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Effects of Acoustic Perception on Outdoor Thermal Comfort in Campus Open Spaces in China's Cold Region

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Abstract: To explore the effects of acoustic perception on outdoor thermal comfort, acoustic perception in five typical open spaces in a campus in China's cold region with common soundscapes was evaluated by using meteorological measures, sound level devices, and a questionnaire survey. Eight adjectives were used to evaluate an individual's acoustic perception, and the physiological equivalent temperature (PET) was selected as a thermal index. The correlations between acoustic perception and thermal comfort in these typical open spaces were further analyzed. We demonstrated that: (1) Acoustic sensation and comfort varied significantly among sound types (STPs). Respondents reported pleasant perceptions of broadcasting music, running water and birdsong, and wind (a gentle breeze) and insects. (2) Although there was no significant difference in the thermal sensation vote (TSV), we found large differences in the thermal comfort vote (TCV) among STPs. (3) The respondents' neutral PET (NPET) varied among STPs. In autumn, the ranked order of NPET was machines > running water and birdsong > crowds > broadcasting music > wind (a gentle breeze) and insects. In winter, the order of the NPET was machines > wind (a gentle breeze) and insects > crowds > broadcasting music > running water and birdsong. (4) When people perceived "acoustic comfort", their TSV improved, and vice versa.

Keywords: outdoor thermal comfort; acoustic perception; sound type (STP); physiological equivalent temperature (PET); campus open spaces; China's cold region

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1. Introduction

Campus open spaces are conducive to improving the staff's and students' physical and psychological health, relieving their pressure, and strengthening their learning and cognitive abilities [1,2]. High-quality campus open spaces can enrich campus life, improve the ability to adapt socially, and promote healthy growth and development. Among them, thermally comfortable environments play an important role in promoting physical health, altering psychology, and improving the emotional state of both staff and students [3].

The perception of human comfort is often defined as an individual's satisfaction with a specific environment and is influenced by factors, both psychological and physical [4]. In addition to the significant influence of the thermal environment, the acoustic environment is also considered to be a very important factor inhuman comfort [5,6]. An uncomfortable acoustic environment has negative impacts on teaching, learning, and the health of staff and students [7], while a high-quality acoustic environment may provide positive impacts on social welfare, quality of life, and environmental health [8].

The factors influencing outdoor thermal comfort (OTC) can be divided into four levels: physical, physiological, psychological, and social/behavioral [9]. On the physical level, air temperature (T_a) is viewed as the primary influencer [10–14]. Moreover, solar radiation, wind velocity (V_a), relative humidity (RH), surface type, vegetation, and water bodies can influence OTC to some extent [15–26]. On the physiological level, some studies demonstrated that physical indices, such as skin temperature, heart rate, and sweat feeling index can be used as thermal comfort indices [11,27–30]. Additionally, metabolic rate and activity type also may, to some extent, influence OTC [28,31–33]. At the social/behavioral level, social characteristics (e.g., gender, age, socioeconomic status, and cultural background) and thermal adaptation are all contributing factors [18,34–39].

Acoustic perception is usually defined as the "acoustic environment that an individual, a group or a community perceives in a given scene" [40]. Existing studies generally suggested that the subjective acoustic evaluation had a negative correlation to the sound pressure level [41], and natural sound is more easily accepted by respondents than other sound types (STPs) [42,43]. Moreover, age, gender, career, and the purpose of the visit of the respondents can all affect acoustic perceptions [44,45].

Acoustic perceptions in outdoor open spaces are vital to thermal comfort. Some scholars have conducted studies regarding this cross-modal effect on OTC. Tsai and Lin showed that neutral thermal conditions were related to a higher Leq, and a lower Leq was recorded under 'hot' to 'very hot' condition [46]. Under the same acoustic conditions, individuals tended to be more tolerant in the square where the ambiance and thermal conditions were better [47], and noise annoyance was related to thermal sensation [48,49]. Additionally, subjects felt more thermally unpleasant when the noise level increased [6]. It suggested that the outdoor acoustic environment is associated with individuals' thermal perception [49–51], and the sound type and level have significant influences on thermal comfort [52].

In addition to healthy humans, the acoustic-thermal perceptual characteristics of atypically developed individuals in relation to the acoustic and thermal environment have received increasing attention worldwide. Such interest deals with both the functional and visual settings of their living spaces and other intangible aspects such as thermal and acoustic comfort [53–59]. Previous studies showed that noise and an overload of sounds should be avoided and that clients displaying challenging behavior should be taught how to deal with noises and sounds. The sound environment, however, might also have relaxing, comforting, and encouraging influences on people displaying challenging behavior [60].

To date, some studies on the acoustic–thermal correlation have been conducted in urban squares, parks, and residential areas across many climatic zones [49,61]. However, few studies have examined the cross-modal influence of acoustic perception on OTC for different sound types (STPs) in campus open spaces. In our study, five typical spaces in a campus in Xi'an, China were chosen to explore the relationship between acoustic perception and OTC. The primary objectives of this study were to: (1) determine the influences of the acoustic environment of typical open spaces on acoustic perception and comfort, and (2) withstand the influencing characteristics of the acoustic perception of typical open spaces on thermal comfort. Our results could provide theoretical references and technical guidance to create comfortable campus open spaces concerning the combined effects of acoustic and thermal perceptions.

2. Methods

2.1. Study Area

This study was carried out on a campus in Xi'an, a typical city in China's cold region. Xi'an is located on the border between the humid subtropical climate area and the tropical and subtropical steppe climate area (Cwa to BSk) [62]. This places it in the warm temperate sub-humid continental monsoon climate. It is warm and windy in spring, hot and rainy in summer, cool and pleasant in autumn, and cold and dry in winter. According to meteorological data from 2011–2021, the highest monthly average T_a is in July (27.21 °C) with the highest value of 38.10 °C. The lowest monthly average T_a is in January (−0.92 °C) and the lowest value is −11.65 °C. The annual average *RH* is between 57.58 and 79.45% [63].

Our trials were carried out on a university campus (108°04′37″ E, 34°15′44″ N). It covers about 170 ha with diverse sound environments (broadcasting music, running water and birdsong, and machines), landscape types, and abundant outdoor spaces; 66% of the campus is green. Hence, it is an ideal place to study the acoustic comfort and thermal comfort of campus open spaces. T_a in urban spaces is influenced by the surrounding environment within a radius of 10–150 m centered at the site [64]. A circle within a radius of 10 m was used as the spatial scope in the experiment. Five representative outdoor spaces were chosen on campus with consideration to the sky view factor (SVF) and seasonal landscape that included a peony garden (PG), campus square (CS), wooded area (WA), ecological garden (EG), and patio space (PS) (Table 1).

Table 1. Site descriptions.

