Journal of Asian Architecture and Building Engineering

ISSN: 1346-7581 (Print) 1347-2852 (Online) Journal homepage: www.tandfonline.com/journals/tabe20

Unveiling the effect of visual openness on engagement and creativity through electroencephalograms

Ju Eun Cho, Na Hyeon Park & Han Jong Jun

To cite this article: Ju Eun Cho, Na Hyeon Park & Han Jong Jun (2026) Unveiling the effect of visual openness on engagement and creativity through electroencephalograms, Journal of Asian Architecture and Building Engineering, 25:4, 3130-3142, DOI: 10.1080/13467581.2025.2526192

To link to this article: https://doi.org/10.1080/13467581.2025.2526192

Published online: 07 Jul 2025.

JOURNAL OF ASIAN ARCHITECTURE AND BUILDING ENGINEERING
2026, VOL. 25, NO. 4, 3130–3142
https://doi.org/10.1080/13467581.2025.2526192

Taylor & Francis
Taylor & Francis Group

ARCHITECTURAL PLANNING AND DESIGN

Unveiling the effect of visual openness on engagement and creativity through electroencephalograms

Ju Eun Cho, Na Hyeon Park and Han Jong Jun

School of Architecture, Hanyang University, Seoul, Republic of Korea

ABSTRACT
This study aimed to investigate the effect of visual openness on cognitive function, specifically creativity and engagement. This study, grounded in cognitive load theory, involved the collection of real-time electroencephalogram data from participants undertaking engagement and creativity tasks at different levels of blind openness (0%, 25%, 50%, 75%, and 100%). Our multivariate analysis shows that a moderate degree of blind openness (50% and 75%) is positively associated with creativity. Further, the interaction between blind openness and engagement has a positive influence on creativity. This implies that cognitive function may be improved under an optimal level of visual openness. The findings suggest that an optimal level of visual openness in educational and workplace settings may enhance cognitive function and productivity, potentially informing the design of indoor environments. This study contributes to understanding how physical environmental factors, specifically visual openness, influence cognitive performance. Additionally, electroencephalograms provide more objective data compared with traditional self-reported measures.

ARTICLE HISTORY
Received 6 August 2024
Accepted 23 June 2025

KEYWORDS
Creativity; engagement; EEG; cognitive function; office environment

1. Introduction

Cognitive ability, particularly creativity and engagement, is crucial for human performance (Cheng and Furnham 2012). The physical environment has a significant influence on cognitive function, in turn affecting individuals' learning and work-related performance (Wang et al. 2021). Creativity and engagement are essential for decision-making, problem-solving, and generating new ideas, directly influencing organizational performance (Shi and Qu 2021). While numerous researchers have investigated the effect of the physical environment on cognitive function (Karol and Smith 2019), the findings have been mixed (Choi, van Merriënboer, and Paas 2014). One physical environmental factor is visual openness (e.g., the level of natural light and views of landscapes), which is highly correlated with cognitive function (Goldschmidt and Smolkov 2006; Tabbers, Martens, and van Merriënboer 2004). Scholars are increasingly acknowledging the importance of optimizing the indoor physical environment to improve cognitive function and productivity (Wang et al. 2021).

In this study, visual openness is defined as the extent to which indoor spaces connect with the outdoors through windows, encompassing the amount of natural light, external views, and the perceived degree of openness formed by windows. This concept integrates various visual and psychological elements, such as brightness and spatial perception, that directly influence users' cognitive functions. Thus, given the importance of creativity and engagement, optimizing the physical environment is crucial in educational and workplace settings (Moraru and Popa 2019; Rozi and Yahya 2023).

The study aimed to analyze the effect of blind openness on creativity and engagement. Thus, we aim to answer the following research question: *Is the level of visual openness associated with creativity and engagement?* To answer this question, we posit the following two hypotheses:

> **H1**. EEG-based measures can provide immediate and objective insights into cognitive changes caused by varying levels of visual openness, offering a higher degree of precision and timeliness compared with subjective assessments.

> **H2**. When examining the relationship between visual openness and creativity, considering engagement as a mediating factor may clarify this relationship. Specifically, higher engagement levels may amplify the positive effects of visual openness on creativity.

The remainder of this paper is organized as follows. Section 2 reviews the literature on creativity and engagement, cognitive load theory (CLT), and the use of EEGs to measure cognitive function. Section 3 presents the research design and methodology. Section 4

CONTACT Han Jong Jun hanjong@hanyang.ac.kr School of Architecture, Hanyang University, 407, (No. 203) Engineering Science and Technology Building, Seongdong-gu, Seoul 04763, Republic of Korea

presents the results. Section 5 discusses the findings and presents the theoretical and practical implications. Section 6 concludes the paper and makes recommendations for future research.

2. Literature review

2.1. Creativity and engagement

Creativity and engagement are important aspects of cognitive function, influencing how individuals interact with their environment and perform various tasks (Burmeister, Moskaliuk, and Cress 2018; Pera 2013). Creativity refers to the ability to formulate original ideas, examine problems from multiple perspectives and identify novel solutions, and it promotes collaboration and the exchange of ideas (Abraham and Windmann 2007; Adeoye and Jimoh 2023; Davies et al. 2013; Dul and Ceylan 2011). Engagement is the ability to focus on a task or activity and is crucial for learning, retention, task efficiency, and productivity (Dalimunthe and Chondro 2022; Hastari et al. 2020; Yesavage and Rose 1983).

Both creativity and engagement are critical for individual and organizational success (Mumford et al. 2002; Silva 1979) because they enable individuals and organizations to solve complex problems and find innovative solutions (Sari and Manoy 2022; Yamnenko 2021). Research shows that modifications to the physical environment can significantly influence cognitive function (Springer 2022; Wang et al. 2021). For example, indoor environmental quality (i.e., thermal, air, visual, and acoustic quality) (Park, Loftness, and Aziz 2018; Xu et al. 2022) directly affects occupants' cognitive performance and work efficiency (Yang and Mak 2020).

The presence of windows may enhance cognitive function by increasing natural light and providing a connection to the outdoors. Using a visual analog scale and a mood checklist, Kaida et al. (2006) found that natural light improves cognitive function. Based on the findings of a questionnaire, Tennessen and Cimprich (1995) demonstrated that windows with nature views foster creative thinking and a sense of psychological security. Similarly, Moscoso et al. (2021) used a questionnaire to explore the effect of window size on users' spatial perception and visual satisfaction, finding that window size was rated higher in larger spaces than in smaller spaces. Ko et al. (2020) surveyed participants on their responses to spaces with windows, which were found to improve working memory, engagement, and satisfaction compared with spaces without windows. While these studies offer valuable insights into the relationship between visual openness and cognitive function, they are based on subjective self-reports rather than real-time physiological data, potentially affecting the reliability of findings. In contrast, Mihara, Hasama, and Takasuna (2022) examined both psychological and physiological responses to window views using questionnaires and measures of heart rate, skin temperature, skin conductance, and brain waves. Window views were associated with lower stress levels compared with closed blinds. These results indicate that visual openness may improve occupants' satisfaction and cognitive function.

We used EEGs to objectively capture brain activity in real time to complement previous subjective measures such as self-reporting and biometric surveys. Further, we employed multiple correlations to analyze the data and generate objective results.

