PROPOSAL OF HUMAN-SENSORED ARCHITECTURE FRAMEWORK BY INTRODUCING MIXED REALITY

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Abstract

Remote work has increased the need to understand how indoor spatial design affects occupants' cognitive performance and physiological states. This study proposes a Human-sensored Architecture framework integrating Mixed Reality (HoloLens 2) for real-time spatial manipulation and EEG (Emotiv EPOC+) for physiological measurement. Following a network analysis of 124 publications, experiments with 30 participants revealed that red walls enhanced short-term executive function through stress-induced arousal, whereas preferred, low-stress settings improved long-term memory and productivity. These findings demonstrate the value of human-centered spatial design tailored to specific cognitive tasks and provide a foundation for personalized, adaptive architecture.

Introduction

Since the onset of the COVID-19 pandemic in 2020, the prevalence of remote work has increased significantly. As individuals spend more time indoors, there is a growing demand for environments that facilitate diverse tasks and activities effectively. Given that changes in the indoor environment profoundly affect the emotional and physiological states of occupants, research is continuously being conducted to identify which spatial configuration factors enhance user convenience and task efficiency (Lee et al., 2022). Historically, researchers have primarily focused on analyzing human states relative to environmental variables such as building facilities, temperature, and humidity to determine optimal conditions (Banaei et al., 2020). However, there remains a critical lack of analysis regarding the physiological responses to fundamental design elements—such as wall and floor colors, ceiling heights, and materials—that dictate the overall ambiance of a space (Lee et al., 2022). This gap is largely attributed to the technical limitations previously associated with modifying indoor designs in real-time.

Nevertheless, with the emergence of Extended Reality (XR) technologies, particularly Virtual Reality (VR) and Mixed Reality (MR), it has become possible to alter spatial designs instantaneously while incorporating real-time client feedback (Han et al., 2021). As a bridge between digital experiences and physical reality, these technologies—encompassing both AR and VR—serve as powerful tools for visualizing structures and environments (Portman et al., 2015). MR, in particular, has emerged as a significant paradigm in user interface systems, augmenting human perception by overlaying computer-generated information onto the real world. In this context, user interaction and immersion within the virtual environment are vital parameters that must be optimized for practical application (Chamilothori et al., 2019). While virtualization in MR enhances efficiency and productivity while mitigating risks (Portman et al., 2015), the most critical factor is interoperability. Since visual designs are superimposed on reality, maximizing interaction is essential. Furthermore, as MR devices often operate without external trackers or remotes, gesture-based recognition is paramount. Despite the potential of Head-Mounted Displays (HMDs) to enable accurate task performance and convenient daily life through 3D information, challenges remain. Mismatches or conflicts during the brain's information processing can induce cybersickness, leading to visual fatigue, anxiety, nausea, and disorientation (Im et al. 2022). Physical discomfort, such as the weight of the device, also necessitates further technological refinement (Rehring et al., 2019). Consequently, the MR market is expanding, with increasing adoption in the construction industry due to its interoperability and the convenience of controller-free operation.

To evaluate the physical and mental states of individuals within these spaces, psycho-physiological indicators are utilized. These indicators facilitate the assessment of human states through biological responses, identifying sympathetic and parasympathetic nervous system reactions to visual stimuli via metrics such as EEG, heart rate variability (HRV), and electrocardiogram (ECG) (Lee et al., 2022). Previous studies applying these metrics to the architectural field have found that white or green walls tend to induce a sense of psychological comfort, characterized by increased Alpha wave activity associated with reduced tension (Lee, Shin, and Lee, 2020). However, prior research has frequently focused on isolated components (e.g., a single wall or material) rather than the holistic design of a space. Moreover, while studies have analyzed physiological indicators to maintain a state of rest, research aimed at proposing optimal spatial designs for high task performance based on such indicators remains scarce.