Space	Aerial Photograph	Autumn	Winter
Peony garden (PG)		 SVF = 0.7385	 SVF = 0.7500
Wooded area (WA)		 SVF = 0.1356	 SVF = 0.2480
Campus square (CS)		 SVF = 0.8602	 SVF = 0.8674
Ecological garden (EG)		 SVF = 0.3004	 SVF = 0.5163
Patio space (PS)		 SVF = 0.1515	 SVF = 0.1517

2.2. Experimental Design

The experiment was carried out in 7 days in the autumn and winter of 2020 (7, 17, 18, and 24 October; 11–13 December). The meteorological variables during the experiments are characteristic of the seasonality in Xi'an. When the sound pressure level (SPL) is between 65 and 70 dBA, the acoustic comfort vote is related to the acoustic source and user characteristics [64–68]. Therefore, the SPL was maintained to within 60–70 dBA during trials (Leq = 60–70 dBA) [69].

The trials were carried out simultaneously at the measured points. Before the trial, each respondent was briefed on the purpose of the experiment, methodology, and procedure. The respondents were then divided into five groups, and each group was randomly assigned to go to a space where they listened to a random sound in each space. A sound speaker was hidden at each measured point. Testers controlled the sound speaker so that it was set to play before each group of respondents arrived. Upon arrival, respondents were instructed to listen to the sounds and experience the environment for 15 min. The respondents were then asked to fill in the subjective questionnaire for 5 min. The respondents then moved to another trial site within 10 min. During the trial, the testers were asked to keep silent and static to prevent disturbing the respondents, and respondents were asked to stand throughout the experiment to prevent influences of different activity metabolism. The respondents visited five spaces and the five STPs randomly in half a day, without repetition (Figure 1). Such design controls for the order effect of an individual's experimental results eliminated order bias [70].

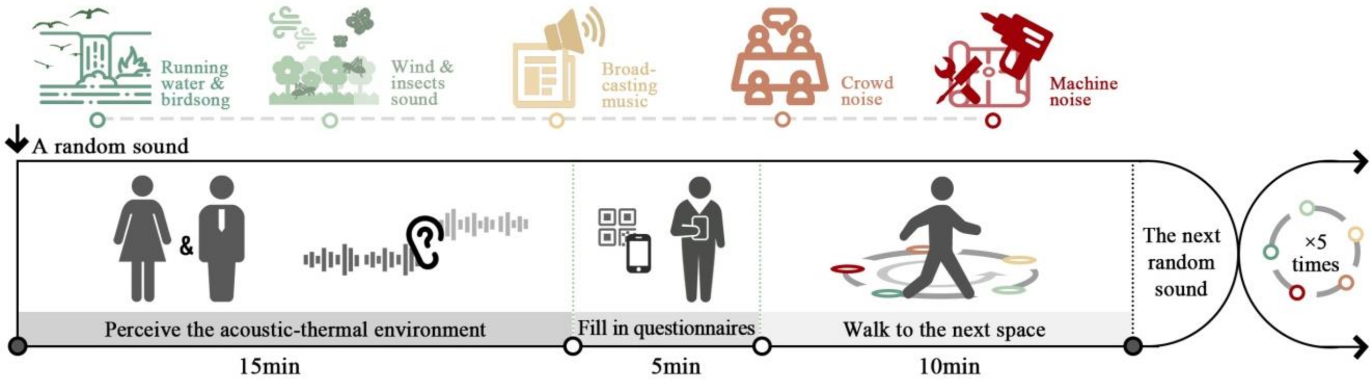


Figure 1. Experimental process.

2.2.1. Sound Selection

There is currently no fully standardized classification of sound types [71]. Axelsson et al. proposed a five-classification system of sound sources (vehicular traffic, fans, other noise, human sound, and natural sound) as a specification for acoustic assessment [72,73]. Other studies often classified sound types as 'traffic', 'human voice', 'bird song', 'water', and 'music' [74–76]. The overall environment on campus is quiet due to the constraints of teaching activities, and there is no traffic noise as in other outdoor experiments, with little difference in the sound levels between the various types of sound. Based on the previous studies [72,73,77], five types of sound (broadcasting music (Brm), running water and birdsong (Rus), wind (a gentle breeze) and insects (Wis), crowds (Crn), and machines (Macn) were obtained in advance using mobile phones as recording devices in real campus scenarios (e.g., after class, by the water in the spring garden, next to a construction site being renovated). The most representative sound clip of each sound was selected, the sound pressure level was adjusted at 10 dB (A) intervals using the Adobe Audition software, and each sound was edited into a 20-min sample. Each sample played one sound type repeatedly and it was used as the sound stimulus during trials [78]. The SPL was measured using an AWA5688 multi-functional sound level meter, and the SPL playing the sound equipment was controlled at 60–70 dB. During trials, we conducted a pre-site selection in advance and tried to choose some quiet sites to eliminate the influence of the background. Additionally, the wind speed during the experiment was 2.0 m/s for the maximum and 0.3 m/s for the minimum. The effect of wind sound on the experimental results was minimal [79]. Meanwhile, we arranged with the campus administration to ensure that there was no collective activity with loud sounds surrounding the measured sites.

2.2.2. Meteorological Measures

Physical measurement refers to the meteorological data by installing relevant apparatus in measured sites. Instruments were selected with reference to ASHRAE 55 and ISO 7726 [80,81] (Table 2). Each measured space was equipped with a meteorological station installed 1.1 m above the ground and data were recorded every 1 min. The monitored meteorological data include T_a, RH, V_a, solar radiation (G), and the globe temperature (T_g). The mean radiant temperature (T_{mrt}) was calculated by the following equation [82].

$$T_{mrt} = \left[(T_g + 273)^4 + \frac{1.10 \times 10^8 V_a{}^{0.6}}{\varepsilon D^{0.4}} (T_g - T_a) \right]^{0.25} - 273 \quad (1)$$

where ε refers to the black globe reflectivity (ε = 0.95 in this study). D is the diameter of the black globe (D = 0.05 m in this study).

Table 2. Instrument information.

Instrument	Parameters	Range	Precision
HOBO onset U23-001	Air temperature	−40–70 °C	±0.21 °C
	Relative humidity	0–100%	±2.5%
Kestrel 5500	Wind speed	0–40 m/s	0.1 m/s
Delta OHM HD2107.2	Globe temperature	−30–120 °C	±0.25 °C
JTR05	Global radiation	0–2000 W/m^2	≤±2%
AWA5688	A weighted sound pressure level	28 dBA–133 dBA	

The respondents were required to stay in measured spaces for 20 min, during which SPL was controlled at 60–70 dBA. Therefore, an AWA5688 multi-functional sound level meter was used to measure the SPL every 20 min when recording meteorological parameters in each space.

2.3. Questionnaire Survey

Part I of the questionnaire captured the general respondents' information, including gender, age, height, body weight, and clothing. The clothing insulation and metabolism referred to standards in ASHRAE 55 and ISO 7726 [80,81].

Part II investigated the respondents' acoustic perception, including acoustic sensation, acoustic comfort, and acoustic acceptability. Eight adjectives, including eventful, exciting, pleasant, calm, uneventful, monotonous, annoying, and chaotic, were selected to evaluate the acoustic perception of each space [72,73,83]. A 5-level scale was applied to evaluate respondents' acoustic perception of each adjective: −2: strongly disagree; −1: somewhat disagree; 0: neutral; +1, somewhat agree; +2 strongly agree. A 5-level scale was used to evaluate acoustic comfort: −2: discomfort; −1: slight discomfort; 0: neutral; 1: slight comfort; 2: comfort. A 3-level scale was used to evaluate the acoustic acceptability: −1: unwilling; 0: neutral; 1: willing [76].

