sustainability

MDPI

Article

The Effects of Microclimate Parameters on Outdoor Thermal Sensation in Severe Cold Cities

Ming Lu [1], Tuoyu Hou [1,*], Jingwan Fu [1] and Yuan Wei [2]

1 Key Laboratory of Cold Region Urban and Rural Human Settlement Environment Science and Technology, Ministry of Industry and Information Technology, School of Architecture, Harbin Institute of Technology, Harbin 150001, China; hitlm1969@hit.edu.cn (M.L.); 15b934010@hit.edu.cn (J.F.)
2 College of Urban and Rural Construction, Shanxi Agricultural University, Jinzhong 030801, China; mawenda@hit.edu.cn
* Correspondence: 13b334014@hit.edu.cn

Received: 18 January 2019; Accepted: 12 March 2019; Published: 15 March 2019

check for updates

Abstract: This study investigated the outdoor thermal sensation characteristics in severe cold cities, and the effects of four microclimate parameters on outdoor thermal sensation. A one-year investigation of public spaces in Harbin, China, as an example of a severe cold city, was carried out. Volunteers were randomly invited to fill out a microclimate perception questionnaire, and the real-time microclimate data were measured and recorded at the same time on site. The relationship between the outdoor actual thermal sensation and the perception of microclimate parameters was analyzed quantitatively. The results showed that the effect of microclimate parameters on the actual thermal sensation was very significant. The actual thermal sensation varies greatly from the seasons. People feel the most comfortable in the transition season. Among the four parameters, temperature has the greatest effect on ATSV in cold season and severe cold season, solar radiation has the greatest effect on ATSV in transition season and hot season. In the severe cold season and hot season, the wind speed also has a significant effect on ATSV.

Keywords: microclimate; thermal sensation; severe cold cities

1. Introduction

In recent years, people have paid great attention to the comfort of outdoor activities, and the impact of outdoor microclimate on health. The field research has found that the description of microclimate perception often begins with 'feeling cold or hot', which means that the most intuitive perception of microclimate is the actual thermal sensation. In the severe cold cities of northern China, the cold and windy climate has adversely affected residents' winter activities. There are also persistent high temperature and high humidity weather in summer in these cities, with the increasing effect of urban heat island, which makes the impact of microclimate perception more complicated. Therefore, how to make the microclimate parameters meet the requirement of thermal sensation, this is very important for people living in severe cold cities.

The outdoor thermal sensation is affected by the microclimate parameters, including air temperature, air humidity, air velocity (wind speed) and thermal radiation (solar radiation). At present, researchers have paid attention to the effect of microclimate parameters on thermal sensation. Gaitani et al. studied the thermal sensation of the activists in the outdoor environment [1–3]. Nikolopoulou et al. compared the thermal comfort of different urban spaces [4]. These studies show that the influence of air temperature and solar radiation on the outdoor thermal sensation is the most significant, while the influence of air humidity and wind speed on the thermal sensation depends on the range of outdoor air temperature [5–8]. These studies indicate that the microclimatic parameters not only affect the thermal sensation, but also interact with each other.

The ultimate goal of this study on thermal sensation is to achieve microclimate comfort, overall comfort is also an important indicator. 'When the temperature is close to the neutral temperature, the microclimate is considered comfortable.' This finding has been proven by the studies of neutral temperature in different cities [9–14]. Neutral temperature is a temperature that makes people feel neither cold nor hot. Liu et al. compared neutral temperatures in some cities, pointed out that neutral temperatures were lower in cold cities than in hot ones, especially in winter [15]. These studies have proved that the numerical range of the thermal sensation was entirely different in different climate and areas [14,15].

Therefore, many research results would not be applicable to severe cold cities. In severe cold cities, researchers are trying to establish a set of criteria to evaluate the quality of the outdoor public space microclimate, and to help designers create a comfortable environment. Chen et al. studied the acceptability range of severe cold cities in China [16]. Lai et al. studied the neutral physiological equivalent temperature (PET) range [17]. Zhang et al. studied an integrated design approach to systematically evaluate and optimize school design parameters at different design stages for summer outdoor thermal comfort demand [18].

