Online Journal of Art and Design
volume 14, issue 3, July 2026
DOI: https://doi.org/10.30935/ojad/2513105

Non-linear Relationships Between Daylight Illuminance, Individual User Characteristics, and Cognitive Performance in an Educational Interiors

Inst. Dr. Mine YAZICIOĞLU
Interior Architecture Department, Çankaya University, Ankara, TURKEY.
micelebi@cankaya.edu.tr

Prof. Dr. Fatih CANAN
Architecture Department, Konya Technical University, Konya, TURKEY.
fcanan@ktun.edu.tr

Abstract

Daylight is a critical factor in educational interiors, yet its impact on cognitive performance is often overlooked in favor of energy efficiency. This study investigates the relationship between daylight illuminance and cognitive performance within a university design studio, focusing on the non-linear interactions between seating positions as daylight illuminance level (K1–K4) and individual user characteristics.

An experimental field study was conducted with undergraduate interior architecture students using the Raven Standard Progressive Matrices Test (RSPM) across five complexity levels (Sets A–E). Results indicate that cognitive performance is not a direct consequence of illuminance alone but emerges from complex interactions with gender, visual status, chronotype, and sleep duration. Findings challenge uniform lighting standards by revealing multiple optimal conditions; while higher illuminance improved performance for specific groups, moderate or lower levels were more favorable for others. The study highlights the necessity of shifting toward user-sensitive and spatially adaptive daylight strategies. By demonstrating the non-linear nature of environmental interaction, it contributes to design-oriented discussions aimed at enhancing both cognitive success and environmental satisfaction in learning environments.

Keywords: Daylight Illuminance, Cognitive Performance, Educational Interior Design, Non-linear Interaction

1. Introduction

Daylight has been extensively studied as a fundamental component of indoor environmental quality (IEQ), particularly in educational buildings where visual, cognitive, and psychological demands are high. Within architectural and interior design research, daylight is commonly associated with improved visual comfort, reduced energy consumption, and enhanced user satisfaction (Boyce, 2014; Edwards & Torcellini, 2002; Dubois & Blomsterberg, 2011). In learning environments such as classrooms, studios, and laboratories, daylight is often considered a prerequisite for supporting sustained attention, spatial orientation, and task-related performance.

A substantial body of literature has examined the effects of daylight illuminance on visual comfort and perceived quality of learning spaces. Studies have shown that adequate daylight access contributes positively to students' subjective evaluations of comfort and well-being (Heschong et al., 2002; Aries, Veitch, & Newsham, 2010). Consequently, daylight design guidelines frequently rely on recommended illuminance thresholds, typically expressed as fixed lux values, to ensure minimum visual requirements are met. These recommendations, while valuable, tend to imply a linear relationship between illuminance level and performance-related outcomes.

However, recent research increasingly challenges the assumption that "more light is always better." Empirical findings suggest that excessively high illuminance levels or poorly distributed daylight may lead to glare, visual fatigue, and cognitive distraction (Boyce, Hunter, & Howlett, 2003; Veitch & Galasiu, 2012). In educational interiors, such discomfort can counteract the presumed benefits of daylight, especially during cognitively demanding tasks. This has led scholars to argue that the relationship between daylight illuminance and human performance is not linear but context-dependent and potentially non-monotonic (Boubekri, 2008; Smolders, de Kort, & Cluitmans, 2012).

Beyond spatial parameters, individual user characteristics significantly modulate responses to lighting conditions. Gender-related perceptual differences, variations in visual acuity, and age-related sensitivity to brightness have all been reported to influence visual comfort and task performance under different lighting conditions (Küller & Lindsten, 1992; Boyce, 2014). Similarly, chronotype—a person's circadian preference for morning or evening activity—has been shown to affect alertness, cognitive efficiency, and tolerance to environmental stimuli at different times of day (Adan et al., 2012; Schmidt et al., 2007). Sleep duration further interacts with circadian rhythms, influencing cognitive flexibility, attention span, and problem-solving ability (Killgore, 2010).

Despite these findings, many architectural lighting studies continue to evaluate daylight performance independently of user-related variables. Experimental designs often isolate illuminance as a single factor, overlooking how personal characteristics may alter the effectiveness of a given lighting condition. As a result, design recommendations derived from such studies risk oversimplifying complex human–environment interactions.

Cognitive performance assessment within architectural research has also been limited in scope. While subjective measures such as perceived concentration or self-reported productivity are frequently employed, fewer studies incorporate standardized cognitive tests capable of capturing variations in abstract reasoning and problem-solving performance. The Raven Standard Progressive Matrices Test (RSPM), widely used in cognitive psychology and neuroscience, provides a robust, non-verbal measure of cognitive performance across increasing levels of task complexity (Raven, Raven, & Court, 1998). Its application in real educational interiors offers a valuable methodological bridge between cognitive science and spatial design research.