Part III investigated the respondents' outdoor thermal perception, including thermal sensation and thermal comfort. The respondents were asked about their comfort and acceptability of the whole environment. A 7-level scale (−3: cold; −2: cool; −1: slightly cool; 0: moderate; 1: slightly warm; 2: warm; 3: hot) was used to evaluate the thermal perception of residents. Thermal comfort was measured by a 5-level scale (−2: discomfort; −1: slight discomfort; 0: moderate; 1: slight comfort; 2: comfort) [84].

2.4. Statistical Analysis

In this study, physiological equivalent temperature (PET), based on the theoretical foundation of the MEMI model (human heat balance model), has been used extensively to predict thermal comfort in complex outdoor environments [85]. Meteorological parameters and individual parameters (height, body weight, age, gender, clothing insulation, and metabolic rate) were input into the Rayman to calculate the PET [86,87].

All original data were recorded and processed in Microsoft Excel. The linear regression equation was fitted, and the corresponding diagram was plotted. The one-way analysis of variance (ANOVA) in SPSS23.0 was used to analyze the data.

2.5. Respondents' Attribute

A total of 241volunteers were recruited; 137 in autumn and 104 in winter. The volunteers were aged 17–27 years, with a height range of 1.52–1.90 m and a weight range of 42–96 kg (Table 3). The respondents were asked to stand during the experiment (70 W/m^2). All respondents were staff or students who had lived in Xi'anfor more than a year and had adapted to the local climate and were able to accurately perceive temperature changes and adjust their clothing appropriately [88]. Each participant was informed of the procedure, requirements, and precautions prior to the trial, and they had normal hearing and were able to forma reasonable assessment of their acoustic surroundings.

Table 3. Respondents' attribute.

Season	Age	Gender	Number	Height (cm)	Weight (kg)
autumn	18–26	male	35	177.1 ± 6.32	67.4 ± 10.42
	17–25	female	102	163.9 ± 5.42	53.4 ± 5.99
winter	21–27	male	20	176.0 ± 3.5	71.6 ± 8.7
	18–27	female	84	163.0 ± 4.8	54.0 ± 7.1

3. Results

3.1. Meteorological Parameters

The average T_a of spaces PG and CS was high, but the value in space PS was relatively low, which is related to the space's shadiness. There is relatively high SVF in both spaces, PG and CS. Without overhead shade, the T_a in these spaces increased quickly due to the direct sunshine. Since spaces WA and PS were completely shaded at the top, the T_a fluctuated slightly during the day. Space WA is covered overhead by trees, but some sunlight penetrates through the canopy. Space PS is surrounded by buildings, which makes it difficult for sunlight to penetrate. Hence, the mean T_a of WA was higher than that of PS. Since space EG is a square space, partially shaded by arbors, the mean T_a was lower than those of PG and CS, but it was higher than those of WA and PS.

Spaces WA and PS showed the highest average *RH*, followed by EG and PG. The average *RH* in space CS was the lowest, which is related to its morphology and vegetation planting. Space WA, with its high proportion of plants, had a higher average *RH*. Space PS is surrounded by high-rise buildings with small rainwater ponds, resulting in the relatively high average *RH*. Although there are relatively high proportions of plants in spaces EG and PG, these are open spaces with high T_a. Hence, the average *RH* of spaces EG and PG was relatively low.

The average V_a of space CS was the highest, which is related to its morphological layout. Space CS is an open square in front of the administration building, with good ventilation and few barriers. The average V_a of PS was0.3 m/s (autumn) and0.5 m/s (winter). Since there are tall buildings in the south and north of space PS, but good ventilation to the east and west, the courtyard formed a wind corridor.

Space CS had the highest average *G* in autumn. Space WA had the lowest average *G* in winter. Similar to T_a, this is related with overhead shade in these spaces. In spaces CS and PG without overhead shade, the average *G* and average T_g were relatively high. The T_g of PG was slightly lower than that of CS, which is due to its lawns. Since the plant shade is denser than the building shade, the average *G* and average T_g of space PS were higher than those of space WA in autumn (Table 4).

Table 4. Meteorological parameters.

Season	Meteorological Factor	PG	CS	WA	EG	PS
Autumn	T_a (°C)					
	Max.	19.7	20.1	18.9	19.1	18.4
	Min.	10.7	11.0	10.2	10.4	10.4
	Mean ± SD	15.6 ± 2.6	15.8 ± 2.7	14.8 ± 2.6	15.1 ± 2.6	14.7 ± 2.4
	RH (%)					
	Max.	82.5	81.1	87.6	87.1	87.0
	Min.	40.6	36.0	43.0	42.9	42.4
	Mean ± SD	59.0 ± 12.8	57.3 ± 13.2	62.7 ± 12.7	61.6 ± 12.9	62.6 ± 12.4
	V_a (m/s)					
	Max.	0.9	1.3	0.5	0.5	1.1
	Min.	0.0	0.0	0.0	0.0	0.0
	Mean ± SD	0.3 ± 0.3	0.6 ± 0.4	0.1 ± 0.2	0.2 ± 0.1	0.3 ± 0.3
	G (W/m^2)					
	Max.	706.7	689.4	81.2	44.0	105.6
	Min.	0.4	62.9	9.1	2.2	22.3
	Mean ± SD	254.4 ± 221.9	255.6 ± 160.6	26.7 ± 14.0	19.5 ± 13.6	51.6 ± 21.1
	T_g (°C)					
	Max.	28.4	29.6	19.7	21.2	19.4
	Min.	13.5	13.4	10.5	11.5	11.1
	Mean ± SD	21.5 ± 3.6	22.1 ± 3.9	15.6 ± 2.4	16.7 ± 2.5	15.8 ± 2.2
	T_{mrt} (°C)					
	Max.	50.2	59.9	21.5	24.4	21.5
	Min.	13.5	17.9	10.5	11.8	12.0
	Mean ± SD	28.3 ± 9.5	32.8 ± 9.5	16.1 ± 2.5	18.3 ± 2.8	17.3 ± 2.8
Winter	T_a (°C)					
	Max.	11.2	11.1	10.4	10.9	10.0
	Min.	−0.1	−0.1	−0.2	0.1	0.4
	Mean ± SD	5.4 ± 4.1	5.5 ± 4.0	5.0 ± 3.8	5.3 ± 3.9	5.0 ± 3.5
	RH (%)					
	Max.	70.9	69.2	70.8	70.7	70.7
	Min.	33.2	33.6	35.2	34.7	33.7
	Mean ± SD	51.9 ± 13.2	51.7 ± 12.8	53.5 ± 12.5	53.2 ± 13.0	54.3 ± 12.6
	V_a (m/s)					
	Max.	0.8	2.0	1.2	1.0	1.4
	Min.	0.0	0.0	0.0	0.0	0.1
	Mean ± SD	0.1 ± 0.2	0.7 ± 0.5	0.3 ± 0.3	0.3 ± 0.2	0.5 ± 0.3
	G (W/m^2)					
	Max.	394.3	327.4	77.4	303.3	62.1
	Min.	27.5	28.4	8.7	21.0	17.9
	Mean ± SD	175.9 ± 124.6	157.9 ± 107.8	29.2 ± 18.0	120.9 ± 99.1	36.5 ± 11.7
	T_g (°C)					
	Max.	19.5	20.2	12.6	17.6	10.5
	Min.	0.2	0.5	−0.1	0.6	0.7
	Mean ± SD	9.7 ± 6.5	10.2 ± 6.5	5.8 ± 4.4	7.9 ± 5.5	5.6 ± 3.7
	T_{mrt} (°C)					
	Max.	25.0	40.8	18.7	30.7	12.9
	Min.	0.2	1.8	0.0	0.9	0.4
	Mean ± SD	10.5 ± 7.4	18.0 ± 12.4	6.8 ± 5.4	11.7 ± 9.1	6.9 ± 4.0

