Physiological and Mental Effects of Membrane-Structured Architectural Spaces

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***Abstract*—Membrane structures of architecture that provide a naturally bright light space are increasingly used for various facilities. In this study, we investigated the physiological and mental effects of membrane-structured architectural spaces by comparing them to conventional architectural spaces with a crossover study design. We observed that a membrane-structured warehouse reduces alertness, improves continuous performance, and causes positive subjective feelings, although there was no significant effect on operational accuracy, autonomic function, or sleep quality of the day.**

***Index Terms*— alertness, architectural space, autonomic nervous system, heart rate variability, membrane architecture, metal sheet, psychomotor vigilance, sleep quality, tent**

I. Introduction

Membrane structures are increasingly used for a wide range of architectures including those for sports, commerce, transportation, industry, and hospitality. Because membrane structures provide naturally bright light space due to their translucency, they are expected to have beneficial effects on biomedical factors and work/learning performances. However, there are few studies to examine such effects objectively. We performed a crossover study to investigate the differences in physiological and psychological parameters and work performance between conventional systems architectural space and membrane-structured architectural space.

II. Methods

This study was performed according to the protocol that was approved by the Ethics Review Committee of Nagoya City University Graduate School of Medical Sciences and Nagoya City University Hospital (No. 60-18-0211).

A. Subjects

We studied 14 healthy subjects who gave written informed consent to participate in this study. They were divided into groups A and B (Table I).

TABLE I. Subjects' Characteristics and Protocol

Group	N (female)	Age Median [IQR]	Day 1	Day 2
A	7 (1)	23 [22-38] y	Tent	Metal sheet
B	7 (1)	22 [21-45] y	Metal sheet	Tent

B. Protocol

Experiments were conducted in Miyagi prefecture, Japan for two days (day 1 and day 2) in August, separated by two weeks. As conventional system architecture and membrane structure warehouses, we used a tent warehouse and a metal-sheet warehouse, respectively. On day 1, subjects in groups A and B spent 11:00-15:00 in the tent warehouse and in the metal-sheet warehouse, respectively, and on day 2 in the other warehouse (Table I and Fig. 1).

On both days, the subjects underwent continuous electrocardiographic (ECG) monitoring for 24 hours until the next morning with a small wearable Holter ECG recorder (Cardy pico 303 plus, Suzuken Co. Ltd., Japan) attached on their chest wall. On both mornings and afternoons, we conducted the following three types of reaction tasks, an autonomous functional evaluation using a standing test, and a questionnaire on subjective feelings. In addition, subjective sleep quality was assessed when waking up the morning after each experimental day.

C. Measurements

Psychomotor vigilance test (PVT): For PVT, we used the software of PC-PVT [1] on a notebook personal computer (Let's note CF-S10, Panasonic Co., Osaka, Japan). The anticipation was set at 100 ms, deadline at 65000 ms, and minor lapse at 500 ms. PVT measures sustained or vigilant attention by recording reaction times (RTs) to visual stimuli occurring at random inter-stimulus intervals. The software presented abruptly a time counter on computer display that incremented the number at

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every 1 ms. In this study, the total trial time was set at 300 sec, during which 46 to 51 stimuli were presented. According to the earlier studies [2] , we measured the fastest and slowest 10th percentile RTs, difference between fastest and slowest RTs, and the number of short, minor, and major lapse frequencies (RTs ≥250 ms, ≥500 ms, and ≥1000 ms, respectively).

