Combined effects of the thermal-acoustic environment on subjective evaluations in urban squares

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Abstract[1]: Because human beings live in an environment in which various factors interact, it is necessary to study the effects of these factors on environmental evaluations. This study employs a questionnaire survey to explore the effects of the thermal-acoustic environment in urban squares on subjective evaluations (thermal evaluations, acoustic evaluations, and overall comfort) in severe cold regions. It also evaluates and predicts equivalent overall comfort under different conditions of the thermal-acoustic environment. The results indicate that with respect to thermal evaluations, a higher temperature causes a significant increase in thermal sensation in all the three seasons (summer, the transitional season, and winter) while traffic noise causes a slight increase in thermal sensation only in summer. Meanwhile, both temperature and traffic noise affect thermal comfort in all three seasons, with higher traffic noise causing lower thermal comfort. With respect to acoustic evaluations, higher traffic noise results in a more negative evaluation of subjective loudness and acoustic comfort, while the low temperature in winter and high temperature in summer increase acoustic discomfort. However, the interaction of temperature and traffic noise has an effect on acoustic comfort only in summer. In addition, temperature significantly affects overall comfort in all three seasons, while traffic noise has an effect only in the transitional season and summer; however, their interaction affects overall comfort only in winter.

Keywords: severe cold region, urban squares, temperature, traffic noise, combined effects, subjective evaluations

1. Introduction

Although considerable research has been conducted on subjective evaluations with regard to connecting human sensation and comfort with different levels of specific environmental factors, research on the

[1]Abbreviations: TSV: Thermal Sensation Vote; TCV Thermal Comfort Vote; SLV: Subjective Loudness Vote; ACV: Acoustic Comfort Vote; OCV: Overall Comfort Vote; UTCI: Universal Thermal Climate Index; LAeq: A weighted equivalent continuous sound level; ANOVA: Analysis of Variance; S.D.: Standard deviation.

combined effects of various factors is still insufficient. As human beings live in an environment in which many factors constantly interact, research into the effect of a single factor on human sensation or comfort cannot perfectly represent their authentic evaluations of the environment; thus, it is necessary to study the effects of multiple factors on the environmental evaluations of human beings.

In terms of the effects of multiple factors on environmental evaluations, there has been considerable research about the effects of multiple factors on acoustic evaluations. Some studies have pointed out that human beings' visual sensation had an effect on acoustic sensation: Southworth discovered that in a visual-acoustic environment, focusing on the visual landscape will lead to a reduction in acoustic sensation and vice versa [1]. Carles et al. discovered that the greater the number of urban landscapes, the more complex the corresponding acoustic sensation became [2]. Maffei et al. found that when wind turbines were farther in distance, smaller in number, and green or white in colour, people better endured the noise they made [3]. Liu et al. analysed the effect of the physical characteristics of a visual landscape on the evaluation of the sound landscape in urban parks [4]. Ren and Kang found that visual factors, such as waterscape types and distance from people affect acoustic comfort [5]. Meanwhile, some previous studies revealed that the thermal environment had a certain effect on the evaluation of the sound landscape: Zhang and Kang pointed out that among all factors involved in the evaluation of the sound landscape in an open space, including environmental (temperature, lighting, brightness, wind, etc.), visual, and acoustic factors, environmental factors were most significant [6]. Yu and Kang indicated that discrepancies in temperature, humidity, and illumination might have an effect on the evaluation of the sound landscape [7]. Some other scholars studied the effect of odour on acoustic sensation: Jiang et al. studied its effect on the evaluation of traffic noise and found that odours had the potential to adjust the sensation of traffic noise and the visual landscape [8]. Ba and Kang demonstrated that the existence of odour hardly had any effect on the evaluation of birdsong or low-volume sound, but in certain other conditions, a higher odour concentration resulted in a more positive evaluation [9].

With regard to the combined effects of the thermal-acoustic environment, some scholars have studied the effects of temperature and noise on sensations of the indoor physical environment and on human performance [10-14]. Regarding the effects of the thermal-acoustic environment on human comfort, Fanger et al. found that colour or noise had no significant effect on thermal comfort [15]. Nagano and Horikoshi indicated that thermal conditions significantly affected noisy/quiet sensations. While temperature showed a slight effect on acoustic comfort, temperature and noise significantly affected overall comfort and thermal comfort/discomfort. Meanwhile, studies also showed that the noise level caused a slight increase in thermal sensation [16, 17]. Pellerin and Candas revealed that noise could alter thermal comfort in warm conditions. Besides, acoustic sensation would decrease when the thermal environment greatly deviated from thermal neutrality; with an increase in the noise level, the unpleasantness of the thermal environment would be intensified regardless of the ambient temperatures [18, 19]. Yang and Moon showed that noise had no effect on thermal sensation and the thermal environment had no effect on loudness and noisiness. However, either the effect of noise levels and types on thermal comfort or that of the predicted mean vote on acoustic comfort and annoyance was significant [20]. In addition, some scholars studied the effects of multiple factors including temperature and noise on human comfort [21, 22]. Horie et al. studied the combined effects of multiple factors including acoustic and thermal conditions on subjective comfort and found that the negative effect caused by the increase in indoor temperature from 27 ℃ to 30 ℃ was the same as that caused by an increase in the noisiness level from 40 dB to 70 dB [23]. Clausen et al. explored the effects of air quality, noise, temperature, and odour on human comfort and found that within the temperature range of 23 ℃ to 29 ℃, the effect of a temperature change of 1 ℃ was the same as that of an air quality change of 2.4 decipol or a noise level change of 3.9 dB [24]. Huang et al. suggested that people's satisfaction with temperature and noisiness could override their satisfaction with the entire indoor environment; for example, even when the illumination surpassed the tolerable range, the entire environment could still be regarded as tolerable [25]. Yang and Moon indicated that in steady-state thermal and illumination conditions with time-varying sound stimuli, the effect of acoustic factors was greatest on indoor environmental comfort [26].

A summary of the methods of previous studies reveals that researchers usually select experimental chambers or controllable indoor environments as research sites to explore the effects of the thermal-acoustic environment on the subjective evaluations of human beings. Because these sites have a relatively stable thermal environment and the factors can be well controlled, no studies have yet been conducted on the subjective evaluations of human beings under different thermal-acoustic conditions in a real outdoor environment. Urban squares, one of the main public spaces for residents to engage in daily activities, were chosen as the outdoor research sites in this study. Generally speaking, an urban square connects the main road with the sub-main road, which is greatly affected by traffic noise. Meanwhile, owing to the dramatic variations in temperature throughout the year, there are significant discrepancies in the thermal environment of the urban squares in different seasons in severe cold regions, resulting in effects on the environmental evaluations of residents. Therefore, considering the number of subjects, the condition of the thermal-acoustic environment, the demand for improvement, and other factors, urban squares in severe cold regions are conducive to studying the subjective evaluations of human beings under different thermal-acoustic conditions. It is noted that, although the state of residents' activities in the urban square had an effect on environmental evaluations, in this study, all the subjects were standing or sedentary when answering the questionnaire. Therefore, the instantaneous thermal-acoustic environment had a more significant effect on subjective evaluations.