3.2. Thermal Perception

We calculated that the $NPET_{autumn}$ = 18.7 °C and the NPETR = 14.6−22.9 °C in autumn; the $NPET_{winter}$ = 11.6 °C and the NPETR = 7.3–15.9 °C in winter. The NPET in winter and autumn, with the regression models of MTSV and PET, indicates that people can tolerate cold more in winter than in autumn. This may be because people have adapted to the cold environment (Figure 2).

$$MTSV_{autumn} = 0.1192\ PET - 2.2343\ (R^2 = 0.9203) \quad (2)$$

$$MTSV_{winter} = 0.1164\ PET - 1.3458\ (R^2 = 0.9194) \quad (3)$$

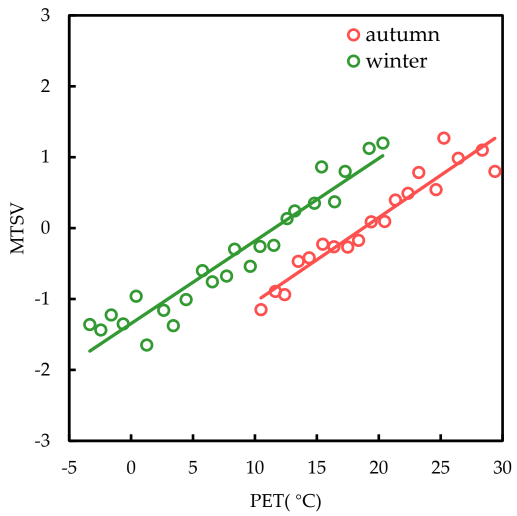


Figure 2. Correlation between MTSV and PET in autumn and winter.

3.3. *Acoustic Perception*

ANOVA of acoustic sensation vote (ASV), acoustic comfort vote (ACV), and acoustic unacceptable vote (AUV) showed that there were significant differences between ASV, ACV, and AUV at different STPs ($F > 1$; $p < 0.01$).

3.3.1. Acoustic Sensation

When calculating the percentages of the ASV of different levels in the total number of votes at different STPs, ASVs for "−3: very quiet", "−2: quiet" and "−1: relatively quiet" were viewed as votes for "quiet", and ASVs for "0: moderate" were viewed as neutral votes. ASVs for "3: very noisy", "2: noisy" and "1: relatively noisy" were viewed as votes for "noisy" (Figure 3).

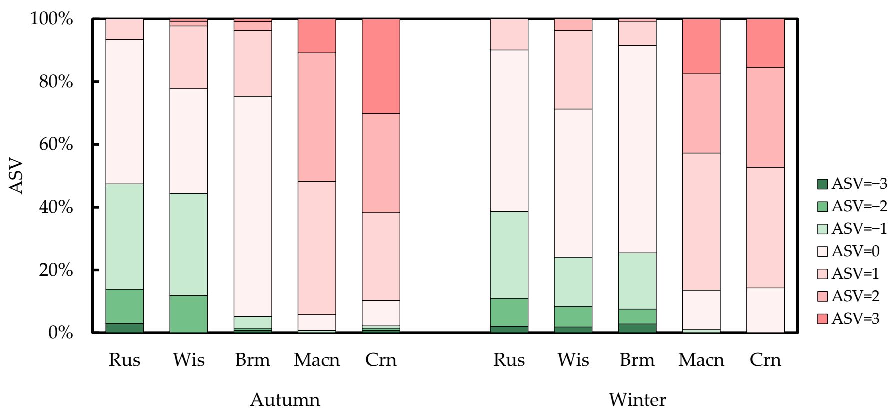


Figure 3. Distribution of the ASV among sound types.

Given a constant SPL, we found a significant difference in the ASVs at different STPs. In autumn, the percentage of ASVs for "moderate" with broadcasting music was the highest (70.1%). The percentages of ASVs for "noisy" with crowds (94.2%) and machines (89.7%) were far higher than those with other STPs. In other words, crowds and machines made most respondents feel their environment was "noisy". The percentage of ASVs for "3:

very noisy" and "2: noisy" with running water and birdsong was 0, and only 6.6% of respondents voted for "relatively noisy". This reflected that most respondents felt they were in a relatively quiet environment with running water and birdsong.

In winter, the percentage of ASVs for "moderate" with broadcasting music remained the highest (66.0%), followed by those with running water and birdsong (51.5%) and wind (a gentle breeze) and insects (47.2%). With running water and birdsong and broadcasting music, the percentage of ASVs for "quiet" was higher than that of votes for "noisy". With crowd noise, the percentage of ASVs for "−3: very quiet" and "−2: quiet" was 0. With machines, the percentage of ASVs for "−3: very quiet", "−2: quiet" and "−1: relatively quiet" was 0. In other words, the respondents felt that the environment was "noisy" by the sounds after class and machine noise. This was consistent with results in autumn. In this study, crowds and machines were perceived as noises, and we found that noise perception was insensitive to ambient T_a.

3.3.2. Acoustic Comfort

We calculated the percentage of ACVs from the total number of votes at different STPs. ACVs for "−2: discomfort" and "−1: slightly discomfort" were perceived as votes for "discomfort". ACVs for "0: neutral" were perceived as neutral. ACVs for "1: slightly comfort" and "2: comfort" were perceived as the votes for "comfort" (Figure 4).