Accordingly, this study aims to elucidate the relationship between indoor spatial design and human affective-physiological responses through empirical analysis. Since modifying physical indoor environments in real-time is practically infeasible due to construction and material constraints, Mixed Reality (MR, Microsoft HoloLens 2) was adopted as a specialized experimental apparatus. MR serves as a medium to overcome these limitations, enabling the instantaneous and controlled manipulation of spatial configurations to observe their direct impact on human states. To establish a robust theoretical foundation for the experimental design, a *bibliometric analysis* and network analysis were conducted. Based on the clusters derived from core descriptors, a theoretical framework was proposed, which subsequently guided the experimental protocol. Based on this framework, experiments were conducted with 30 participants across four spatial configurations: a baseline white space, a preferred space, a non-preferred space, and a self-selected space. During each session, two cognitive tests were administered to assess task efficiency. Concurrently, EEG data were collected and preprocessed to calculate Mental Stress and Mental Workload indices using established neuroscientific formulas. Through repeated measures statistical analysis, this study identifies fluctuations in affective-physiological indicators and task efficiency, ultimately proposing the optimal spatial configuration for specific task types.

Research Design

Methodology

This study aims to elucidate the intricate relationship between humans and spatial environments through empirical analysis. To achieve this, a theoretical framework was established via a literature review, followed by the development of an experimental environment capable of real-time modifications to indoor spatial designs. The review process involved curating scholarly publications from Web of Science and Scopus, with a subsequent network analysis performed on the extracted keywords. By identifying and synthesizing key thematic clusters, a comprehensive framework was constructed to map the connectivity between human subjects and spatial variables. Based on this framework, an experimental protocol was implemented. Technically, HoloLens-based mixed reality was utilized for spatial selection and manipulation. Human physiological responses were captured using electroencephalogram (EEG) to assess cognitive states, while spatial activities were defined and evaluated through task performance, enabling a multi-dimensional understanding of human reactions within diverse spatial configurations.

Establishment of experimental environment

Development of Theoretical Framework

To develop the proposed framework, research papers were extracted in accordance with a four-stage process. This process consists of the following: Stage 1, the selection of search engines and keywords; Stage 2, the screening and extraction of literature based on the selected keywords; Stage 3, quantitative literature analysis; and Stage 4, the analysis of results and the subsequent discussion process (Kim and Hyun, 2019). Initially, papers were retrieved from Web of Science and Scopus, which are recognized as representative academic databases. The temporal scope for the literature search was set from approximately 2000 to 2023. Specifically, in Web of Science, papers were extracted using the search string: TS=(interior AND space AND building) AND AK=(design) NOT AK=(Thermal AND Ventilation AND Energy). For Scopus, the search was conducted based on the query: ALL ("space" AND "building" AND "interior") AND KEY ("design") AND KEY ("interior") AND NOT ("Thermal") AND NOT ("ventilation") AND NOT ("energy").

Following this systematic screening as previously mentioned, a final total of 124 papers were selected, which provided the foundation for constructing the framework. In conducting the network analysis, a keyword co-occurrence network was constructed from the abstracts and keywords of the selected papers, and PageRank centrality (Brin and Page, 1998) was computed using the R programming environment. PageRank centrality was originally developed for ranking web pages based on hyperlink structures; however, it has been increasingly adopted in bibliometric research to evaluate the relative importance of keywords within co-occurrence networks, as the structural logic of interconnected nodes applies analogously to both domains (Ding et al., 2009). Through this approach, core keywords were identified based on their centrality scores, and the resulting network was subsequently visualized to delineate thematic clusters. Finally, after identifying the core values of the major clusters, the theoretical framework was established based on the synthesis of these cohesive factors.

Experiment Plan

The experimental protocol was meticulously designed to comprehensively reflect the components of the proposed framework. To investigate the fluctuations in affective-physiological indicators relative to indoor spatial design, it was essential to establish an experimental environment capable of real-time modifications. In this study, a Mixed Reality (MR) environment was introduced—a technology that enhances realism by superimposing virtual holographic information onto the physical environment (Im et al., 2022; Han et al., 2021). For the implementation of this MR setting, Microsoft HoloLens 2 was utilized, allowing for the manipulation of wall colors, materials, floor textures, and ceiling heights within a standardized indoor space measuring 5,500 mm × 7,000 mm × 3,600 mm.

