 https://doi.org/10.1051/e3sconf/202671608001

From Simulation to Space: Impacts of Green Coverage Ratio and Spaciousness on Occupant Well-being in a Semi-outdoor Atrium

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Abstract. Our previous study explored how green coverage ratio and spaciousness influence self-reported performance and mood using a virtual reality (VR) head-mounted display. A semi-outdoor atrium was built in Singapore in the tropical climate to reflect the optimal conditions identified through VR experiments. This study aims to evaluate the effects of green coverage ratio and spaciousness on occupants' self-reported performance and mood in the actual built environment, and to validate the prediction model developed from the VR study. A field survey was conducted in five locations within the atrium, each representing different combinations of high/low green coverage ratio and spaciousness from March to April 2024. Thirty-five occupants participated by completing a questionnaire after a 2-minute break during their working hours. We asked for their environmental satisfaction, moods, and self-reported performance such as work efficiency, mental fatigue and recovery. Temperature, relative humidity, illuminance, and noise level were measured during the experiment. The results showed that participants in high greenery spaces demonstrated higher visual comfort, concentration and more positive moods, as well as reduced mental fatigue, compared with the baseline workplace environment. Interestingly, even though air temperature was approximately 5 °C higher and noise levels were 6–8 dBA higher than in the workplace, occupants in the high greenery spaces reported feeling more comfortable both thermally and acoustically. The analysis further indicated that green coverage ratio tended to have a particularly strong effect on relaxed mood, while spaciousness tended to influence self-reported concentration and work efficiency. These findings support the notion that well-designed semi-outdoor environments with high greenery coverage ratio and sufficient spaciousness can promote psychological restoration and enhance workplace performance through strategies that optimize break intervals.

Keywords. Indoor environmental quality, Biophilic design, Occupant well-being, Post-occupancy evaluation

1 Introduction

Green buildings that enhance occupants' well-being has garnered attention in the market. In both LEED and WELL certification systems, biophilic design—which connects people with nature within the built environment—is encouraged [1-2]. Elements such as greenery and prospect are recognized as one of key components of biophilic design [3]. Ulrich [4] proposed the *Stress Recovery Theory*, suggesting that exposure to natural environments contributes to stress reduction. Several studies [5-6] have shown that natural elements such as indoor greenery and daylight can reduce stress and improve cognitive performance. Regarding prospect, the *Prospect–Refuge Theory* suggests that humans feel secure in spaces where they can both observe their surroundings and find opportunities for concealment; this concept has been discussed from architectural and interior design perspectives [7]. However, only a few studies have examined the combined effects of natural elements and spatial configuration on physiological and psychological responses. Furthermore, most previous research has been conducted in virtual environments, video-based settings, or chambers, with few examples investigating these effects in actual buildings.

In our previous study [8], we examined how variations in green coverage ratio (0%, 25%, 60%), room volume (two levels), and window size (two levels) influenced physiological and psychological responses in an atrium environment by using a VR head-mounted device. The results indicated that both the green coverage ratio and spaciousness contributed to improvements in visual comfort, moods, and self-reported productivity. Subsequently, we applied these findings to the design of an actual atrium in Singapore (SG). The aim of this study is to evaluate how green coverage ratio and spaciousness affect occupants' self-reported performance and mood in an actual environment, and to validate the predictive model that was developed based on our previous VR study.

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2 Methods

2.1 Measurement location

This study was conducted in a semi-outdoor space called Kajima Park (K/PARK), located within The GEAR Building, the headquarters of Kajima Corporation Singapore [9]. As shown in Figure 1, K/PARK is a two-story space measuring 62 m in width, 13.5 m in depth, and 3.5 m in height per floor. The space is flanked by air-conditioned office areas on the north and south sides, while large openings measuring 10 m × 3 m per floor are installed on the east and west façades to maximize natural ventilation potential from the two predominant monsoon wind directions of northeast and southwest. The K/PARK serves multiple functions—including a workspace, resting area, and social interaction activity zone—and provides flexibility for various uses. In addition, semi-outdoor decks are provided at both the eastern and western ends of the space, offering areas for meetings and relaxation. K/PARK is typically operated with natural ventilation and ceiling fans, and it is abundantly planted with greenery. The space functions as a biophilic environment within the office, allowing occupants to experience a close connection with nature in their daily work setting.