In this context, the present study investigates the effects of daylight illuminance on cognitive performance in a university design studio, explicitly adopting a non-linear analytical framework. Rather than assuming a direct positive correlation between illuminance and performance, the study examines how performance outcomes vary across different daylight ranges, seating positions, and individual characteristics, including gender, visual status, chronotype, and sleep duration. By integrating objective cognitive performance data obtained through RSPM with subjective IEQ evaluations, the research aims to reveal differentiated performance patterns that cannot be explained through linear models alone.

The originality of this study lies in its combined consideration of spatial daylight distribution, individual user variables, and graded cognitive task complexity within a real educational setting. The findings are expected to contribute not only to daylighting research but also to interior architectural design practice, offering evidence-based insights for creating learning environments that respond to diverse user needs rather than relying on uniform illuminance standards.

1.1 Daylight and Visual Comfort in Educational Spaces

Visual comfort is a fundamental component of indoor environmental quality and is closely related to users' physiological and psychological responses to light. In educational environments, visual comfort plays a decisive role in sustaining attention, reducing visual fatigue, and supporting learning-related tasks. It is commonly defined as the condition in which lighting enables users to perform visual tasks efficiently without discomfort or strain (Boyce, 2010).

Daylight is widely acknowledged as the preferred primary light source in learning environments due to its dynamic nature, spectral quality, and positive psychological effects. Previous studies have demonstrated that daylight contributes to improved spatial perception, enhanced visual acuity, and increased user satisfaction compared to exclusively artificial lighting conditions (Begemann et al., 1997; Veitch et al., 2004). In addition to its visual benefits, daylight has been shown to support well-being and motivation, particularly in environments requiring prolonged cognitive engagement.

However, visual comfort cannot be evaluated solely through illuminance values. Excessive daylight exposure may result in glare, high contrast ratios, and reflections on working surfaces, all of which can negatively affect visual performance and comfort (Onaygil & Tenner, 1993; Reinhart, 2011). Research conducted in educational settings has revealed that users may perceive spaces with illuminance levels below standardized recommendations as comfortable, while environments with higher illuminance values may be rated negatively due to glare and visual fatigue (Veitch et al., 2013).

Design studios present a particularly complex case for visual comfort evaluation. These spaces are characterized by visually demanding tasks such as drawing, modeling, screen-based work, and spatial analysis. Moreover, design studios often feature large glazed surfaces and deep-plan layouts, resulting in uneven daylight distribution. This variability emphasizes the need to assess daylight performance not only through quantitative measurements but also through users' perceptual and experiential responses.

Standards such as EN 12464-1 define minimum illuminance levels for educational spaces; however, these values are primarily task-oriented and do not account for individual differences or spatial characteristics specific to design education environments European Standard EN 12464-1 (Light and lighting – Lighting of work places), specifies that the minimum maintained illuminance on the task area for standard classrooms and lecture halls should be 500 lux. For specific spaces such as technical drawing and design studios, where visual precision and detailed manual tasks are paramount, the required illuminance level is significantly higher, targeted at 750 lux (EN 12464-1, 2013). Similarly, IESNA (Illuminating Engineering Society of North America) recommendations categorize educational lighting requirements based on task complexity and age-related visual needs, generally targeting a range of 300 to 750 lux for most classroom environments to ensure adequate visual performance across diverse activities.

Design studios present a particularly complex case for visual comfort evaluation. These spaces are characterized by visually demanding tasks such as drawing, modeling, screen-based work, and spatial analysis. Moreover, design studios often feature large glazed surfaces and deep-plan layouts, resulting in uneven daylight distribution. This variability emphasizes the need to assess daylight performance not only through quantitative measurements but also through users' perceptual and experiential responses.

2.2 Cognitive Performance, Circadian Rhythm, and Light

Cognitive performance encompasses a range of mental processes, including attention, memory, reasoning, problem-solving, and decision-making. These processes are directly influenced by environmental conditions, among which lighting plays a significant role. Light affects cognitive performance not only through visual mechanisms but also via non-visual pathways related to circadian rhythm regulation (Boyce et al., 2003).

Circadian rhythm, often referred to as the biological clock, regulates physiological and psychological processes over a 24-hour cycle. Daylight exposure is the primary synchronizer of this rhythm, influencing alertness levels, mood, and cognitive efficiency (Horne & Östberg, 1976; Vandewalle et al., 2011). Insufficient or poorly timed daylight exposure has been associated with reduced concentration, lower performance, and negative affective states (Leslie, 2003).

Individual differences further complicate the relationship between light and cognition. Chronotype, which categorizes individuals as morning-oriented, evening-oriented, or intermediate types, has been shown to influence cognitive performance depending on the time of day and lighting conditions (Horne & Östberg, 1976; Cavallera & Giudici, 2008). Studies indicate that cognitive tasks are performed more efficiently when environmental conditions align with individuals' circadian preferences (May et al., 1993; Bennett et al., 2008).

