Effects Of The Biophilic Design Density Of Transitional Spaces On Human Stress Recovery In A Virtual Reality Environment

Zhixian Li[1] and Sisi Zlatanova[2]
[1,2]The University of New South Wales
[1]zhixian.li@unsw.edu.au, 0000-0003-2649-8137
[2]s.zlatanova@unsw.edu.au, 0000-0002-8766-0487

Abstract. Previous research has demonstrated that biophilic design has a significant impact on human emotion and stress. However, most research has been limited to indoor and outdoor spaces, and there is still limited research on transitional spaces. The effects of different density biophilic designs on human stress have also not been adequately researched. Transitional spaces are areas located between indoor and outdoor environments, such as building entrance canopies and semi-open cafés. This study used virtual reality (VR) to conduct a between-subjects experiment with 40 participants to investigate the impact of biophilic design density levels on human stress recovery in transitional spaces. Four virtual reality environments, including one non-biophilic environment and three biophilic environments with different density levels, were created. After participants experienced the Trier Social Stress Test (TSST), they were randomly assigned to one of the virtual reality environments for stress recovery. The participants' physiological indicators, including heart rate, diastolic blood pressure, and systolic blood pressure, were collected during the experiment. Psychological indicators were measured using the State-Trait Anxiety Inventory (STAI). Generally, the experimental results indicated that the relationship between the density of biophilic environments and human stress recovery in transitional spaces follows a U-shaped dose-response relationship. A medium-density biophilic environment had the most effective stress recovery outcome, while both higher and lower densities resulted in weaker restorative effects.

Keywords. Biophilic Design, Stress Recovery, Transitional Space, Virtual Reality, Human Well-being, Physiological Indicators

1. Introduction

The built environment plays a critical role in shaping human perceptions, preferences and reactions (Li et al., 2025). Modern urban lifestyles often reduce contact with nature, contributing to increased stress-related conditions and poorer psychological health. Biophilic design has therefore emerged as a key approach for integrating natural systems into constructed environments. Rooted in the *Biophilia Hypothesis*, it emphasizes humans' innate connection to nature (Kellert & Wilson, 1993), and

HUMANISTIC COMPUTATION AND INTELLIGENCE, Proceedings of the 31st International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2026, Volume 3, 215-224.

incorporates elements such as daylight, trees, grass, vegetation, and natural landscapes into architectural design. Recent developments in this field highlight its potential to improve health, well-being, and productivity, with numerous studies demonstrating its benefits for enhancing perception, supporting creativity, reducing fatigue, and promoting stress recovery (Gillis & Gatersleben, 2015).

In indoor spaces, biophilic design effectively enhances individuals' psychological and behavioral performance. For instance, the introduction of natural elements into office environments has been shown to improve employee well-being, work performance, creativity, and overall health (Al Horr et al., 2016). In educational environments, natural elements help reduce student stress (Li et al., 2024). In commercial environments, biophilic elements have also been found to enhance customer pleasure and satisfaction. Beyond indoor environments, biophilic design plays an equally vital role in enhancing human well-being in outdoor spaces. For instance, hospital healing gardens incorporate biophilic design to create restorative experiences for patients, thereby promoting recovery. Moreover, in community environments, biophilic design not only encourages physical activity but also effectively alleviates stress and fosters social interaction (Peters et al., 2010).

However, existing research has primarily focused on traditional indoor and outdoor spaces, while limited attention has been given to the intermediate zones that connect them. According to Winnicott (1971), transitional spaces are zones situated between the internal and external realms, possessing characteristics of both. In the context of the built environment, transitional spaces generally refer to buffer and connective areas linking indoor and outdoor environments, such as entrance canopies, foyers, elevator lobbies, corridors, and stairwells, as shown in Figure 1 (Gehl, 2011; Yan et al., 2019).