2.2 Participants

Table 1 summarized the experimental participants. A total of 35 office workers (25 males and 10 females) took part in the study. All participants had lived in Singapore for more than three years and had been employed in the target office for over one year and were therefore assumed to be acclimatized to the local environmental conditions. The experimental protocol was reviewed and approved by the Kajima Institutional Review Board. All participants were informed about the details of the experiment and provided written informed consent prior to participation.

2.3 Data collection

Air temperature and relative humidity were measured at a height of 1.1 m using a T&D data logger at 1-minute intervals (Figure 1). Illuminance was measured on the vertical plane at eye level of a seated person (1.2 m above the floor) using a T&D data logger at 10-second intervals. The A-weighted sound pressure level (LAeq) was measured at a height of 1.2 m using a RION sound level meter at 1-second intervals.

2.4 Questionnaire

Participants were asked to complete questionnaires on environmental satisfaction, mood, and self-reported performance—once before the break while in their

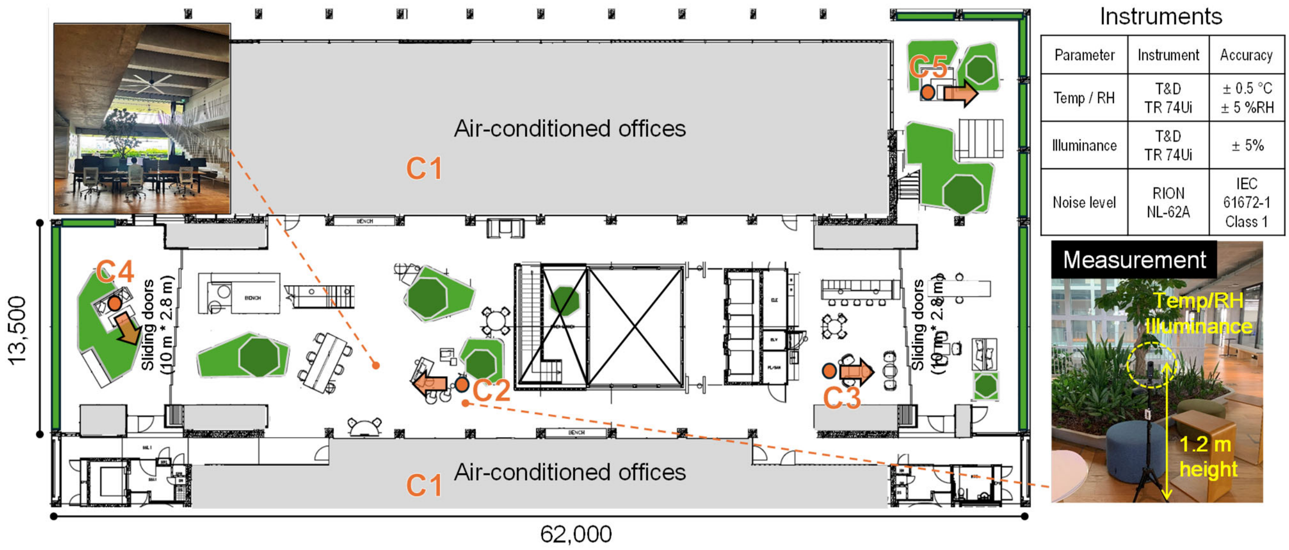


Fig. 1. Measurement location (K/PARK) and instruments.

Table 1. Anthropometric data.