The relationship between spatial layout and microclimatic parameters is very close. In urban planning and design, a more comfortable microclimate is often obtained by adjusting the site scale. Hedquist et al. investigated outdoor human comfort, utilizing output from the microclimate model ENVI-met, and predicted mean vote outcomes at key points within each of the three areas [19]. Limor et al. investigated how to reduce, by appropriate urban design, air temperature at the street level and to improve pedestrian thermal conditions in summer [20]. Gruchy et al. considered the effects of urban layout and architectural form on the microclimate, and proposed indicators of urban and architectural design [21]. These studies show that we can adjust the microclimate by adjusting the aspect ratio of the street, the orientation of the street, the open degree of the site, the high-rise building and the multi-storey building, the greening, the setting of sunshade and so on. At the same time, many kinds of computer simulation techniques are widely used, such as CFD, ENVI-met and GIS etc. Taleghani et al. simulated outdoor air temperature, mean radiant temperature, wind speed and relative humidity, and the effects of urban and architectural forms on microclimate parameters and thermal comfort were studied [22,23].

There are some limitations in the existing studies. First, the studies for severe cold area are still insufficient. Second, the actual thermal sensation is also affected by the psychological and physiological factors of the environmental perception. When the environment changes, it stimulates the human body, and people adapt to the stress by changing clothes and using sunshade to achieve physical and mental balance. As such, behavior changes are difficult to quantify. Third, the existing studies did not reveal the effects of the outdoor microclimate parameters on actual thermal sensation, which can provide more useful basis for the design of public spaces in severe cold cites.

The characteristics and influencing factors of thermal sensation in severe cold cities are of great value, and the effect of microclimate parameters on actual thermal sensation is the focus of this study. Additionally, time periods in the existing studies are selected according to the four seasons [24–27]. However, the temperature of cities in the north and south regions varies significantly from season to season in countries such as China, where the latitudes on the north and south borders are entirely different. Therefore, to study thermal sensation, the investigation period should be selected according to the temperature variation of the target city. Finally, the relationship between spatial layout and microclimatic parameters is very close. The actual thermal sensation can be used as an important index of environmental quality assessment. The study has considered the impact of behavior on evaluation results. This effect is different from the indoor environment, not just the movement or rest, or what kind of clothing people wear. The subjects are not individuals, but a group of people who were purposefully active. Their state is likely to change and they can make themselves more comfortable by taking the initiative, such as opening the neckline, taking off their coats or gloves, or choosing a more comfortable environment. These factors are closely related to actual engineering projects and that is valuable to urban planners. Therefore, the study of microclimate and thermal sensation can be used to guide urban planning.

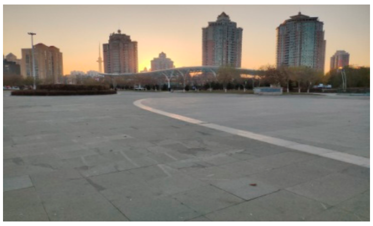
In this study, a one-year investigation of public spaces in Harbin, China, as an example of severe cold cities, was carried out. The objective of this study was to investigate the effect of outdoor microclimate on the actual thermal sensation in public spaces of severe cold cities.

2. Methods

2.1. Survey Site

Harbin (125°42′ E–130°10′ E, 44°04′N–46°40′ N) is the capital of Heilongjiang Province in northeast China and is also a typical severe cold city. Four typical outdoor public spaces were selected as the field investigation locations, as shown in Table 1. The public spaces are large parks in the central urban area of Harbin, with a large number of activists. The types and activities of these spaces are different, and there is a steady flow of people. Moreover, people can access these public spaces freely. The influence of different spatial forms on outdoor microclimate was considered in the selection of these locations. Abundant microclimate data could be acquired as the spatial morphology was entirely different.

Table 1. Basic spatial information of the locations.