2.2. Research gap

Previous studies on cognitive function have employed cognitive function tests, self-reported measures of mental effort, behavioral measures, and task performance measures Bethel et al. (2007); Tabbers, Martens, and van Merriënboer (2004). Although these methods can record objective metrics such as reaction time and accuracy, they are susceptible to significant variability owing to subjective factors like emotional states and fatigue. For example, in the Stroop Test, identical reaction times may mask underlying differences in cognitive load or psychological engagement among individuals, making it challenging to determine the reasons behind specific responses based on numerical data alone.

Moreover, prior research exploring the effects of visual openness on cognitive function has often relied on self-reported data or behavioral observations, failing to capture real-time brain responses. Studies that objectively and dynamically measure the interaction between visual openness and cognitive functions such as creativity and engagement remain relatively scarce. Addressing this research gap requires an approach that quantifies brain responses, such as Electroencephalography (EEG), to track and analyze cognitive changes in real time as levels of visual openness vary.

Recent advancements in virtual reality (VR) environments have enabled researchers to control variables such as window views and field of vision while simultaneously measuring objective physiological indicators, including heart rate and skin conductance, to assess the psychological and cognitive impacts of indoor environments (Abd-Alhamid et al. 2020).

Electroencephalograms (EEGs) can be used to measure the electrical activity of the brain in real time, enabling a more accurate analysis of the relationship between the physical environment and cognitive function (Gevins and Smith 2003; Jin and Kim 2020). Therefore, we use EEGs to analyze the effect of visual openness on engagement and creativity. The findings of this study may be used to inform the design environments in which engagement and creativity are important, including workplace and educational settings.

2.3. Cognitive load theory

Developed by John Sweller (1988), CLT explains the effect of information processing demands on learner outcomes. Sweller (1988) argued that complex problems exert a high cognitive load, reducing learning efficiency. CLT emphasizes the use of learning strategies and instructional materials that optimize working memory (Paas, Renkl, and Sweller 2003). Additionally, the physical environment may significantly influence cognitive load, affecting learners' engagement and creativity (Paas and Ayres 2014). Optimizing the physical environment has been shown to trigger positive emotions, reduce cognitive load, and improve learning outcomes (Choi, van Merriënboer, and Paas 2014). Table 1 outlines the three main types of cognitive load.

The present study examines the effect of visual openness on cognitive function, specifically engagement and creativity. It aims to identify environmental factors that may optimize cognitive function and, thus, individual and organizational growth.

2.4. Use of electroencephalograms to measure cognitive function

Through scalp electrodes, an EEG can be used to record the real-time electrical activity of the brain, thus is a valuable tool for examining the effect of the physical environment on cognitive processes such as attention, memory, and problem-solving (Fink and Benedek 2014; Harmony et al. 2004; Millett 2001). Previous research on the relationship between the environment and cognitive function has mainly been based on subjective measures or conducted in natural settings with fluctuating variables. For example, Schertz and Berman (2019) found that exposure to natural stimuli improves working memory, while Sudimac, Sale, and Kühn (2022) found that walking in natural environments lowers amygdala activity more so than walking in urban environments. However, natural environments can fluctuate because of weather factors and the time of day. Smolders and de Kort (2014) found that bright light reduces fatigue and improves engagement. In contrast, Leichtfried et al. (2015) found that although bright light improves mood and alertness, it reduces sustained attention. These studies have mostly been based on simple biometric data, cognitive tests, and surveys. Because individuals experience stimuli differently, the use of simple surveys and tests could lead to inaccurate generalizations.

Given the mixed results from previous subjective measures, we used objective EEG data to analyze the effect of the physical environment on cognitive function. Various EEG metrics can be used to examine cognitive function, enhancing the reliability and accuracy of results (Ismail, Karwowski, and Mumtaz 2020). For example, Holm et al. (2009) employed the theta Fz/alpha Pz ratio to evaluate the workload – cognitive load relationship, while Nishizawa et al. (2021) utilized the beta/theta + alpha ratio to assess engagement and cognitive decline. Formulating and assessing the index by each researcher is based on the specific intent of their research. We estimated a composite creativity index and an engagement index based on real-time EEG data to objectively identify the effect of the physical environment on cognitive function.

3. Materials and methods

3.1. Experimental setup

The primary visual stimulus in this study was the amount of visual openness, which reflects visual openness. This variable was manipulated by opening window blinds to five different levels: 0%, 25%, 50%, 75%, and 100% (see Table 2). As the degree of visual openness increased, external landscapes became more visible, and the intensity of natural light entering the room also increased. The experiment was conducted in a 5.0 m × 5.0 m × 2.6 m comfortable single-person office setting, with one wall featuring a 4.7 m × 2.4 m window overlooking an urban cityscape. Participants performed tasks while seated at a workstation facing the window (see Figure 1). Lighting was adjusted according to the amount of natural light to complement visual openness, ensuring diverse environmental conditions. This was introduced to account for cognitive

Table 1. Types of cognitive load.

Cognitive load type	Definition [a]	Application to our study
Intrinsic cognitive load	Inherent complexity of the learning materials and task; varies according to content and learner knowledge.	Optimize study design by considering participants' background knowledge.
Extraneous cognitive load	Unnecessary load determined by how information is presented (i.e., the design of instructional materials).	Minimize unnecessary cognitive load through optimal blind openness and lighting settings.
Germane cognitive load	Contributes to schema formation and automation, enhancing learning.	Create environments that enhance creativity and engagement through optimal openness conditions.

[a]Sourced from Sweller (2010).

Table 2. Degree of blind opening and corresponding conditions.

Degree of opening	Description	Experimental conditions in VR
0% open	Blinds fully closed, no natural light, only artificial lighting.	
25% open	Blinds slightly open, limited natural light, partial external view.	
50% open	Blinds half open, moderate natural light, clear external view.	
75% open	Blinds mostly open, abundant natural light, wide external view.	
100% open	Blinds fully open, maximum natural light, complete external view.	

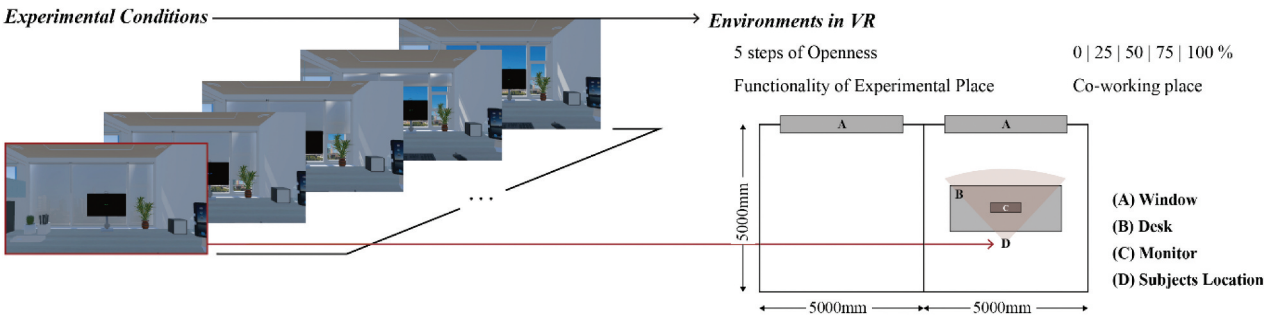


Figure 1. Experimental setup.

responses that could not be fully explained by visual openness alone in previous studies.