Considering the limitations of previous studies and the necessity of improving the thermal-acoustic environment in urban squares, in this study, a questionnaire survey was conducted and the thermal-acoustic environment was monitored in winter, the transitional season, and summer. The collected data objectively reflect the environmental evaluations in urban squares in the different seasons. The purpose of this study is to not only analyse whether the thermal-acoustic environment affects subjective evaluations but also to determine how it affects thermal evaluations, acoustic evaluations, and overall comfort. In addition, this study also suggests an evaluation and prediction method of equivalent overall comfort under the different conditions of the thermal-acoustic environment in severe cold regions.

2. Method

2.1 Locations

The research was conducted in Harbin, a typical city in a severe cold region in China. In order to study the combined effects of the thermal-acoustic environment on subjective evaluations in urban squares, three small-sized squares located in the central regions of the city were chosen: Gexin Cathedral Square, Sports Square, and Century Square. All three squares are located in residential areas and are main public spaces where people carry out their daily leisure activities. Large areas of the main activity spaces of the three squares are covered by cement and are devoid of any greening. During the period of conducting the questionnaires, there was no broadcast sound, music and so on. Thus, the acoustic environment of the three squares was mainly affected by traffic noise. As shown in Fig. 1, four groups of measurement points were set in these three squares: P1 and P2 were in Gexin Cathedral Square; P1 was near the main road where there was considerable traffic noise, and P2 was near the minor road that was relatively quiet. P3 was set in the Sports Square surrounded by minor roads only, where the environment was quiet; P4 was set in the Century Square, which was adjacent to main roads and where the traffic noise was relatively louder. Two dates with typical meteorological conditions were selected in winter (in January and March), the transitional season (in May and November), and summer (in July and August) to conduct the subjective questionnaire survey and monitor the thermal-acoustic environment.

Fig. 1 Locations of the measurements and questionnaire surveys.

2.2 Questionnaires

This study utilized the questionnaire method to conduct a subjective evaluation survey in urban squares. As shown in Table 1, subjects' Thermal Sensation Vote (TSV), Thermal Comfort Vote (TCV), Subjective Loudness Vote (SLV), Acoustic Comfort Vote (ACV) and Overall comfort Vote (OCV) were evaluated. Overall comfort refers to the comfort of the human body under the combined effects of multiple factors, it is determined by various factors including physical environments and other factors. Among these factors, the effects of physical environments are more significant, and previous studies showed that thermal and acoustic environments have a more significant effect on overall comfort and satisfaction than a luminous environment [25-27]. Therefore, this study seeks to determine the effects of the thermal-acoustic environment on overall comfort under the combined action of multiple factors.

Most previous studies used 5 or 7-point Likert scales in subjective evaluations. In this study, since there were differences in the subjects' sensations in different seasons, a 7-point Likert scale was used to explore their subjective evaluations more accurately. Meanwhile, because the options of 'very hot' and 'very cold' were added to the TSV to reflect the extreme weather conditions in winter and summer in severe cold regions, the thermal sensation was evaluated on a 9-point Likert scale in this study.

Scores	**Thermal comfort**	**Acoustic comfort**	**Overall comfort**	**Subjective loudness**
3	Very comfortable	Very comfortable	Very comfortable	Very quiet
2	Comfortable	Comfortable	Comfortable	Quiet
1	Slightly comfortable	Slightly comfortable	Slightly comfortable	Slightly quiet
0	Neutral	Neutral	Neutral	Neutral
-1	Slightly uncomfortable	Slightly uncomfortable	Slightly uncomfortable	Slightly loud
-2	Uncomfortable	Uncomfortable	Uncomfortable	Loud
-3	Very uncomfortable	Very uncomfortable	Very uncomfortable	Very loud

Scores	**Thermal sensation**
4	Very hot
3	Hot
2	Warm
1	Slightly Warm
0	Neutral
-1	Slightly cool
-2	Cool
-3	Cold
-4	Very cold

Table 1 Subjective evaluations of the questionnaire surveys.

2.3 Measurements

BES-01 temperature recorders were selected to measure global temperature. The diameter of the blackball was 0.08 m and the scattering coefficient of the surface material was 0.95; BES-02 temperature and humidity recorders were selected to measure air temperature and humidity. Portable Kestrel 5500 weather stations were used to record the wind velocity and orientation, and BSWA801 noise vibration analysers were used to record the sound pressure level of traffic noises. The characteristics of the instruments are shown in Table 2. All these instruments were calibrated before operation; the temperature recorders were placed within a radiation-resistant aluminium hood to avoid any interference from the sun's radiation and winds. Meanwhile, the microphones of the analysers were placed inside the wind shield for a more accurate recording. The instruments were set up in accordance with the ISO 7726 [28] and held by the tripod at a height of approximately 1.2 m from the ground.

Type	**Range**	**Precision**	**Sampling period**	**Sampling rate**
Kestrel 5500 weather station	0.4~40 m/s	±0.1 m/s	2 s~12 h	1 min
BES-01 temperature recorder	-30 ℃~50 ℃	±0.5 ℃	10 s~24 h	1 min
BES-02 temperature and humidity recorder	-30 ℃~50 ℃ 0 %~99 % RH	±0.5 ℃ ±3 % RH	10 s~24 h	1 min
BSWA801 noise vibration analyser	19 dB(A)~137 dB(A)	<0.7 dB(A)	>10 s	30 s

Table 2 The characteristics of the instruments.

2.4 Subjects

A total of 1495 valid questionnaires were collected for this study: 488 in winter, 505 in the transitional season, and 502 in summer. All of the subjects were in the squares, informed about the purpose of the questionnaire, and volunteered to participate in the questionnaire survey. The subjects comprised 49.6% males and 50.4% females; their average age and metabolic rate were 39 years and 1.4 met, respectively. Their average clothing insulation was 1.89 clo in winter, 0.79 clo in the transitional season, and 0.48 clo in summer.

2.5 Procedures

With respect to the evaluation index of the acoustic environment, owing to the discontinuous traffic noise, the LAeq (a weighted equivalent continuous sound level) was selected as the evaluation index in this study. The change ranges of the sound pressure level in the squares in the three seasons showed relatively similar consistencies. The measured data of LAeq ranged from 55 dB(A) to 75 dB(A), which was divided into four levels by a unit of 5 dB: 55~60 dB(A), 60~65 dB(A), 65~70 dB(A), and 70~75 dB(A).

With respect to the evaluation index of the thermal environment, as the outdoor thermal environment was unstable and there were differences among subjects' clothing and exercise status, the Universal Thermal Climate Index (UTCI) was selected to assess the thermo physiological effects of the thermal environment. The UTCI was expressed as an equivalent ambient temperature (°C) of a reference environment providing the same physiological response of a reference person in the actual environment. The index combined individual subjective factors and objective environmental parameters taking into account the thermal adaptability of the human body [29-32]. The stress category corresponding to the range of UTCI is shown in Table 3. The corresponding UTCI was calculated according to the thermal environment parameters monitored during the questionnaire survey, and its variation range was -35.0~8.9 ℃ in winter, 0.4~35.0 ℃ in the transitional season, and 15.0~45.0 ℃ in summer. As shown in Table 4, the UTCI in different seasons was divided into four levels corresponding to four different stress categories. The data presented reflect the average value at different levels.

Stress category	UTCI / °C
Extreme heat stress	Above +46
Very strong heat stress	+38~+46
Strong heat stress	+32~+38
Moderate heat stress	+26~+32
No thermal stress	+9~+26
Slight cold stress	0~+9
Moderate cold stress	-13~0
Strong cold stress	−27~−13
Very strong cold stress	−40~−27
Extreme cold stress	Below −40

Table 3 UTCI equivalent temperature categories in terms of thermal stress [33].