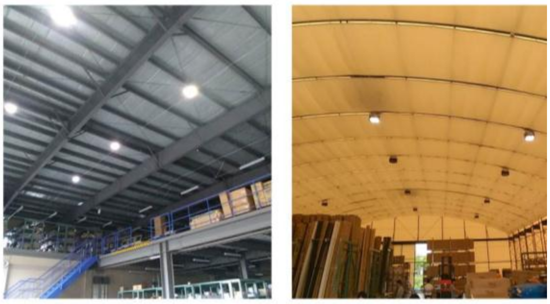

Figure 1. Metal-sheet warehouse (left) and tent warehouse (right)

Pedal-selective PVT (PS-PVT): We developed a system for PS-PVT [3]. It consisted of a notebook personal computer (Let's note CF-N10, Panasonic Co., Osaka, Japan), a three-pedal foot mouse (RI-FP3BK, Route-R co., Ltd., Tokyo, Japan), and custom-made software created with Microsoft Visual Basic (Microsoft, Co., USA). The software is available from the corresponding author on reasonable request. Initially, two horizontally arranged open circles with a diameter of 5 cm were displayed horizontally on the computer display with a center-to-center distance of 15 cm. Then, either one of the circles was lit at random order and interval (blue for the left circle and red for the right circle). The subjects were instructed to press a foot pedal with their right leg as prompt as possible when the circle illuminated. In parallel mode, they were asked to press the pedal ipsilateral to the lit circle, while in cross mode, they were asked to press the contralateral pedal. When the correct pedal was pressed, the light turns off immediately, but when the wrong pedal was pressed, the light did not turn off and instead the buzzer sounded until the correct pedal was pressed. The trial lasted 6 min, during which time the mode was switched between parallel and cross every min. During the cross mode, a cross mark appears on the display. The system recorded when and which circle was lit, when and which pedal was pressed, and the operation mode of the time. From these records, six indicators concerning the pedal response characteristics were calculated; average response time (RTs) excluding hesitation, relative frequency of wrong pedal to total responses (pedal error frequency), relative frequency of response freezing >3 s (hesitation frequency), mean RTs of hesitation (hesitation length), time to press correct pedal after wrong pedal (error correction time), and difference in RT between parallel and cross modes (cross-pedal RT difference).

Visual continuous performance test (VCPT): We developed a system for VCPT. It consisted of a notebook personal computer (Let's note CF-N10, Panasonic Co., Osaka, Japan), a mouse, and custom-made software created with Microsoft Visual Basic (Microsoft, Co., USA). The software is available from the corresponding author on reasonable request. The software presented a single digit (an integer from 0 to 9) in white color at a random interval. Subjects were instructed to click the mouse button only if the number was odd and not click if the number was even. If the mouse was clicked on an odd number or if the mouse was not clicked on an even number for 2 sec, the next number was displayed after a randomized interval. If the mouse was not clicked on an odd number within 2 sec or if the mouse was clicked on an even number, the number was displayed in red until the mouse was clicked (when the number was odd) or 2 sec passed (when the number was even). Then, the next number was displayed after a randomized interval. The test continued for 15 min and mean response time (RTs), SD of RTs, and error response frequency during the first, second, and last 5 minutes separately. VCPT was developed for evaluating sustainable working ability (response speed, attention, concentration) and its fluctuations.

Autonomic functions: We used a system (Kiritsu Meijin, Crosswell Co., Ltd., Japan) for evaluating the postural cardiovascular regulations. The system recorded continuous ECG and intermittent (every minute) blood pressure in a sitting position for 5 min and in an upright position for 5 min after active standing. Then, it analyzed low-frequency (LF, 0.04-0.15 Hz) and high-frequency (HF, 0.15-0.45 Hz) components of heart rate variability (HRV) and their responses to postural change.

We also analyzed average autonomic functions during the time in the warehouses (11:00-15:00) and during sleep of the experiment days by HRV analysis of Holter ECG data. HRV was analyzed separately for each period according to the published standard methods [4]. For ECG during sleep, we also analyzed cyclic variation of heart rate (CVHR) [5], an ECG maker of sleep apnea, with custom-made software [6]. We computed and the frequency and amplitude of CVHR as the estimates of frequency of apnea episodes [6, 7]and cardiac autonomic responsiveness to apneas [8], respectively.

Questionnaire on subjective feelings: We developed a questionnaire for this study. Using visual analog scales (VAS) between adjectives representing opposite emotions, we measured subjective emotions for the warehouse's indoor environment. The same questionnaire was conducted at the start, mid-term, and end of the experiment at each warehouse.