The study involved eight adult participants (two males and six females) with an average age of 24.1 years (SD = ± 2.14). All participants were neurologically and psychiatrically healthy and confirmed to have normal color vision through the Ishihara color vision test (Birch 1997). Participants were also instructed to control for potential confounding variables, including sleep, caffeine, and alcohol. All participants were required to sign an informed consent form.

The experiment was conducted in a VR coworking space constructed using the Unity software platform. Participants wore Oculus VR headsets.

The decision to use a VR environment stemmed from the challenges of controlling variables such as natural light, weather, external noise, and time of day in a physical setting. VR technology allows precise manipulation of critical factors, including lighting, color temperature, external views, and blind openness, making it particularly advantageous for repeated measurements under identical conditions. Additionally, VR experiments have been reported to provide levels of immersion and learning motivation comparable to or even superior to those of physical environments (Parong and Mayer 2018). VR also offers advantages in terms of safety and reproducibility.

Similarly, Abd-Alhamid et al. (2020) demonstrated the utility of VR in systematically controlling window views and observation positions. Using Stroop tests and physiological signals, they quantitatively measured the cognitive and emotional impacts of window views, highlighting VR's suitability for fixing environmental variables and conducting repeated experiments with dynamic elements such as field of view and window size.

In this study, these advantages were leveraged to simulate an urban landscape visible through a VR-rendered window. This approach enabled controlled and repeated measurements of how "visual openness" affects brain activity and cognitive function. By uniformly controlling dynamic factors such as daylight and visual discomfort, the study focused on quantifying the holistic experience of openness associated with different blind openness levels. While VR does differ from actual daylit settings, its ability to control variables such as time of day and weather enhances the validity of the experimental design. Future studies could build on this by incorporating more diverse real-world window conditions, such as skylights or windows facing walls, to further strengthen ecological validity.

VR blinds were opened to various levels in a randomized order to prevent bias. Participants sat in a booth enclosed by aluminum film on five sides to minimize noise and interference (see Figure 2).

EEG data were collected using the Enobio 32-channel system (Neuroelectrics, Barcelona), which adheres to the internationally standardized 10–20 system for electrode placement. The 32 channels included electrodes covering the frontal (Fp1, Fp2, F3, F4, Fz), central (C3, C4, Cz), parietal (P3, P4, Pz), temporal (T7, T8), and occipital (O1, O2) regions, enabling data collection from a wide range of brain areas. All EEG signals were recorded using bilateral mastoids (A1, A2) as reference electrodes to minimize noise and ensure stable data acquisition. The data were sampled at 500 Hz, and the Enobio system provides a 24-bit dynamic range (0.05 µV) and a bandwidth of 0 to 125 Hz (Neuroelectrics 2024). Its wireless data transmission technology also ensures a data loss rate of less than 0.01%, guaranteeing high data accuracy and reliability.

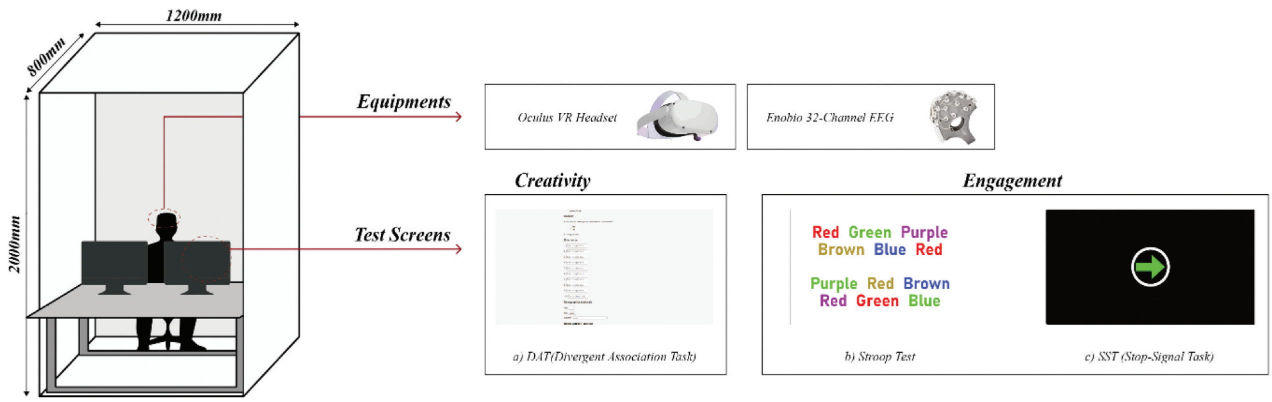


Figure 2. Experimental environment and equipment.

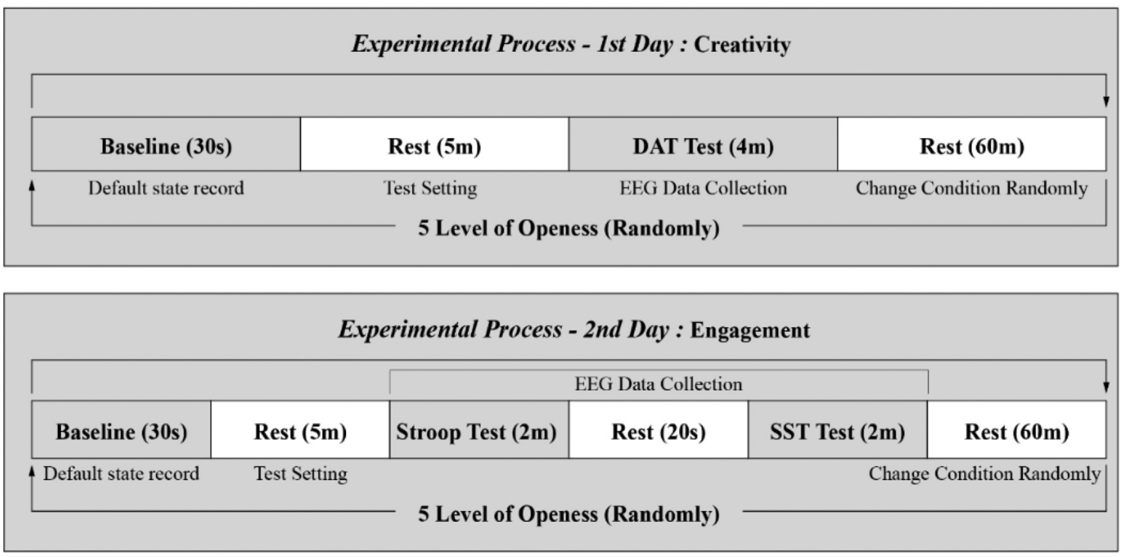


Figure 3. Study procedure. DAT: Divergent Association Test; SST: Stop Signal Task.

3.2. Study procedure

Figure 3 shows the study procedure, which was conducted over 2 days, with different cognitive tests applied each day. On the first day, creativity was assessed using the Divergent Association Task (DAT). On the second day, attention and executive control were evaluated using the Stroop Test and the Stop Signal Task (SST).

On Day 1, the DAT was implemented to measure creative thinking and associative ability. Participants were instructed to generate ten unrelated words within a time limit. For example, the researcher provided a sample word such as "car" and instructed participants to list ten words they perceived as entirely unrelated to the provided word. Alternatively, participants were allowed to generate ten words of their choice, ensuring the associations between the words were as minimal as possible (e.g., low association scores). The DAT was conducted for 4 minutes per condition across five blind openness levels (0%, 25%, 50%, 75%, and 100%). EEG signals were recorded in real time during this task, and the word generation process was monitored. In the post-experimental analysis, the degree of association between generated words was evaluated quantitatively to assess creativity.