Stress category	Winter		Transitional season		Summer	
	Range /°C	Average value /°C	Range /°C	Average value /°C	Range /°C	Average value /°C
Very strong heat stress					38.0~45.0	40.4
Strong heat stress			32.1~35.0	33.6	32.0~38.0	35.3
Moderate heat stress			26.0~31.9	29.0	26.0~31.7	28.3

No thermal stress			9.0~25.9	16.5	15.0~25.9	21.6
Slight cold stress	0.0~8.9	4.2	0.4~8.9	6.1		
Moderate cold stress	-13.0~-0.4	-7.8				
Strong cold stress	-26.9~-13.0	-19.8				
Very strong cold stress	-35.0~-27.1	-29.7				

Table 4 UTCI classification by stress.

3. Results

3.1 Combined effects on thermal evaluations

The effects of the thermal-acoustic environment on thermal evaluations included the effects on TSV and TCV. Table 5 shows the significances of the indicators under the main effect and interaction (TSV and TCV). The analysis of variance (ANOVA) of TSV revealed that the main effect of UTCI on TSV was significant in the three seasons ($p<0.01$) and that LAeq had an effect on TSV in summer ($p<0.05$). However, the interaction of UTCI and LAeq had no effect on TSV in the three seasons ($p>0.05$).

Fig. 2 shows the values of TSV under different conditions of the thermal-acoustic environment. A comparison of ranges in different seasons revealed that there were considerable differences in TSV. In winter, TSV mainly ranged from-3.0 to -1.0: When UTCI was below-19.8 ℃, TSV was inclined to be cold, and when UTCI ranged from-7.8 ℃ to 4.2 ℃, TSV was inclined to be cool. In the transitional season, TSV mainly ranged from -1.0 to 0.5: when UTCI was below 6.1℃, TSV was inclined to be slightly cool, but when UTCI ranged from 6.1 ℃ to 33.6 ℃, TSV was nearly neutral. In summer, TSV mainly ranged from -0.5 to 3.0: when UTCI was below 21.6 ℃, TSV was slightly below the neutral level, but when UTCI was at 28.3 ℃, TSV was nearly neutral. When UTCI was over 35.3 ℃, TSV was warm, being inclined to be hot. In terms of the effect of the thermal environment on TSV, at the same level of LAeq, TSV increased significantly with an increase in UTCI. The average Range (the difference between the maximum and minimum) was 1.6 in winter, 0.8 in the transitional season, and 2.1 in summer. In terms of the effect of the acoustic environment on TSV, at the same level of UTCI, TSV increased slightly with an increase in LAeq in summer. When LAeq was 55~60 dB(A) and 70~75 dB(A), the average difference of TSV was 0.4, which indicated that a high level of traffic noise would aggravate the sensation of heat in summer. However, the acoustic environment had no effect on TSV in the transitional season and summer.

The ANOVA of TCV revealed that the main effect of UTCI on TCV was significant in the three seasons ($p<0.01$). Meanwhile, LAeq also had an effect on TCV in the three seasons ($p<0.05$), while the interaction of UTCI and LAeq had no effect on TCV in the three seasons ($p>0.05$).

Subjective evaluation	Winter			Transitional season			Summer		
	UTCI	LAeq	UTCI* LAeq	UTCI	LAeq	UTCI* LAeq	UTCI	LAeq	UTCI* LAeq
TSV	**.000**	.633	.951	**.000**	.305	.675	**.000**	**.031**	.169
TCV	**.000**	**.047**	.522	**.000**	**.032**	.695	**.000**	**.044**	.835

Table 5 The significances of the indicators under the main effect and interaction (TSV and TCV).

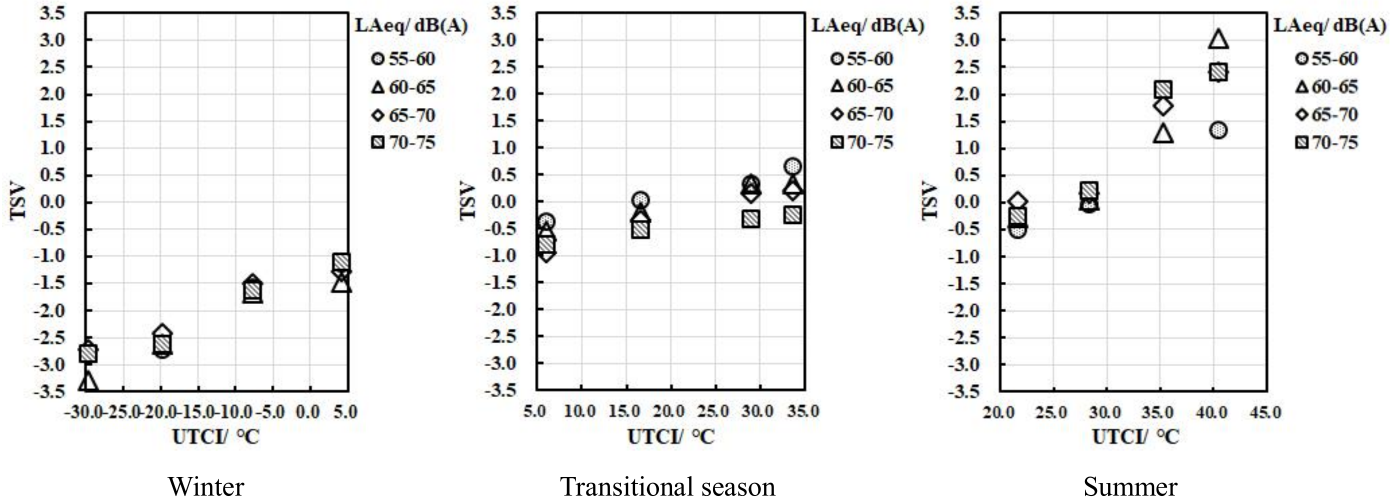


Fig. 2 The values of TSV under different conditions of the thermal-acoustic environment.

Fig. 3 shows the values of TCV under different conditions of the thermal-acoustic environment. A comparison of ranges in different seasons revealed that there were great differences in TCV. In winter, TCV mainly ranged from -1.5 to 0.0: when UTCI was below -19.8 ℃, TCV was slightly uncomfortable and when UTCI ranged from -7.8 ℃ to 4.2 ℃, TCV was slightly lower than the neutral level. In the transitional season, TCV mainly ranged from 0.0 to 1.5, which was slightly uncomfortable. In summer, TCV mainly ranged from -1.5 to 1.0. When UTCI was below 28.3 ℃, TCV was slightly uncomfortable. TCV was slightly lower than the neutral level when UTCI was at 35.3 ℃ and slightly uncomfortable when UTCI was at 40.4 ℃. In terms of the effect of the thermal environment on TCV, at the same level of LAeq, TCV increased significantly with an increase in UTCI in winter and the transitional season, the average Range being 1.3 and 0.8, respectively. On the contrary, TCV decreased considerably with an increase in UTCI in summer, with the average Range being 1.8. In terms of the effect of the acoustic environment on TCV, at the same level of UTCI, TCV decreased with an increase in LAeq in the three seasons, the average Range being 0.3 in both winter and summer and 0.8 in the transitional season. It can thus be concluded that higher traffic noise led to a reduction in TCV and the effect was more significant in the transitional season; TCV was highest when LAeq was 55~60 dB(A).