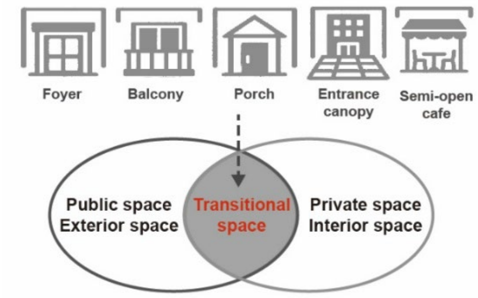


Figure 1. Definition of transitional space

Although numerous studies have demonstrated that biophilic design can promote emotional regulation and stress recovery, its effects within transitional spaces remain underexplored. Given that transitional spaces are frequently encountered in daily life and play an important role in shaping human environmental experience, understanding their restorative potential is essential (Li et al., 2022). Moreover, research examining how different densities of biophilic design influence human stress recovery in these spaces remains scarce. Therefore, this study aims to investigate the relationship between varying densities of biophilic design and human stress recovery within transitional spaces.

2. Research Methodology

2.1. EXPERIMENTAL ENVIRONMENT

The study opted to construct the experimental environment using Virtual Reality (VR) technology to achieve precise manipulation of the varying levels of biophilic design density. VR technology has been widely applied in environmental psychology research, as its primary advantage lies in its capacity to offer a highly immersive, realistic experience while maintaining a strictly controllable experimental setting (Gao & Mandryk, 2011). Compared to traditional methods, VR enables the precise isolation and control of key variables (e.g., spatial layout, lighting, and the density of biophilic elements), thereby ensuring the reproducibility and comparability of the experimental scenarios.

2.2. PHYSIOLOGICAL AND PSYCHOLOGICAL STRESS ASSESSMENT

This study employed a combined approach using physiological and psychological measurements to assess the participants' stress state and restoration more comprehensively. For the psychological assessment, the short-form of State-Trait Anxiety Inventory (STAI-S) was used to evaluate participants' anxiety and stress (Spielberger & Gonzalez-Reigosa, 1971; Marteau & Bekker, 1992). This is a widely used scale for measuring human stress. Furthermore, this study included three physiological indicators as objective criteria for stress recovery assessment: heart rate (HR), systolic blood pressure (SBP), and diastolic blood pressure (DBP). Multiple prior studies have demonstrated the efficacy of these indicators in measuring human stress recovery across different environments (Li et al., 2022).

3. Experimental Design

3.1. PARTICIPANTS

Forty healthy adults (>18 years) were recruited via campus announcements and social media. Participants with a history of mental illness or psychotropic medication use were excluded. All had normal or corrected-to-normal vision and no adverse reactions to VR. To minimize physiological confounding, participants avoided intense exercise, alcohol, and caffeine for 24 hours before testing. The study was approved by the UNSW Institutional Review Board (iRECS4558).

3.2. ENVIRONMENTAL SIMULATION

In this study, the VR environments were first constructed through 3D modeling in Rhinoceros, then imported into *Unity* software for immersive rendering and interactive programming. The final scenarios were presented to participants via an Oculus Quest 2 VR headset. This study employed a typical transitional space, a semi-open café as the base environment. Within this space, four experimental conditions were developed (Figure 2) to examine the effect of biophilic design density on stress recovery. These included one control scenario (non-biophilic space) and three experimental scenarios with low, medium, and high levels of biophilic density.

Scenario A (non-biophilic / control): Contained only standard café furnishings (tables, chairs, paved flooring) with no biophilic elements. **Scenario B** (low density): Added a small number of biophilic elements, including plant stands, sand landscaping, and a fountain. **Scenario C** (medium density): Added a moderate amount of biophilic elements, including plant stands, sand landscaping, a fountain, and rows of trees. **Scenario D** (high density): Added extensive biophilic elements, including plant stands, sand landscaping, a fountain, distant trees, and grass-covered ground.