Despite extensive evidence linking light, circadian rhythm, and cognition, most lighting guidelines applied in educational environments remain generalized and static. They often overlook individual variability and the dynamic nature of daylight. This limitation underscores the necessity of research approaches that integrate cognitive performance measures, affective states, and user characteristics into the evaluation of daylight performance in learning environments.

2. Methodology

This study adopts a user-centered, non-linear methodological framework to investigate the relationship between daylight illuminance conditions and cognitive performance. Rather than assuming a direct linear relationship between lighting levels and performance outcomes, the methodology is designed to capture interaction-based effects, in which individual user characteristics moderate cognitive responses to daylight conditions. The methodological structure integrates environmental measurements, individual variables, cognitive testing, and statistical analyses to enable a multidimensional evaluation of performance outcomes.

2.1 Research Design and Conceptual Framework

The research is based on an experimental design conducted in an educational interior space, where participants were exposed to varying daylight illuminance conditions determined by seating position. The conceptual framework is grounded in the assumption that cognitive performance emerges from a non-linear pathway, shaped by the interaction between physical daylight conditions and individual user characteristics.

Previous studies have highlighted that optimal lighting conditions for performance are not universal but vary according to user profiles and task demands (Veitch & Newsham, 2000; Boyce, 2014). Accordingly, this study conceptualizes daylight illuminance as an enabling or constraining factor whose cognitive impact is contingent upon individual differences rather than as a standalone determinant.

2.2 Experimental Setting and Daylight Illuminance Conditions

The experimental setting was a university design studio primarily illuminated by daylight. Four distinct seating positions (K1–K4) were identified within the space based on their proximity to daylight openings and corresponding illuminance levels. These positions represented a gradient of daylight exposure, ranging from high illuminance near the window zone (K1) to low illuminance in areas distant from daylight sources (K4). To operationalize this non-linear framework within a real-world context, the experiment was conducted in the Çankaya University Balgat Campus design studio, which is characterized by extensive daylight exposure and visually demanding academic activities. The studio features a linear façade with continuous window openings, allowing daylight to penetrate the interior at varying depths (Picture 1).

The experimental phase involved a total of 171 undergraduate students and was carried out across six sessions between April 10th and April 19th. All sessions were scheduled during the afternoon peak, specifically from 13:30 to 15:00. The selection of this time frame was intentional, as design studio courses in the architecture curriculum are typically scheduled during afternoon hours; thus, the experiment aimed to capture cognitive performance data during the students' actual period of intensive academic engagement.

Picture 1. An experiment session at Çankaya University Balgat Campus Design Studio

Horizontal daylight illuminance was measured at desk height, and the space was divided into four seating zones based on measured illuminance ranges:

- **K1:** ≥1000 lx (window-adjacent zone)
- **K2:** 301–700 lx (intermediate zone)
- **K3:** 101–300 lx (rear-intermediate zone)
- **K4:** 50–100 lx (deep interior zone)

Daylight illuminance levels were measured at desk height to reflect the visual task plane, following standard lighting assessment practices (IES, 2011; EN 12464-1, 2013). The seating positions were used as categorical representations of daylight exposure, allowing performance comparisons across distinct illuminance zones rather than relying on continuous lux values. This approach supports the identification of non-linear performance patterns across spatial lighting conditions.

2.3 Individual User Characteristics

To capture individual variability in cognitive responses to daylight, the study incorporates gender, visual status, chronotype, and sleep duration as moderating variables. Research has consistently shown that visual perception, circadian alignment, and cognitive readiness differ substantially across individuals, influencing both environmental evaluation and task performance (Chellappa et al., 2011; Smolders, de Kort, & Cluitmans, 2012).

Gender was included due to documented differences in brightness preference, glare tolerance, and stress-related cognitive processing (Boyce et al., 2003; Andreano & Cahill, 2009). Visual status was considered to account for differences in visual acuity and contrast sensitivity, even when corrective devices are used (Sheedy et al., 2003; Wilkins et al., 2011). Chronotype was integrated to reflect circadian preferences that influence alertness and cognitive efficiency throughout the day (Horne & Östberg, 1976; Schmidt et al., 2007). Sleep duration prior to the experiment was included as an indicator of short-term cognitive readiness, given its established relationship with attention and problem-solving performance (Pilcher & Huffcutt, 1996; Killgore, 2010).

Together, these characteristics form a moderating layer within the conceptual framework, enabling the examination of user-dependent and non-linear performance outcomes.

2.4 Cognitive Performance Assessment

Cognitive performance was assessed using Raven's Standard Progressive Matrices (RSPM), a non-verbal test measuring abstract reasoning and visual–spatial problem-solving ability independent of language and cultural background (Raven, Raven, & Court, 2003). RSPM was selected due to its strong reliance on visual processing and logical inference, making it particularly suitable for investigating lighting-related performance effects (Carpenter, Just, & Shell, 1990; Boyce, 2014).