Specifically, the wall color palette included white, blue, beige, green, and red. Flooring materials ranged from epoxy, stone, and wood to carpet, tile, and PVC, while wall finishes included brick, wood, paint, stone, concrete, and wallpaper. Additionally, the ceiling height was adjusted between high and low configurations. Based on a preliminary survey, participants were presented with three distinct spatial scenarios: a baseline white space, a preferred space, and a non-preferred space. Furthermore, participants were encouraged to engage in decision-making by directly configuring their own preferred spaces. Findings indicated that participants predominantly preferred a configuration consisting of beige walls, PVC flooring, a wooden ambiance, and high ceilings, citing a sense of comfort and warmth. In contrast, a configuration featuring red walls, concrete and tile textures, and low ceilings was identified as non-preferred, with participants describing it as visually overstimulating and oppressive.

Subsequently, task efficiency within each spatial configuration was evaluated while concurrently measuring affective-physiological indicators. EEG data were collected using the Emotiv EPOC+ device, with 14-channel signals recorded in accordance with the international 10-20 system. This enabled the measurement of brainwave activity across four regions: the frontal, temporal, occipital, and parietal lobes (Lee, Shin, and Lee, 2020). Task performance and corresponding EEG patterns were analyzed through the Stroop test, which assesses short-term executive function, and the Reading Span Test, which evaluates working memory and long-term performance efficacy.

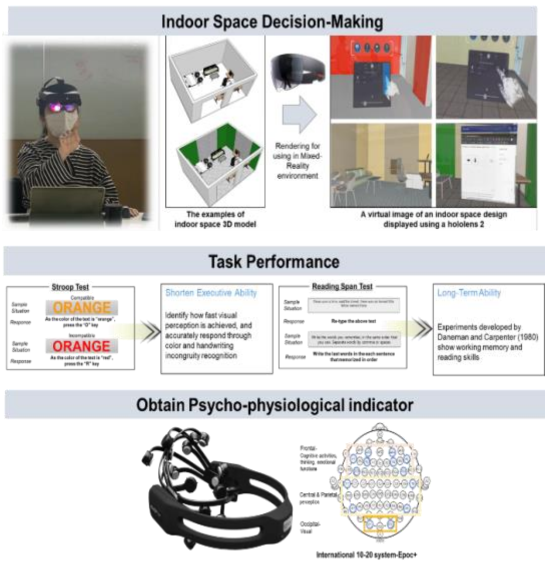

Figure 1. Process of experiment and activities

Data Collection

Experiment Participants

The experimental protocol of this study was conducted following approval from the Institutional Review Board (IRB) (Approval No. HYUIRB-2022202-005), after which participants were recruited. A total of 30 participants in their 20s and 30s were enrolled. The sample size was determined using G*Power 3.1 software and validated with reference to prior research in the field (Banaei et al., 2020). The participant pool comprised 30 Architectural Engineering students, balanced by gender (N=30; 15 males and 15 females). To eliminate potential bias arising from prior exposure, the selection was restricted to individuals who had never experienced Mixed Reality. Prior to the data collection phase, an introductory session on the MR device was conducted, followed by a 10-minute period for participants to independently adapt to the virtual environment. To ensure the integrity of the physiological data, all participants were screened to confirm they had no history of mental illness, were not suffering from sleep deprivation, and had no visual impairments. Furthermore, they were required to abstain from alcohol and smoking for 24 hours prior to the experiment. The Short Portable Mental Status Questionnaire (SPMSQ) was administered to verify that all participants possessed normal cognitive function. The SPMSQ, a 10-item screening instrument developed by Pfeiffer (1975) to detect cognitive impairment, was administered to all participants. The SPMSQ evaluates basic orientation, memory, and general knowledge through brief verbal questions of relatively low difficulty, serving as a preliminary screening tool rather than a comprehensive cognitive assessment. In this study, all 30 participants answered all items correctly (i.e., zero errors), confirming that the entire sample possessed intact cognitive function suitable for the experimental tasks. Before proceeding the experiment, participants wore the Microsoft HoloLens 2 and the Emotiv EPOC+ device, allowing them to engage in spatial decision-making tasks while their EEG signals were concurrently collected and recorded throughout the activities.