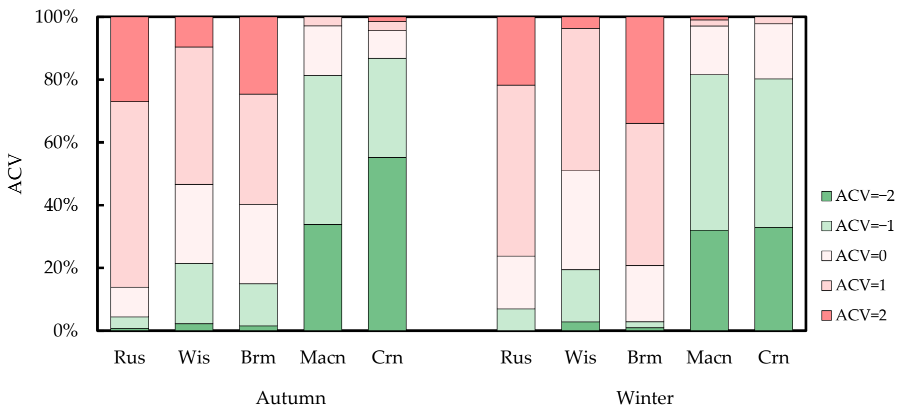


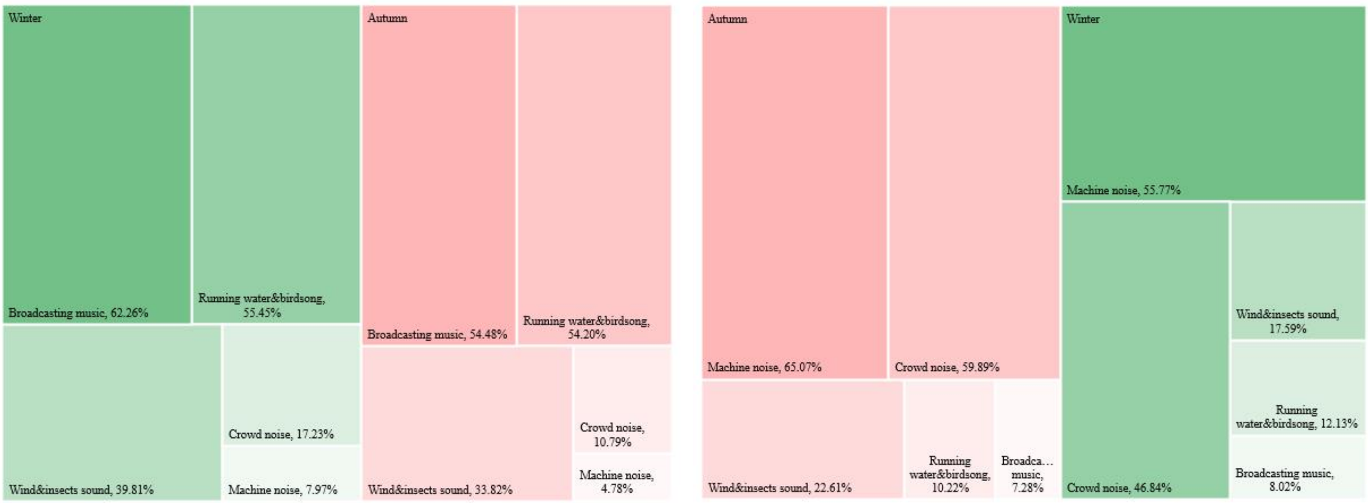
Figure 4. Distribution of the ACVs among sound types.

In autumn, the percentage of ACVs for acoustic comfort was relatively high with broadcasting music (86.3%), running water and birdsong (53.3%), and wind (a gentle breeze) and insects (59.7%). More than 50% of the respondents perceived a comfortable acoustic environment. Nevertheless, ACVs for acoustic comfort provided the completely opposite results with crowds and machines. Most respondents perceived that these two sound types brought them acoustic discomfort. Results demonstrated that different STPs influenced the acoustic comfort of people differently. We found no difference between winter and autumn ACVs despite different STPs.

In winter, the percentage of ACVs for "discomfort" and "moderate" at different STPs was higher compared to those in autumn. This appeared to be because a low T_a in winter increased acoustic discomfort. The percentages of ACVs for "comfort" with broadcasting music were the highest in both autumn and winter. In other words, acoustic comfort might not be influenced by low temperatures when it is accompanied by pleasant music. However, low T_a may increase acoustic discomfort with other STPs. Running water and birdsong and wind (a gentle breeze) and insects are often viewed as pleasant sounds. Running water and wind may increase the cold sensation of respondents, thus decreasing their TSV.

3.3.3. Acoustic Evaluation

The acoustic environment at each site was evaluated using eight adjectives. Specifically, "eventful, exciting, pleasant, and calm" were used as positive evaluations, whereas "uneventful, monotonous, annoying, and chaotic" were used as negative evaluations. Moreover, votes for "somewhat agree" and "strongly agree" were grouped as "agree". Votes for "strongly disagree" and "somewhat disagree" were grouped as "disagree". In autumn, proportions of votes for "agree" with positive evaluations were broadcasting music > running water and birdsong > wind (a gentle breeze) and insects >crowds > machines. The proportions of votes for "disagree" with negative evaluation were: machines > crowds > wind (a gentle breeze) and insects (22.6%) > running water and birdsong > broadcasting music. The adjective evaluation in winter was consistent with that in autumn. Positive and negative evaluations represent respondent preferences for different sounds. The respondents gave more positive evaluations of broadcasting music and running water and birdsong, but more negative evaluations of machines and crowds. With broadcasting music and running water and birdsong, the respondents perceived a pleasant acoustic environment with a better space landscape experience. With machines and crowd noises, the respondents perceived a poor acoustic environment, thus influencing their space landscape experiences. Broadcasting music achieved the highest positive evaluation and the lowest negative evaluation (Figure 5).



(**a**) (**b**)

Figure 5. Proportion of positive adjectives (**a**) and negative adjectives (**b**).

3.4. Effects of Acoustic Perception on Thermal Perception

An ANOVA of TSV and TCV was carried out on each STP. There were different TSVs at different STPs, but such differences were not significant ($F > 1$; $p > 0.05$). There were significant differences among STPs in terms of TCV ($F > 1$; $p < 0.01$).

3.4.1. Thermal Sensation at Different STPs

The TSV distributions at different STPs were similar in autumn and winter. In autumn, the proportions of "TSV = 0" in broadcasting music, running water and birdsong, wind (a gentle breeze) and insects, crowds, and machines were similar. In winter, the proportions of "TSV = −2" (25.71%) and "TSV = −3" (5.71%) in wind (a gentle breeze) and insects were the highest. This revealed that people preferred the colder TSV with wind (a gentle breeze) and insects (Figure 6).

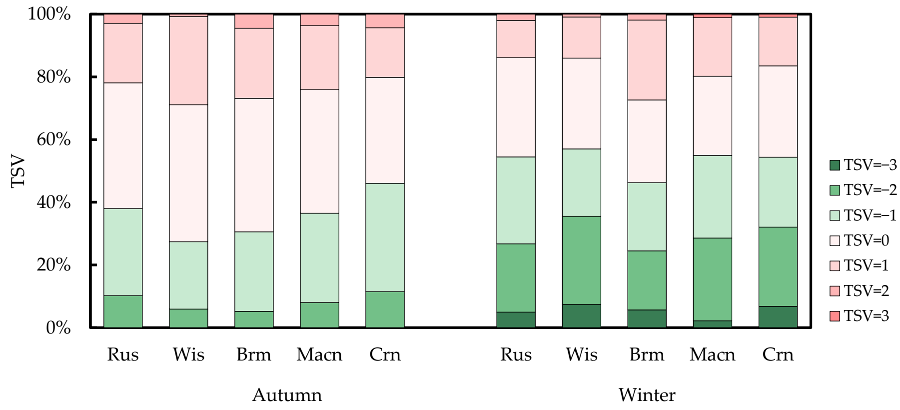


Figure 6. Distribution of the TSV among sound types.