Subjective sleep quality: Subjective sleep quality was assessed with the Oguri-Shirakawa-Azumi sleep questionnaire MA version (OSA-MA sleep inventory) [9]. OSA-MA is a standardized sleep inventory consisted of 16 items of question with a 4-point Likert scale. It provided 5 factor scores concerning sleep qualities: less sleepiness on rising (factor 1), good initiation and maintenance of sleep (factor 2), less frequency of dreaming (factor 3), refreshing feeling (factor 4)), and subjective sleep length (factor 5). The factor scores had been standardized to have average ± SD of 50 ± 10 for the general population [9].

D. Statistical Analysis

Statistical analyses were performed with Statistical Analysis System program package (Version 9.4, SAS institute Inc., Cary, NC, USA). We used the Mixed procedure for crossover design, in which group (A and B), day (1 and 2), and warehouse structure (tent and metal sheet) were treated as fixed effects and subject as random effect. P <0.05 was recognized as statistically significant.

III. Results

A. Warehouse's Indoor Environment

Table II shows the indoor environmental parameters in the metal-sheet and tent warehouses on days 1 and 2. Illuminance was much brighter in the tent warehouse than in the metal-sheet warehouse, and in the tent warehouse, day 2 was brighter than day 1, while in the metal-sheet warehouse day 2 was darker than day 1. Temperature was higher on day 2 than day 1 in both warehouses, but on day 2, it was hotter in the tent warehouse than in the metal-sheet warehouse. Humidity was higher on day 1 than on day 2 in both warehouses.

TABLE II. Warehouse Indoor Environment

Day and time	Metal-sheet warehouse			Tent warehouse		
	Temperature °C	Humidity %	Illuminance lx	Temperature °C	Humidity %	Illuminance lx
Day 1						
11:00	27.6	79	303	27.6	79	1074
12:00	27.7	77	356	28.6	73	1704
13:00	28.8	76	382	29.3	70	2090
14:00	28.3	76	319	28.7	72	950
15:00	28.1	78	315	28.0	75	1416
Mean ±SD	28.1 ±0.4	77 ±1	335 ±29	28.4 ±0.6	74 ±3	1447 ±416
Day 2						
11:00	30.1	60	132	32.0	55	2753
12:00	30.1	62	54	32.5	55	2519
13:00	30.5	62	55	32.4	58	2281
14:00	30.7	62	65	32.2	59	1910
15:00	30.7	61	49	31.9	58	1757
Mean ±SD	30.4 ±0.3	61 ±1	71 ±31	32.2 ±0.2	57 ±2	2244 ±370

TABLE III. Comparisons of Psychomotor Vigilance Test (PVT)

PVT index	Warehouse structure		Significance of effect (*P*)			
	Metal sheet	Tent	Structure	Day 1/2	Group A/B	AM/PM
RTs median, ms	245 ±7	267 ±7	<0.0001	0.003	0.07	0.6
RTs longest 10th percentile, ms	367 ±2447	5289 ±2447	0.1	0.1	0.1	0.1
RTs shortest 10th percentile, ms	209 ±4	227 ±4	<0.0001	0.002	0.009	0.8
RTs range, ms	158 ±2447	5062 ±2447	0.1	0.1	0.1	0.1
Short lapses >250 ms	20.5 ±2.7	27.8 ±2.7	<0.0001	0.008	0.1	0.7
Minor lapses > 500 ms	1.1 ±0.3	1.3 ±0.3	0.6	0.3	0.7	0.6
Major lapses >1000 ms	0.3 ±0.1	0.1 ±0.1	0.4	0.7	0.8	0.7

RTs = response time.

B. PVT

The median and shortest 10-percentile values of RTs in PVT were shorted and the frequency of short lapses was higher in the metal-sheet warehouse than in the tent warehouse (Table III). There was interaction on the shortest 10-percentile RTs between structure and day; in the metal-sheet warehouse, it was shorter on day 1 than day 2, but it was shorter on day 2 in the tent warehouse (Table IV). These patterns suggest that group B subjects were more vigilant than group A subjects.