Data Pre-processing

First, to evaluate the task performance data obtained from the experiments, accuracy (%) and response time (ms) were recorded for each session. These metrics were subsequently converted into a 'Learning Ability Index' for comparative analysis, as defined in Equation (1).

$$\text{Learning Performance} = \left[(Accuracy)^{0.5} * \frac{1}{(Response\ time)^{0.5}}\right]^2 * 100 \qquad (1)$$

Following this, electroencephalogram (EEG) was utilized as an affective-physiological indicator to analyze human responses. As a non-invasive method, EEG facilitates the practical measurement of neuronal activity and synaptic signals within the brain. The captured brainwaves were categorized into specific frequency domains to identify the underlying relationship between emotional states and indoor spatial configurations. For data processing, the frequency and spatial coordinates of each electrode were initially identified using the EEGLAB toolbox in MATLAB. Given that EEG signals are prone to artifacts such as eye blinks, muscle movements, and respiratory cycles, a rigorous preprocessing stage was essential to isolate the 2–39 Hz frequency range suitable for empirical analysis. As illustrated in Figure 2, this study employed the Blackman Window, characterized by low side-lobe levels and high frequency resolution. Through Independent Component Analysis (ICA) and Fast Fourier Transform (FFT), the signals were decomposed into distinct bands: Theta ($4-8$ Hz), Alpha ($8-13$ Hz), Beta ($13-30\ Hz$), and Gamma (30-39 Hz). Since lower frequencies are typically associated with resting states, these values were converted into 'Relative Power' to ensure an objective comparison of cognitive activity

(Kamzanova et al., 2014). Finally, two key indices established by previous researchers—Mental Workload and Mental Stress—were calculated to perform a spatial comparison, based on Equations (2) and (3), respectively.

$$\text{Mental workload} = \frac{(Relative\ Beta)_{Frontal}}{(Relative\ Theta)_{Frontal} + (Relative\ Alpha)_{Frontal}} \quad (2)$$

$$\text{Mental Stress} = \frac{(Relative\ Theta)_{Frontal}}{(Relative\ Alpha)_{Parietal}} \quad (3)$$