Gender	Number	Age [yrs]	Height [m]	Weight [kg]	BMI [kg/m2]	Duration living in SG [yrs]	Clothing value [clo]
Male	25	41±11	1.74±0.06	72±10	23.9±2.8	13.9±12.7	0.45±0.06
Female	10	37±8	1.61±0.03	49±5	19.1±1.4	30.3±9.9	0.48±0.11
All	35	40±11	1.71±0.08	67±13	22.8±3.2	18.6±14.1	0.46±0.08

workplace, and again after the break at the resting location. Environmental satisfaction included assessments of thermal comfort, visual comfort, and acoustic comfort, each rated on a five-point scale (from *satisfied* to *dissatisfied*). Mood was evaluated using the circumplex model consisting of eight affective states—enthusiastic, dull, surprised, quiet, relaxed, nervous, pleased, and sad—rated on a five-point scale (4: *Extremely* – 0: *not at all*) [10–11]. Self-reported performance included seven indicators: alertness, easy to concentration, stress, work efficiency, mental fatigue, recovery, and favorable space for break, all rated on a five-point scale (4: *extremely* – 0: *not at all*).

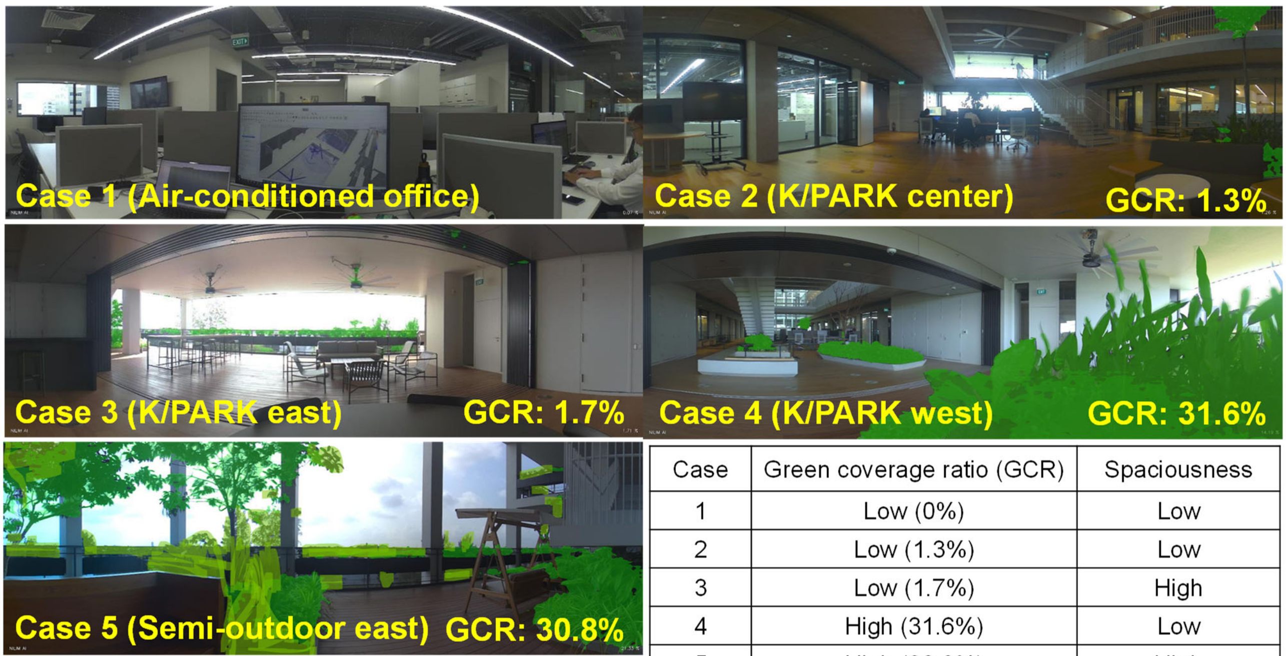
2.5 Procedure

The experiment was conducted from February 27 to May 8, 2024, starting at either 10:00 a.m. or 11:30 a.m in hot and humid climate. The experimental scenario assumed a short break taken after 1.5 or 3 hours of morning work beginning at 8:30 a.m. The experiment was conducted in the morning to control for circadian variations and to ensure stable physiological and psychological conditions after awakening. The experimental procedure was conducted as follows. First, participants completed a questionnaire on background information, environmental satisfaction, mood, and self-reported performance using a tablet while at their workplaces. Next, they moved to the designated resting area and took a two-minute break facing a planned field of view without any interferences from digital devices or people. Finally, they completed the same questionnaire again after the break.