The test consists of five sets (A–E), each representing a progressive increase in cognitive complexity and perceptual demand. Set A involves simple perceptual completion tasks, while subsequent sets require higher-order relational reasoning, visual integration, and abstract rule identification. This graded structure enabled the analysis of performance not only as an overall outcome but also in relation to task complexity, allowing the investigation of whether daylight illuminance interacts differently with cognitive load across performance levels (Carpenter, Just, & Shell, 1990).

Performance was quantified as the percentage of correct responses for each set, allowing both overall performance evaluation and analysis across different complexity levels. This structure supports the investigation of non-linear performance trajectories under varying daylight conditions.

2.5 Experimental Procedure

Participants completed the cognitive assessment individually while seated at one of the predefined seating positions. Prior to the test, participants provided information regarding their gender, visual status, chronotype, and sleep duration through a structured questionnaire.

During the assessment, participants responded to RSPM items under existing daylight conditions without artificial lighting intervention with their own computer. This procedure ensured ecological validity by reflecting real-world educational settings while maintaining controlled comparisons across daylight illuminance level.

2.6 Statistical Analysis

Statistical analyses were conducted to examine the relationships between daylight illuminance conditions, individual user characteristics, and cognitive performance outcomes. One-way Analysis of Variance (ANOVA) was used to evaluate mean differences across seating positions and user groups, with statistical significance interpreted using F values, degrees of freedom (df), and p-values (Field, 2018; Tabachnick & Fidell, 2019).
To assess associations between categorical variables and performance distributions across RSPM sets, Chi-square (χ^2) tests of independence were applied (Agresti, 2013). This combined analytical approach supports the interpretation of performance outcomes as interaction-driven and non-linear, consistent with the study's conceptual framework (Veitch & Newsham, 2000; Boyce, 2014).

3. Findings

The findings of this study provide a comprehensive analysis of the relationship between daylight illuminance levels and cognitive performance within a design studio environment. Instead of evaluating cognitive success as a isolated result of light intensity, the data is interpreted through the lens of individual biological and physiological moderators. The analysis is structured around the five sets of the Raven Standard Progressive Matrices (RSPM) test (Sets A–E), representing an increasing gradient of cognitive complexity.

Statistical evaluations, primarily utilizing Chi-Square tests, examine the interaction between seating positions (K1–K4) and four key user variables: gender, sleep duration, chronotype, and visual status· While many interactions fall within the range of statistical trends rather than absolute significance ($p < 0.05$), the results consistently point toward a non-linear performance model. This section details how different user profiles optimize their cognitive output at varying illuminance thresholds, challenging the efficacy of uniform lighting standards in educational interiors.

3.1. Interaction Between Chronotype and Seating Position

The interaction between participants' chronotypes and their seating positions (illuminance levels) reveals distinct cognitive success patterns. During the experiment conducted between 13:30 and 15:30, the lighting requirements for different chronobiological profiles were found to diverge significantly.

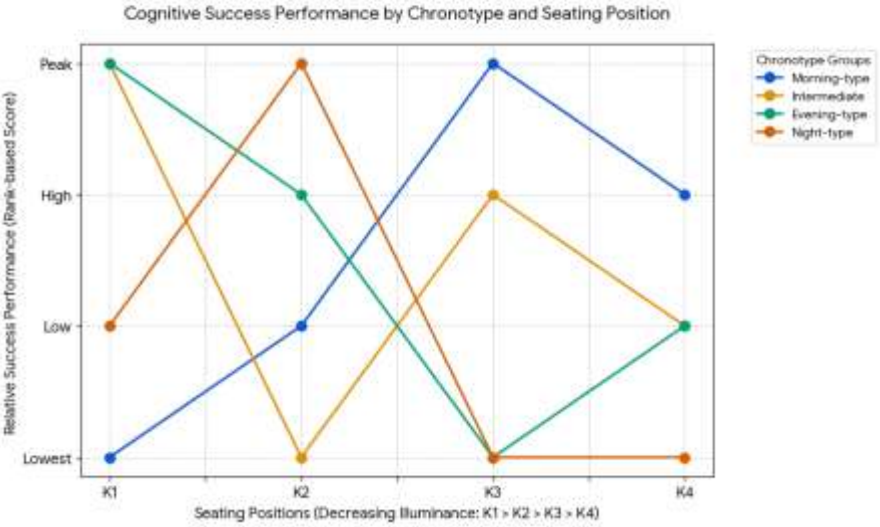

Figure 1. Cognitive Success Performance by Chronotype and Seating Position

Morning-type group reached their peak performance at Position K3 (101-300 lx). Their success rates showed a notable decline as illuminance levels increased toward K1 and K2 (above 300 lx). Intermediate and Evening-type group demonstrated a higher dependency on daylight intensity to maintain cognitive focus during the afternoon. They achieved their highest correct answer percentages at Position K1 (1000 lx and above). The optimal performance for Night-type group was recorded at Position K2 (301-700 lx), while their lowest success occurred in the lower illuminance zones of 50-300 lx (K3 and K4)(Figure 1).