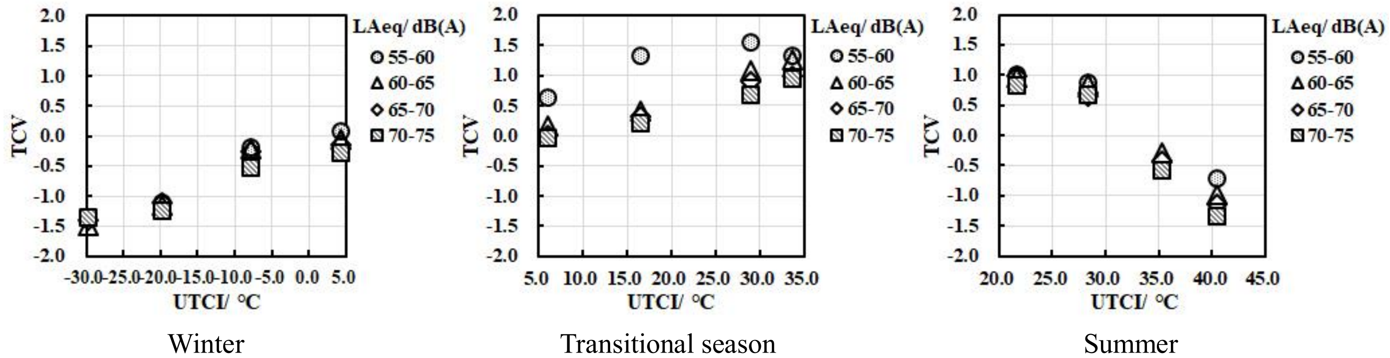


Fig. 3 The values of TCV under different conditions of the thermal-acoustic environment.

Table 6 shows the means and standard deviations of TSV and TCV. The former were larger in the transitional season and relatively smaller in summer, indicating that the dispersion of TSV under the same condition of the thermal-acoustic environment was greater in the transitional season and lower in summer.

The standard deviations of TCV were also larger in the transitional season, indicating that the dispersion of TCV under the same condition of the thermal-acoustic environment was greater.

SPL/ dB(A)	Winter					Transitional season					Summer				
	UTCI / ℃	TSV	S.D.	TCV	S.D.	UTCI / ℃	TSV	S.D.	TCV	S.D.	UTCI / ℃	TSV	S.D.	TCV	S.D.
55~60	**-29.7**					**6.1**	-0.38	0.87	0.63	1.02	**21.6**	-1.00	0.80	1.00	0.85
60~65		-3.29	0.75	-1.50	0.88		-0.56	0.88	0.17	0.88		-0.27	0.75	0.95	0.76
65~70		-2.71	0.96	-1.41	1.03		-0.95	1.03	0.00	1.06		0.02	0.84	0.98	0.95
70~75		-2.81	0.93	-1.37	1.01		-0.79	1.06	-0.04	0.98		-0.24	0.75	0.84	0.96
55~60	**-19.8**	-2.72	1.03	-1.11	0.91	**16.5**	0.04	0.89	1.32	0.92	**28.3**	0.33	0.67	0.87	0.84
60~65		-2.62	0.87	-1.15	0.84		-0.18	0.95	0.41	0.99		0.04	0.56	0.86	1.02
65~70		-2.43	0.83	-1.12	0.81		-0.34	0.86	0.33	1.03		0.17	0.79	0.65	0.97
70~75		-2.61	0.84	-1.24	0.96		-0.52	0.98	0.21	1.05		0.22	0.85	0.68	0.93
55~60	**-7.8**	-1.58	0.80	-0.19	1.04	**29.0**	0.33	0.99	1.56	1.06	**35.3**				
60~65		-1.67	0.95	-0.21	0.88		0.33	0.85	1.09	0.99		1.29	0.83	-0.29	0.95
65~70		-1.49	0.87	-0.26	0.92		0.16	0.98	0.89	0.92		1.79	0.93	-0.43	0.84
70~75		-1.63	0.97	-0.52	0.97		-0.33	1.07	0.69	1.01		2.08	0.99	-0.58	0.86
55~60	**4.2**	-1.12	0.87	0.08	0.98	**33.6**	0.67	0.89	1.33	1.08	**40.4**	2.33	0.77	-0.71	1.04
60~65		-1.47	0.83	-0.06	0.85		0.33	0.85	1.25	0.92		3.03	0.78	-0.98	0.91
65~70		-1.27	0.90	-0.15	0.91		0.21	0.86	1.00	1.03		2.42	0.83	-1.13	0.82
70~75		-1.11	0.95	-0.29	0.83		-0.25	1.04	0.95	0.99		2.40	1.02	-1.35	1.02

Table 6 The means and standard deviations of TSV and TCV.

3.2 Combined effects on acoustic evaluations

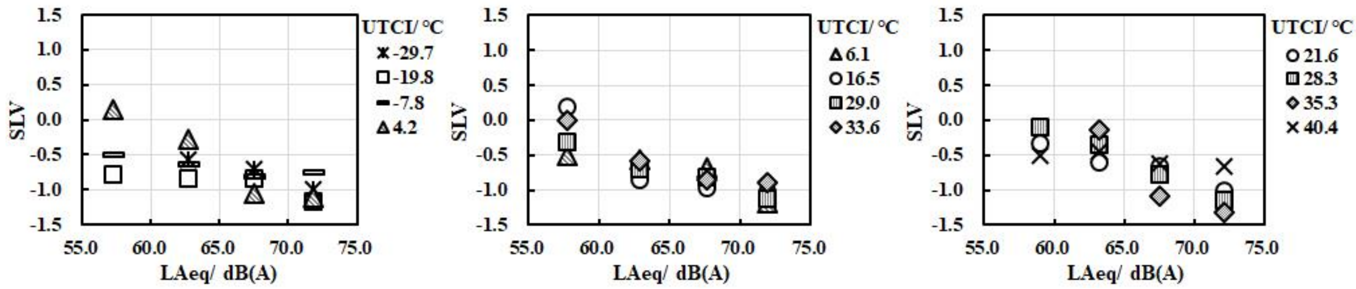
The effects of the thermal-acoustic environment on acoustic evaluations included the effects on SLV and ACV. Table 7 shows the significance of the indicators under the main effect and interaction (SLV and ACV). The ANOVA of SLV revealed that the main effect of LAeq on SLV was significant in the three seasons ($p<0.01$).However, both UTCI and the interaction had no effect on SLV in the three seasons ($p>0.05$).

Fig. 4 shows the values of SLV under different conditions of the thermal-acoustic environment. In terms of the effect of the acoustic environment on SLV, at the same level of UTCI, SLV decreased significantly with the enhancement of LAeq. The average Range was 0.6 in winter, 0.9 in the transitional season, and 0.4 in summer. However, both UTCI and the interaction had no effect on SLV, whose variation trends were basically consistent at different temperatures. Meanwhile, a comparison of the SLV in different seasons revealed that its main ranges were basically identical, all being in the -1.5~0.0 range. When the LAeq of traffic noise was 55~60 dB(A), SLV was slightly lower than the neutral level, and when LAeq was 60~75 dB(A), SLV was slightly loud.

The ANOVA of ACV revealed that the main effect of LAeq on ACV was significant in the three seasons ($p<0.01$). Meanwhile, UTCI had an effect on ACV in winter ($p<0.05$), while both UTCI and the interaction had effects on ACV in summer ($p<0.05$).

