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Research Article

Differences in Human Subjective and Objective Responses Depending on Concentrations of Indoor Air Chemicals

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Abstract

Background: The idea that adverse health effects such as sensory irritation and declining cognitive performance can be caused by exposure to indoor air pollutants is controversial because the occurrence of these symptoms depends largely on a person's sensitivity and state of mind. Therefore, the relationship between the indoor environment and adverse health effects needed to be explored using both subjective and objective data. In November 2017, two laboratory houses (LH) were built on the campus of Chiba University, Japan, to facilitate a new project called the "Chemiless Town Project Phase 3". The project was undertaken to investigate the impact of indoor environments on physical and mental health, with the goal of creating healthy indoor environments. The interior and exterior of the two LHs looked the same, but the concentrations of indoor air chemicals were different because the building and interior materials were different.

Method: From 2017 to 2018, 86 healthy volunteers participated in the experiment and evaluated the air quality of the LHs both objectively and subjectively. The objective evaluation methods included measuring brainwaves and heart rate variability. The subjective evaluation methods included asking participants to complete questionnaires while staying in the LH. Simultaneously, indoor air samples were collected from the LHs, and Volatile Organic Compounds (VOC) and aldehydes were analyzed.

Result: The mean concentrations of total VOCs (TVOC) in LHs A and B were 2269 and 76μg/m3, respectively. In the objective evaluation, there was a significant difference in participants' alpha brainwaves between the two LHs. In the subjective evaluation, there were differences in odor intensity, odor pleasantness, indoor air freshness, participants' comfort, and how relaxed the participants felt in each of the two LHs.

Conclusion: In this study, it was indicated that TVOC levels and the odor strength could affect human's quality of life such as indoor comfort and their degree of relaxation through objective and subjective methods.

Keywords: Indoor air quality; Brainwaves; Healthy indoor environment; Heart rate variability; Physical and mental health

Abbreviations: DNPH: 2,4-Dinitrophenylhydrazine; EPM: Environmental Preventive Medicine; GC: Gas Chromatography-Mass; GC-MS: Gas Chromatography-Mass Spectrometry; LH: Laboratory Houses; MVOC: Microbial Volatile Organic Compounds; PC: Personal Computer; QEESI: Quick Environmental Exposure and Sensitivity Inventory; SBS: Sick Building Syndrome; TVOC: Total Concentrations of Volatile Organic Compounds; VOC: Volatile Organic Compounds

Background

The indoor environment has significant impacts on human health [1-4] because almost all individuals living in developed countries spend more than 90 percent of their lives indoors [5]. However, the complexity of indoor environments, which Comprise Chemical, Biological, Physical, And Social Factors, makes the subject challenging. According to several studies, it has been suggested that indoor airborne chemicals and molds could cause Sick Building Syndrome (SBS) symptoms and some allergic symptoms [6-9]. Obviously, it is best to avoid chemical and biological exposure as much as possible to prevent such symptoms [10-13]. Reducing the number of chemicals that diffuse from building materials, furniture, electronic appliances, and other sources and molds in indoor residential air environment could be one of the effective ways to prevent SBS symptoms; However, the adverse health effects related to indoor air pollutants, including sensory irritation, fatigue, and difficulty of concentration, are not easy to quantify objectively. That is because the occurrence of symptoms or health disorders related to indoor air pollutants may depend largely on an individual's sensitivity and mental state [14-18]. It is one of the reasons that there is a lack of objective biomarkers relating symptoms to indoor environmental exposure. To clarify the difference between physical factors and mental factors, further exploration of the relationship between the indoor environment and adverse health effects using subjective and objective data is required [19,20].