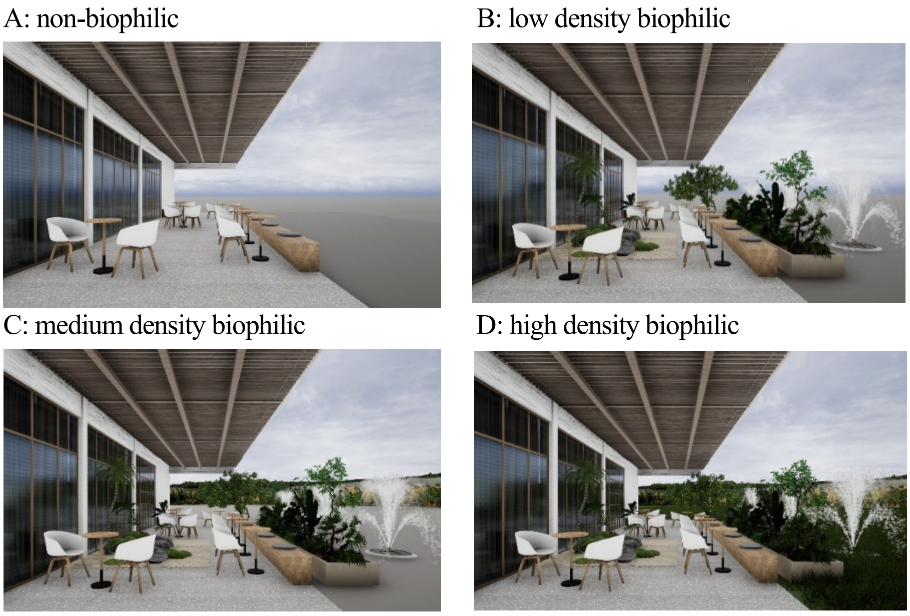


Figure 2. Four comparative experimental VR scenarios

3.3. EXPERIMENTAL PROCEDURE

The experimental procedure (Figure 3) lasted approximately 30 minutes. After reviewing instructions, providing consent, and completing demographic information, participants were equipped with HR and BP devices. EQ parameters (PM2.5, temperature, humidity, and CO_2) were continuously monitored.

Baseline Measurement. The experiment began with a 5-minute baseline measurement to acquire individual physiological indicators in a relaxed state. HR recording commenced at this point and continued until the end of the experiment. At the end of this phase, the baseline BP data (BP baseline) was recorded.

Stress Induction Phase. Then, participants performed the Trier Social Stress Test (TSST) to induce acute psychological and physiological stress (Kirschbaum, Pirke, & Hellhammer, 1993). This procedure involved two consecutive tasks: 5-minute speech and a 5-minute arithmetic task, with an audible alert for errors. Following the TSST, the pre-experimental BP data and pre-experimental STAI was measured immediately.

Stress Recovery Phase. Participants were randomly assigned to one of four VR scenarios for a 5-minute stress recovery. Previous research indicates that five minutes is sufficient for individuals to recover from acute stress (Suppakittpaisarn et al., 2023). Each participant experienced only one VR scenario to mitigate potential VR-induced discomfort (such as motion sickness or headaches), and performed the TSST only once to avoid potential residual stress effects.

Post-Recovery Measurement and Equipment Removal. The post-recovery BP (BP post) was immediately recorded, and participants completed the STAI-S questionnaire again (STAI post), after which the HR recording was terminated.

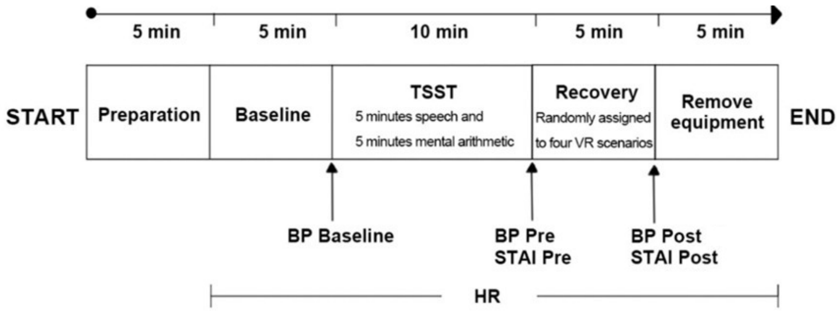


Figure 3. Experimental procedure

4. Data Analysis

All 40 participants completed the experiment. Data analysis was conducted using *SPSS Statistics* software. First, to verify the effectiveness of the random assignment, a one-way analysis of variance (ANOVA) was performed to examine whether there were significant differences among participants in their psychological and physiological baseline data before the TSST, as well as in the Environmental Quality (EQ) indicators recorded during the experiment. Second, to validate the effectiveness of the TSST stress induction procedure, paired-samples t-tests were conducted to compare participants' psychological and physiological indicators before and after the TSST. Furthermore, to evaluate the effect of different virtual scenarios on stress recovery, the difference between pre-test and post-test values (ΔD = pre-test − post-test) was calculated as the dependent variable and analyzed using a one-way ANOVA.