C. PS-PVT

Table V shows the results of PS-PVT. There was no significant difference in PS-PVT performance between metal-sheet and tent warehouses or between days 1 and 2. No significant interaction between warehouse structure and day (Table VI). Hesitation frequency and cross-parallel RT difference were greater in AM than in PM.

TABLE IV. Interactions of Warehouse Structure and Day on PVT

PVT index	Metal-sheet warehouse		Tent warehouse		*P*
	Day 1	Day 2	Day 1	Day 2	
RTs median, ms	225 ±10	265 ±10	272 ±10	262 ±10	0.05
RTs longest 10th percentile, ms	346 ±3461	388 ±3461	374 ±3461	10204 ±3461	0.1
RTs shortest 10th percentile, ms	191 ±6	226 ±6	234 ±6	220 ±6	0.003
RTs range, ms	155 ±3461	161 ±3461	140 ±3461	9984 ±3461	0.1
Short lapses >250 ms	13.8 ±3.9	27.3 ±3.9	30.3 ±3.9	25.2 ±3.9	0.08
Minor lapses > 500 ms	0.79 ±0.45	1.36 ±0.45	1.14 ±0.45	1.43 ±0.45	0.7
Major lapses >1000 ms	0.29 ±0.14	0.21 ±0.14	0.14 ±0.14	0.14 ±0.14	0.8

TABLE V. COMPARISONS OF PEDAL-SELECTIVE PVT (PS-PVT)

PS-PVT index	Warehouse structure		Significance of effect (*P*)			
	Metal sheet	Tent	Structure	Day 1/2	Group A/B	AM/PM
RTs, ms	549 ±18	556 ±18	0.4	0.7	0.2	0.6
Pedal error frequency	5.0 ±0.8	6.0 ±0.8	0.1	0.8	0.9	0.5
Hesitation frequency	0.08 ±0.05	0.11 ±0.05	0.5	0.1	0.8	0.01
Length of hesitation, ms	3632 ±507	3425 ±428	0.7	0.7	0.7	0.7
Correcting time, ms	1701 ±110	1616 ±108	0.3	0.4	0.2	0.1
Cross-parallel RT difference, ms	63 ±8	73 ±8	0.2	0.1	0.4	0.04

D. VCPT

Table VII shows the results of VCPT. While no significant effect of warehouse structure on VCPT performance during the first and second 5 min, RTs during the last 5 min was shorter in the tent warehouse than in the metal-sheet warehouse. Also, SD of RTs was longer on day 2 than on day 1 (Tables VII AND VIII).

TABLE VI. INTERACTIONS OF WAREHOUSE STRUCTURE AND DAY ON PS-PVT

PS-PVT index	Metal-sheet warehouse		Tent warehouse		*P*
	Day 1	Day 2	Day 1	Day 2	
RTs, ms	528 ±26	570 ±26	579 ±26	528 ±26	0.2
Pedal error frequency	5.1 ±1.1	4.8 ±1.1	6.0 ±1.1	5.1 ±1.1	0.9
Hesitation frequency	0.11 ±0.08	0.05 ±0.07	0.15 ±0.07	0.11 ±0.08	0.8
Length of hesitation, ms	3528 ±678	3736 ±754	3679 ±524	3528 ±678	0.7
Correcting time, ms	1622 ±158	1780 ±153	1755 ±153	1622 ±158	0.2
Cross-parallel RT difference, ms	64 ±11	63 ±11	83 ±11	64 ±11	0.4

TABLE VII. COMPARISONS OF VISUAL CONTINUOUS PERFORMANCE TEST (VCPT)