Subjective evaluation	Winter			Transitional season			Summer		
	UTCI	LAeq	UTCI* LAeq	UTCI	LAeq	UTCI* LAeq	UTCI	LAeq	UTCI* LAeq
SLV	.236	**.008**	.060	.652	**.002**	.184	.535	**.002**	.540
ACV	**.022**	**.004**	.140	.388	**.000**	.066	**.047**	**.009**	**.041**

Table 7 The significances of the indicators under the main effect and interaction (SLV and ACV).



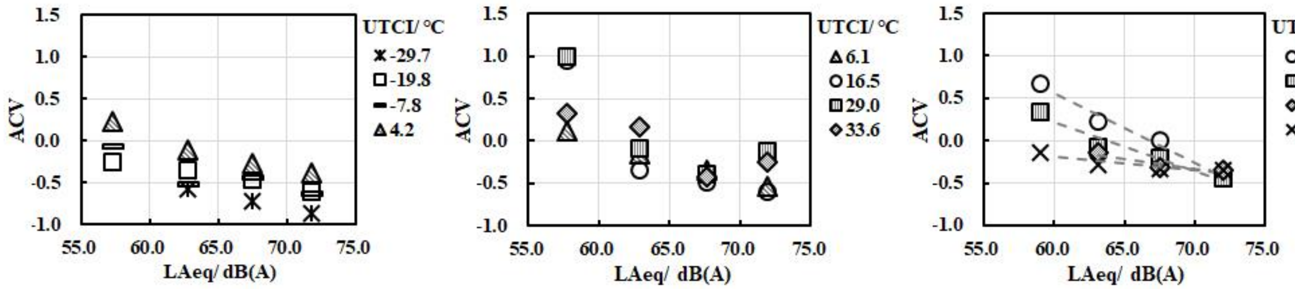
Winter Transitional season Summer

Fig. 4 The values of SLV under different conditions of the thermal-acoustic environment.

Fig. 5 shows the values of ACV under different conditions of the thermal-acoustic environment. With respect to the effect of the acoustic environment on ACV, at the same level of UTCI, ACV decreased significantly with the enhancement of LAeq. The average Range was 0.5 in winter, 1.0 in the transitional season, and 0.5 in summer. With respect to the effect of the thermal environment on ACV, at the same level of LAeq, ACV revealed a general ascending trend with an increase of UTCI in winter. When UTCI was at -29.7 ℃ and 4.2 ℃, the average ACV difference was 0.5. However, when the stress category was strong cold stress and moderate cold stress (UTCI was at -19.8 ℃ and -7.8 ℃, respectively), the ACV differences were small. This indicated that when the temperature was relatively low, with the subjects being exposed to strong cold stress, the ACV decreased for the same level of traffic noise; thus, the low temperature in winter aggravated the acoustic discomfort to a certain extent. On the contrary, ACV decreased with an increase of UTCI in summer. When UTCI was at 21.6 ℃ and 40.4 ℃, the average ACV difference was 0.4. This indicated that in the hot summer when the inhabitants were exposed to more intense heat stress, the ACV decreased for the same level of traffic noise. The high temperature in summer also aggravated the acoustic discomfort to a certain extent. However, the thermal environment had no effect on ACV in the transitional season. The interaction of the thermal-acoustic environment had an effect on ACV only in summer, which meant that the effect of LAeq on ACV varied at different levels of UTCI. With an increase in UTCI, the discrepancy of ACV corresponding to different LAeq at the same UTCI decreased significantly. The Range of ACV was 1.1 when UTCI was at 21.6 ℃, but merely 0.2 when UTCI was at 40.4 ℃. This illustrated that when the temperature was too high in summer with high heat stress, the ACV of subjects was affected significantly and it always remained low regardless of the variation of LAeq.

Meanwhile, a comparison of the ACV in different seasons revealed that the main ACV ranges differed in different seasons. In winter, the main range of ACV was from -1.0 to 0.0; ACV was slightly below the neutral level when LAeq was 55~65 dB(A). When LAeq was 65~75 dB(A), ACV was inclined to be slightly comfortable. In the transitional season and summer, the main range of ACV was from -0.5 to 0.5. When LAeq was 55~65 dB(A), ACV was slightly higher than the neutral level, but slightly lower than it when

LAeq was 65~75 dB(A). Therefore, ACV in winter was lower than that in the other two seasons, and subjects felt greater discomfort for the same level of traffic noise in winter. The reason for this might be that as the weather was too cold in the severe cold regions, the thermal discomfort of the subjects in low-temperature areas affected their evaluation of acoustic comfort.



Winter　　Transitional season　　Summer

Fig. 5 The values of ACV under different conditions of the thermal-acoustic environment.

Table 8 shows the means and standard deviations of SLV and ACV. The former were smaller in winter, indicating that the dispersion of SLV under the same condition of the thermal-acoustic environment was relatively small. The standard deviations of ACV were smaller in winter, indicating that the dispersion of ACV under the same condition of the thermal-acoustic environment was limited.

SPL/ dB(A)	Winter					Transitional season					Summer				
	UTCI / ℃	SLV	S.D.	ACV	S.D.	UTCI / ℃	SLV	S.D.	ACV	S.D.	UTCI / ℃	SLV	S.D.	ACV	S.D.
55~60	**-29.7**					**6.1**	-0.50	1.00	0.13	0.63	**21.6**	-0.33	0.87	0.67	0.95
60~65		-0.57	0.73	-0.57	0.88		-0.57	0.87	-0.15	1.06		-0.61	0.98	0.23	0.92
65~70		-0.71	0.70	-0.71	0.97		-0.67	0.96	-0.35	0.98		-0.67	1.07	0.00	1.02
70~75		-1.00	0.91	-0.86	0.91		-1.18	0.89	-0.54	0.94		-1.00	1.01	-0.44	0.95
55~60	**-19.8**	-0.78	0.79	-0.26	0.83	**16.5**	0.18	0.94	0.95	1.07	**28.3**	-0.10	0.69	0.33	0.77
60~65		-0.85	0.83	-0.35	0.84		-0.86	1.07	-0.35	0.82		-0.36	0.93	-0.07	1.03
65~70		-0.84	0.86	-0.47	0.83		-0.97	0.92	-0.49	1.01		-0.77	1.03	-0.20	0.91
70~75		-1.16	0.89	-0.60	0.96		-1.03	0.93	-0.60	1.02		-1.14	0.88	-0.45	1.04
55~60	**-7.8**	-0.50	0.96	-0.06	0.94	**29.0**	-0.31	1.01	1.00	0.97	**35.3**				
60~65		-0.62	0.92	-0.52	0.73		-0.71	0.89	-0.09	0.85		-0.14	0.83	-0.14	0.83
65~70		-0.81	0.83	-0.43	1.01		-0.82	0.98	-0.38	1.03		-1.10	0.81	-0.32	1.05
70~75		-0.74	0.84	-0.63	0.82		-1.13	0.89	-0.13	1.02		-1.32	0.86	-0.35	0.94
55~60	**4.2**	0.15	0.63	0.23	0.70	**33.6**	0.00	0.66	0.33	0.77	**40.4**	-0.50	0.76	-0.14	0.83
60~65		-0.28	0.85	-0.11	1.01		-0.58	0.94	0.17	1.04		-0.44	0.96	-0.28	0.73
65~70		-1.05	0.78	-0.27	0.62		-0.86	1.02	-0.43	0.98		-0.62	0.85	-0.33	0.91
70~75		-1.11	0.74	-0.39	0.74		-0.90	0.87	-0.25	0.73		-0.65	0.91	-0.35	0.96

Table 8 The means and standard deviations of SLV and ACV.