On Day 2, the Stroop Test and SST were conducted sequentially to evaluate participants' attention and inhibitory control. The Stroop Test measured participants' ability to respond quickly and accurately when the word meaning and font color were incongruent. This test was conducted for 2 minutes, using four colors (red, blue, green, and yellow) to construct stimuli. Each block lasted approximately 30 seconds to 1 minute, with a fixed number of stimuli presented per block. The proportion of incongruent stimuli was set to 50% to maintain sustained attention. Participants were instructed to respond based on the font color, not the word's meaning. During this test, reaction time, accuracy, and EEG synchronization signals were collected.

The SST assessed participants' inhibitory control and executive function through 60 trials. In each trial, participants were instructed to respond quickly to stimuli, but a "Stop Signal" would randomly appear in approximately 25% of trials, requiring participants to immediately inhibit their initiated response. The SST differentiated between successful and failed inhibitions, and reaction times were synchronized with EEG data for further analysis.

Before the start of each session (e.g., DAT at 0% blind openness), baseline EEG was recorded for 30 seconds to capture resting-state brain activity. A 5-minute rest period was provided between conditions to minimize fatigue. This process was repeated across all five blind openness levels. A 60-minute extended break was included during certain intervals to mitigate excessive mental fatigue when transitioning between conditions. Previous research on EEG experiments and VR use shows that prolonged exposure can lead to visual fatigue and motion sickness, reducing measurement accuracy. Thus, a 60-minute break was implemented to ensure sufficient recovery, though future studies may consider reducing it to 30 minutes depending on feasibility.

This two-day experimental procedure allowed participants to directly experience various blind openness conditions in a VR environment that closely mimicked real-world settings. The study ensured reproducibility by standardizing the task protocols (e.g., time limits, trial counts, and stimulus configurations). Dividing the tasks into Day 1 and Day 2 minimized participant fatigue, enabling a more precise evaluation of creativity and attention. The collected EEG data and task performance records provide a robust foundation for multidimensional analysis of changes in creativity and engagement across varying levels of visual openness.

3.3. Data collection and preprocessing

Data were obtained and recorded using a Neuroelectrics Enobio 32 EEG headset. EEGs were monitored in real time via the Enobio 32 software. The data were preprocessed using the following steps:

First, high- and low-frequency filters were applied to reduce interference from electrical noise and artifacts, thereby enhancing the overall signal quality. Specifically, bandpass filtering was conducted within the 1–30 Hz range to isolate the frequencies most relevant to cognitive processes and minimize the impact of irrelevant signals.

Second, independent component analysis (ICA) was used to eliminate artifacts caused by blinking and muscle movements, which could otherwise compromise data accuracy. The ICA algorithm, implemented using the EEGLAB toolbox, automatically identified components corresponding to these artifacts. Following automatic detection, visual inspection was conducted to confirm and remove any remaining blink or muscle-induced artifacts, ensuring the reliability of the preprocessed data.

Third, signals from the occipital lobe were excluded to align the data with the study's primary focus on engagement and creativity. Although all 32 channels of the EEG system were initially recorded, occipital signals were removed during preprocessing. These signals are known to primarily reflect visual suppression processes (Worden et al. 2000), which were not directly related to the study's objectives. By eliminating these signals, the analysis was refined to focus on the neural activities most relevant to the cognitive responses elicited by varying levels of visual openness.

Fourth, EEG data were normalized according to each participant's baseline condition. We then applied a fast Fourier transform to the preprocessed data to transform the signals from the time domain to the frequency domain. This is a fundamental step in EEG because it enables the examination of neural activity fluctuations by frequency over time. This enabled us to analyze participants' cognitive activities at different levels of blind openness. We calculated the power of each frequency band for the subsequent metric calculations.

3.4. Calculation and analysis of indicators

We used the preprocessed EEG data to calculate the following indices. First, we assessed participant creativity using the creative alpha index, which measures the increase in alpha wave (8–13 Hz) activity. Alpha waves are associated with relaxation and creative thinking (Lustenberger et al. 2015). CAI (Creative Alpha Index) is calculated by dividing the alpha power during the creative task by the baseline alpha power (Mateos et al. 2022). The creative alpha index is calculated as follows:

$$CAI = \frac{Alpha\ Power\ during\ Creativity\ Task}{Baseline\ Alpha\ Power}$$

Next, we assessed creative thinking using the creative theta index, which measures the increase in theta wave (4–8 Hz) activity. Theta waves are associated with deep relaxation, internal engagement, and memory formation. CTI (Creative Theta Index) is calculated by dividing the theta power during the creative task by the baseline theta power (Mateos et al. 2022). The CTI is calculated as follows:

$$CTI = \frac{Theta\ Power\ during\ Creativity\ Task}{Baseline\ Theta\ Power}$$

Alpha waves are primarily associated with relaxation, focus, and memory formation, while theta waves are associated with deep engagement and inner thought processes. Therefore, integrating the creative alpha and creative theta indices offers a more comprehensive assessment of creativity (Stevens and Zabelina 2019). Thus, we summed the scores of the creative alpha and creative theta indices to create a composite creativity index:

$$CCI = CAI + CTI$$

Second, we assessed participant engagement using an engagement index, which calculates the ratio of beta waves (13–30 Hz) to alpha waves (8–13 Hz) (MacLean, Arnell, and Cote 2012). Beta waves are associated with elevated cognitive activity and attention, while alpha waves are associated with relaxation. The engagement index was calculated as follows:

$$EI = \frac{Beta\ Power}{Alpha\ Power},$$

where a higher EI value indicates higher engagement. This engagement index has been used in several studies. For example, Nuamah and Seong (2018) used it to assess attention and cognitive load during cognitive tasks. The index offers the advantage of being able to monitor attention during task performance (Allen, Coan, and Nazarian 2004).

Table 3 shows each type of brain wave and its associated frequencies and cognitive functions.

4. Results

This chapter evaluates the effect of blind openness on participants' engagement and creativity through a two-step analytical procedure. First, a multivariate analysis of variance (MANOVA) was performed to analyze the comprehensive impact of blind openness conditions on the two cognitive outcomes. Second, regression analysis, including interaction terms, was conducted to further examine the specific interaction effects of blind openness and engagement on creativity. Creativity (measured through DAT) was assessed on Day 1, and engagement (measured through Stroop and SST) on Day 2. The experimental design ensured that the same blind openness conditions were randomly applied, allowing the two tests to be conducted independently. This approach ensured validity and consistency in comparing and analyzing the results across conditions.

4.1. Effect of visual openness on engagement and creativity

The MANOVA results demonstrated that blind openness had a statistically significant overall effect on engagement and creativity (Wilks' Lambda = 0.116, $F = 296.17$, $p < 0.001$). This indicates that variations in blind openness influence both engagement and creativity simultaneously and that these two dependent

Table 3. Electroencephalogram waves, frequencies, and roles.