The Centre for Preventive Medical Sciences of Chiba University (Chiba, Japan) started the "Chemiless Town Project" in 2007 to study the adverse health effects of exposure to indoor air pollution [21]. This project is based on the concept of Environmental Preventive Medicine (EPM), which attempts to prevent diseases caused by pollutants by improving the overall environment [22,23]. "Chemiless Town" is a small model town on the university campus; experiments are conducted there to apply the principles of EPM in a practical setting. Through this project, we have attempted to develop relevant evaluation methods for assessing indoor air quality based on the total concentrations of VOCs (TVOC) and odors. It became clear that building materials, construction methods, furniture, and housewares principally contributed to the concentrations of chemicals in indoor air. It also became clear that if the concentrations of TVOC and odors were sufficiently low, the number of individuals suffering from symptoms significantly decreased [24].

In 2017, two new LH were built in Chemiless Town to conduct a new project. The evaluation was performed using objective methods, including measuring participants' brainwaves while they complete tasks, and subjective methods, wherein participants completed self-report questionnaires while staying in each LH for approximately 90 minutes. Simultaneously, indoor air samples were collected from each LH and analyzed. The aims of this project were to investigate the impact of the indoor air environment on physical and mental health and to use our findings to contribute to the construction of healthy indoor environments in the future.

Method

Experimental design

As the first step of the project, a primary study was conducted from November 16, 2017 to July 05, 2018. This step was designed to monitor the brainwaves of participants while they performed three tasks (as instructed by a Personal Computer (PC): Single-digit addition, the N-back task, which is a working memory test, and a task involving deep breathing to help them relax) in the LHs. Simultaneously, the participants were asked to complete self-report questionnaires, including the Quick Environmental Exposure and Sensitivity Inventory (QEESI) questionnaire [25,26]. Indoor air samples from each LH were collected and analyzed on the morning of each experimental day, prior to the evaluation. The evaluation was performed using objective methods, such as the monitoring of brainwaves, and subjective methods, including the completion of self-report questionnaires. The experiments were conducted with a maximum of four people. Each LH had two rooms with identical environments. Each subject entered one of the rooms and conducted an experiment.

Test sites

In November 2017, two LHs, LH-A and LH-B, were constructed (Figure 1) in Chemiless Town as a part of the new project, which was named the "Chemiless Town Project Phase 3." While both the interior and exterior of the two LHs appeared the same, the concentrations of indoor air chemicals differed owing to different construction methods and building materials (interior and exterior): LH-A was timber framed, whereas LH-B was a light-gauge steel structure. There were two bedrooms and a living room in each LH; the bedrooms were used for this study.

Figure 1: Experiments for this study were performed in laboratory houses (LH). Upper left: LH-A (timber-framed structure); Upper middle: LH-B (light-gauge steel structure); Upper right: LH-A & LH-B (3D floor plans); bottom left: LH-A living room, bottom right: LH-B bedroom.

Indoor air sampling and analysis

Figure 2: Indoor air sampling and analysis. Left: active air sampling; Middle: the VOC analysis was performed using GC-MS; Right: the aldehyde analysis was performed using LC-MS.

Before air sampling, the windows and doors were kept open for 30 minutes for ventilation, after which they were closed for at least two hours (Figure 2). Starting at 13:00, indoor air samples were collected for 30 minutes by active sampling using pumps (Shibata MP-Σ30N and MP-Σ100HN, Shibata Scientific Technology Ltd. Saitama, Japan) in the two bedrooms of each LH. Simultaneously, environmental factors such as temperature and humidity were recorded. A total of 63 VOCs and 16 aldehydes were identified and analyzed (Table 1). Mechanical ventilation systems were operated in the rooms during sampling. Measurements were taken in accordance with the standard methods of air sampling and measurement issued by the Ministry of Health, Labor, and Welfare of Japan [27]. A Tenax TA thermal desorption tube (Supelco, Sigma-Aldrich Co. LLC, MO, United States) was used to capture the VOCs, and a 2,4-dinitrophenylhydrazine (DNPH) active gas tube (Shibata Scientific Technology Ltd. Saitama, Japan) was used to capture the aldehydes. Air passed through the Tenax TA and DNPH samplers at flow rates of 100 and 1000mL/min, respectively.