3.3 Combined effects on overall comfort

Table 9 shows the significance of the indicators under the main effect and interaction (OCV). The main effect of UTCI on OCV was significant in the three seasons ($p<0.01$), LAeq had an effect on OCV in the transitional season and summer ($p < 0.05$). The interaction of UTCI and LAeq had an effect on OCV only in winter ($p<0.05$).

Subjective evaluation	Winter			Transitional season			Summer		
	UTCI	LAeq	UTCI* LAeq	UTCI	LAeq	UTCI* LAeq	UTCI	LAeq	UTCI* LAeq
OCV	**.001**	.467	**.042**	**.000**	**.040**	.213	**.000**	**.035**	.066

Table 9 The significances of the indicators under the main effect and interaction (OCV).

Fig. 6 shows the values of OCV under different conditions of the thermal-acoustic environment. In terms of the effect of the thermal environment on OCV, at the same level of LAeq, although OCV showed a general ascending trend with the increase in UTCI in winter, UTCI had an insignificant effect on OCV in winter when LAeq was 70~75 dB(A). When UTCI was below 29.0 ℃, OCV increased significantly with the increase in UTCI in the transitional season and reached its peak when the temperature was at 29.0 ℃; OCV then showed a slight decrease when UTCI was at 33.6 ℃. At the same level of LAeq, OCV decreased significantly as UTCI increased in summer. In terms of the effect of the acoustic environment on OCV, at the same level of UTCI, OCV decreased with an increase in LAeq in the transitional season and summer. The average Range was 0.9 in the transitional season and 0.8 in summer. However, the acoustic environment had no effect on OCV in winter. The interaction of the thermal-acoustic environment had an effect on OCV only in winter, which meant that the effect of UTCI on OCV varied at different levels of LAeq. With the enhancement of LAeq, the discrepancies of OCV corresponding to different UTCI at the same LAeq decreased significantly. The Range of OCV was 1.1 when LAeq was 55~60 dB(A), but merely 0.3 when LAeq was 70~75 dB(A). This indicated that when the LAeq of traffic noise was high in winter, OCV was observably affected and remained at a low level regardless of the variation in UTCI. Table 10 shows the means and standard deviations of OCV, which mainly ranged from 0.80 to 1.05 in the three seasons.

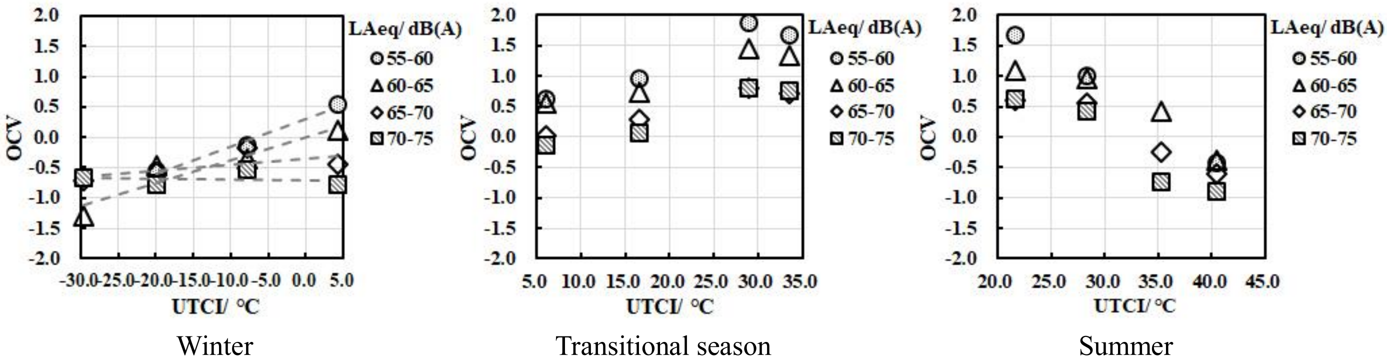


Fig. 6 The values of OCV under different conditions of the thermal-acoustic environment.

SPL/ dB(A)	Winter			Transitional season			Summer		
	UTCI/ ℃	OCV	S.D.	UTCI/ ℃	OCV	S.D.	UTCI/ ℃	OCV	S.D.
55~60	**-29.7**			**6.1**	0.63	1.01	**21.6**	1.67	0.87
60~65		-1.29	1.03		0.56	0.91		1.09	0.95
65~70		-0.71	0.98		0.02	0.98		0.61	1.01
70~75		-0.67	0.85		-0.14	0.83		0.62	0.93

55~60	**-19.8**	-0.56	0.97	**16.5**	0.95	0.98	**28.3**	1.00	0.81
60~65		-0.47	1.01		0.73	0.90		0.97	0.92
65~70		-0.57	0.84		0.29	1.02		0.56	1.02
70~75		-0.78	0.98		0.07	0.92		0.42	0.91
55~60	**-7.8**	-0.14	0.82	**29.0**	1.88	0.86	**35.3**		
60~65		-0.34	0.92		1.45	0.97		0.43	0.97
65~70		-0.19	1.06		0.81	1.02		-0.24	0.84
70~75		-0.54	1.02		0.80	0.75		-0.74	0.96
55~60	**4.2**	0.54	0.93	**33.6**	1.67	0.77	**40.4**	-0.43	0.96
60~65		0.11	1.05		1.33	0.85		-0.39	0.95
65~70		-0.45	0.98		0.71	0.88		-0.60	0.81
70~75		-0.78	1.03		0.75	0.73		-0.89	0.88

Table 10 The means and standard deviations of OCV.

4. Discussion

4.1 The interaction of the thermal-acoustic environment

The results of this study reveal that the interaction of the thermal-acoustic environment had an effect on ACV in summer and OCV in winter.

In terms of the effect on ACV in summer, the effect of LAeq on ACV varied at different levels of UTCI. When the UTCI increased from 21.6 ℃ to 40.4 ℃, the Range of ACV corresponding to different levels of LAeq decreased by 0.9 and the ACV difference at the same UTCI decreased significantly. It indicated that when the temperature was too high in summer with high heat stress, the ACV was observably affected and remained low regardless of the variation of LAeq.

In terms of the effect on OCV in winter, the effect of UTCI on OCV varied at different levels of LAeq. When the LAeq increased from 55~60 dB(A) to 70~75 dB(A), the Range of OCV corresponding to different levels of UTCI decreased by 0.8 and the OCV difference at the same LAeq decreased significantly. It indicated that when the LAeq of traffic noise was high in winter, OCV was observably affected and remained at a low level regardless of the variation in UTCI.