Brain wave	Range (Hz)	Cognitive functions
Alpha waves	8–13	Relaxation and creative thinking
Beta waves	13–30	Engagement and active thinking
Theta waves	4–8	Drowsiness and creativity
Gamma waves	30 +	Higher cognitive processes, complex problem-solving, and deep focus

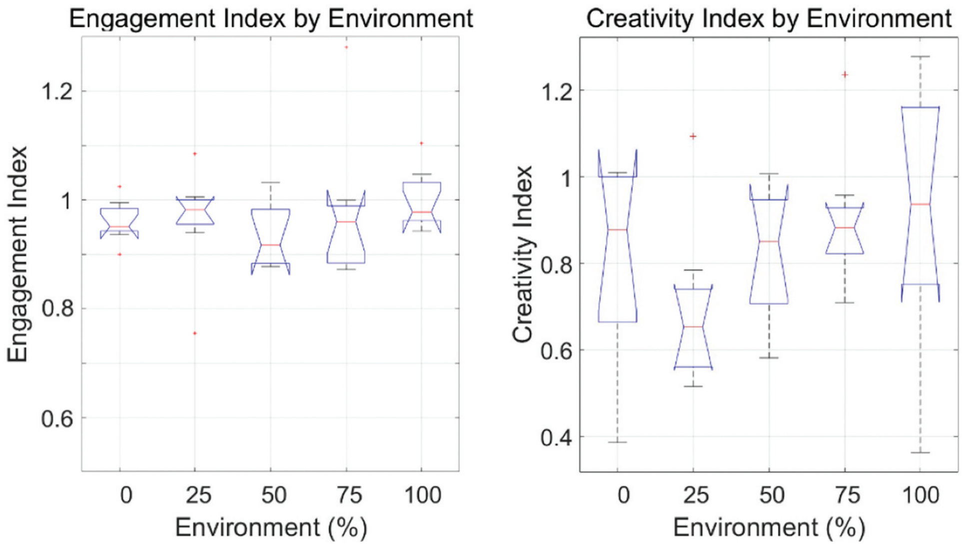


Figure 4. Box plot of engagement and creativity by blind openness level. 1) The y-axis is scaled starting from 0.5 to better visualize differences in the data. 2) Each box represents the interquartile range, with the center line representing the median value and the whiskers representing the minimum and maximum values. 3) The red plus signs indicate outliers, which are not shown when they exceed 1.5 times the interquartile range.

variables, when analyzed as a single vector, show statistically significant changes.

The distributions of engagement (left) and creativity (right) indices for each blind openness condition are visualized in box plots (see Figure 4). Creativity was observed to be higher at moderate (50%, 75%) and high (100%) levels of blind openness, with 50% openness exhibiting the highest creativity scores and the smallest interquartile range (IQR), suggesting it is favorable for stable creative performance. In contrast, a blind openness level of 25% resulted in the lowest creativity scores, indicating a less favorable environment for creative output.

These findings highlight the critical role of moderate blind openness in enhancing creativity. Furthermore, the MANOVA results, which confirmed the statistically significant joint influence of blind openness on both engagement and creativity, support the notion that visual openness has a multifaceted impact on cognitive function. Environments that provide optimal visual stimuli and openness can significantly enhance creativity, potentially improving productivity and workplace efficiency.

4.2. *Interaction between engagement and creativity*

In Section 4.1, MANOVA results confirmed that the level of blind openness (independent variable) significantly affects engagement and creativity (dependent variables). To further explore the interaction effect of engagement and blind openness on creativity, we conducted a supplementary regression analysis, including an interaction term (Engagement × Environment). This mixed approach of combining MANOVA (group differences) and regression analysis (interaction effects) ensures a more comprehensive interpretation, clarifying that the conclusions are not based solely on simple regression analysis.

Figure 5 illustrates the effect of engagement on creativity at different blind openness levels. In the contour plot, the x-axis represents the engagement index (ranging approximately from − 2 to + 1.5), the y-axis represents the blind openness level (0 ~ 100%), and the color represents creativity. In the line plot, each line represents a different degree of blind openness.

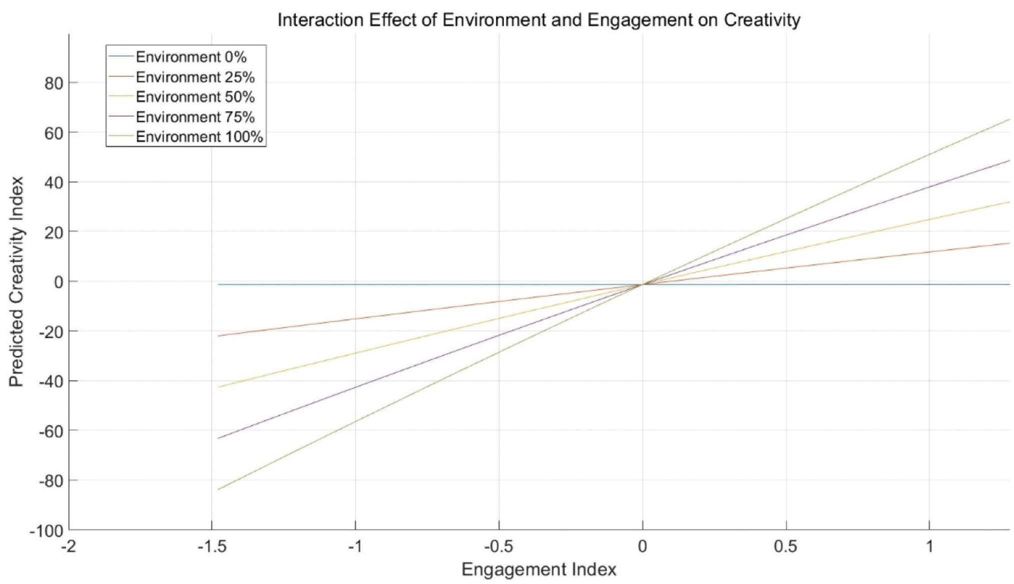
The findings show that as visual openness increases, the influence of engagement on creativity significantly increases (see Table 4).

5. Discussion

The results of this study indicate that a moderate level of light (approximately 50% blind openness) is most conducive to creativity. Figure 4 clearly shows that moderate blind openness levels (50% and 75%) are the most favorable for enhancing creativity. Specifically, the creativity index was highest and most stable at the 50% openness condition. While the 75% openness condition demonstrated similar levels of creativity, it exhibited slightly more variability. In contrast, conditions with low visual openness (0–25%) or excessive openness (>75%) resulted in lower creativity indices or greater variability.

These findings are consistent with the MANOVA analysis presented in Section 4.1, which demonstrated that blind openness significantly affects creativity and

(a) Contour plot



(b) Line plot

Figure 5. Interaction effect of environment and engagement on creativity.

Table 4. Effect of engagement on creativity at different blind openness levels.

Blind openness level	Outcome
0%	Engagement has no effect on creativity
25%	Engagement has a slight positive effect on creativity
50%	Engagement has a moderate positive effect on creativity
75%	Engagement has a considerable positive effect on creativity
100%	Engagement has the highest positive effect on creativity

engagement. Conversely, low visual openness (0–25%) or excessive visual openness (>75%) may not be favorable for creativity. High levels of visual openness may be distracting and impede creative thinking, whereas low levels of visual openness may lead to low visibility, impeding creativity.

5.1. Theoretical implications

This study has several theoretical implications. First, our finding that moderate levels of visual openness enhance creativity supports CLT, which emphasizes the importance of an optimal learning environment for learners to process new information effectively. Therefore, moderate visual openness may be the optimal visual stimulus to facilitate creative thinking and problem-solving.