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Table 1: Volatile Organic Compounds (VOCs) and aldehydes analysed in this study.

63 VOCs		16 Aldehydes
2-Propanol	2-Butoxyethanol	Formaldehyde
Pentane	Nonane	Acetaldehyde
Methyl acetate	Tricyclene	Acetone
Dichloromethane	α-Pinene	Acrolein
1-Propanol	3-Ethyltoluene	Propanal
Ethyl acetate	Camphene	2-Butanone
Hexane	4-Ethyltoluene	Butanal
Chloroform	1,3,5-Trimethylbenzene	Benzaldehyde
1,2-Dichloroethane	2-Ethyltoluene	Cyclohexanone
2,4-Dimethylpentane	β-Pinene	Pentanal
1,1,1-Ttrichloroethane	1,2,4-Trimethylbenzen	Tolualdehyde
Butanol	Octamethylcyclotetrasi-loxane	Hexaldehyde
Benzene	Decane	Heptanal
Carbon tetrachloride	Isododecane	Octanal
Cyclohexane	p-Dichlorobenzene	Nonanal
1,2-Dichloropropane	2-Ethyl-1-hexanol	Decanal
Bromodichlorometh-ane	3-Carene	
Trichloroethylene	1,2,3-Trimethylbenzene	
2,2,4-Trimethylpen-tane	p-Cymene	
Heptane	Limonene	
4-Methyl-2-penta-none	4-Ethyl-1,2-dimethylben-zene	
Methylcyclohexane	Undecane	
Toluene	1,2,4,5-Tetramethylben-zene	
Dibromochlorometh-ane	decamethylcyclopentasi-loxane	
Butyl acetate	Dodecane	
Octane	Tridecane	
Tetrachloroethylene	Dodecamethylcyclohexas-iloxane	
Ethylbenzene	Texanol	
m, p-Xylene	Tetradecane	
Styrene	Pentadecane	
TXIB	Hexadecane	
o-Xylene		

The collected analytes of the VOCs were extracted by thermal desorption and analyzed by gas chromatography-mass spectrometry (GC-MS). A Turbo Matrix ATD650 gas chromatography system (Perkin Elmer Inc. MA, United States) was used to conduct the thermal desorption of the Tenax TA sampler. The analysis of VOCs was performed using an Agilent 5977A (GC7890B, MSD5977A) series mass selective detector (Agilent Technologies Inc. CA, United States) in the SCAN mode (m/z, 40-350). The split ratio was 20:1, and the transfer line temperature was 230 °C. A 30m×0.25mm column with a film thickness of 1.0μm (Agilent J&W DB-1) (Agilent Technologies Inc., CA, United States) was used as the GC analytical column.

Helium (Purity:>99.999999%) at a column flow rate of 1.0mL/min was used as the GC carrier gas. The GC oven temperature was maintained at 35 °C for five minutes and then increased to 240 °C at a rate of 10 °C/min. The analysis of aldehydes was performed using a Prominence UFLC pump with two LC-20AD liquid supply pumps, a SIL-20AC auto sampler and an SPD M20A photodiode array detector (Shimadzu Co., Kyoto, Japan). A 150mm×4.6mm I.D. Ascentis RP-Amide column with 2.7μm particle size (Sigma-Ardrich Co. LLC, MO, United States) was used. The flow rate was 1.0mL/min, and the mobile phase was a mixed solution of acetonitrile/water at 40/60 (solution A) and 80/20 (solution B). This flow rate was maintained for 30 minutes with 100% solution A followed by 55 minutes with 25% solution B, after which solution B was increased to 100% and maintained for five minutes.

The quantification limit for each of the chemicals was 1.0μg/m^3. The concentration level of each compound was calculated using its response factor. In this study, TVOC was calculated as the toluene equivalent of all substances with carbon lengths from C6(n-Hexane) to C16(Hexadecane).