Across all Raven Standard Progressive Matrices (RSPM) sets (A-E), the relationship between chronotype and position did not reach statistical significance at the $p < 0.05$ level (e.g., Set A:\x^{2}: 20.190a, p=0.165). However, these directional performance trends align with the participants' spatial preferences; 46.7% of morning-types preferred K3, whereas intermediate and evening-types predominantly gravitated toward K1. However, these directional performance trends align with the theory that daylight acts as a necessary stimulant for evening-oriented individuals to overcome their biological "circadian dip" during afternoon hours (Walker, 2017).

3.2. Interaction Between Sleep Duration and Seating Position

Sleep duration is recognized as a fundamental biological process essential for maintaining cognitive agility and task accuracy (Alhola & Polo-Kantola, 2007). Sleep plays a vital role in the consolidation of processes essential for academic success, such as attention, memory, and executive functions (Curcio, Ferrara, & De Gennaro, 2006). Furthermore, sleep deprivation is known to significantly impair the prefrontal cortex, which is responsible for higher-order cognitive tasks (Walker, 2017). In the context of this study, the interaction between nightly sleep duration and the chosen seating position (illuminance level) produced distinct performance patterns across all task complexity levelsand cognitive success.

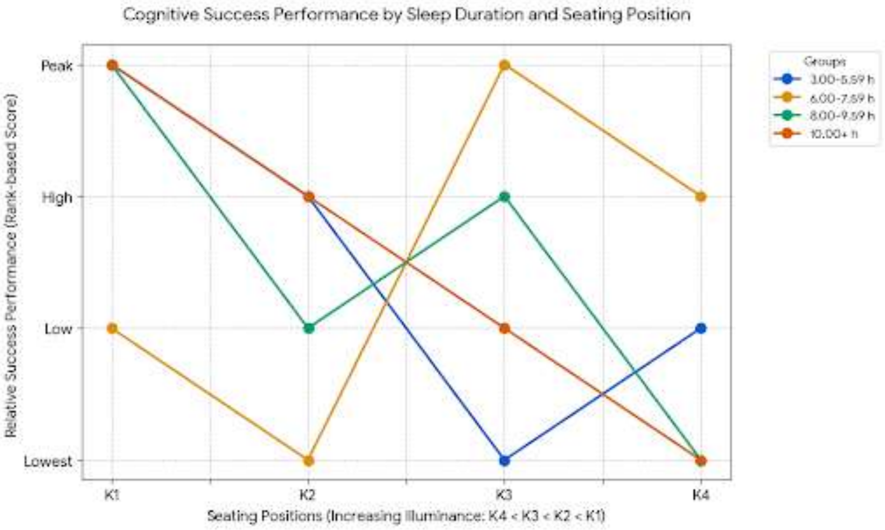

Figure 2. Cognitive Success Performance by Sleep Duration and Seating Position

Participants with the shortest sleep duration(3.00-5.59 h) achieved their peak performance at Position K1 (1000 lx and above). This suggests that high-intensity daylight functions as a powerful external stimulant, helping to counteract the cognitive impairment and fatigue associated with sleep deprivation (Curcio, Ferrara, & De Gennaro, 2006). Ideal Sleep (6.00-7.59 h) group demonstrated a preference for more moderate lighting, reaching their highest success rate at Position K3 (101-300 lx). Their performance showed a notable decline in both the highest (K1) and lowest (K4) illuminance zones. For participants with extended sleep durations (10.00+ h), success rates were highest at Position K1, but followed a strictly decreasing trend as illuminance levels dropped, reaching the lowest point at Position K4 (50-100 lx)(Figure 2).

Although the differences in correct answer percentages are visible, the Chi-Square tests did not yield a statistically significant relationship at the $p < 0.05$ level (e.g., Set E: x^2:40,068a df: 33, Sig: 0,185). Nevertheless, the observed trends confirm that daylight intensity can act as a compensatory mechanism for physiological states (Walker, 2017).

4.5. Interaction Between Gender and Seating Position

This section examines the relationship between the gender of participants and their seating positions (illuminance levels) in terms of cognitive success. The research findings indicate that optimal daylight levels for performance differ significantly between female and male participants.