Our finding that the level of visual openness has no significant effect on engagement aligns with the findings of Paas, Renkl, and Sweller (2003), who argue that reducing extraneous cognitive load and optimizing intrinsic cognitive load is crucial for learning effectiveness. However, engagement may be influenced by other factors such as noise, temperature, and lighting.

The interaction effect of visual openness and engagement on creativity may also be interpreted according to CLT. A moderate level of blind openness (50%) was shown to facilitate creative thinking by providing a proper cognitive load. This is related to intrinsic cognitive load in CLT, which refers to the inherent difficulty of the information a learner must process. Extraneous cognitive load refers to the unnecessary information a learner must process, which may impede engagement and creative thinking. Excessive visual openness (i.e., a blind opening of > 75%) may represent an extraneous cognitive load, thus inhibiting creative thinking through distraction. Conversely, low visual openness (i.e., a blind opening of 0–25%) may be insufficient for creative thinking because of low intrinsic cognitive load. A lack of adequate stimulation may impede the ability of learners to obtain sufficient information to engage in creative thinking.

5.2. Practical implications

The VR environment employed in this study offered significant advantages by effectively controlling various variables, such as daylight, external noise, and visual discomfort, which fluctuate depending on climate and time of day. This level of control enhanced the precision and reproducibility of the experiment, enabling consistent data collection across diverse conditions. However, in real-world scenarios, such as skylights or windows facing blank walls, the lack of external connectivity might limit the perception of "visual openness." Future research should address this limitation by incorporating various real-world window types and external conditions into experimental designs, thereby facilitating the direct application of findings to real-life environments.

The findings of this study provide critical insights for designing workspaces and educational settings. It is particularly recommended to implement adjustable window designs that offer a moderate level of visual openness, approximately 50–75%, as this can provide optimal visual stimuli to enhance both creativity and engagement. However, shades are not solely for securing views; they also serve multiple purposes, such as glare protection, thermal comfort, and privacy. Architects and designers should, therefore, focus on creating customized or adaptive shading systems that meet these multifaceted requirements.

Given the variability in individual responses, personalized workspace design is also beneficial. Allowing users to adjust their environment to match their optimal cognitive load can improve both creativity and engagement. This principle applies not only to workspaces but also to educational settings. For example, moderate window openness can provide appropriate visual stimulation during learning, improving academic performance. According to Sweller (1988), learners achieve better outcomes in environments that provide appropriate cognitive loads. Additionally, a comprehensive approach that considers other physical factors, such as noise, lighting, and temperature, is essential for designing environments that effectively enhance creativity and engagement.

6. Conclusion

This study examined the effect of natural light levels on engagement and creativity by analyzing EEG data. The findings indicate that moderate natural light (i.e., a blind opening of 50%–75%) significantly enhances creativity but not engagement. However, multivariate analysis suggests that natural light positively correlates with engagement and creativity. This suggests that natural light affects cognitive function overall. Additionally, we observed that engagement led to increased creativity at a moderate level of natural light (50%). These results illustrate the difference between subjective and objective assessments of cognitive function. This supports H1, indicating that EEG was effectively utilized to observe the cognitive changes induced by visual openness in real time. EEG-based indices complemented subjective reporting methods by addressing potential biases and accurately capturing brainwave changes associated with variations in lighting conditions.

While subjective analyses can lead to inconsistent findings, the use of EEG data enabled a more objective and accurate analysis of the effect of the physical environment on cognitive function. By measuring brain activity in real time, we demonstrated the relationship between natural light level and cognitive function. Specifically, we found that a 50% blind opening provides the optimal cognitive load for creative thinking. Additionally, as proposed in H2, the findings suggest that engagement should be considered when examining the relationship between visual openness and creativity. Specifically, under moderate blind openness conditions, an increase in engagement was observed to lead to a more pronounced enhancement in creativity. This highlights the potential interaction pathway: "Visual openness → Engagement → Creativity."

This study has some limitations. First, the small, homogeneous sample size limits the generalizability of findings. Additionally, VR environments may not fully stimulate the complexity of real-world environments, potentially influencing the results. Future studies should extend this research by incorporating diverse window typologies, including wall-facing windows, skylights, and various external conditions. Such expansion would enhance the ecological validity of the findings and facilitate more direct applications to real architectural environments. Nevertheless, this study offers a novel and objective approach to understanding the effect of natural light on cognitive function.

Despite its limitations, this study empirically supports the effect of the physical environment on cognitive function and demonstrates the value of EEG in this type of research. The findings may inform future research and the design of work and learning environments to facilitate creativity and cognitive performance. Future researchers could investigate the long-term effects of natural light levels on cognitive function and explore the effect of other environmental factors, such as temperature and noise. This study implemented measures to minimize the effects of simulation sickness, such as extended rest periods and baseline EEG recordings between sessions. However, simulation sickness, which may influence participant performance and data quality in VR-based experiments, was not explicitly evaluated. Future studies should incorporate systematic assessments of simulation sickness to better understand its impact and develop strategies to mitigate its effects. Moreover, adaptable environments based on real-time EEG feedback could be developed to gain deeper insights into how environmental factors affect cognition over time. These results may be beneficial for both individuals and organizations.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

This research was funded by the National Research Foundation of Korea (NRF) grant funded by the Korean government (MSIT) [No. NRF 2022R1A2C3011796].

ORCID

Ju Eun Cho http://orcid.org/0009-0005-3884-0843
Na Hyeon Park http://orcid.org/0009-0003-3272-8338
Han Jong Jun http://orcid.org/0000-0003-1798-183X

Data availability statement

Participants gave their informed consent before participating in the study. The study was approved by the Hanyang University ethics committee (HYUIRB-202407-023).

References

Abd-Alhamid, F., M. Kent, J. Calautit, and Y. Wu. 2020. "Evaluating the impact of viewing location on view perception using a virtual environment." *Building and Environment* 180:106932. https://doi.org/10.1016/j.buildenv.2020.106932.

Abraham, A., and S. Windmann. 2007. "Creative cognition: The diverse operations and the prospect of applying a cognitive neuroscience perspective." *Methods* 42 (1): 38–48. https://doi.org/10.1016/j.ymeth.2006.12.007.

Adeoye, M. A., and H. A. Jimoh. 2023. "Problem-solving skills among 21st-century learners toward creativity and innovation Ideas." *Thinking Skills and Creativity Journal* 6 (1): 52–58. https://doi.org/10.23887/tscj.v6i1.62708.

Allen, J. J. B., J. A. Coan, and M. Nazarian. 2004. "Issues and assumptions on the road from Raw signals to metrics of frontal EEG asymmetry in emotion." *Biological Psychology* 67 (1–2): 183–218. https://doi.org/10.1016/j.biopsycho.2004.03.007.

Bethel, C. L., K. Salomon, R. R. Murphy, and J. L. Burke. 2007. "Survey of Psychophysiology Measurements Applied to Human-Robot Interaction." RO-MAN 2007 - The 16th IEEE International Symposium on Robot and Human Interactive Communication, Jeju, Korea (South), 26–29 August 2007, 732–737. Piscataway, NJ: IEEE. https://doi.org/10.1109/ROMAN.2007.4415182.

Birch, J. 1997. "Efficiency of the ishihara test for identifying red-green colour deficiency." *Ophthalmic and Physiological Optics* 17 (5): 403–408. https://doi.org/10.1111/j.1475-1313.1997.tb00072.x.