Evaluation by human sensory perception

Between November 16, 2017 and July 05, 2018, 34 healthy female and 52 healthy male volunteers were recruited to evaluate the indoor air quality of the LHs based on sensory perception. Before the evaluation, the aims of the study and test procedures (Figure 3) were explained to each participant and their informed consent was obtained.

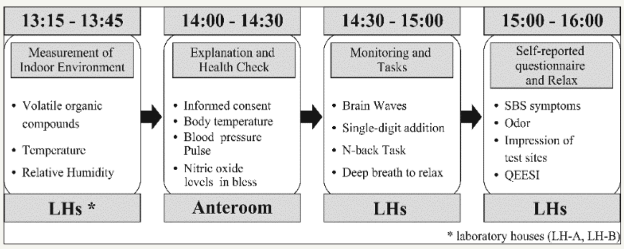

Figure 3: Test procedure of the preliminary study.

The body temperatures, systolic/diastolic blood pressures, and pulses of each participant were measured before the experiments in the anteroom. The participants then entered the LH and stayed there for approximately 90 minutes. Almost all of the experiments were conducted with four participants simultaneously, one per bedroom. Each participant was seated in front of a PC, wearing sensory bands (two electrodes) to measure brainwaves at their forehead. Brainwaves were measured using a BrainPro FM-929 brainwave analyzer (Futek Electronics Co., Ltd. Yokohama, Japan) for over 30 minutes. Electroencephalography is a medical imaging technique used to reflect brain state or activity [28].

While brainwaves were monitored, the participants performed three tasks as instructed by the PC: single-digit addition, the N-back task, which is a working memory test, and a task involving deep breathing to help them relax. Additionally, each participant completed a questionnaire on SBS symptoms, odor, and their impressions of the test site (Figure 4). After the QEESI questionnaire was answered on the PC, each participant relaxed on a chair or bed. The QEESI questionnaire is a tool to screen for the sensitivity to chemcals [25,26]. The criteria for the classification of sensitivity were described by Hojo et al. [29,30]. In the present study, "QEESI (+) Positive" means "More Sensitive to Chemicals" and "QEESI (-) Negative" means "Less Sensitive to Chemicals." The self-report questionnaire investigated indoor air quality using questions about the perceived strength of odor, preference of odor, indoor air freshness, indoor comfort, and how relaxed the participants felt. Strength of odor was scored from 1 to 6 (1: Odorless; 2: Slight odor; 3: Weak odor; 4: Distinct odor; 5: Strong odor; 6: Pungent odor). Preference for odor was scored from 1 to 5 (1: Very pleasant; 2: Pleasant; 3: neither Pleasant nor Unpleasant; 4: Unpleasant; 5: Very Unpleasant). Indoor air freshness was scored from 1 to 5 (1: Stagnant; 2: somewhat Stagnant; 3: neither Fresh nor Stagnant; 4: somewhat Fresh; 5: Fresh). Indoor comfort was scored from 1 to 5 (1: Uncomfortable; 2: Slightly Uncomfortable; 3: neither Comfortable nor Uncomfortable; 4: Slightly Comfortable; 5: Comfortable). Finally, the participants' level of relaxation was scored from 1 to 5 (1: Very Tense; 2: somewhat Tense; 3: neither Relaxed nor Tense; 4: somewhat Relaxed; 5: Very Relaxed) (Figure 5).

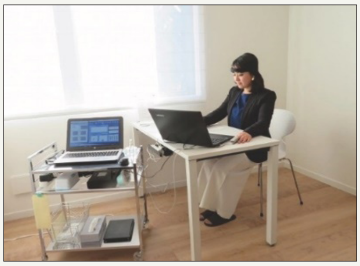

Figure 4: Experimantal conditions.

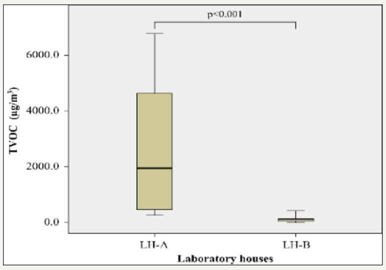

Figure 5: Comparison of the TVOC values of each LH.