The green coverage ratio was calculated as the ratio of the total green area visible within the analytical range, assuming a horizontal field of view of 180° and a vertical field of view of 60°, since participants were instructed to face forward during the break. At the experimental sites, 360° images were captured at 1.2 m height (eye level) using a RICOH THETA 360 camera, cropped to the specified viewing angles, and analyzed using an AI-based greenery detection program to determine the green coverage ratio [12]. The index of spaciousness was defined as the visual perception of openness, and was calculated from the average horizontal illuminance, room volume, and solid angle of window projection [13]. In this study, a BIM model identical to the experimental space was created, and spaciousness for each case was computed from the visible volume at the participant's viewpoint, the window solid angle projection, and the measured vertical illuminance. According to previous research [14], participants reported dissatisfaction when spaciousness was below 90, and satisfaction when it exceeded 150. As shown in Figure 2, five experimental cases were established: one control case (workplace) and four combinations of green coverage ratios (1%: low greenery; 30%: medium greenery) and openness levels (50: low; ≥100: high). The order of experimental cases was randomized, and all participants took part in every condition.

2.6 Data analysis

Differences in environmental satisfaction, mood, and self-reported performance before and after the break in each case were analyzed using the Kruskal–Wallis test



Case	Green coverage ratio (GCR)	Spaciousness
1	Low (0%)	Low
2	Low (1.3%)	Low
3	Low (1.7%)	High
4	High (31.6%)	Low
5	High (30.8%)	High

* Spaciousness low: 50-60, high: >100

Fig. 2. Experimental cases.

followed by Steel–Dwass post-hoc comparisons. A two-factor, two-level factorial design was employed, and a two-way ANOVA was conducted to evaluate the effects of green coverage ratio and spaciousness on environmental satisfaction, mood, and self-reported performance. The relationships among green coverage ratio, spaciousness, and psychological responses were examined using polynomial regression analysis based on the least squares method. The test statistic (Z) and effect size (Pearson's r) were calculated [15] to evaluate the strength of associations. Pearson's *r* was derived from Cohen's d, which had been obtained from the results of a one-way analysis of variance (ANOVA). According to conventional guidelines [15], Pearson's *r* values of 0.10, 0.30, and 0.50 were interpreted as small, medium, and large effect sizes, respectively. Cohen's f values of 0.10, 0.25, and 0.40 are interpreted as indicating small, medium, and large effects, respectively. A statistical significance level of 5% ($p < 0.05$) was adopted for all analyses.

3 Results and discussion

3.1 Physical environment

In the workplace (Case 1), the average environmental conditions were with an air temperature of 24.6 °C and 58% Relative Humidity (RH), with an illuminance of 735 lx as well as a noise level of 47 dBA, indicating a comfortable indoor environment (Table 2). In contrast, Cases 2–5 were in semi-outdoor spaces, where the temperature and humidity were approximately 30 °C and 70% RH, respectively. The center of semi-outdoor area in Case 2 had a relatively low illuminance of 299 lx being in the deepest part of the building, whereas the locations facing east from the semi-outdoor space in Cases 3 and 5 exhibited higher illuminance levels of 2,376 lx and 10,458 lx, respectively. The location surrounded by greenery in Case 4 had a moderate illuminance of 617 lx as it faced

Table 2. Environmental conditions.