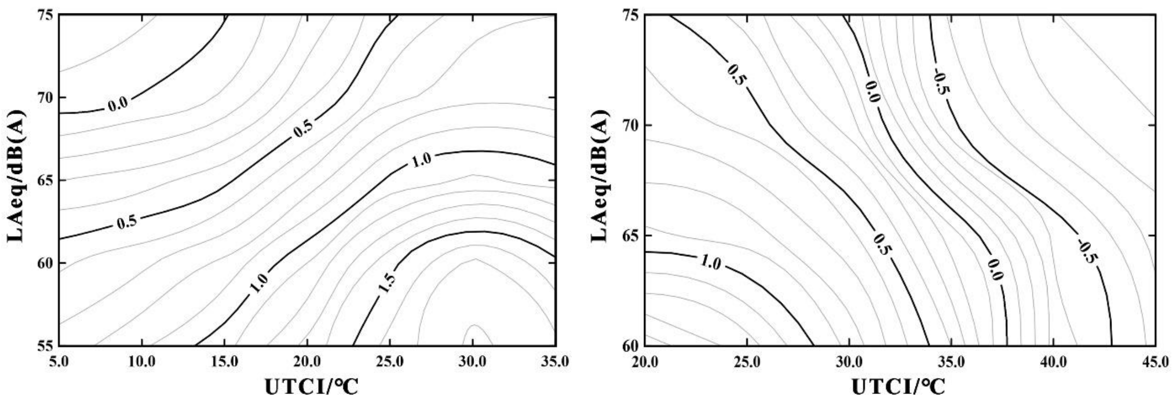
Nagano and Horikoshi indicated that the interaction had effects on noisy sensation, quiet sensation, and auditory discomfort [16]. Although the interaction had no effects on SLV in this study, it affected the ACV in summer, moreover, the effect of LAeq on ACV varied at different levels of UTCI, which is consistent with the findings of previous studies. Their study also showed that the interaction of temperature and noise had an effect on hot sensation when the temperature was 28.0 °C, there was a significant difference in hot sensation corresponding to the LAeq of 46.6 dB(A) and 79.9 dB(A) [17]. This inconsistency may be because the range of LAeq in this study was smaller than that in the previous study; thus, no significant effect of interaction was found.

4.2 Evaluation of equivalent OCV under different conditions

Nagano and Horikoshi indicated that when the temperature ranged from 27.0 ℃ to 39.0 ℃, an increase in operating temperature caused a decrease in OCV, but OCV increased when the temperature ranged from

19.0 ℃ to 28.0 ℃ [16, 17]. The results of not only previous studies but also of this study show that the effect of the thermal environment on OCV is significantly different under its different conditions. In addition, when there is an extreme condition in the thermal or acoustic environment, OCV is reported to be uncomfortable as long as subjects feel uncomfortable in such environments.

By interpolating OCV under different conditions of the thermal-acoustic environment, the ranges of equivalent OCV in different seasons were obtained. As shown in Fig. 7, the conditions of the thermal-acoustic environment affected OCV, and there were discrepancies of the effects in different seasons. In winter, as the correlation between OCV and different levels of LAeq was not significant, the equivalent OCV of the thermal-acoustic environment could not be obtained directly. However, OCV was correlated with the interaction of UTCI and LAeq in that the effect of UTCI on OCV varied at different levels of LAeq. When the LAeq increased by about 15 dB(A), the Range of OCV corresponding to different levels of UTCI decreased by 0.8 and the OCV differences at the same LAeq decreased significantly. In the transitional season, when UTCI was between 5.0 ℃ and 35.0 ℃ and LAeq was between 55~75 dB(A), the variation range of OCV was from 0.0 to 1.5. When UTCI was over 23.0 ℃ and LAeq was below 62 dB(A), OCV was the highest, being inclined to be comfortable. In summer, when UTCI was between 20.0 ℃ and 45.0 ℃ and LAeq was between 60~75 dB(A), the variation range of OCV was from -0.5 to 1.0. When UTCI was below 28.0 ℃ and LAeq was not higher than 64 dB(A), OCV was the highest, being slightly comfortable. Moreover, when UTCI was over 37.0 ℃, under the effect of hot temperature, OCV was constantly below the neutral level regardless of the variation of the traffic noise level.



Transitional season　　　　Summer

Fig. 7 Equivalent OCV under different conditions of the thermal-acoustic environment.

As the thermal experiences and psychological expectations of human beings are not identical under different thermal conditions, their acceptance and evaluation of thermal environments are different [34, 35]. For example, when the UTCI was 28.0 ℃ ~ 29.0 ℃, the TSV, SLV, and ACV were close in the transitional season and summer, with all differences being about 0.1; however, the TCV and OCV were 0.3 and 0.5 higher than that in summer, respectively. Therefore, because of the thermal experiences and psychological expectations, there was a difference in TCV, resulting in significant differences in the evaluation of OCV in the transitional season and summer. Though there were certain limitations to the sample and scope of the data, this study suggests the possibility of predicting the equivalent overall comfort in different seasons; in other words, overall comfort can be reasonably predicted based on the known conditions of the thermal-acoustic environment.

5. Conclusions

Through questionnaire surveys and by monitoring the thermal-acoustic environment in different seasons, this study analyses whether the thermal-acoustic environment has any effect on subjective evaluations and seeks to determine how the thermal-acoustic environment affects thermal evaluations, acoustic evaluations, and overall comfort.

(1) With respect to thermal evaluations, the thermal environment has a significant effect on both TSV and TCV in the three seasons. Higher temperature results in a significant increase in TSV in three seasons; the average Range is from 0.8 to 2.1. With the increase in temperature, TCV increases significantly in winter and the transitional season but decreases in summer. The acoustic environment has an effect on TSV only in summer, higher traffic noise aggravates the sensation of heat when the UTCI ranges from 21.6 ℃ to 40.4 ℃; the average Range is 0.4. Meanwhile, the acoustic environment has an effect on TCV, as higher traffic noise leads to the reduction in TCV in the three seasons; the average Range is from 0.3 to 0.8. However, the interaction of the thermal-acoustic environment has no effect on thermal evaluations.

(2) With respect to acoustic evaluations, the acoustic environment has a significant effect on SLV and ACV in the three seasons, with higher traffic noise resulting in a more negative evaluation of both SLV and ACV; the average Range is from 0.4 to 0.9 and from 0.5 to 1.0, respectively. Though the thermal environment has no effect on SLV, it has an effect on ACV both in winter and summer. The increase in temperature causes ACV to increase in winter and decrease in summer, with both the low temperature in winter and the high temperature in summer aggravating acoustic discomfort. However, the interaction affects ACV only in summer; when the UTCI reaches 40.4 ℃, ACV remains constantly low regardless of the variation in traffic noise.

(3) With respect to overall comfort, the effect of the thermal environment on OCV is significant in the three seasons: OCV increases in winter and decreases in summer with the increase in temperature. The acoustic environment has an effect on OCV in the transitional season and summer, where higher traffic noise leads to the decrease in OCV; the average Range is from 0.8 to 0.9. However, the interaction affects OCV only in winter; when traffic noise ranges between 70~75 dB(A), OCV remains constantly low regardless of the variation in temperature.

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References

[1] M.F. Southworth, The Sonic Environment of Cities, Doctoral dissertation, Massachusetts Institute of Technology, 1967.