Location Number	Image of the Space	Description of the Space
1		Space type: road Subsurface: pavement Natural elements: trees
2		space type: square subsurface: masonry pavement natural elements: trees, shrubs, grass
3		space type: forest subsurface: vegetation, soil natural elements: trees, grass
4		space type: waterfront subsurface: masonry pavement natural elements: trees, shrubs, grass, water

2.2. Procedure

The air temperature, air humidity, wind speed and solar radiation were measured and recorded continuously at each observation point. The average was acquired every 5 min. The globe temperature was recorded every 15 min. The volunteers were randomly selected from the sites at the same time. A total of 895 questionnaires were distributed including 886 valid questionnaires. The microclimate perceived voting results were obtained from these questionnaires. Finally, each sample consists of a set of real-time microclimate monitoring data and a perceived vote, which was applied to the analysis of the relationship between thermal sensation and microclimate.

According to the daily average temperature data in Harbin, and the investigation on the site, the research time was divided into four intervals including severe cold season (the temperature was below −10 °C in January, February and December), cold season (the temperature at about −10–10 °C in March, April, October and November), transition season (the temperature at about 10–20 °C in May and September) and hot season (the temperature was above 20 °C in June, July and August). The continuous sunny days (from 9:00 to 18:00) before and after the typical days of each season were selected to be observed using the weather forecast. The observation dates are shown in Table 2.

Table 2. The observation dates.

Time Interval	Observation Dates
severe cold season	22 and 26 December, 2 and 22 January
cold season	21 and 22 March, 15 and 30 October
transition season	10 and 15 May, 17 and 28 September
hot season	5 and 22 June, 9 and 23 July

2.3. Tools

The outdoor microclimatic parameters including air temperature, relative humidity, mean wind speed and solar radiation were monitored by a TESTO435 multifunction measuring instrument and JTR05 solar radiation tester. The globe temperature was recorded with a JTR04A black bulb thermometer. The measurement height of outdoor microclimate parameters was 1.5 m [13,15]. The accuracy of each instrument is shown in Table 3.

Table 3. Instrument for measuring outdoor microclimatic parameters.

Parameters	Instrument	Range	Accuracy
air temperature	TESTO435-1	−20–70 °C	±0.3 °C
wind speed	TESTO435-1	0 m/s–20 m/s	±0.03 m/s
relative humidity	TESTO435-1	0–100%	0.2%
solar radiation	JTR05	0–2000 W/m^2	±2% annual mean
globe temperature	JTR04A	−20–125 °C	±0.2 °C

2.4. Questionnaire

The surveys were compliant with the ISO 10551 standard [28]. The questionnaire included the following primary information:

- Personal data, included age, gender, height, body weight, birthplace, profession, education and duration in the observation point.
- Current clothing and activity types. We had recorded all users' activity types at the same time.
- Subjective votes to outdoor microclimate, included actual thermal sensation vote (ATSV), overall comfort vote (OCV), and various responses to outdoor temperature, humidity, wind speed and solar radiation. The voting and quantification scale are shown in Table 4. In this study, a seven-point scale was used to evaluate the thermal sensation, and the five-point scale was used to evaluate the overall comfort.

- Related psychological factors. For example, he would untie his collar when he felt hot and put his hands in his pocket when he felt cold.

Table 4. Voting content and quantification scale.

Voting Content	Rating Scale
actual thermal sensation vote (ATSV)	−3 (cold) −2 (cool) −1 (slightly cool) 0 (neutral) +1 (slightly warm) +2 (warm) +3 (hot)
overall comfort vote (OCV)	0 (comfortable) 1 (slightly uncomfortable) 2 (uncomfortable) 3 (very uncomfortable) 4 (extremely uncomfortable)

2.5. Statistical Analysis

The effect of outdoor microclimate parameters on human outdoor thermal sensation was analyzed using statistical analysis methods. Multiple linear regression analysis was used to establish the models to quantify the relationship between multiple outdoor microclimate parameters and the actual thermal sensation in severe cold cities. To evaluate the regression equations, the fitting degree was expressed by R^2, and the significance level was set at $p < 0.05$.