3.4.2. Thermal Comfort at Different STPs

We calculated the percentages of TCVs at different levels in the total number of votes at different STPs. In autumn, TCVs for "discomfort" (TCV = −2, −1) were relatively high with machines (35.3%) and crowds (39.6%). The TCVs for "comfort" (TCV = 1, 2) with running water and birdsong (57.7%), wind (a gentle breeze) and insects (57.0%), and broadcasting music (56.7%) exceeded 50% and were basically equal, indicating the high thermal comfort of respondents. In winter, the TCVs for "discomfort" at different STPs were higher than that in autumn, which might be related to the meteorological environment in winter. The percentage of TCVs for "discomfort" was the highest with crowds (65.0%), but the percentage of TCVs for "comfort" was the highest with broadcasting music (45.3%). In autumn and winter, the respondents reported high thermal comfort with broadcasting music, but low with machines and crowd noise (Figure 7). This may be because different STPs caused different acoustic comfort, thus influencing the respondents' thermal comfort.

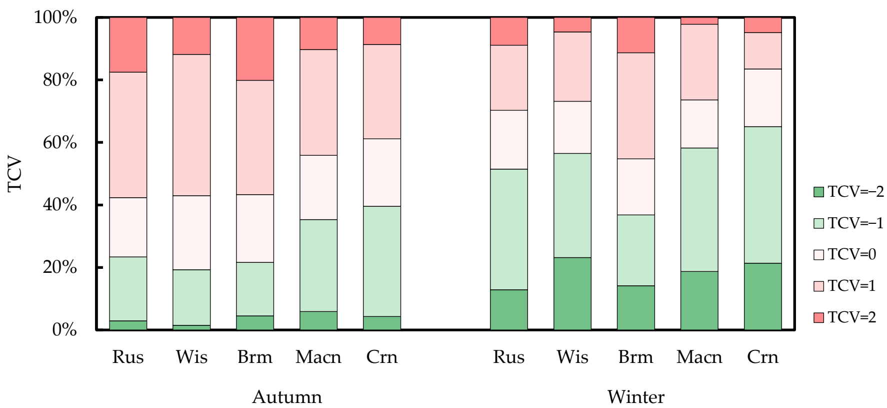


Figure 7. Distribution of the TCVs among sound types.

3.4.3. NPET at Different STPs

We calculated the weighted mean TSV for every 1 °C bin of PETs at different STPs in autumn and winter. NPETs at different STPs in autumn and winter were compared. In autumn, machines > running water and birdsong > crowds > broadcasting music > wind (a gentle breeze) and insects. In winter, machines > wind (a gentle breeze) and insects > crowds > broadcasting music > running water and birdsong. The NPETs with machines were the highest both in autumn and winter, accompanied by a higher TSV compared to those at other STPs. The influence of STP on thermal sensation had no significant patterns in autumn. The influences of STP on thermal sensation in winter were more significant compared to those in autumn (Figure 8, Table 5).

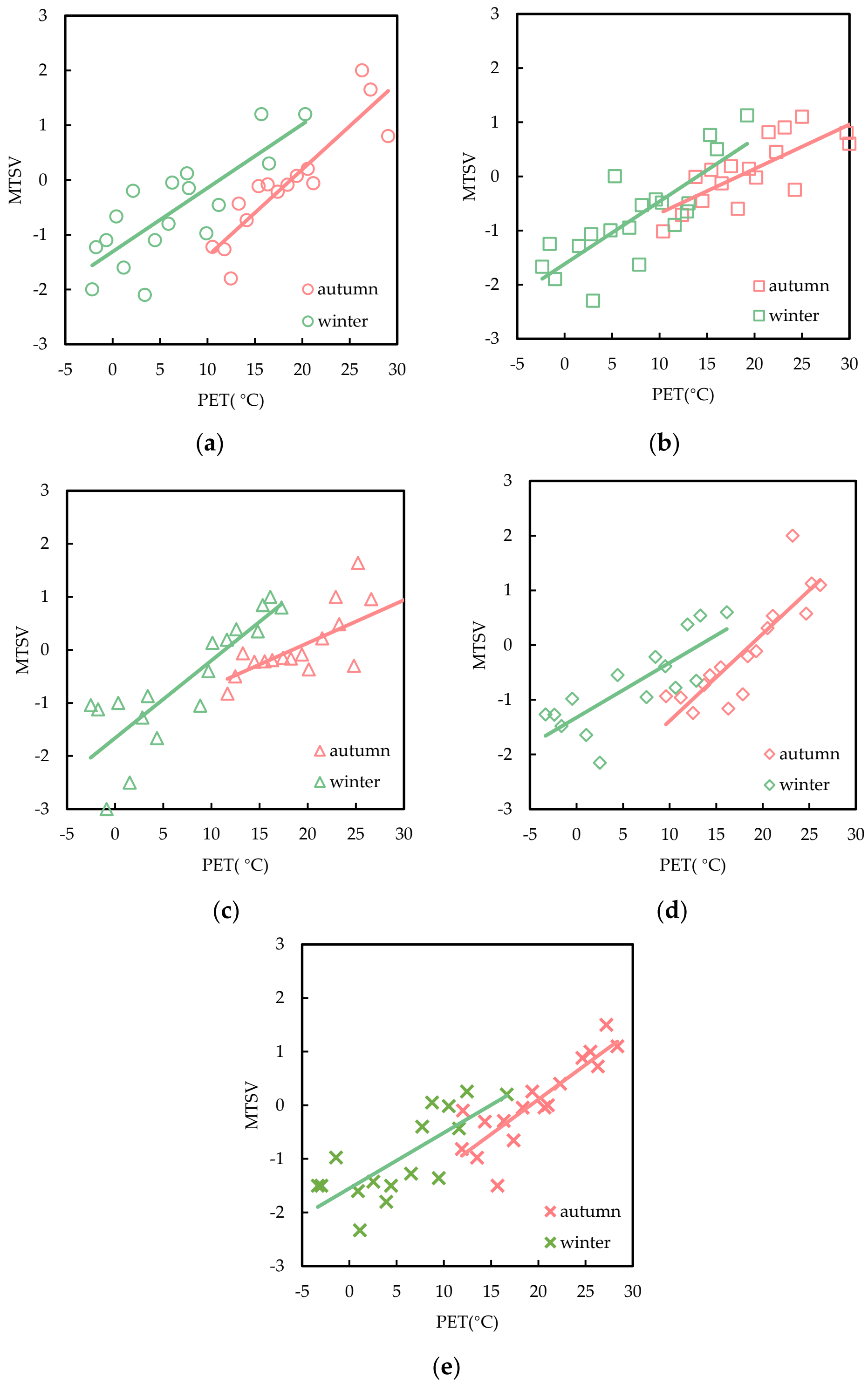


Figure 8. Correlation between PET and MTSV in different sound types: running water and birdsong (**a**), wind (a gentle breeze) and insects (**b**), broadcasting music (**c**), crowds (**d**), and machines (**e**).

Table 5. Correlation between PET and MTSV in different sound types.