5. Results

5.1. PARTICIPANTS INFORMATION

Table 1 presents the demographic characteristics of the 40 participants. Each experimental condition included an equal number of participants, and the male female ratio was controlled across conditions to minimize potential gender effects on stress responses and recovery.

Table 1. Demographics of all participants

	Overall	A	B	C	D
Number of Participants	40	10	10	10	10
Age	28±3	28±3	27±2	28±4	29±4
Gender	--	--	--	--	--
Female	20	5	5	5	5
Male	20	5	5	5	5

5.2. EXPERIMENTAL RANDOMIZATION

HR, SBP, DBP, and STAI data from the pre-TSST and post-TSST periods were tested using ANOVA to validate the experimental randomization (Table 2). During the pre-TSST period, ANOVA results showed that there were no statistically significant differences in HR ($F = 0.863$, $p = 0.469$), SBP ($F = 0.794$, $p = 0.505$), and DBP ($F = 0.912$, $p = 0.445$) among participants. HR ($F = 0.732$, $p = 0.540$), SBP ($F = 0.052$, $p = 0.984$), DBP ($F = 0.563$, $p = 0.643$), and STAI ($F = 1.113$, $p = 0.356$) also showed no significant differences among participants during the post-TSST period. Therefore, the randomization of the experiment was considered valid.

In addition, due to the potential impact of EQs on human perception, EQ parameters were recorded once every five minutes and analyzed by a one-way ANOVA (Table 2). The results showed no significant differences in CO^2 ($F = 0.455$, $p = 0.719$), $PM_{2.5}$ ($F = 0.971$, $p = 0.438$), temperature ($F = 0.800$, $p= 0.517$), and humidity ($F = 2.111$, $p = 0.152$) across the four scenarios. Therefore, in this experiment, EQ was considered to have no significant effect on the experimental results.

Table 2. Test on whether participants' physical data and psychological data at baseline (pre-TSST), post-TSST and EQ among four environments were similar or not

Measures	Method	*F*	*df*	*P*-value
Pre-TSST				
Heart Rate (bpm)	ANOVA	0.863	3	0.469
Systolic Blood Pressure (mmHg)	ANOVA	0.794	3	0.505
Diastolic Blood Pressure(mmHg)	ANOVA	0.912	3	0.445
Post-TSST				
Heart Rate (bpm)	ANOVA	0.732	3	0.540
Systolic Blood Pressure (mmHg)	ANOVA	0.052	3	0.984
Diastolic Blood Pressure(mmHg)	ANOVA	0.563	3	0.643
State-Anxiety Inventory	ANOVA	1.113	3	0.356
EQ				
CO^2 (ppm)	ANOVA	0.455	3	0.719
$PM_{2.5}$ (μg/m3)	ANOVA	0.971	3	0.438
Temperature (℃)	ANOVA	0.800	3	0.517
Humidity (%)	ANOVA	2.111	3	0.152

Furthermore, the data collected before and during the TSST among the four scenarios were analyzed using paired-samples t-tests to measure the effectiveness of the TSST (Table 3). The results showed that HR (T = -15.967, $p < 0.001$), SBP (T = -3.201, $p = 0.003$), and DBP (T = -3.404, $p = 0.002$) all showed significant differences before and during the TSST. Thus, participants' stress levels were effectively increased after the TSST experience.

Table 3. Test on whether 10-minutes of TSST produced significant stress on participants

Measures	Method	*T*	*df*	*P*-value
Heart Rate (bpm)	Paired t-test	-15.967	39	0.000
Systolic Blood Pressure (mmHg)	Paired t-test	-3.201	39	0.003
Diastolic Blood Pressure(mmHg)	Paired t-test	-3.404	39	0.002

5.3. STRESS RECOVERY EFFECTS

Figure 4 and 5 show the median, quartiles, and maximum and minimum values of pre-test and post-test data for HR, DBP, SBP and STAI.