VCPT index	Warehouse structure		Significance of effect (*P*)			
	Metal sheet	Tent	Structure	Day 1/2	Group A/B	AM/PM
0-5 min						
RTs, ms	264 ±13	243 ±13	0.1	0.09	0.9	0.8
SD of RTs, ms	81 ±7	77 ±7	0.7	0.9	0.3	0.7
Frequency of error response, %	3.2 ±1.1	4.4 ±1.1	0.4	0.4	0.5	0.005
5-10 min						
RTs, ms	259 ±15	253 ±15	0.7	0.7	0.7	0.4
SD of RTs, ms	80 ±7	83 ±7	0.6	0.2	0.6	0.1
Frequency of error response, %	2.4 ±1.2	2.0 ±1.2	0.8	0.2	0.3	0.3
10-15 min						
RTs, ms	267 ±8	250 ±8	0.04	0.8	0.9	0.9
SD of RTs, ms	107 ±6	108 ±6	0.7	0.004	0.9	0.7
Frequency of error response, %	1.7 ±0.6	1.7 ±0.6	0.9	0.5	0.9	0.2

SD = standard deviation

E. Autonomic Functions

Table IX shows the results daytime and nighttime autonomic functions. There was no significant effect of warehouse structure on any autonomic indices for average during 11-15 h or in the sitting or upright position, but significant differences were observed between days 1 and 2. Heart rate was higher and HF power was lower on day 2 than on day1 particularly in the tent warehouse (Table X). The pattern was consistent with the effect of higher temperature in the tent warehouse on day 2.

In addition, median and basal heart rate was higher at night on day 2 than on day1 particularly after spending in the metal-sheet warehouse (Table X). The metal-sheet warehouse on day 2 is that it was the darkest.

F. Subjective Sleep Quality

Table XI shows the results of OSA-MA sleep inventory. There was no significant effect of warehouse structure on any factor scores, but subjective sleep length was significantly shorter on days 2 after spending in the metal-sheet warehouse (Table XII).

G. Sujective Feelings with VAS

Table XIII shows the results of the questionnaire for subjective feelings. Although significant effects of warehouse structure were observed on many items, there were significant interactions between structure and day on some of them (Table XIV), indicating the differences with structure may be caused by the effects of day and/or group on these items. The items without such interaction were Q1, Q5, and Q8; they showed that the tent warehouse was felt brighter, motivating, and active.

TABLE VIII. INTERACTIONS OF WAREHOUSE STRUCTURE AND DAY ON VCPT

VCPT index	Metal-sheet warehouse		Tent warehouse		*P*
	Day 1	Day 2	Day 1	Day 2	
0-5 min					
RTs, ms	277 ±18	250 ±18	255 ±18	231 ±18	0.9
SD of RTs, ms	85 ±10	77 ±10	73 ±10	82 ±10	0.3
Frequency of error response, %	3.4 ±1.6	3.1 ±1.6	5.4 ±1.6	3.4 ±1.5	0.5
5-10 min					
RTs, ms	252 ±21	266 ±21	254 ±21	251 ±21	0.7
SD of RTs, ms	72 ±10	88 ±10	81 ±10	85 ±10	0.6
Frequency of error response, %	4.3 ±1.8	0.4 ±1.8	2.2 ±1.8	1.7 ±1.8	0.3
10-15 min					
RTs, ms	267 ±11	267 ±11	251 ±11	248 ±11	0.9
SD of RTs, ms	100 ±9	114 ±9	103 ±9	114 ±9	0.8
Frequency of error response, %	1.9 ±0.8	1.5 ±0.8	1.8 ±0.8	1.6 ±0.8	0.9