Burmeister, C. P., J. Moskaliuk, and U. Cress. 2018. "Office versus leisure environments: effects of surroundings on concentration." *Journal of Environmental Psychology* 58:42–51. https://doi.org/10.1016/j.jenvp.2018.07.011.

Cheng, H., and A. Furnham. 2012. "Childhood cognitive ability, education, and personality traits predict attainment in adult occupational prestige over 17 years." *Journal of Vocational Behavior* 81 (2): 218–226. https://doi.org/10.1016/j.jvb.2012.07.005.

Choi, H.-H., J. J. G. van Merriënboer, and F. Paas. 2014. "Effects of the physical environment on cognitive load and learning: towards a new model of cognitive load." *Educational Psychology Review* 26 (2): 225–244. https://doi.org/10.1007/s10648-014-9262-6.

Dalimunthe, I. K., and F. Chondro. 2022. "Concentration with fitness leads to more work productivity." *Jurnal Biomedika dan Kesehatan* 5 (3): 171–181. https://doi.org/10.18051/JBiomedKes.2022.v5.171-181.

Davies, D., D. Jindal-Snape, C. Collier, R. Digby, P. Hay, and A. Howe. 2013. "Creative learning environments in education—a systematic literature review." *Thinking Skills and Creativity* 8:80–91. https://doi.org/10.1016/j.tsc.2012.07.004.

Dul, J., and C. Ceylan. 2011. "Work environments for employee creativity." *Ergonomics* 54 (1): 12–20. https://doi.org/10.1080/00140139.2010.542833.

Fink, A., and M. Benedek. 2014. "EEG alpha power and creative ideation." *Neuroscience & Biobehavioral Reviews* 44 (100): 111–123. https://doi.org/10.1016/j.neubiorev.2012.12.002.

Gevins, A., and M. E. Smith. 2003. "Neurophysiological measures of cognitive workload during human–computer interaction." *Theoretical Issues in Ergonomics Science* 4 (1–2): 113–131. https://doi.org/10.1080/14639220210159717.

Goldschmidt, G., and M. Smolkov. 2006. "Variances in the impact of visual stimuli on design problem solving performance." *Design Studies* 27 (5): 549–569. https://doi.org/10.1016/j.destud.2006.01.002.

Harmony, T. A., T. A. Fernández, J. Gersenowies, L. D. Galán, A. Fernández-Bouzas, E. Aubert, and L. Díaz-Comas. 2004. "Specific EEG frequencies signal general common cognitive processes as well as specific task processes in man." *International Journal of Psychophysiology* 53 (3): 207–216. https://doi.org/10.1016/j.ijpsycho.2004.04.006.

Hastari, T. B., Y. Bakhtiar, D. S. Wibisono, and Z. Muttaqin. 2020. "The Effect of Circuit Training on Concentration of Medical Students in Diponegoro University." *Diponegoro International Medical Journal* 1 (1): 1–4. https://doi.org/10.14710/dimj.v1i1.7746.

Holm, A., K. Lukander, J. Korpela, M. Sallinen, and K. M. I. Müller. 2009. "Estimating Brain Load from the EEG." *The Scientific World Journal* 9:639–651. https://doi.org/10.1100/tsw.2009.83.

Ismail, L. E., W. Karwowski, and W. Mumtaz. 2020. "Applications of EEG Indices for the Quantification of Human Cognitive Performance: A Systematic Review and Bibliometric Analysis." *PLOS ONE* 15 (12): e0242857. https://doi.org/10.1371/journal.pone.0242857.

Jin, L., and E. Y. Kim. 2020. "Interpretable cross-Subject eeg-Based Emotion Recognition Using channel-Wise Features." *Sensors (Switzerland)* 20 (23): 6719. https://doi.org/10.3390/s20236719.

Kaida, K., M. Takahashi, T. Haratani, Y. Otsuka, K. Fukasawa, and A. Nakata. 2006. "Indoor Exposure to Natural Bright Light Prevents Afternoon Sleepiness." *Sleep* 29 (4): 462–469. https://doi.org/10.1093/sleep/29.04.462.

Karol, E., and D. Smith. 2019. "Impact of Design on Emotional, Psychological, or Social well-Being for People with Cognitive Impairment." *HERD: Health Environments Research & Design Journal* 12 (3): 220–232. https://doi.org/10.1177/1937586718813194.

Ko, W. H., S. Schiavon, H. Zhang, L. T. Graham, G. Brager, I. Mauss, and Y.-W. Lin. 2020. "The Impact of a View from a Window on Thermal Comfort, emotion, and Cognitive Performance." *Building and Environment* 175:106779. https://doi.org/10.1016/j.buildenv.2020.106779.

Leichtfried, V., M. Mair-Raggautz, V. Schaeffer, A. Hammerer-Lercher, G. Mair, C. Bartenbach, M. Canazei, and W. Schobersberger. 2015. "Intense Illumination in the Morning Hours Improved Mood and Alertness but Not Mental Performance." *Applied Ergonomics* 46 (Pt. A): 54–59. https://doi.org/10.1016/j.apergo.2014.07.001.

Lustenberger, C., M. Boyle, A. Foulser, J. Mellin, and F. Fröhlich. 2015. "Functional Role of Frontal Alpha Oscillations in Creativity." *Cortex, A Journal Devoted to the Study of the Nervous System and Behavior* 67:74–82. https://doi.org/10.1016/j.cortex.2015.03.012.

MacLean, M., K. Arnell, and K. Cote. 2012. "Resting EEG in Alpha and Beta Bands Predicts Individual Differences in Attentional Blink Magnitude." *Brain and Cognition* 78 (3): 218–229. https://doi.org/10.1016/j.bandc.2011.12.010.

Mateos, D., G. Krumm, V. Filippetti, and M. Gutiérrez. 2022. "Power Spectrum and Connectivity Analysis in EEG Recording During Attention and Creativity Performance in Children." *NeuroSci* 3 (2): 347–365. https://doi.org/10.3390/neurosci3020025.

Mihara, K., T. Hasama, and H. Takasuna. 2022. "Physiological and Psychological Responses and Cognitive Performance with a Window View." *Science and Technology for the Built Environment* 28 (4): 547–556. https://doi.org/10.1080/23744731.2022.2049639.

Millett, D. 2001. "Hans Berger: From Psychic Energy to the EEG." *Perspectives in Biology and Medicine* 44 (4): 522–542. https://doi.org/10.1353/pbm.2001.0070.

Moraru, G.-M., and D. Popa. 2019. "Proposals for a More Creative Education System." In *MATEC Web of Conferences*, 13009. Vol. 290. Les Ulis, France: EDP Sciences. https://www.matec-conferences.org/articles/matecconf/pdf/2019/39/matecconf_mse2019_13009.pdf.

Moscoso, C., K. Chamilothori, J. Wienold, M. Andersen, and B. Matusiak. 2021. "Window Size Effects on Subjective Impressions of Daylit Spaces: Indoor Studies at High Latitudes Using Virtual Reality." *LEUKOS* 17 (3): 242–264. https://doi.org/10.1080/15502724.2020.1726183.

Mumford, M. D., G. M. Scott, B. Gaddis, and J. M. Strange. 2002. "Leading Creative People: Orchestrating Expertise and Relationships." *The Leadership Quarterly* 13 (6): 705–750. https://doi.org/10.1016/S1048-9843(02)00158-3.