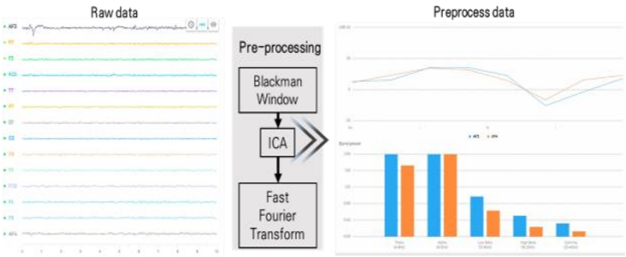

Figure 2 Data pre-processing method

Data Analysis

Statistical analysis in this study was performed using SPSS version 26.0 (IBM Corp., Armonk, NY, USA). To determine the appropriate statistical methods, the Kolmogorov-Smirnov (K-S) test was first conducted to assess the normality of the data distribution. For datasets that satisfied the normality assumption, a Repeated Measures Analysis of Variance (RM-ANOVA) was employed to compare EEG responses and task efficiency across the different indoor spatial configurations. Prior to the RM-ANOVA, the fundamental statistical assumptions were verified. First, the homoscedasticity of the dependent variables was confirmed, with all variables satisfying the requirement ($p \geq .05$). Second, Mauchly's test was employed to assess the assumption of sphericity. In instances where sphericity was violated, the Greenhouse-Geisser correction was applied to adjust the degrees of freedom and ensure the validity of the F-statistics (Yang et al., 2021). In instances where the normality assumption was violated, the non-parametric Friedman test was utilized for the comparative analysis (Han et al., 2021). To further identify specific differences between spatial conditions, post-hoc analyses were performed: Tukey's Honestly Significant Difference (HSD) test was applied following RM-ANOVA, whereas the Bonferroni correction was implemented for pairwise comparisons following the Friedman test.

Results

Proposal of theoretical Framework

As illustrated in Figure 3, the network analysis results reveal that the data are structured into four distinct primary clusters. Within each cluster, the size of the nodes (circles) corresponds to the frequency of the terms, indicating their significance as core keywords. As previously discussed, by employing PageRank centrality, the underlying main topics of each cluster were identified based on the inter-node connectivity between terms. Table 1 defines the representative keywords for each cluster, focusing on those descriptors that exhibit large node diameters and high degrees of connectivity as depicted in Figure 3.

Furthermore, terms associated with each primary keyword were systematically organized, providing a comprehensive basis for synthesizing the thematic focus and intended subjects represented by each individual cluster.


Figure 3 Result of Network Analysis

Based on a bibliometric analysis centered on Table 1, this study analyzed the interplay between humans and spatial design, called human-sensored architecture. The human component is broadly categorized into two dimensions: the cognitive dimension and the psycho-physiological reaction. Within the cognitive dimension, perception encompasses both innate temperament and accumulated experience, representing the diverse knowledge and empirical background individuals develop throughout their lives. Simultaneously, humans exhibit various psycho-physiological reactions in response to spatial configurations.

Table 1 Main topic of each cluster

Cluster	Main keyword	Other keyword	Main topic
Cluster 1 (red)	color	furniture object, light, textile, wall, height, surface, aesthetic, ceiling	Space Configuratio n Component
Cluster 2 (green)	experienc e	perception, psychology, behavior, decision, creativity, trait	Temperamen t of Human
Cluster 3 (blue)	technolog y	computer, quality, building information modeling, artificial intelligent, virtual reality technology	Smart construction technology
Cluster 4 (yellow)	human	comfort, satisfaction, safety, privacy, productivity, health	Status of human in indoor space

Specifically, as indoor environments undergo modifications, fluctuations are observed not only in physiological markers—such as electroencephalogram (EEG) and heart rate variability (HRV)—but also in psychological emotional states. Consequently, this study identified the cognitive dimension (conceptualized as the x-axis) and the psycho-physiological response (conceptualized as the y-axis) as the fundamental pillars influencing human spatial decision-making. Ultimately, the human state, which is modulated by the indoor environment, dictates the nature of human activity. These activities, typically manifested as work productivity or rest, necessitate that environmental configuration be proposed based on a comprehensive understanding of human factors. The resulting theoretical framework synthesized from these relationships is illustrated in Figure 4.

Differences in work efficiency by space

The results of the comparative analysis regarding short-term executive function and long-term working memory across the four spatial configurations (Baseline, Preferred, Non-preferred, and Self-selected/Decision-making space) are as follows. To determine the appropriate statistical method for evaluating task efficiency, the Kolmogorov-Smirnov (K-S) test was conducted. The results yielded p-values of 0.200 (D(30)=.113) for executive function and 0.178 (D(30)=.136) for working memory, confirming that both datasets satisfied the normality assumption. Consequently, a Repeated Measures ANOVA (RM-ANOVA) was performed to examine the differences based on spatial design, the results of which are summarized in Table 2. The RM-ANOVA revealed significant differences in both executive function and working memory depending on the spatial configuration. Regarding executive function, the highest performance levels were observed in the non-preferred space. Subsequent Tukey post-hoc analysis further elucidated that while performance was significantly higher in the non-preferred environment, no statistically significant differences were found between the baseline, preferred, and self-selected spaces. Conversely, the analysis of working memory showed that performance was lowest in the non-preferred space, whereas the highest performance was recorded in the self-selected (decision-making) space. Post-hoc results for working memory indicated that while no significant differences existed among the non-preferred, baseline, and preferred spaces, the self-selected configuration yielded a significantly superior performance outcome. In summary, the impact of indoor spatial design on task efficiency varied by cognitive demand: short-term executive function was enhanced in non-preferred environments, whereas long-term working memory performance was optimized in self-selected spatial configurations.