TABLE IX. COMPARISONS OF AUTONOMIC FUNCTIONS

HRV index	Warehouse structure		Significance of effect (*P*)			
	Metal sheet	Tent	Structure	Day 1/2	Group A/B	AM/PM
Average between 11 and 15 h						
HR, bpm	78 ±2	80 ±2	0.5	0.1	0.3	-
SDNN, ms	88 ±6	84 ±6	0.1	0.2	0.6	-
LF power, ln(ms^2)	6.8 ±0.2	6.8 ±0.2	0.8	0.01	0.6	-
HF power, ln(ms^2)	5.4 ±0.3	5.4 ±0.3	0.9	0.04	0.7	-
LF/HF	4.5 ±0.5	4.5 ±0.5	0.8	0.4	0.9	-
DFA α_1	1.39 ±0.05	1.36 ±0.05	0.4	0.7	0.6	-
Sitting						
HR, bpm	75 ±3	75 ±3	0.8	0.008	0.3	0.3
LF power, ln(ms^2)	5.8 ±0.4	6.0 ±0.4	0.2	0.04	0.7	0.6
HF power, ln(ms^2)	4.8 ±0.5	4.9 ±0.5	0.3	0.005	0.9	0.8
LF/HF	4.9 ±1.5	4.2 ±1.5	0.5	0.8	0.9	0.7
SBP, mm Hg	122 ±5	118 ±4.5	0.1	0.8	0.9	0.06
DBP, mm Hg	71 ±3	72 ±3	0.5	0.4	0.6	0.5
Standing						
HR, bpm	84 ±4	85 ±4	0.6	0.0009	0.7	0.06
LF power, ln(ms^2)	5.5 ±0.5	5.6 ±0.5	0.6	0.09	0.6	0.2
HF power, ln(ms^2)	4.0 ±0.4	3.8 ±0.4	0.2	0.007	0.9	0.9
LF/HF	6.6 ±1.5	8.0 ±1.5	0.2	0.2	0.5	0.2
SBP, mm Hg	121 ±4	118 ±4	0.2	0.9	0.60	0.2
DBP, mm Hg	72 ±3	71 ±3	0.7	0.6	0.7	0.2
Nighttime						
HR, bpm	58 ±2	56 ±2	0.2	0.02	0.1	-
Basal HR, bpm	48 ±2	46 ±2	0.1	0.005	0.3	-
Fcv, cph	6.4 ±1.0	6.2 ±1.0	0.8	0.7	0.4	-
Acv, ln(ms)	5.1 ±0.1	5.2 ±0.1	0.2	0.03	0.7	-

HR = heart rate, SDNN = standard deviation of normal-to-normal R-R intervals, LF = low frequency, HF = high frequency, DFA = detrended fluctuation analysis, SBP = systolic blood pressure, DBP = diastolic blood pressure, Fcv = frequency of cyclic variation of heart rate, Acv = amplitude of cyclic variation of heart rate.

TABLE X. INTERACTIONS OF WAREHOUSE STRUCTURE AND DAY ON AUTONOMIC FUNCTION

HRV index	Metal-sheet warehouse		Tent warehouse		*P*
	Day 1	Day 2	Day 1	Day 2	
Average between 11 and 15 h					
HR, bpm	75 ±3	82 ±3	80 ±3	79 ±10	0.3
SDNN, ms	93 ±9	84 ±9	83 ±9	85 ±9	0.6
LF power, ln(ms^2)	6.9 ±0.3	6.8 ±0.3	7.1 ±0.3	6.6 ±0.3	0.6
HF power, ln(ms^2)	5.5 ±0.4	5.3 ±0.4	5.6 ±0.4	5.2 ±0.3	0.7
LF/HF	4.4 ±0.8	4.5 ±0.8	4.3 ±0.8	4.7 ±0.7	0.9
DFA α_1	1.38 ±0.07	1.41 ±0.07	1.39 ±0.07	1.33 ±0.07	0.5
Sitting					
HR, bpm	69 ±3	76 ±3	72 ±3	72 ±3	0.4
LF power, ln(ms^2)	5.6 ±0.4	5.7 ±0.4	6.2 ±0.4	5.5 ±0.4	0.4
HF power, ln(ms^2)	4.8 ±0.5	4.5 ±0.5	5.1 ±0.5	4.5 ±0.5	0.7
LF/HF	5.1 ±1.4	4.8 ±1.4	3.9 ±1.4	4.6 ±1.4	0.7
SBP, mm Hg	122 ±5	123 ±4	118 ±4	119 ±4	0.9
DBP, mm Hg	73 ±3	72 ±2	72 ±2	75 ±2	0.4
Standing					
HR, bpm	77 ±4	86 ±4	81 ±4	84 ±4	0.6