Statistical analysis

The data from all of the participants were statistically analyzed. To determine the statistical differences in TVOC concentrations, objective parameters (i.e., Brainwaves), and subjective parameters (i.e., Questionnaire Responses) between the LHs, the Mann-Whitney U-test was used. A p-value of<0.05 was considered statistically significant. SPSS version 25 for Windows (SPSS Inc., Chicago, IL, United States) was used to perform the statistical analyses.

Result

Participants and indoor environmental factors

Table 2: Characteristics of the participants.

Total LH-A			Laboratory Houses (LHs) LH-B			
	n=86		n=42		n=44	
	N	%	N	%	N	%
Age (Years)						
20-29	41	45.6	22	50	19	41.3
30-39	20	22.2	8	18.2	12	26.1
40-49	16	17.8	8	18.2	8	17.4
50-59	9	10	4	9.1	5	10.9
≧60	0	0	0	0	0	0
Age (mean ± SD)	(33.9 ± 12.5)		(33.1 ± 12.1)		(34.8 ± 12.9)	

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Sex						
Male	52	57.8	28	63.8	24	52.2
Female	34	37.8	14	31.8	20	43.5
QEESI						
Low (-)	50	57.8	28	63.6	22	52.2
High (+)	36	40	14	31.8	22	47.8

Table 2 shows the characteristics of the participants in this study. A total of 42 participants (14 Females and 28 Males) evaluated the indoor air quality of LH-A, and 44 participants (20 Females and 24 Males) evaluated that of LH-B. The mean ± standard deviation age of the participants was 33.9±12.5 years. A total of 36 participants (40percent) were found to be more sensitive to chemicals based on the QEESI questionnaire.

Objective parameters (α/β Brainwaves)

As an objective parameter of the degree of relaxation, the participants' α/β brainwaves were measured (Figure 6). The means of α/β brainwaves during the early part of Task 1 (Single-Digit Addition, 0-5min) were 1.75 in LH-A and 1.79 in LH-B. During the last part of Task 1 (single-digit addition, 5-10min), they were 1.77 in LH-A and 2.04 in LH-B. During Task 2, the N-back for 0-5min in LH-A was 1.74; in LH-B it was 1.81. During Task 2, the N-back for 5-10min in LH-A was 1.69; in LH-B it was 1.64. During Task 3, deep-breath relaxation for 0-5min in LH-A was 2.23; in LH-B it was 2.48. Finally, during Task 3, deep-breath relaxation for 5-10min in LH-A was 2.54; in LH-B it was 2.88. In most cases, there was a significant difference in α/β waves between participants in LH-A and those in LH-B ($p<0.05$).

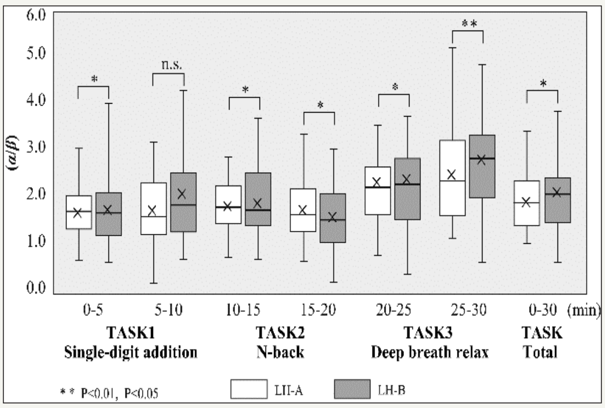

Figure 6: Comparison of the α/β waves of each LH.

Subjective parameters (questionnaire survey on indoor air quality)

Mean scores for the strength of odor for LH-A was 3.64; for LH-B it was 2.13. Preference of odor of for LH-A was 1.28; for LH-B it was 2.07. The indoor air freshness score for LH-A was 2.98; for LH-B it was 3.41. Indoor comfort of LH-A was 3.47, LH-B was 4.09. Participants' level of relaxation in LH-A was 3.56; for LH-B it was 3.83 (Figure 7).