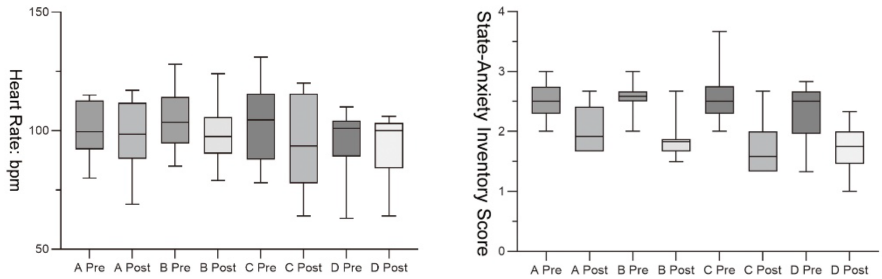


Figure 4. Pre-test and post-test of heart rate and blood pressure data among four scenarios

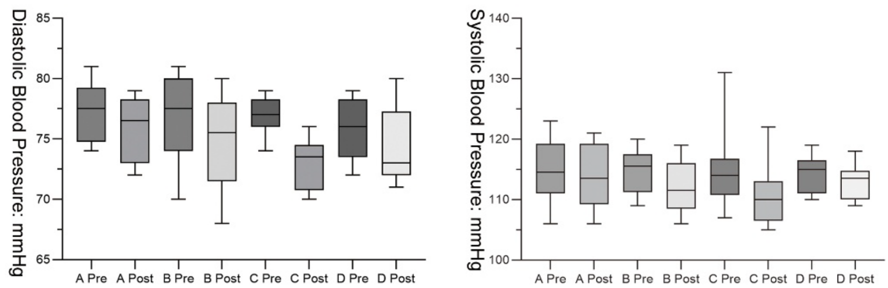


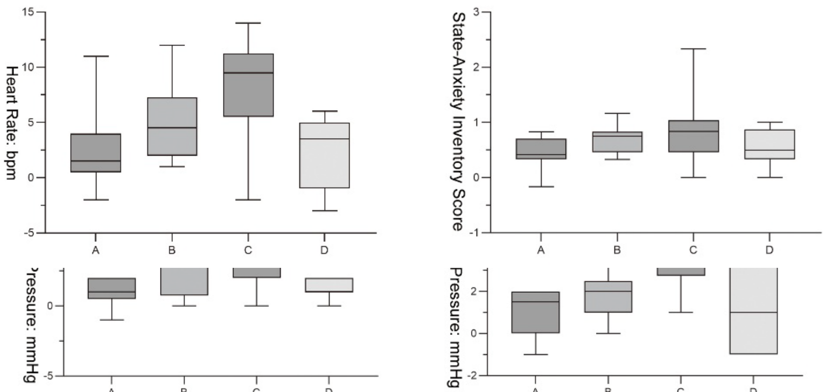
Figure 5. Pre-test and post-test of diastolic and systolic blood pressure data among four scenarios

The ΔD (ΔD = pre-test - post-test) of the psychological and physiological data was analyzed using a one-way ANOVA to investigate the differences in the stress recovery effects of the four scenarios on the participants (Figure 6 & Figure 7). Physiological data, i.e., HR, DBP and SBP showed statistically significant differences among the four scenarios ($p < 0.05$), while psychological data, i.e., STAI did not show statistically significant differences ($p = 0.201$). The ΔD of HR ($F = 5.558$, $p = 0.003$) showed that $C_{\text{medium-density}}$ ($M \pm SD = 8.300 \pm 4.644$) demonstrated the greatest stress recovery effect, followed by $B_{\text{low-density}}$ ($M \pm SD = 5.200 \pm 3.676$). $A_{\text{non-biophilic}}$ ($M \pm SD = 2.400 \pm 3.596$)

had poorer stress recovery than $B_{\text{low-density}}$, and the worst effect was observed in $D_{\text{high-density}}$ ($M \pm SD = 2.200 \pm 3.327$). The results of one-way ANOVA for STAI ΔD ($F = 1.623$, $p = 0.201$) showed that $C_{\text{medium-density}}$ ($M \pm SD = 0.850 \pm 0.631$) had the best stress recovery and the worst was $A_{\text{non-biophilic}}$ ($M \pm SD = 0.467 \pm 0.302$). $B_{\text{low-density}}$ ($M \pm SD = 0.700 \pm 0.258$) and $D_{\text{high-density}}$ ($M \pm SD = 0.583 \pm 0.326$) showed moderate stress recovery effects.