Case	Temperature [°C]	Relative humidity [%]	Illuminance [lx]	Noise level [dBA]	Spaciousness
1	24.6 ± 0.6	58 ± 6	735 ± 366	47 ± 7	33 ± 19
2	29.6 ± 0.8	71 ± 6	299 ± 83	47 ± 2	43 ± 5
3	30.0 ± 0.9	68 ± 5	2376 ± 919	57 ± 3	107 ± 19
4	30.0 ± 0.7	67 ± 6	617 ± 424	53 ± 2	47 ± 11
5	30.9 ± 1.0	67 ± 7	10458 ± 3963	55 ± 3	375 ± 16

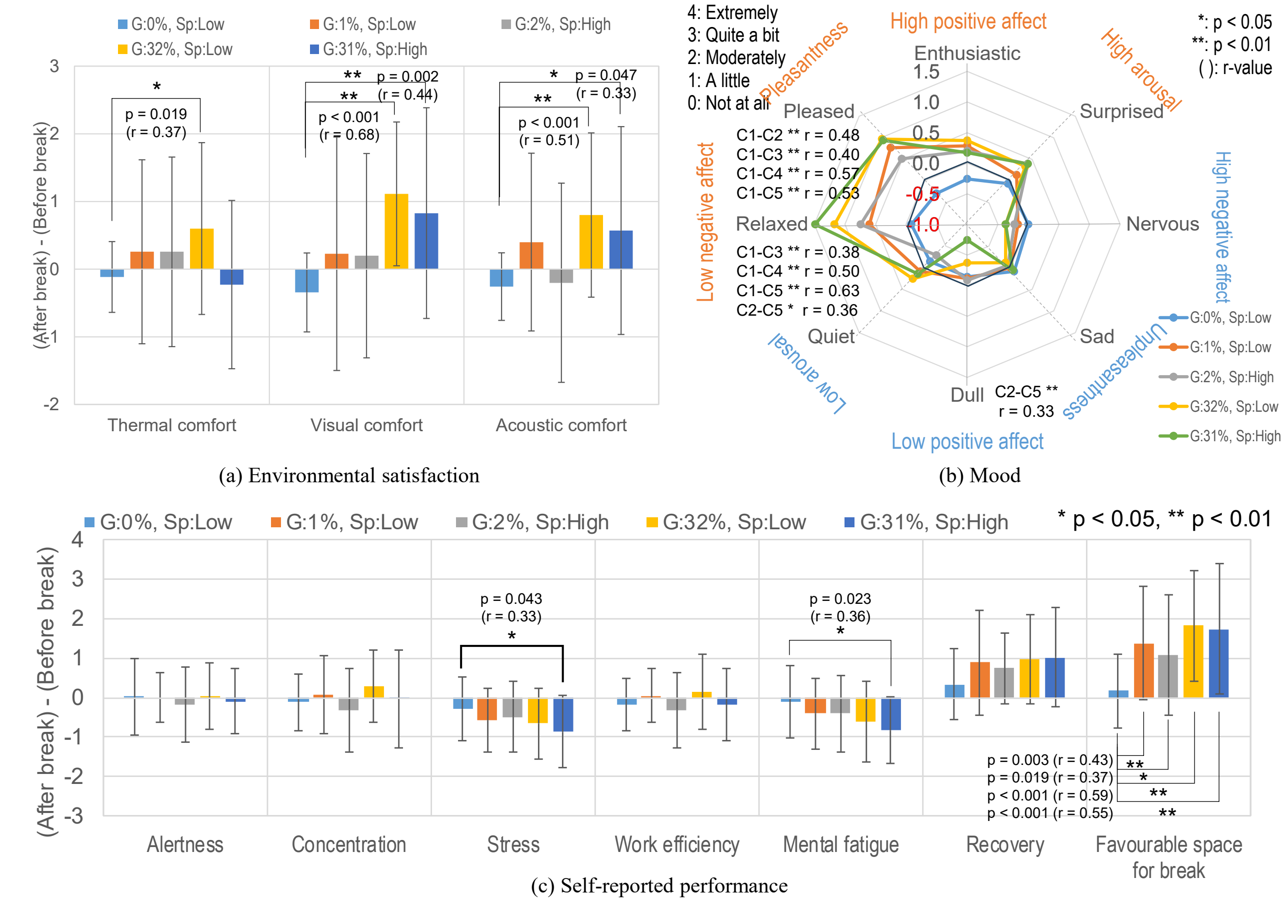


Fig. 3. Questionnaire results of environmental satisfaction, mood and self-reported performance.