	Autumn	Winter
Machine noise	MTSV = 0.1294 PET − 2.4824 (R^2 = 0.7473)	MTSV = 0.1037 PET − 1.5505 (R^2 = 0.575)
Crowd noise	MTSV = 0.1594 PET − 2.98 (R^2 = 0.7419)	MTSV = 0.1003 PET − 1.3249 (R^2 = 0.6347)
Running water and birdsong	MTSV = 0.1599 PET − 3.0671 (R^2 = 0.7539)	MTSV = 0.1163 PET − 1.3098 (R^2 = 0.6469)
Broadcasting music	MTSV = 0.1128 PET − 2.0213 (R^2 = 0.7122)	MTSV = 0.146 PET − 1.6612 (R^2 = 0.7254)
Wind and insects sound	MTSV = 0.1198 PET − 2.1037 (R^2 = 0.6948)	MTSV = 0.1156 PET − 1.6189 (R^2 = 0.6554)

3.4.4. NPET at Different ACV Levels

The relationship between PET and MTSV with different acoustic comfort levels was calculated and fitted linearly (Figure 9). With different ACV levels, the relationship between PET and MTSV was:

$$\text{ACV} = 1, 2 \text{ (comfort level)} \quad \text{MTSV} = 0.0769\ \text{PET} - 1.4875\ (R^2 = 0.7787) \tag{4}$$

$$\text{ACV} = 0 \text{ (moderate level)} \quad \text{MTSV} = 0.0586\ \text{PET} - 1.068\ (R^2 = 0.6195) \tag{5}$$

$$\text{ACV} = -2, -1 \text{ (discomfort level)} \quad \text{MTSV} = 0.0767\ \text{PET} - 1.1989\ (R^2 = 0.823) \tag{6}$$

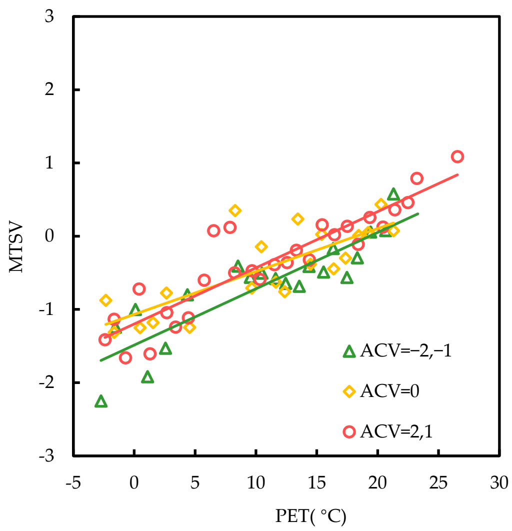


Figure 9. Correlation between PET and MTSV at different ACV levels.

The NPET at corresponding ACV levels were calculated: $\text{NPET}_{\text{comfort}}$ = 15.6 °C, $\text{NPET}_{\text{moderate}}$ = 18.2 °C, and $\text{NPET}_{\text{discomfort}}$ = 19.3 °C. It shows an order of $\text{NPET}_{\text{comfort}} \leq \text{NPET}_{\text{moderate}} < \text{NPET}_{\text{discomfort}}$. The TSV was low in autumn and winter when the sound was uncomfortable. The TSV was high with acoustic comfort, but the respondents' thermal sensation was lower when the sound was uncomfortable.

4. Discussion

4.1. Thermal Perception

We found no significant difference in the TSVs among different STPs, but a significant difference in TCVs. This result agrees with Guan's study [89]. Some studies found that noise did not affect the cold sensations, but it affected thermal comfort and discomfort [90]. People were more sensitive to the perception of noise in hot environments [91]. The respondents' TCVs were higher with broadcasting music, wind (a gentle breeze) and insects, and running water and birdsong compared to other STPs. With crowd and machine noises, the TCVs were relatively low, intensifying the respondents' thermal discomfort. Yang and Moon found that sound types had significant effects on TCVs, ACVs, and OCVs [92,93]. Generally, TCVs were higher with acoustic comfort, but it was worse when acoustic discomfort was reported. Overall comfort is influenced by the interaction of SPL and T_a. Thermal, acoustic, and total comforts in a musical environment were all better than in a noisy environment [89]. This is similar to our results. Our experiments were conducted in autumn and winter, when a low T_a reduced the sensitivity of the respondents' sound perception, resulting in differences in TSVs between sound types but not significantly. The TCVs in different sound types are not affected by temperature. A comfortable acoustic environment increases positive emotions, thus improving their thermal comfort.

4.2. Acoustic Perception

There were significant differences among STPs in terms of acoustic perception, acoustic comfort, and acoustic acceptability even though the SPL was similar among trials. Broadcasting music, running water and birdsong, and wind (a gentle breeze) and insects can make respondents feel more pleasant, thus receiving higher scores on acoustic evaluation. However, crowd and machine noises are viewed as too loud and unpleasant, thus resulting in low scores on acoustic evaluation. When experiencing a pleasant sound, the overall preference for the acoustic environment was higher [94]. People like street music, tramcar sounds, and birdsong. Residents living in rural areas prefer natural sounds and rhythms and reported a neutral attitude toward livestock sounds and communication sounds, but strongly disliked noises from traffic and machines [95]. Similar results are found in this study.

Independent sample t-tests were conducted on male and female subjects' sound and thermal evaluations. The results showed there were no significant differences between gender on ASVs, ACVs, and TCVs, but significant differences were found in TSVs. This agrees with the conclusions of Yang and Kang's study [68]. Additionally, analysis of the respondents' TSVs under different STPs showed that male subjects that perceived 'moderate' (TSV = 0) were more than that of female subjects, while female subjects were more sensitive to thermal stress under the same sound stimuli during autumn and winter.

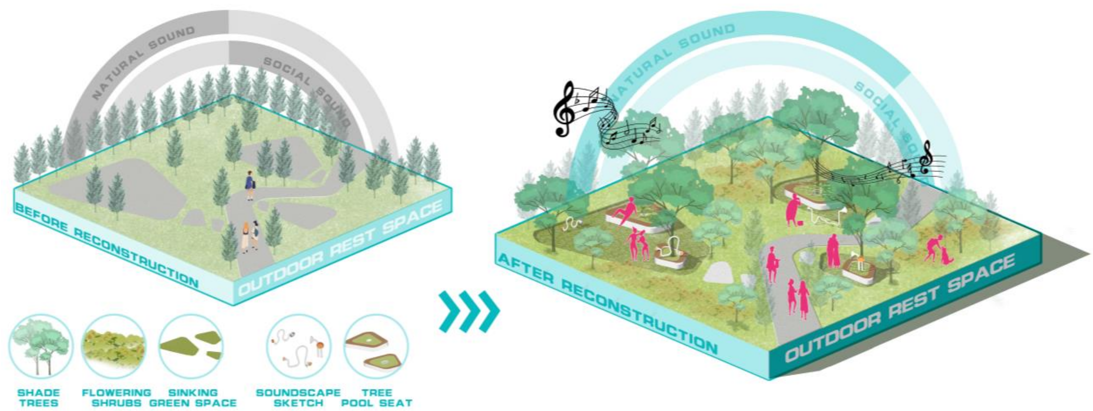
4.3. Strategies Based on Thermal–Acoustic Effects