Figure 6. △D one-way ANOVA results for HR and STAI among the four scenarios

The results of the one-way ANOVA for SBP ΔD ($F = 5.562$, $p = 0.003$) indicated that $C_{\text{medium-density}}$ ($M \pm SD = 4.400 \pm 3.239$) achieved the greatest stress recovery among the four scenarios, followed by $B_{\text{low-density}}$ ($M \pm SD = 2.800 \pm 2.300$). $D_{\text{high-density}}$ ($M \pm$



$SD = 1.300 \pm 0.675$) showed poorer stress recovery than scenarios B and C, while $A_{\text{non-biophilic}}$ ($M \pm SD = 1.000 \pm 1.155$) exhibited the weakest recovery effect. ΔD of DBP ($F = 4.553$, $p = 0.008$) results showed that $C_{\text{medium-density}}$ ($M \pm SD = 4.100 \pm 1.969$) had the best stress recovery, followed by $B_{\text{low-density}}$ ($M \pm SD = 2.200 \pm 1.989$), $D_{\text{high-density}}$ ($M \pm SD = 1.500 \pm 2.550$) and $A_{\text{non-biophilic}}$ ($M \pm SD = 1.100 \pm 1.101$), respectively.

Figure 7. △D one-way ANOVA results for SBP and DBP among the four scenarios

6. Discussion

This study investigated the effects of different biophilic densities in transitional spaces on human stress recovery. Forty participants were randomly assigned to four VR scenarios: a non-biophilic space (control), low-density, medium-density, and high-density biophilic spaces. During the experiment, both psychological data (STAI) and physiological data (HR, DBP, SBP) were collected to evaluate the recovery effect across scenarios. The results revealed significant differences in HR, DBP, and SBP among the four scenarios ($p < 0.05$), indicating that biophilic density significantly affected physiological recovery, while the STAI differences were not statistically significant. Overall, the medium-density biophilic space demonstrated the most effective stress recovery, followed by the low-density, high-density, and non-biophilic conditions. These findings align with most previous studies conducted in indoor and outdoor environments, suggesting an inverted U-shaped relationship between biophilic density and stress recovery (Tekin et al., 2022; Suppakittpaisarn et al., 2023). Moderate biophilic elements most effectively promote physical and mental recovery, whereas excessive biophilic elements may induce visual clutter, a sense of spatial closure, and perceptual overload, thereby reducing their restorative effects.

This pattern can be interpreted through several environmental psychology frameworks. Specifically, the *Prospect–Refuge Theory* (Appleton, 1975) posits that humans are biologically inclined to seek a balance between prospect (an unobstructed view allowing for the detection of opportunities or threats) and refuge (a protected location offering concealment and safety). Medium-density biophilic spaces achieve an ideal equilibrium between openness and enclosure, promoting comfort and safety. In contrast, low-density or non-biophilic spaces may lack sufficient refuge, while high-density spaces may obstruct prospect. Additionally, *Environmental Load Theory* (Berlyne, 1971) provides a cognitive-based explanation. This framework posits that the level of environmental complexity is critical: environments that are too simple fail to provide the necessary stimulation for positive affective responses, whereas environments that are excessively complex increase the individual's cognitive and sensory load, ultimately hindering restorative processes. Thus, the medium-density biophilic space, with its optimal level of stimulus complexity, is best suited for facilitating both psychological and physiological stress recovery.

7. Conclusion

This study investigated the effects of varying biophilic design densities within transitional spaces on human stress recovery, in response to the growing environmental stress and health challenges associated with urbanization. The results revealed that the medium-density biophilic environment produced the most effective stress recovery, compared with low-density and high-density settings. This finding presents an inverted U-shaped relationship and can be understood through environmental psychology perspectives. Medium-density environments offer the optimal degree of sensory stimulation, which is greater than that provided by low-density environments, while also reducing the perceptual overload caused by excessive complexity in high-density environments. These findings offer important empirical insights for the biophilic design of transitional spaces. They demonstrate that optimizing the density of natural elements can enhance the restorative potential of built environments and contribute positively to public mental well-being in rapidly urbanizing contexts.