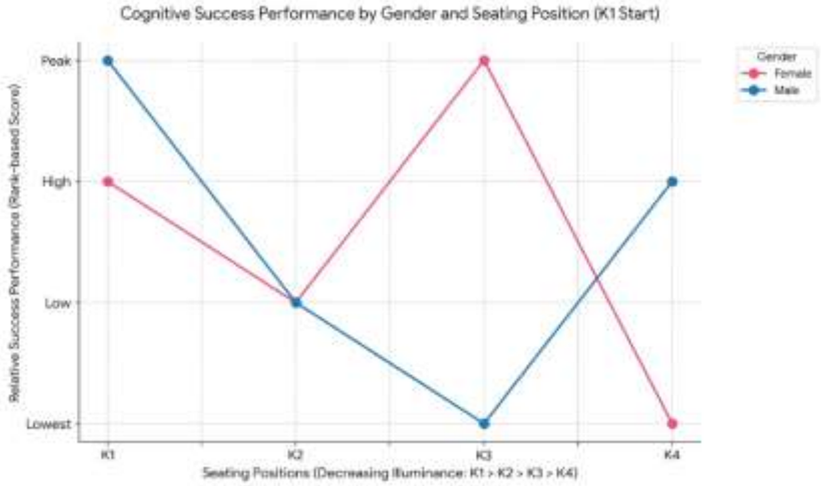

Figure 3. Cognitive Success Performance by Gender and Seating Position

Cognitive performance for males showed a trend directly proportional to light intensity. Male participants reached their highest correct answer percentages at Position K1 (1000 lx and above). The performance ranking was generally observed as K1 > K4 > K2 > K3. In contrast to males, female participants reached their cognitive peak at Position K3 (101-300 lx), which offers moderate-to-low illuminance. For females, the performance ranking was identified as K3 > K1 > K2 > K4, with the lowest success recorded at Position K4, where daylight was at its minimum (Figure 3).

Summary of the Chi-Square test results evaluating the relationship between gender and seating position across five levels of task complexity. While the results for the general group did not reach the standard threshold for statistical significance ($p < 0.05$), $p < 0.10$ denotes marginal significance ($p = 0.074$), particularly observed within the female participant group in Sets A and C.

The elevated Chi-Square value in **Set E** (40.068) indicates a stronger interaction as task difficulty increases, although the high degrees of freedom (df: 33) prevent it from reaching full statistical significance. This table statistically supports the argument that gender-based lighting needs follow non-linear trends rather than a single uniform rule.

4.6. Interaction Between Visual Status and Seating Position

Visual health is a significant factor in how individuals interact with the luminous environment and process cognitive tasks (Boyce, 2014). This section evaluates the relationship between participants' visual status (those with impairments—such as myopia or astigmatism—versus those without) and their performance across different daylight zones.

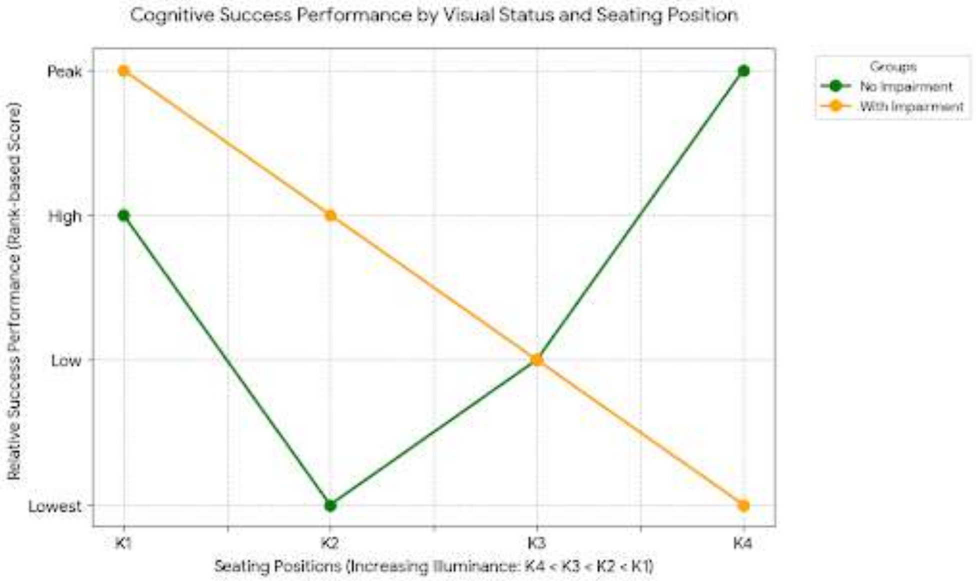

Figure 4. Cognitive Success Performance by Visual Status and Seating Position

Participants with visual impairment group, despite using corrective tools like glasses or contact lenses, consistently achieved their peak performance at Position K1 (1000 lx and above). Their success rates followed a downward trend as illuminance decreased, reaching their lowest point at Position K4 (50-100 lx). In contrast, participants with natural vision reached their cognitive peak at Position K4, where illuminance levels were at their minimum. Their lowest performance was recorded at Position K2 (301-700 lx). Spatial Preference vs. Performance: The data reveals that 29.9% of impaired participants preferred to sit in the high-illuminance K1 zone, while 28.9% of non-impaired participants gravitated toward the lower-light K4 zone (Figure 4).

Although the differences in correct answer percentages across the sets (Sets A-E) did not reach the $p < 0.05$ significance level the inverse success patterns between the two groups are highly relevant for inclusive design.