LF power, ln(ms^2)	5.2 ±0.4	5.4 ±0.4	5.8 ±0.4	5.0 ±0.4	0.3
HF power, ln(ms^2)	4.0 ±0.4	3.8 ±0.4	4.1 ±0.4	3.4 ±0.4	0.6
LF/HF	4.3 ±1.4	7.4 ±1.4	7.6 ±1.4	6.9 ±1.4	0.2
SBP, mm Hg	121 ±4	118 ±4	115 ±4	118 ±4	0.5
DBP, mm Hg	73 ±3	72 ±2	70 ±2	74 ±2	0.4
Nighttime					
HR, bpm	53 ±3	62 ±3	56 ±3	55 ±10	0.1
Basal HR, bpm	45 ±2	51 ±2	46 ±2	46 ±2	0.3
Fcv, cph	7.1 ±1.0	5.6 ±1.0	5.8 ±1.0	6.5 ±1.0	0.4
Acv, ln(ms)	5.2 ±0.1	5.0 ±0.1	5.2 ±0.1	5.1 ±0.1	0.7

TABLE XI. COMPARISONS OF SUBJECTIVE SLEEP QUALITY

Factor	Warehouse structure		Significance of effect (*P*)		
	Metal sheet	Tent	Structure	Day 1/2	Group A/B
F1: Less sleepiness on rising	44. 1 ±2.7	44.2 ±2.8	0.9	0.04	0.6
F2: Good initiation and maintenance	44.6 ±2.9	48.3 ±3.0	0.1	0.9	0.8
F3: Less frequency of dreaming	52.7 ±2.0	54.5 ±2.0	0.4	0.6	0.07
F4: Refreshment feeling	44.7 ±2.5	47.7 ±2.6	0.3	0.4	0.2
F5: Subjective sleep length	42.3 ±2.9	44.2 ±3.0	0.6	0.2	0.04

Data are standardized scores with an average of 50 and SD of 10 in the healthy general population [9].

TABLE XII. INTERACTIONS OF WAREHOUSE STRUCTURE AND DAY ON HEART RATE INDICES DURING SLEEP OF THE DAY

Factors	Metal-sheet warehouse		Tent warehouse		*P*
	Day 1	Day 2	Day 1	Day 2	
F1: Less sleepiness on rising	47.9 ±3.8	40.3 ±3.8	45.5 ±4.0	42.9 ±3.8	0.6
F2: Good initiation and maintenance	45.0 ±4.1	44.1 ±4.1	47.9 ±4.3	48.8 ±4.1	0.8
F3: Less frequency of dreaming	56.4 ±2.8	49.0 ±2.8	51.8 ±3.0	57.2 ±2.8	0.07
F4: Refreshment feeling	48.3 ±3.5	41.0 ±3.5	46.3 ±3.8	49.0 ±3.5	0.2
F5: Subjective sleep length	49.4 ±4.1	35.1 ±4.1	41.6 ±4.4	46.9 ±4.1	0.04

Data are standardized scores with an average of 50 and SD of 10 in the healthy general population [9].

TABLE XIII. COMPARISONS OF SUBJECTIVE FEELINGS WITH VISUAL ANALOG SCALE (VAS)

Item	Meaning		Warehouse structure		Significance of effect (*P*)			
	Small value	Larger value	Metal sheet	Tent	Structure	Day 1/2	Group A/B	Time
Q1	Bright	Dark	3.0 ±0.1	1.8 ±0.1	<0.0001	0.2	0.07	0.9
Q2	Feel breadth	Feel narrowness	2.8 ±0.1	1.8 ±0.1	<0.0001	0.001	0.1	0.7
Q3	Good lookout	Bad lookout	3.0 ±0.1	1.9 ±0.1	<0.0001	0.08	0.008	0.9
Q4	Feel refreshed	Feel depressed	2.8 ±0.2	2.3 ±0.1	0.04	0.2	0.009	0.7
Q5	Motivated	Not motivated	3.1 ±0.2	2.6 ±0.2	0.01	0.1	0.4	0.7
Q6	Comfortable	Uncomfortable	2.9 ±0.2	2.5 ±0.2	0.05	0.1	0.06	0.6
Q7	Easy to get ideas	Hard to get ideas	3.2 ±0.1	2.8 ±0.1	0.2	0.3	0.8	0.80
Q8	Feeling active	Feeling passive	3.0 ±0.1	2.4 ±0.1	0.001	0.1	0.07	0.7
Q9	Calm down	Restless	2.5 ±0.2	2.2 ±0.2	0.1	0.1	0.01	0.6
Q10	Sultry	Cool	2.0 ±0.2	2.1 ±0.2	0.4	0.05	0.08	0.7
Q11	Attention increases	Attention decreases	2.9 ±0.1	2.6 ±0.1	0.1	0.3	0.008	0.8
Q12	Feel tired	Not tired	2.1 ±0.2	2.1 ±0.2	0.9	0.4	0.2	0.003
Q13	Easy to see things	Difficult to see things	3.0 ±0.1	2.3 ±0.1	0.0008	0.3	0.003	0.7