Differences in Psycho-physiological indicators by space

Following the preprocessing of EEG data, the physiological indicators derived from Equations (2) and (3) were subjected to normality testing. The Kolmogorov-Smirnov (K-S) test revealed that while Mental Stress satisfied the normality assumption (D(30)=.109, $p > .200$), Mental Workload violated it (D(30)=.168, $p = .030$). Consequently, Mental Stress was analyzed using RM-ANOVA, whereas the Mental Workload was evaluated via the non-parametric Friedman test. Regarding Mental Stress, Mauchly's test indicated that the sphericity assumption was satisfied for the executive function test. In contrast, the assumption was violated for the working memory test; consequently, the Greenhouse-Geisser correction was applied to adjust the degrees of freedom for the subsequent analysis. Figure 5 presents box plots illustrating the distribution of Mental Stress and Mental Workload across the different spatial configurations. In the case of Mental Stress during the executive function test, the highest levels were observed in the preferred space, followed by the self-selected and non-preferred spaces. Post-hoc analysis indicated no significant difference between the non-preferred and

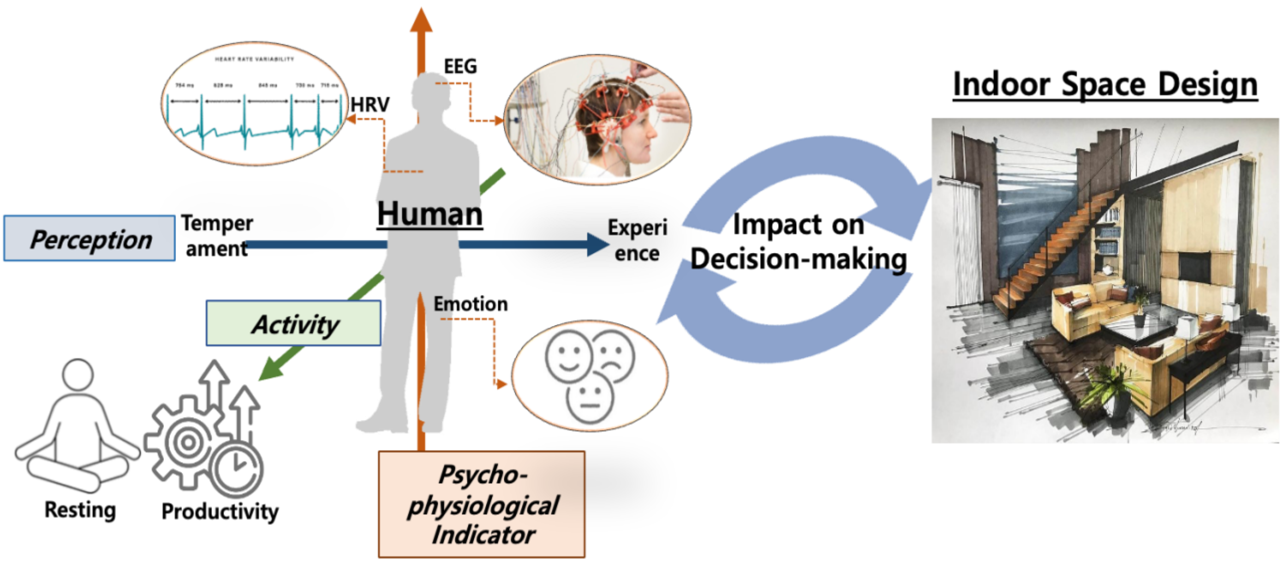

Figure 4. Proposal of Human-sensored Architecutre Framework

Table 2 Statistical analysis of taskperformance among space design

Task Performance	Interior design	Mean	Standard deviation	Tests of within subject effects					Post hoc
				Type Ⅲ Sum of squares	Df	Mean square	F-Statistics	Sig.	Tukey HSD
Executive ability	Basic	9.349	4.063	549.384	2.572	213.564	27.966	.000**	1=2=4<3
	Prefer	12.203	3.960						
	Non-Prefer	14.790	4.088						
	Personal	12.275	4.044						
Working Memory	Basic	1.046	0.753	2.319	2.600	.892	2.815	.042*	3=1=2<4
	Prefer	1.055	-.656						
	Non-Prefer	0.916	0.660						
	Personal	1.301	0.492						

Note *: p-value<0.05, **: p-value<0.001

baseline spaces; however, participants experienced significantly higher stress in the preferred space. Similarly, significant spatial variations in Mental Stress were observed during the working memory test. Post-hoc comparisons confirmed that the preferred space induced the highest stress levels. Notably, in contrast to the executive function results, stress levels in the self-selected space during the working memory task were found to be lower than those in the non-preferred space. Regarding Mental Workload, analyzed via the Friedman test, the results for the executive function test showed the most intense workload in the non-preferred