[2] J. Carles, F. Bernáldez, J.D. Lucio, Audio-visual interactions and soundscape preferences, Landscape Research 17(2) (1992) 52-56 https://doi.org/10.1080/01426399208706361

[3] L. Maffei, T. Iachini, M. Masullo, F. Aletta, F. Sorrentino, V.P. Senese, F. Ruotolo, The effects of vision-related aspects on noise perception of wind turbines in quiet areas, International Journal of Environmental Research and Public Health 10(5) (2013) 1681-1697 https://doi.org/10.3390/ijerph10051681

[4] J. Liu, J. Kang, H. Behm, T. Luo, Effects of landscape on soundscape perception: Soundwalks in city parks, Landscape and Urban Planning 123(1) (2014) 30-40 https://doi.org/10.1016/j.landurbplan.2013.12.003

[5] X. Ren, J. Kang, Effects of the visual landscape factors of an ecological waterscape on acoustic comfort, Applied Acoustics 96 (2015) 171-179 https://doi.org/10.1016/j.apacoust.2015.03.007

[6] M. Zhang, J. Kang, Towards the evaluation, description, and creation of soundscapes in urban open spaces, Environment and Planning B Planning and Design 34(1) (2007) 68-86 https://doi.org/10.1068/b31162

[7] L.Yu, J. Kang, Modeling subjective evaluation of soundscape quality in urban open spaces: An artificial neural network approach, Journal of the Acoustical Society of America 126(3) (2009) 1163-1174 https://doi.org/10.1121/1.3183377

[8] L. Jiang, M. Masullo, L. Maffei, Effect of odour on multisensory environmental evaluations of road traffic, Environmental Impact Assessment Review 60 (2016) 126-133 https://doi.org/10.1016/j.eiar.2016.03.002

[9] M. Ba, J. Kang, A laboratory study of the sound-odour interaction in urban environments, Building and Environment 147(2019) 314-326 https://doi.org/10.1016/j.buildenv.2018.10.019

[10] R.D. Dean, C.L.McGlothen, Effects of combined heat and noise on human performance, physiology and subjective estimates of comfort and performance, Proceedings of the Institute of Environmental Science Annual Technical Meeting, Mount Prospect, (1965) 55–64.

[11] P.A. Bell, Effects of noise and heat stress on primary and subsidiary task performance, Human Factors 20(6) (1978) 749-752 https://doi.org/10.1177/001872087802000614

[12] D.P. Wyon, R. Kok, M.I. Lewis, G.B. Meese, Combined noise and heat stress effects on human performance, Indoor Climate, Copenhagen, (1978) 857–881.

[13] T. Witterseh, D.P. Wyon, G. Clausen, The effects of moderate heat stress and open-plan office noise distraction on SBS symptoms and on the performance of office work, Indoor Air 14(s8) (2004) 30-40 https://doi.org/10.1111/j.1600-0668.2004.00305.x

[14] G. Clausen, D.P. Wyon, The Combined Effects of Many Different Indoor Environmental Factors on Acceptability and Office Work Performance, HVAC & R Research 14(1) (2008) 103-113 https://doi.org/10.1080/10789669.2008.10390996

[15] P.O. Fanger, N.O. Breum, E. Jerking, Can colour and noise influence man's thermal comfort ?, Ergonomics 20(1) (1977) 11-18 https://doi.org/10.1080/00140137708931596

[16] K. Nagano, T. Horikoshi, New index of combined effect of temperature and noise on human comfort: summer experiments on hot ambient temperature and traffic noise, Archives of Complex Environmental Studies 13 (2001) 3-4.

[17] K. Naganoa, T. Horikoshi, New comfort index during combined conditions of moderate low ambient temperature and traffic noise, Energy and Buildings 37(3) (2005) 287-294 https://doi.org/10.1016/j.enbuild.2004.08.001

[18] N. Pellerin, V. Candas, Combined effects of temperature and noise on human discomfort, Physiology & Behavior 78(1) (2003) 99-106 https://doi.org/10.1016/s0031-9384(02)00956-3

[19] N. Pellerin, V. Candas, Effects of steady-state noise and temperature conditions on environmental perception and acceptability, Indoor Air 14(2) (2004) 129-136 https://doi.org/10.1046/j.1600-0668.2003.00221.x

[20] W. Yang, H.J. Moon, Cross-modal effects of noise and thermal conditions on indoor environmental perception and speech recognition, Applied Acoustics 141 (2018) 1-8 https://doi.org/10.1016/j.apacoust.2018.06.019

[21] E.L. Krüger, P.H.T. Zannin, Acoustic, thermal and luminous comfort in classrooms, Building and Environment 39(9) (2004) 1055-1063 https://doi.org/10.1016/j.buildenv.2004.01.030

[22] C. Buratti, E. Belloni, F. Merli, P. Ricciardi, A new index combining thermal, acoustic, and visual comfort of moderate environments in temperate climates, Building and Environment 139 (2018) 27-37 https://doi.org/10.1016/j.buildenv.2018.04.038

[23] G. Horie, Y. Sakurai, T. Narguchi, N. Matsubara, Synthesized evaluation of noise, lighting and thermal conditions in a room, Proceedings of the International Conference on Noise Control Engineering, Krakow, Poland, (1985) 491–496.

[24] G. Clausen, L. Carrick, P.O. Fanger, W.K. Sun, T. Poulsen, J.H. Rindel, A Comparative Study of Discomfort Caused by Indoor Air Pollution, Thermal Load And Noisec, Indoor Air 3(4) (1993) 255-262 https://doi.org/10.1111/j.1600-0668.1993.00006.x

[25] L. Huang, Y. Zhu, Q. Ouyang, B. Cao, A study on the effects of thermal, luminous, and acoustic environments on indoor environmental comfort in offices, Building and Environment 49(1) (2012) 304-309 https://doi.org/10.1016/j.buildenv.2011.07.022

[26] W. Yang, H.J. Moon, Combined effects of acoustic, thermal, and illumination conditions on the comfort of discrete senses and overall indoor environment, Building and Environment 148 (2019) 623-633 https://doi.org/10.1016/j.buildenv.2018.11.040

[27] M.A. Humphreys, Quantifying occupant comfort: are combined indices of the indoor environment practicable?, Building Research & Information, 33(4) (2005) 317-325 https://doi.org/10.1080/09613210500161950

[28] ISO, International Standard 7726, Ergonomics of the Thermal Environment Instruments and Method for Measuring Physical Quantities, International Standard Organization, Geneva, 1998 .

[29] G. Jendritzky, G. Havenith, UTCI—Why another thermal index?, International Journal of Biometeorology 56(3) (2012) 421-428 https://doi.org/10.1007/s00484-011-0513-7

[30] K. Blazejczyk, Y. Epstein, G. Jendritzky, H. Staiger, B. Tinz, Comparison of UTCI to selected thermal indices, International Journal of Biometeorology 56(3) (2012) 515-535 https://doi.org/10.1007/s00484-011-0453-2

[31] K. Pantavou, G. Theoharatos, M. Santamouris, D. Asimakopoulos, Outdoor thermal sensation of pedestrians in a Mediterranean climate and a comparison with UTCI, Building and Environment 66 (2013) 82-95 https://doi.org/10.1016/j.buildenv.2013.02.014

[32] Z. Fang, Z. Lin, C.M. Mak, J. Niu, K.T. Tse, Investigation into sensitivities of factors in outdoor thermal comfort indices, Building and Environment 128 (2018) 129-142 https://doi.org/10.1016/j.buildenv.2017.11.028

[33] P. Bröde, D. Fiala, K. Blazejczyk, et al., Calculating UTCI Equivalent Temperatures, 2009, http://www.utci.org/utci_poster.pdf

[34] A. Pitts, Thermal comfort in transition spaces, Buildings 3 (2013) 122–142 https://doi.org/10.3390/buildings3010122

[35] T.P. Lin, R.D. Dear, R.L. Hwang, Effect of thermal adaptation on seasonal out- door thermal comfort, International Journal of Climatology 31 (2011) 302–312 https://doi.org/10.1002/joc.2120