inwards as opposed to Cases 3 and 5. The noise levels were higher near the openings to the outdoor environment, with Cases 3–5 recording 53–57 dBA, compared to the quieter Cases 1 and 2. The spaciousness, calculated from the visible volume at the viewpoint, the solid angle of window projection, and the measured vertical illuminance, was consistent with the intended design conditions. Cases 1, 2, and 4 showed low spaciousness values below 50, whereas Cases 3 and 5 exhibited high spaciousness values above 100. Case 5 especially, which had the highest illuminance, showed an average spaciousness value of 375.

3.2 Questionnaire results

Figure 3 illustrates the differences in environmental satisfaction, self-reported performance, and mood before and after the break for each case. Participants in spaces with high greenery (Cases 4 and 5) reported greater visual comfort compared with those in the workplace (C1-C4: $p < 0.001$, $r = 0.68$; C1-C5: $p = 0.002$, $r = 0.44$). This trend is consistent with the results of our previous VR study [8]. Participants in Case 4 reported higher thermal comfort levels than in Case 1 ($p = 0.019$, $r = 0.37$). This can be attributed to the higher wind speed from the west and the fact that the area was shaded from solar radiation in the morning. In addition, as suggested in [16], thermal adaptation may have broadened the acceptable comfort range in the semi-outdoor space. Interestingly, acoustic comfort in Cases 4 and 5 was also rated higher than in the workplace (C1-C4: $p < 0.001$, $r = 0.51$; C1-C5: $p = 0.047$, $r = 0.33$), even though the measured noise levels in Cases 4 and 5 (53–57 dBA) were higher than in Case 1 (47 dBA). A possible explanation is that, in Cases 4 and 5, the combination of natural sounds such as birds and insects with background traffic noise may have evoked a sense of nature, leading participants to perceive the environment as more pleasant. Moreover, similar to the adaptive thermal comfort model, moving to an outdoor setting may have lowered participants' acoustic expectations, thereby increasing tolerances to environmental noise.

Participants in the space with high greenery and high spaciousness (Case 5) reported lower stress ($p = 0.043$, $r = 0.33$) and mental fatigue ($p = 0.023$, $r = 0.36$) compared with those in the workplace (Case 1). A similar trend was observed in the VR study [8, 17], where spaces with abundant greenery and a high level of spaciousness were associated with reduced stress and enhanced recovery. In addition, all participants reported that the semi-outdoor spaces (Cases 2–5) were more favorable for taking a break than the workplace ($p \leq 0.019$, $r \geq 0.37$). Participants in the spaces with greenery (Cases 2–5) showed increased positive moods (pleased ($p \leq 0.006$, $r \geq 0.40$) and relaxed ($p \leq 0.024$, $r \geq 0.36$)) and decreased negative moods (dull (C2-C5: $p = 0.045$, $r = 0.33$)) compared with those in Case 1, which is consistent with the findings from the VR study [8, 17].

3.3 Parameter effect analysis

In Cases 2–5, a two-way analysis of variance (ANOVA) was conducted using two factors—green coverage ratio and spaciousness, each with two levels (high and low)—to examine their effects on the differences before and after the break in environmental satisfaction, mood, and self-reported performance (Table 3). The results indicated that green coverage ratio tended to have a considerable effect on relaxed mood ($p = 0.083$, $f = 2.39$), consistent with findings in previous studies [8, 17]. On the other hand, Spaciousness showed a notable tendency to influence both concentration ($p = 0.076$, $f = 1.40$) and work efficiency ($p = 0.053$, $f = 2.74$). These findings suggest that high spaciousness may support an optimal balance between prospect and refuge, as described in the prospect–refuge theory [7], thereby reducing the cognitive load associated with threat monitoring. As a result, attentional resources may be more readily directed toward tasks, enhancing concentration and work efficiency. Furthermore, from the perspective of attention restoration [18], extended views and visual exposure to natural elements may help alleviate directed-attention fatigue, consequently improving executive functioning and focus.