References

Al Horr, Y., Arif, M., Kaushik, A., Mazroei, A., Katafygiotou, M., & Elsarrag, E. (2016). Occupant productivity and office indoor environment quality: A review of the literature. Building and Environment, 105, 369–389. https://doi.org/10.1016/j.buildenv.2016.05.024

Appleton, J. (1975). *The experience of landscape*. London: Wiley.

Berlyne, D. E. (1971). *Aesthetics and psychobiology*. New York: Appleton-Century-Crofts.

Gao, L., & Mandryk, R. L. (2011). The acute effects of immersive virtual reality on cognitive performance. *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, 2657–2666. https://doi.org/10.1145/1978942.1979336

Gehl, J. (2011). *Life between buildings: Using public space* (6th ed.). Washington, DC: Island Press.

Gillis, K., & Gatersleben, B. (2015). A review of the psychological literature on the health and wellbeing benefits of biophilic design. *Buildings*, 5(3), 948–963. https://doi.org/10.3390/buildings5030948

Kellert, S. R. (2008). Dimensions, elements, and attributes of biophilic design. In S. Kellert, J. Heerwagen, & M. Mador (Eds.), *Biophilic design: The theory, science, and practice of bringing buildings to life* (pp. 3–19). New York, NY: Wiley.

Kirschbaum, C., Pirke, K. M., & Hellhammer, D. H. (1993). The 'Trier Social Stress Test'—A tool for investigating psychobiological stress responses in a laboratory setting. *Neuropsychobiology*, 28(1–2), 76–81. https://doi.org/10.1159/000119004

Li, Z., Huang, X., & White, M. (2022). Effects of the visual character of transitional spaces on human stress recovery in a virtual reality environment. *International Journal of Environmental Research and Public Health*, 19(20), 13143. https://doi.org/10.3390/ijerph192013143

Li, Z., Lee, J. H., Yao, L., & Ostwald, M. J. (2025). Impact of built environments on human perception: A systematic review of physiological measures and machine learning. *Journal of Building Engineering*, 112319.

Li, Z., Zu, X., Lee, J. H., & Ostwald, M. J. (2024). The impact of visual character on perceived stress levels: An intelligent approach applied to university campus design. In *Multimodality in Architecture: Collaboration, Technology and Education* (pp. 229–244). Cham: Springer Nature Switzerland.

Marteau, T. M., & Bekker, H. (1992). The development of a six-item short-form of the state scale of the STAI (STAI-S). *British Journal of Clinical Psychology*, 31(3), 301–306. https://doi.org/10.1111/j.2044-8260.1992.tb00997.x

Peters, K., Elands, B., & Buijs, A. (2010). Social interactions in urban parks: Stimulating social cohesion? *Urban Forestry & Urban Greening*, 9(2), 93–100. https://doi.org/10.1016/j.ufug.2009.11.003

Spielberger, C. D., & Gonzalez-Reigosa, F. (1971). *Manual for the State-Trait Anxiety Inventory*. Palo Alto, CA: Consulting Psychologists Press.

Suppakittpaisarn, P., Browning, M. H. E. M., & Sullivan, W. C. (2023). Vegetation density and restorative benefits: Evidence from a cross-cultural virtual reality experiment. *Landscape and Urban Planning*, 232, 104685. https://doi.org/10.1016/j.landurbplan.2023.104685

Tekin, B. H., Manavoglu, E., & Porras, E. (2022). A systematic review and conceptual framework of biophilic design in the built environment. *International Journal of Environmental Research and Public Health*, 19(9), 5338. https://doi.org/10.3390/ijerph19095338

Winnicott, D. W. (1971). *Playing and reality*. London, UK: Tavistock.

Yan, J., Diakité, A. A., Zlatanova, S., & Aleksandrov, M. (2019). Top-bounded spaces formed by the built environment for navigation systems. *ISPRS International Journal of Geo-Information*, 8(5), 224.