TABLE XIV. INTERACTIONS OF WAREHOUSE STRUCTURE AND DAY ON VAS OF SUBJECTIVE FEELINGS

Item	Meaning		Metal-sheet warehouse		Tent warehouse		*P*
	Smaller value	Larger value	Day 1	Day 2	Day 1	Day 2	
Q1	Bright	Dark	3.1 ±0.2	3.0 ±0.2	1.5 ±0.2	2.1 ±0.2	0.05
Q2	Feel breadth	Feel narrowness	2.6 ±0.2	3.0 ±0.2	1.3 ±0.2	2.3 ±0.2	0.1
Q3	Good lookout	Bad lookout	3.1 ±0.2	2.9 ±0.2	1.4 ±0.2	2.4 ±0.2	0.002
Q4	Feel refreshed	Feel depressed	3.0 ±0.2	2.7 ±0.2	1.9 ±0.2	2.7 ±0.2	0.002
Q5	Motivated	Not motivated	3.0 ±0.2	3.1 ±0.2	2.3 ±0.2	2.8 ±0.2	0.3
Q6	Comfortable	Uncomfortable	2.9 ±0.2	2.8 ±0.2	2.1 ±0.2	2.8 ±0.2	0.04
Q7	Easy to get ideas	Hard to get ideas	2.9 ±0.2	3.1 ±0.2	2.7 ±0.2	2.9 ±0.2	0.8
Q8	Feeling active	Feeling passive	3.1 ±0.2	3.0 ±0.2	2.1 ±0.2	2.7 ±0.2	0.05
Q9	Calm down	Restless	2.7 ±0.2	2.2 ±0.2	1.7 ±0.2	2.7 ±0.2	0.003
Q10	Sultry	Cool	2.0 ±0.2	2.0 ±0.2	2.6 ±0.2	1.7 ±0.2	0.06
Q11	Attention increases	Attention decreases	3.2 ±0.2	2.7 ±0.2	2.3 ±0.2	3.1 ±0.2	0.002
Q12	Feel tired	Not tired	1.9 ±0.2	2.2 ±0.2	2.3 ±0.2	1.8 ±0.2	0.2
Q13	Easy to see things	Difficult to see things	3.3 ±0.2	2.8 ±0.2	1.9 ±0.2	2.8 ±0.2	0.0006

IV. Discussions

In this study, we investigated the effects of membrane-structured architectural spaces on biomedical indices, reaction task performance, and subjective feelings by comparing a tent warehouse and a metal-sheet warehouse.

Although this study employed a crossover design, the respectively, the sunshine was stronger and hotter on day 2 than on day 1. Due to translucent nature of membrane, the indoor illuminance was much brighter and temperature was higher in the tent warehouse particularly on day 2. Consequently, the statistical processing required careful considerations of the interactive effects between warehouse structure and day.

As a result, we found that the tent warehouse reduces vigilance, improves continuous performance, and gives brightness and motivating and active feelings. To confirm the findings of this study, comparative studies that match environmental factors are desirable.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

EY conducted the research; YY analyzed the data; JH wrote the paper; all authors had approved the final version.

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