5. DISCUSSION

This research demonstrates that the impact of daylight illuminance—a critical environmental factor in learning spaces—on cognitive performance does not exhibit a uniform structure due to individual physiological and biological differences. The findings confirm that variables such as sleep duration, chronotype, gender, and visual health act as filters that directly influence how individuals respond to environmental lighting in terms of cognitive output.

Sleep and the Stimulatory Effect of Light:
One of the most significant findings of this study is the compensatory relationship between sleep duration and light intensity. The fact that participants with "Short Sleep" (3.00-5.59 h) achieved their peak performance at Position K1 (1000+ lx) confirms that high-intensity daylight functions as an external stimulant that suppresses cognitive fatigue resulting from sleep deprivation (Curcio et al., 2006). Conversely, the peak performance of individuals with ideal sleep at moderate illuminance levels (K3) suggests that intense light stimulation is not a universal requirement for success and may, in some cases, hinder cognitive efficiency for well-rested individuals. Recent neuroscientific reviews confirm that daylight exposure can mitigate the cognitive deficits of sleep deprivation by modulating alertness through non-visual pathways (Cajochen & Münch, 2023). Conversely, the peak performance of individuals with ideal sleep at Position K3 suggests that intense stimulation is not a universal requirement for success.

Chronotype and Circadian Rhythms:
The performance patterns based on chronotypes were consistent with circadian rhythm theory. During the afternoon sessions, evening-type and intermediate-type participants—whose alertness levels naturally tend to dip at this time—achieved success at Position K1. This indicates that these groups require higher photobiological stimulation to maintain cognitive focus (Lockley & Foster, 2012). Inter-individual sensitivity to light, which emphasize that biological clocks dictate the "optimal dose" of illuminance (Souman et al., 2024)On the other hand, the success of morning-types at lower light levels (K3) suggests that their existing alertness level at this hour is sufficient, and intense light might act as a distractor rather than a facilitator.

Gender and Visual Sensitivity:
Gender-based analysis revealed that female participants reached a steady cognitive peak at Position K3 (101-300 lx), with a marginal significance level ($p < 0.10$) detected in their performance data. This suggests that females may have a more sensitive threshold to spatial lighting variations compared to males. This higher sensitivity to lighting variations in females is a phenomenon increasingly documented in recent field studies, suggesting that gender-specific environmental preferences are crucial for designing equitable learning spaces (Dikel, 2023).In contrast, male participants maximized their performance under high-intensity light (K1), indicating that the linear relationship between light intensity and cognitive alertness is more dominant in males. (Boyce, 2014). In contrast, male participants maximized their performance under high-intensity light (K1).

Visual Health and Spatial Compensation:
Participants with visual impairments reached their peak success at Position K1, despite the use of corrective tools (glasses/lenses). This implies that environmental lighting acts as a compensatory mechanism for physiological deficiencies. High illuminance levels likely enhance contrast sensitivity and reduce the cognitive load associated with visual processing for this group (Boyce, 2014). Conversely, the success of non-impaired

participants at Position K4 suggests that lower light levels may prevent glare and visual fatigue for those with optimal visual health.

6. CONCLUSION AND DESIGN IMPLICATIONS

In summary, the variables examined prove that "one-size-fits-all" lighting strategies are insufficient. As advocated in contemporary design discussions, the future of educational architecture lies in "spatially adaptive" strategies that offer a variety of illuminance zones (Altomonte et al., 2024). In university studios, "differentiated illuminance zones" (K1 to K4) should be provided to allow students to self-regulate their environment based on their unique biological and physiological needs. These results align with the growing paradigm shift in environmental psychology, moving from static task-based lighting towards more dynamic, "human-centric" approaches (Altomonte et al., 2024).

6.1. Theoretical Contributions

The research provides empirical evidence for the "biological compensation" role of daylight. Specifically, the peak performance of sleep-deprived individuals and evening-types under high-intensity light (K1) suggests that daylight can serve as a non-pharmacological tool to mitigate circadian dips and alertness deficits in academic settings. Conversely, the success of well-rested individuals and morning-types at moderate levels (K3) challenges the "more light is always better" paradigm, highlighting that excessive stimulation can lead to cognitive fatigue for certain users.

6.2. Design Implications for Educational Spaces

Based on the synthesized data from all variables, the following design strategies are proposed for university studios and learning environments:
Zonal Illuminance Diversity: Instead of providing uniform lighting across a large studio, designers should create "light gradients." Spaces should offer a range from high-intensity zones (K1: >1000 lx) near windows to moderate (K3: 100-300 lx) and lower-intensity zones (K4: 50-100 lx) toward the interior. This allows students to self-regulate their environment according to their immediate biological state (e.g., sleep status or chronotype).

Support for Biological Diversity: Given that females and morning-types showed higher success at K3, while males and evening-types peaked at K1, studios must avoid fixed seating arrangements. Flexible "activity-based" seating is essential to allow students to choose the lighting zone that aligns with their physiological comfort.