Table 3. DOE main effects summary (p-values and effect sizes, Cohen's f).

Parameter		Environmental satisfaction			Mood					
		Thermal comfort	Visual comfort	Acoustic comfort	Enthusiastic	Surprised	Relaxed	Pleased	Dull	Quiet
GCR	p	0.891	0.107	0.196	0.705	0.500	0.083+	0.222	0.263	0.258
	f	0.00	2.74	1.06	0.00	0.00	2.39	1.20	1.06	0.82
Sp	p	0.500	0.437	0.268	0.242	0.361	0.228	0.430	0.549	0.310
	f	0.00	0.11	0.55	1.27	0.61	0.31	0.23	0.00	0.55

- GCR : Green coverage ratio, Sp : spaciousness, * $p < 0.05$, + $p < 0.10$

Parameter		Mood		Self-reported performance						
		Nervous	Sad	Alertness	Concentration	Stress	Work efficiency	Mental fatigue	Recovery	Fav. Space for break
GCR	p	0.105	1.000	0.295	0.111	0.356	0.156	0.222	0.315	0.113
	f	2.96	0.00	0.33	0.66	0.70	0.32	1.28	0.88	2.16
Sp	p	0.500	0.705	0.126	0.076+	0.758	0.053+	0.500	0.742	0.315
	f	0.00	0.00	1.85	1.40	0.00	2.74	0.00	0.00	0.27

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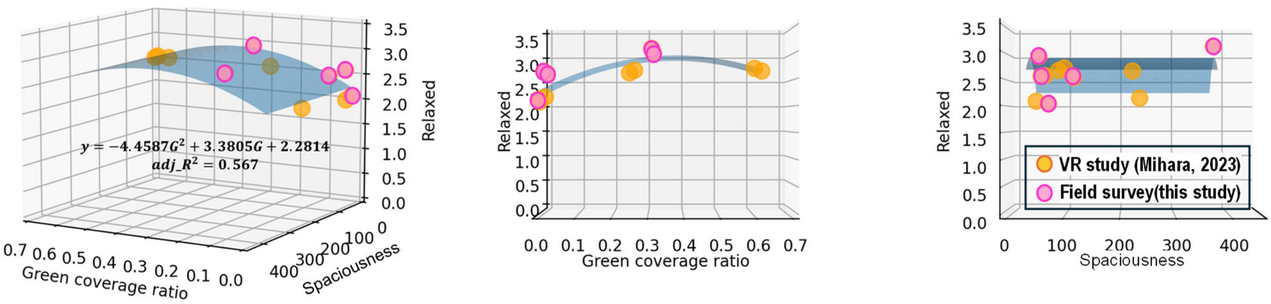
3.4 Prediction for environmental satisfaction, mood and self-reported performance

Figure 4 shows the relationships between green coverage ratio, spaciousness, and mean relaxed mood and recovery. The data include results from both the VR study [8] and this field survey. As in the previous analysis, the adjusted coefficient of determination (adjusted R^2) was calculated to avoid overfitting. Following the VR study, the effects of green coverage ratio and spaciousness on relaxed mood, and recovery were modeled using polynomial regression. Polynomial models were calculated both with and without spaciousness as an explanatory variable, and the model with the higher adjusted coefficient of determination (adjusted R^2) was adopted. In both relaxed mood (VR study: adj. $R^2 = 0.996$; this study: adj. $R^2 = 0.567$) and recovery (VR study: adj. $R^2 = 0.996$; this study: adj. $R^2 = 0.432$), the field survey showed lower explanatory power than the VR study, primarily due to greater variability observed at lower levels of green coverage. Similar tendencies were also observed for other indicators of environmental satisfaction, mood, and self-reported performance. The difference between the VR study and the field survey may be attributed to the limitations of optical reproduction in VR environments, such as the restricted representation of sky luminance, brightness, and contrast [19], and the tendency to underestimate perceived distance in virtual settings [20]. Moreover, unlike the VR study, which focused solely on visual stimuli, the field survey involved multi-sensory experiences—including thermal and acoustic sensations—that likely influenced participants' affective responses, as reflected in the observed differences in thermal and acoustic comfort (Fig. 3 (a)). Considering the relatively low predictive accuracy, future studies should explore alternative modelling approaches to better predict environmental satisfaction, mood, and self-reported performance based on green coverage ratio and spaciousness.