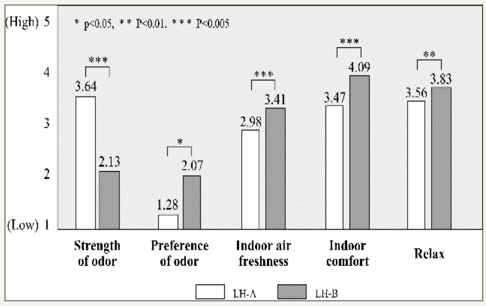

Figure 7: Comparison of the of indoor air quality questionnaires of each LH. There were significant differences ($p<0.05$) between LH-A and LH-B with respect to the participants' evaluations of odor strength, odor pleasantness, indoor air freshness, their comfort, and how relaxed they felt.

Discussion

In the present study, the relationship between indoor air quality and its health effects was examined by objective and subjective methods in two LHs. Indoor environmental factors such as the concentration of VOCs, temperature, and relative humidity were measured. There were significant differences in the concentrations of airborne chemicals between the two LHs. Participants indicated that odor strength was comparatively greater in LH-A, which had higher concentrations of TVOC than LH-B. They also indicated that they could be more "Relaxed" and felt more "Comfortable" in LH-B compared with LH-A. In addition, their "α/β Brainwaves" were higher during their stay in LH-B compared with LH-A. These two LHs had almost the same appearance, and there were no significant differences in environmental factors except for the TVOC concentration values. In this study, the difference in the TVOC values was considered to be one of the causes of the significant difference in the participants' evaluations on "Relax" and "Comfortable.". That is, the low concentration of TVOC may have contributed to the participants' positive evaluation of indoor comfort for LH-B.

In our previous study, it was also revealed that odor strength significantly correlated with SBS symptoms, particularly among sensitive people [24]. In the present study, there was a significant difference in the concentration of airborne VOCs between the two LHs and participants could distinguish a corresponding difference in odor strength. Several combinatons of VOCs frequently result in strong odors. It sometimes induces complaints and claims of SBS symptoms by occupants of houses with high TVOC concentrations [24,31,32]. There is also a study indicating that chemical exposure could result in poorer cognitive performance and odors being perceived as more unpleasant [33,34]. The odor strength, as well as TVOC levels, may have affected participanmts' indoor comfort and their degree of relaxation.

Conclusion

In this study, it was indicated that TVOC levels and the odor strength could affect human's quality of life such as indoor comfort and their degree of relaxation through objective and subjective methods. For the next step of our project, we plan to explore further and analyze indoor air quality using a wider variety of participants and additional variables, such as ventilation frequency (Table 3), noise, lighting, and the presence of indoor greenery to clarify the relationship between the indoor environment and its effects on human health. Because the research is in an indoor environment and focuses on human physical and mental health, we should consider not only airborne chemicals but also issues such as the environment's design, light, noise, and feelings of relief in order to prevent the occurrence of SBS symptoms or the exacerbation of allergy symptoms [4,35-37]. Our ultimate goal is to construct a healthy indoor environment that will allow people to enjoy long and healthy lives.

Table 3: Conditions in the indoor environments.

		LH-A			LH-B		
		Mean	Max	Min	Mean	Max	Min
TVOC	(µg/m^3)	2269	6774	269	76	334	N.D.
Temperature	(°C)	24	28.7	21.2	23.7	29.3	15.3
Humidity	(%)	54.3	72.4	24.6	54.4	77.4	24.7
Noise	(dB)	46.1	60.1	34.1	45.9	54.5	38.5
Illumination	(Lx)	147.8	268.1	130.2	138.7	278.4	127.5
Air pressure	(hPa)	1009	1022	992	1008	1021	991
CO_2	(ppm)	721	1071	470	720	1060	405

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