Neuroelectrics. 2024. "ENOBIO Technical Specifications V5." Accessed August 1, 2024. https://www.neuroelectrics.com/api/downloads/Enobio_Technical_specifications_v5.pdf.

Nishizawa, Y., H. Tanaka, R. Fukasawa, K. Hirao, A. Tsugawa, and S. Shimizu. 2021. "Evaluation of Cognitive Decline Using Electroencephalograph beta/Alpha Ratio During brain–Computer Interface Tasks." Paper presented at the 7th International Symposium on Affective Science and Engineering, Online Academic Symposium, March, 9. Online. https://doi.org/10.5057/isase.2021-C000008.

Nuamah, J. K., and Y. Seong. 2018. "Su Pport Vector Machine (SVM) Classification of Cognitive Tasks Based on Electroencephalography (EEG) Engagement Index." *Brain–Computer Interfaces* 5 (1): 1–12. https://doi.org/10.1080/2326263X.2017.1338012.

Paas, F., and P. Ayres. 2014. "Cognitive Load Theory: A Broader View on the Role of Memory in Learning and Education." *Educational Psychology Review* 26 (2): 191–195. https://doi.org/10.1007/s10648-014-9263-5.

Paas, F., A. Renkl, and J. Sweller. 2003. "Cognitive Load Theory and Instructional Design: Recent Developments." *Educational Psychologist* 38 (1): 1–4. https://doi.org/10.1207/S15326985EP3801_1.

Park, J., V. Loftness, and A. Aziz. 2018. "post-Occupancy Evaluation and IEQ Measurements from 64 Office Buildings: Critical Factors and Thresholds for User Satisfaction on Thermal Quality." *Buildings* 8 (11): 156. https://doi.org/10.3390/buildings8110156.

Parong, J., and R. Mayer. 2018. "Learning Science in Immersive Virtual Reality." *Journal of Educational Psychology* 110 (6): 785–797. https://doi.org/10.1037/edu0000241.

Pera, A. 2013. "The Effect of Social Environments on the Individual's Creativity." *Contemporary Readings in Law and Social Justice* 5 (2): 158–163.

Rozi, F., and M. Yahya. 2023. "Circuit Learning in Improving Concentration Student Learning in Madrasah." *PALAPA* 11 (1): 252–263. https://doi.org/10.36088/palapa.v11i1.3149.

Sari, A. P. J., and J. T. Manoy. 2022. "Junior High School Students' Creativity in Solving Hots Questions Based on Learning Concentration." *MATHEdunesa* 11 (1): 155–168. https://doi.org/10.26740/mathedunesa.v11n1.p155-168.

Schertz, K. E., and M. G. Berman. 2019. "Understanding Nature and Its Cognitive Benefits." *Current Directions in Psychological Science* 28 (5): 496–502. https://doi.org/10.1177/0963721419854100.

Shi, Y., and S. Qu. 2021. "Cognitive Ability and self-Control's Influence on High School Students' Comprehensive

Academic Performance." *Frontiers in Psychology* 12:783673. https://doi.org/10.3389/fpsyg.2021.783673.
Silva, J. M. 1979. "Behavioral and Situational Factors Affecting Concentration and Skill Performance." *Journal of Sport Psychology* 1 (3): 221–227. https://doi.org/10.1123/jsp.1.3.221.
Smolders, K. C. H. J., and Y. A. W. de Kort. 2014. "Bright Light and Mental Fatigue: Effects on Alertness, Vitality, Performance and Physiological Arousal." *Journal of Environmental Psychology* 39:77–91. https://doi.org/10.1016/j.jenvp.2013.12.010.
Springer, L. 2022. "Creative Practice Applied in a Higher Education Class." *Creativity, Innovation and Entrepreneurship: Proceedings of the 13th AHFE International Conference on Creativity, Innovation and Entrepreneurship*, ISEC Lisboa, TGRAF, CIEBA FBAUL, Portugal, edited by E. Markopoulos, R. S. Goonetilleke, and Y. Luximon, Vol. 31, 1–6. AHFE International. https://doi.org/10.54941/ahfe1001500.
Stevens, C., and D. Zabelina. 2019. "Creativity Comes in Waves: An eeg-Focused Exploration of the Creative Brain." *Current Opinion in Behavioral Sciences* 27:154–162. https://doi.org/10.1016/j.cobeha.2019.02.003.
Sudimac, S., V. Sale, and S. Kühn. 2022. "How Nature Nurtures: Amygdala Activity Decreases as the Result of a one-Hour Walk in Nature." *Molecular Psychiatry* 27 (11): 4446–4452. https://doi.org/10.1038/s41380-022-01720-6.
Sweller, J. 1988. "Cognitive Load During Problem Solving: Effects on Learning." *Cognitive Science* 12 (2): 257–285. https://doi.org/10.1207/s15516709cog1202_4.
Sweller, J. 2010. "Element Interactivity and Intrinsic, Extraneous, and Germane Cognitive Load." *Educational Psychology Review* 22 (2): 123–138. https://doi.org/10.1007/s10648-010-9128-5.
Tabbers, H. K., R. L. Martens, and J. J. G. van Merriënboer. 2004. "Multimedia Instructions and Cognitive Load Theory: Effects of Modality and Cueing." *British Journal of Educational Psychology* 74 (1): 71–81. https://doi.org/10.1348/000709904322848824.
Tennessen, C. M., and B. Cimprich. 1995. "Views to Nature: Effects on Attention." *Journal of Environmental Psychology* 15 (1): 77–85. https://doi.org/10.1016/0272-4944(95)90016-0.
Wang, C., F. Zhang, J. Wang, J. K. Doyle, P. A. Hancock, C. M. Mak, and S. Liu. 2021. "How Indoor Environmental Quality Affects Occupants' Cognitive Functions: A Systematic Review." *Building and Environment* 193:107647. https://doi.org/10.1016/j.buildenv.2021.107647.
Worden, M., J. Foxe, N. Wang, and G. Simpson. 2000. "Anticipatory Biasing of Visuospatial Attention Indexed by Retinotopically Specific α-Band Electroencephalography Increases Over Occipital Cortex." *The Journal of Neuroscience* 20 (6): RC63. https://doi.org/10.1523/JNEUROSCI.20-06-j0002.2000.
Xu, J., M. Li, D. Huang, Y. Wei, and S. Zhong. 2022. "A Comparative Study on the Influence of Different Decoration Styles on Subjective Evaluation of Hotel Indoor Environment." *Buildings* 12 (11): 1777. https://doi.org/10.3390/buildings12111777.
Yamnenko, H. 2021. "Creativity as a Condition for Increasing the Competitiveness of the Enterprise." *Path of Science* 7 (2): 1012–1018. https://doi.org/10.22178/pos.67-5.
Yang, D., and C. M. Mak. 2020. "Relationships Between Indoor Environmental Quality and Environmental Factors in University Classrooms." *Building and Environment* 186:107331. https://doi.org/10.1016/j.buildenv.2020.107331.
Yesavage, J. A., and T. L. Rose. 1983. "Concentration and Mnemonic Training in Elderly Subjects with Memory Complaints: A Study of Combined Therapy and Order Effects." *Psychiatry Research* 9 (2): 157–167. https://doi.org/10.1016/0165-1781(83)90037-9.