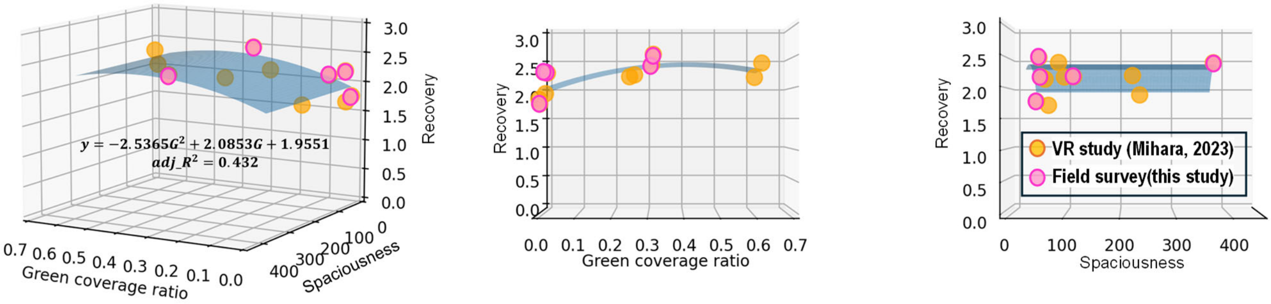
There are some limitations in this study. This study extends prior work by testing the approach in a real-world setting; however, the sample size (n=35) was modest, and several effects in the factorial analysis may be only marginally significant. In addition, the predictive model developed under VR conditions showed limited explanatory power in the field, suggesting that unmeasured confounding factors (e.g., concurrent thermal, acoustic, and lighting conditions, and variability in use context) may have influenced the outcomes. Finally, the analysis was largely based on between-condition comparisons and did not explicitly model inter-individual differences, and the 5-point ratings were treated as continuous outcomes, which may affect estimation accuracy and interpretation.

4 Conclusions

This study investigated the effects of green coverage ratio and spaciousness on occupants' environmental satisfaction, mood, and self-reported performance in an actual building environment. Participants in high greenery coverage ratio spaces reported higher visual comfort and more positive moods, along with reduced negative moods, compared with those in the workplace, which is consistent with the results of the VR study. Similarly, participants in spaces with both high greenery and high spaciousness showed significant reductions in stress and mental fatigue, again in agreement with the VR study findings. Interestingly, despite approximately 5 °C higher air



(a) Relaxed mood



(b) Recovery

Fig. 4. Relationship between green coverage ratio, spaciousness and mean relaxed mood, recovery and work efficiency.

temperatures and 6–8 dBA higher noise levels than in the workplace, participants in high greenery spaces reported higher thermal and acoustic comfort. This discrepancy may be attributed to the limitations of visual and acoustic reproduction in VR devices and the multi-sensory nature of the real-world environment. The two-way ANOVA revealed that the green coverage ratio tended to influence relaxed mood, while spaciousness influenced concentration and work efficiency. These findings suggest that in actual building spaces designed for restoration and relaxation—such as lounges, break spaces, and reception zones—enhancing green coverage can be beneficial. On the other hand, in task-oriented spaces that prioritize concentration and work efficiency, creating a sense of spaciousness through visual spaciousness or layout design may be more effective. Nevertheless, as the predictive performance of the current models based on green coverage ratio and spaciousness remains limited, further research is needed to develop more robust estimation and modeling approaches for predicting occupants' environmental satisfaction and psychological responses.

Acknowledgements: We thank the research assistant, Mr. Vincent Kyle from Kajima Corporation, for conducting the field survey.

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