Based on our results, optimal design strategies to improve outdoor comfortable perceptions using the combined effect of acoustic–thermal comfort were proposed. Machine noises may decrease acoustic and thermal comfort while running water and birdsong have positive effects on the acoustic environment. In an activity space with external noise disturbances, a design with a fountain background wall, tall trees that attract birds, and a large canopy will decrease acoustic discomfort (Figure 10a). In an activity space with few external noises, uneven green land, safety exercise boundaries, and vegetation can be designed to separate activity and rest zones and dampen crowd noise influences (Figure 10b). Soundscape sketches can be designed in outdoor rest spaces. We suggest increasing the duration and frequency of broadcasting music, designing sunken spaces and tree pool chairs, enclosed by flowering shrubs, and creating quiet and comfortable outdoor rest spaces (Figure 10c). Outdoor natural space provides appropriate habitats for animals like insects and birds by providing an appropriate plant community. We suggest designing an ecological drought stream or rainwater garden and increasing wind (a gentle breeze) and insects and running water and birdsong sounds (Figure 10d). Squares should consider designing foundations, pools, flower beds, corridors, and other landscape elements, planting trees with large crowns and deed shade, playing pleasant music, and improving the overall outdoor comfort and satisfaction of teachers and students (Figure 10e).

(**a**)

(**b**)

(**c**)



(**d**)

Figure 10. *Cont*.

(**e**)

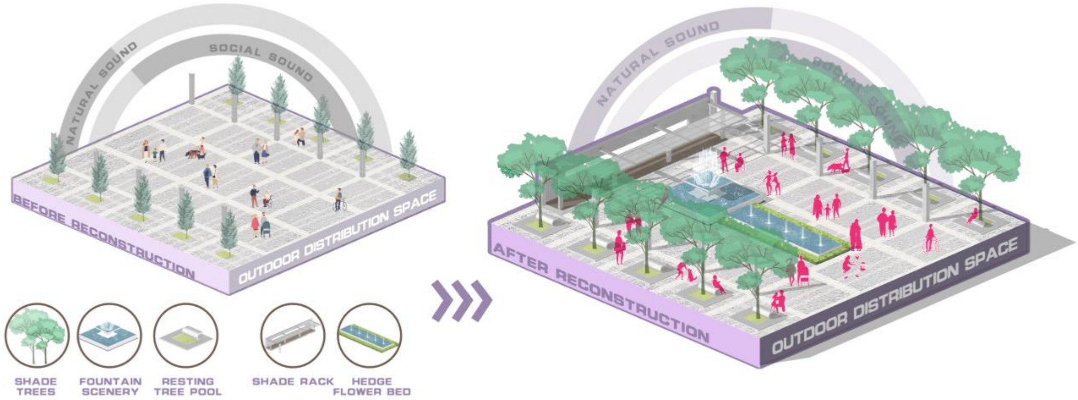


Figure 10. Optimum design strategies: (**a**) design with a fountain background wall and tall trees to attract birds and decrease acoustic discomfort; (**b**) design with uneven green land, safety exercise boundaries, and vegetation to dampen crowd noise influences; (**c**) increase the duration and frequency of broadcasting music to create comfortable outdoor rest space; (**d**) design with an ecological drought stream or rainwater garden to increase wind (a gentle breeze) and insects and running water and birdsong; (**e**) design with foundations, pools, flower beds, and corridors to improve the overall comfort and satisfaction.

A good acoustic–thermal environment can also provide a satisfactory landscape experience for atypical persons. In our design strategy, playing pleasant music can soothe atypical people and have a positive impact, which is similar to what we often call music therapy, where a good mood will enhance the perceptual evaluation (including acoustic–thermal perception); adding natural sounds by improving the natural environment, which is beneficial for the health and therapeutic effects of atypical people; and lower noise levels in open spaces can reduce the stress of atypical people and avoid stress levels.

4.4. Limitations

This study has some limitations. First, we investigated the influences of STPs on acoustic and thermal perception with a fixed SPL. Future studies should explore the influences of STPs on acoustic and thermal perception with different SPLs. Second, our study was conducted in the cold and transition seasons. An experiment may well come to different conclusions with a high T_a in summer. Third, the respondents were exposed to recording sounds from speakers rather than the real sound environment, which may have led to different findings, and the role of the acoustic–thermal interaction in real scenarios should be further investigated in future studies. Fourth, we recruited healthy students for our experiment, but there are also atypical populations on campus, such as depressed and hearing-impaired people, who perceive the environment differently from healthy people. Therefore, future research should further investigate how the acoustic–thermal environment affects the perception of atypical populations.

5. Conclusions

In this study, five typical open spaces with five common STPs (broadcasting music, running water and birdsong, wind (a gentle breeze) and insects, crowds, and machines) on a campus in China's cold region were tested. The acoustic perception in each space is evaluated as eventful, exciting, pleasant, calm, uneventful, monotonous, annoying, and chaotic, during which PET is selected as a thermal index to evaluate OTC. The relationship between acoustic perception and thermal comfort among open spaces during autumn and winter was analyzed. Some major conclusions are drawn:

1. There are significant differences among STPs in terms of acoustic perception and comfort and acoustic acceptability even though the SPLs are controlled. Broadcasting music, running water and birdsong, and wind (a gentle breeze) and insects make respondents feel more pleasant and acceptable, while crowds and machines are too loud and unpleasant.
2. The respondents' thermal comfort is related to STPs. Different STPs influence people's acoustic comfort, thus influencing their thermal comfort. With natural sounds (running water and birdsong) and meaningful sound (broadcasting), people experience higher thermal comfort. In autumn, the thermal comfort order with different STPs is: wind (a gentle breeze) and insects > running water and birdsong > broadcasting music > machines > crowds. In winter, this order is: broadcasting music > wind (a gentle breeze) and insects > running water and birdsong > machines > crowds.
3. The NPET is different for different STPs. In autumn, the NPET of machines, running water and birdsong, crowds, broadcasting music, and wind (a gentle breeze) and insects is 19.184 °C, 19.181 °C, 18.70 °C, 17.92 °C, and 17.56 °C, respectively. In winter, the NPET of machines, wind (a gentle breeze) and insects, crowds, broadcasting music, and running water and birdsong is 14.95 °C, 14.00 °C, 13.21 °C, 11.38 °C, and 11.26 °C, respectively. The NPET with machines is the highest in autumn and winter. People perceived high thermal sensation when they are acoustically comfortable, but low thermal sensation when in acoustic discomfort.

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Nomenclature

PG	Peony garden
CS	Campus square
WA	Wooded area
EG	Ecological garden
PS	Patio space
Brm	Broadcasting music
Rus	Running water and birdsong
Wis	Wind (a gentle breeze) and insects
Crn	Crowds
Macn	Machines
SVF	Sky view factor
ASV	Acoustic sensation vote
ACV	Acoustic comfort vote
TSV	Thermal sensation vote
TCV	Thermal comfort vote
PET	Physiological equivalent temperature
NPET	Neutral PET
STP	Sound type
Leq	Sound pressure level

Ta	Air temperature (°C)
RH	Relative humidity (%)
Va	Wind speed (m/s)
Tg	Globe temperature (°C)
Tmrt	Mean radiant temperature (°C)
G	Global radiation (W/m^2)

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