space. Bonferroni-corrected post-hoc analysis confirmed that these differences were statistically significant, indicating that the non-preferred environment imposed a substantially higher cognitive load, while the workload in the self-selected space was relatively low. Conversely, although the workload during the working memory task appeared higher in the non-preferred space, this difference did not reach statistical significance.

Discussion

With the increasing emphasis on Digital Twin technology, interest in Mixed Reality (MR) has grown significantly. In the construction industry, MR has primarily been utilized for spatial visualization, often limited to safety training and education. This study, however, expands the application of MR by redirecting its focus toward spatial decision-making. A key differentiator of this research lies in its integrated presentation of fluctuating physiological indicators alongside task efficiency across diverse spatial configurations. While traditional approaches have focused on subjective impressions and qualitative expressions of space, future spatial planning will likely transition toward more complex, biometric-centered proposals (Lee et al., 2022). As evidenced by this study, the evolution of MR enhances the decision-making process for stakeholders, fostering greater coherence and streamlining communication (Zaker and Coloma, 2018). Despite current technical limitations—such as resolution constraints and sensitivity to lighting—these challenges are expected to be overcome in the long term. Given its capacity for real-time interaction and 3D visualization, MR is poised to become an efficient tool, particularly in the early stages of construction projects.

The findings confirm that visual information significantly influences biometric responses, which in turn affect behavioral and task performance. Interestingly, the preferred space showed the highest Mental Stress values. This result suggests that Mental Stress should not be interpreted solely as indicating a more adverse or uncomfortable condition. Rather, the non-preferred condition was more consistently associated with elevated Mental Workload, suggesting increased cognitive demand, whereas the preferred space may have elicited greater emotional arousal or attentional engagement. Notably, the superior task performance observed in non-preferred spaces regarding short-term concentration can be elucidated through the 'fight-or-flight response' theory (Cannon, 1915). This theory suggests that when individuals experience stress, the autonomic nervous

