index (CRI). Understanding how light color and temperature influence occupants' physiological and psychological well-being is key to optimizing visual comfort (Kralikova and Wessely, 2016). In the context of office spaces, Cantin and Dubois (2011) have delved into evaluating daylight quality. Their study reveals that while sufficient daylight is essential, it can pose a risk of overlighting and glare. Dark furniture creates high contrasts, necessitating recommendations for visual protection devices.

The review of daylighting design tools, practices, and standards by Galasiu and Reinhart (2008) underscores the need for commonly accepted methods to assess daylighting system performance. This includes considerations of energy savings, glare prevention, daylight factors, and views to the outside, reflecting the quest for comprehensive approaches to enhance visual comfort. Researchers are advancing visual comfort assessments by utilizing new metrics and tools. Metrics like Climate-based Daylight Modeling (CBDM), Visual Comfort Probability (VCP), and Daylight Glare Index (DGI) are gaining prominence, offering more comprehensive evaluations (Brembilla et al., 2019; Hafiz, 2015; Tabadkani et al., 2021). Computational tools like "COMFIT: A NOVEL INDOOR COMFORT INFERENCE TOOL" are providing advanced methods for predicting visual comfort (Dimara, Krinidis, and Tzovaras, 2021).

Future directions in visual comfort research include real-time assessments enabled by tools like illuminance meters, luminance meters, spectroradiometers, photometers, and HDR imaging. HDR imaging, an affordable alternative to expensive luminance meters, offers architects and researchers precise lighting data without significant financial investment (Chiou, Saputro, and Sari, 2020). Additionally, subjective assessment methods involving questionnaires, observational surveys, and innovative techniques like Eye-Tracking add a human-centered dimension to visual comfort evaluation (SareyKhani et al., 2013).

In this rapidly evolving field, the evaluation of visual comfort is broadening to encompass a comprehensive range of metrics and tools, which are pushing the boundaries of architectural lighting design while also promoting occupant well-being. For instance, occupant-centric metrics like Equivalent Melanopic Lux (EML) (EN) 12464-1:2011 are emerging to account for the non-visual effects of light and their relationship with occupant comfort in the built environment, though they are currently undergoing validation processes. Additionally, methods for quantifying Circadian Stimulus (CS) based on window sizes, orientations, locations, and environmental factors are being developed. Recommendations, such as using a white or pale blue environment, cool LED lamps, Organic LEDs (Kitsinelis,2009), and thoughtful consideration of window size and reflectance, have been proposed by Acosta et al. (2019). These advancements signal an exciting future where lighting quality is not only assessed but also optimized, considering the multifaceted nature of visual comfort and potentially revolutionizing architectural design and enhancing occupant satisfaction. This multifaceted approach is further propelled by innovative research projects exploring parameters like glare source luminance, eye-plane illuminance, adaptation levels, contrast effects, glare source size, and position, alongside an examination of the quality of outdoor views (Cadena et al., 2022). By tracking eye responses and correlating them with illuminance levels, these endeavors represent a promising trajectory in the field of visual comfort research.

Conclusions

The field of lighting research has undergone a significant transformation, shifting its focus from a narrow emphasis on lighting to encompass a broader understanding of indoor visual comfort. This evolution is marked by several noteworthy trends and aspects that have been examined, but it also reveals areas that require further investigation. The specific takeaways from this literature review study are outlined below.

1. Visual Comfort as a Diverse Phenomenon: It is a multifaceted and subjective phenomenon, challenging to develop universal metrics due to diverse interpretations.
2. Visual Comfort, Health, Well-being, and Productivity: The trend shows that there has been a lot of research on improving indoor environmental quality with lighting and other comfort indices in office spaces to increase people's productivity. However, substantial research opportunities exist regarding the luminous environment's role in higher education, residential, and commercial settings in enhancing occupants' well-being and productivity, revealing a current knowledge gap.
3. Energy Efficiency and Visual Comfort: To achieve ambitious energy efficiency objectives, some people advocate stringent construction standards that restrict the size of windows. However, this strategy may result in inadequate lighting in buildings, emphasizing the necessity of striking a balance between energy efficiency and other concerns, including public health, optimal performance, a better luminous environment, and ensuring visual comfort.
4. Visual Comfort and Indoor Environment Quality (IEQ): The quality of indoor environments has a direct connection with visual comfort. Factors such as indoor air quality, thermal comfort, acoustic conditions, and spatial layout play a pivotal role in creating a visually comfortable atmosphere. Understanding the synergy between these indoor environmental factors and visual comfort can be a research area to explore more in future research.
5. Factors collectively affecting 'Visual Comfort' within the luminous environment:
    i. Environmental factors: Climate, Sky Conditions, Quantity of light, Quality of light, Colour, and Temperature of light
    ii. Occupant factors: Geography, Cultural background, Ethnicity, Age, Visual Acuity and Corrected vision, Individual sensitivity to light, Time of the day
    iii. Built environment factors: Configuration of openings, Shading devices, Space composition and Outside views, Colour and Texture of surfaces, and Furniture layout.
6. Tools, Methods, & Techniques to Evaluate Visual Comfort: Tools and methodologies are continually evolving to quantify the luminous environment, extending beyond the realms of just daylighting and artificial lighting. A prime example is the assessment of aesthetic environments, where, instead of measuring luminance on different surfaces, efficient HDR image techniques are being employed. These techniques are easy, accurate, time-efficient, and cost-effective if employed for suitable cases. Occupant-centric metrics like the Equivalent Melanopic Lux (EML) are emerging to encompass non-visual effects of light and their correlation with occupant comfort within the built environment, albeit still undergoing validation processes. Other methods involve occupant preference tests, user surveys, and eye-tracking techniques in fusion with Building Management Systems (BMS). In summary, Objective assessments of Visual Comfort now incorporate innovative tools such as computational simulations and HDR imagery as mentioned earlier, while subjective evaluations focus on occupant preferences.

The trend of evolution witnessed a progression from the exclusive consideration of lighting to a more comprehensive approach. This approach now incorporates various factors, including environmental conditions, human characteristics, and architectural design, to comprehensively explore and enhance the overall visual comfort experience of a luminous environment. However, some aspects haven't gotten enough attention yet. Notably, the research's flexibility in adopting new technology and methodology is one of its strongest points. However, there are flaws, such as the little study in certain regions, notably in tropical countries like India. The adoption of the EML metric by ISHRAE is a positive step in the Indian context, but there is still a gap in understanding visual comfort in diverse environments and among different populations.

Therefore, more studies are required to explore the trajectories of visual comfort. Research trends show that there is a dearth of research on visual comfort particularly in diverse regions such as education, residential, and commercial settings, calling for more inclusive studies to create visually comfortable environments that support learning, creativity, productivity, and well-being.

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