Inclusivity for Visual Health: Since visually impaired students required higher illuminance (K1/K2) to compensate for visual processing effort, lighting design must ensure that high-contrast, bright task areas are accessible to all, rather than being a luxury of specific seating.

Dynamic Lighting Control: If natural daylight is insufficient, artificial lighting systems should be designed as "tunable" or "circadian-responsive," allowing for localized adjustments that mimic the stimulatory effects of K1 during peak fatigue hours (e.g., early afternoon).

REFERENCES

Agresti, A. (2013). *Categorical data analysis*. Wiley.

Alhola, P., & Polo-Kantola, P. (2007). Sleep deprivation: Impact on cognitive performance. *Neuropsychiatric Disease and Treatment*, 3(5), 553–567.

Altomonte, S., et al. (2024). The evolution of visual comfort: From task-based to human-centric lighting. *Applied Ergonomics*, 115, 104185.

Andreano, J. M., & Cahill, L. (2009). Sex influences on the neurobiology of learning and memory. *Learning & Memory*, 16(4), 248–266.

Boyce, P. R. (2014). *Human factors in lighting* (3rd ed.). CRC Press.

Boyce, P. R., Hunter, C., & Howlett, O. (2003). *The benefits of daylight through windows*. Lighting Research Center.

Carpenter, P. A., Just, M. A., & Shell, P. (1990). What one intelligence test measures. *Psychological Review*, 97(3), 404–431.

Cajochen, C., & Münch, M. (2023). Impact of daylight on sleep and cognitive health in the digital age. *Nature Reviews Neuroscience*, 24, 451-464.

Chellappa, S. L., Steiner, R., Blattner, P., Lang, D., Götz, T., & Cajochen, C. (2011). Non-visual effects of light on cognition, alertness and regional cerebral blood flow in humans. *Progress in Brain Research*, 190, 119–133.

Curcio, G., Ferrara, M., & De Gennaro, L. (2006). Sleep loss, learning capacity and academic performance. *Sleep Medicine Reviews*, 10(5), 323–337.

Dikel, E. (2023). The impact of daylight on students' cognitive performance in design studios: A field study. *Journal of Interior Design*, 48(2), 112-128.

EN 12464-1. (2013). *Lighting of work places – Part 1: Indoor work places*. European Committee for Standardization.

Field, A. (2018). *Discovering statistics using IBM SPSS Statistics*. Sage.

Horne, J. A., & Östberg, O. (1976). A self-assessment questionnaire to determine morningness–eveningness in human circadian rhythms. *International Journal of Chronobiology*, 4, 97–110.

IES. (2011). *The lighting handbook: Reference and application*. Illuminating Engineering Society.

Killgore, W. D. S. (2010). Effects of sleep deprivation on cognition. *Progress in Brain Research*, 185, 105–129.

Lockley, S. W., & Foster, R. G. (2012). *Sleep: A very short introduction*. Oxford University Press.

Pallant, J. (2020). *SPSS survival manual: A step by step guide to data analysis using IBM SPSS*. McGraw-Hill.

Pilcher, J. J., & Huffcutt, A. I. (1996). Effects of sleep deprivation on performance: A meta-analysis. *Sleep*, 19(4), 318–326.

Raven, J., Raven, J. C., & Court, J. H. (2003). *Manual for Raven's Progressive Matrices and vocabulary scales*. Harcourt Assessment.

Schmidt, C., Collette, F., Cajochen, C., & Peigneux, P. (2007). A time to think: Circadian rhythms in human cognition. *Chronobiology International*, 24(3), 511–528.

Sheedy, J. E., Hayes, J. N., & Engle, J. (2003). Is all visual discomfort created equal? *Optometry and Vision Science*, 80(6), 429–434.

Smolders, K. C. H. J., de Kort, Y. A. W., & Cluitmans, P. J. M. (2012). A higher illuminance induces alertness even during office hours: Findings on subjective measures, task performance and heart rate measures. *Lighting Research & Technology*, 44(1), 110–123.

Souman, J. L., et al. (2024). Inter-individual differences in the effects of light on non-visual functions: A systematic review. *Current Opinion in Behavioral Sciences*, 55, 101341.

Veitch, J. A., & Newsham, G. R. (2000). Determinants of lighting quality I: State of the art. *Journal of the Illuminating Engineering Society*, 29(1), 1–17.

Walker, M. P. (2017). *Why we sleep: Unlocking the power of sleep and dreams*. Scribner.

Webb, A. R. (2006). Considerations for lighting in the built environment: Non-visual effects of light. *Energy and Buildings*, 38(7), 721–727.

Wilkins, A. J., Veitch, J. A., & Lehman, B. (2011). LED lighting receipts: Flicker, color, and visual stress. *Lighting Research & Technology*, 43(1), 27–41.