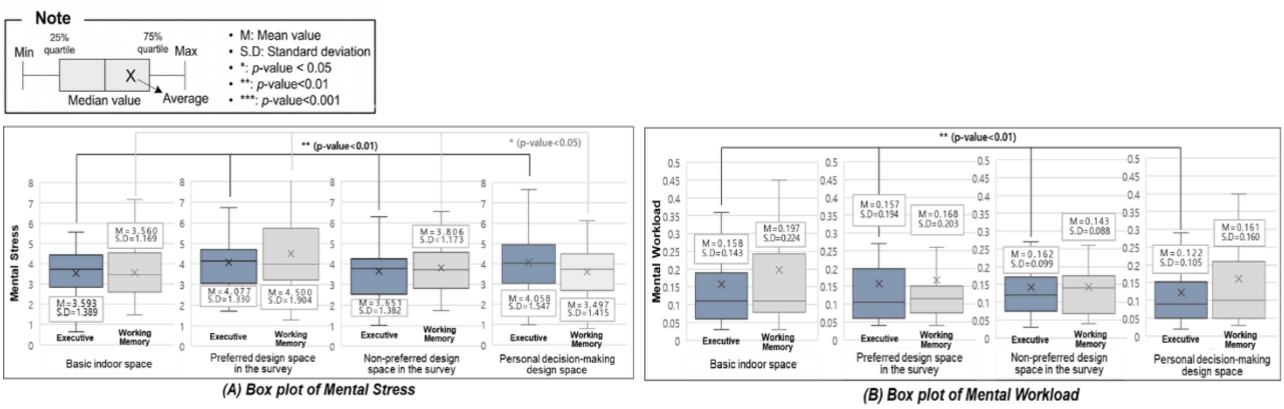

Figure 5 Boxplot of psycho-physiological index

system is activated to heighten focus on the stressor as a survival mechanism. Specifically, exposure to environments with red walls or low ceilings imposed a significantly higher cognitive workload, as evidenced by elevated Mental Workload indices. This heightened cognitive demand can be interpreted through the lens of the fight-or-flight response theory. According to this framework, the autonomic nervous system is activated under demanding conditions to sharpen focus as a survival mechanism, which may paradoxically enhance short-term executive function (Duyan & Ünver, 2016). This explains why participants exhibited improved attention despite the taxing nature of the non-preferred environment. However, considering that long-term capacity is better manifested in preferred spaces due to spatial adaptation, this research underscores the necessity of configuring environments tailored to specific individual competencies and task types. Future interior design should prioritize the emotional responses and cognitive demands of users, ensuring that individuals can successfully adapt their behavior within these optimized spatial configurations.

Conclusions

In conclusion, this study sought to analyze the variations in human affective-physiological responses and task efficiency according to real-time modifications in indoor spatial design. By implementing a Mixed Reality (MR) environment for 30 participants, the research facilitated the collection of EEG data and the comparative analysis of task performance across diverse spatial configurations. The findings revealed that in the short term, although participants experienced a higher cognitive workload in non-preferred spaces, they paradoxically reported lower stress levels and demonstrated superior task performance compared to preferred or self-selected environments. This suggests that visually stimulating or non-preferred environments may heighten acute attention, leading to increased output in brief, execution-oriented tasks.

However, the temporal dynamics of these effects shifted during long-term engagement. While no significant difference was initially observed between spatial design and workload during prolonged tasks, the non-preferred space eventually led to an accumulation of stress, resulting in a subsequent decline in task efficiency. In contrast, participants demonstrated a significant adaptation to self-selected (decision-making) spaces over time. In these configurations, stress levels decreased as individuals acclimated to their environment, which in turn facilitated higher long-term task efficiency. These results underscore that while non-preferred spaces may trigger higher short-term executive function, self-selected environments are optimized for sustained productivity and psychological well-being through spatial adaptation. Therefore, environmental configurations should be proposed dynamically, aligning with specific task types and the required levels of cognitive concentration (Cho et al., 2019).

Despite these insights, this study is subject to certain limitations, particularly its reliance on a Mixed Reality simulation. Future research should strive to validate these findings in full-scale physical environments through longitudinal action research. Furthermore, the scope of inquiry should be expanded by incorporating a broader array of affective-physiological indicators—such as heart rate variability (HRV) and electrocardiogram (ECG)—to achieve a more comprehensive understanding of human biological responses to the built environment.

Acknowledgments

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