Selection of microclimatic parameters was one of the key links, especially with regard to thermal radiation. Thermal radiation contained many items, included solar radiation and infrared radiation. We used JTR04A to measure globe temperature. The difference between the outdoor air temperature and the globe temperature reflected the intensity of outdoor thermal radiation. At the same time, we need volunteers to be able to describe the perception of parameters in words, in order to link up with the follow-up study. Therefore, we used solar radiation as one of the main indicators in multiple linear regression calculations. The tool was JTR05: The spectral range was 0.3–3.2 μm, included solar radiation (0.15–4 μm), near infrared radiation (0.78–2.5 μm) and part of mid-infrared radiation.

3. Results and Analysis

3.1. Microclimate Data and Votes

Measurements of microclimatic parameters in different seasons are shown in Table 5. In the severe cold season, the minimum air temperature is −16.50 °C. However, the average relative humidity could reach 54.8%, which is much higher than in the cold season and transition season because there is snow on the ground. The temperature fluctuates from −9.80 to 17.70 °C in the cold season, the average wind speed is higher than in other seasons, and the maximum wind speed of the whole year also occurs in this season. The average temperature of the transition season is 19.70 °C, and the average of humidity is 26.6%, which is the lowest of the year. In the hot season, the average temperature is 29.62 °C, the highest temperature is over 34.70 °C, and the humidity is high, but the wind speed is low, which makes people feel muggy easily.

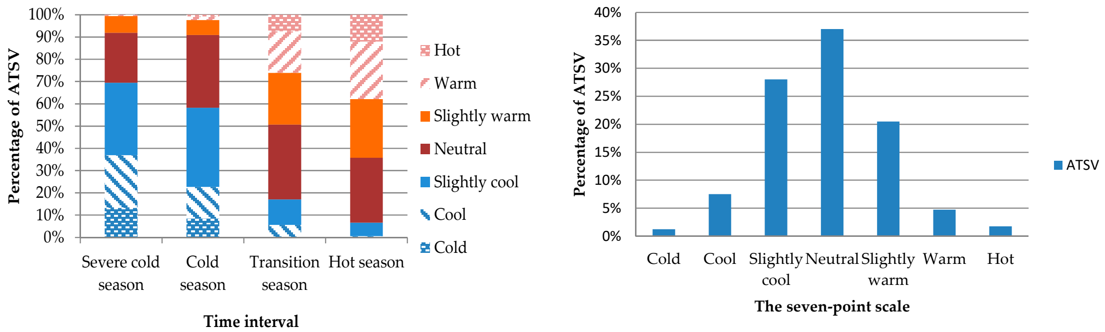
3.2. The Relationship between Actual Thermal Sensation and Overall Comfort

A total of 886 valid questionnaires are obtained from four seasons (18% in the severe cold season, 27% in the cold season, 34% in the transitional season and 21% in the hot season). Of all the samples, 41% are male, and 86% are youth (<45 years old).

We have analyzed and compared the results of the voting for actual thermal sensation in each season. As shown in Figure 1a, the actual thermal sensation varies greatly from the seasons. In the severe cold and cold seasons, the most frequently perceived thermal sensation was 'slightly cool', and the thermal sensation votes were mainly distributed over the 'neutral' and 'slightly cool'. During the transitional season and hot season, the voting is mainly in the range of 'neutral' and 'slightly warm'. However, in the hot season, the proportion of the voting over 1 accounted for 37.9%. The above indicates that people feel cooler in severe cold and cold seasons, while in transitional and hot seasons, the actual thermal sensation is closest to 'neutral', but people feel warmer during the hot season. Although the microclimate varies greatly from the seasons, 'neutral' voting accounts for a large proportion, as shown in Figure 1b. This phenomenon is consistent with the stress reaction of volunteers mentioned in microclimate perception theory.

Table 5. Microclimate survey in different seasons.

Time Interval	Characteristic Value	Temperature (°C)	Humidity (%)	Solar Radiation (W/m^2)	Wind Speed (m/s)
severe cold season	average	−10.68	54.8	109.3	0.48
	maximum	−3.70	78.5	327.0	2.86
	minimum	−16.50	35.5	0.0	0.00
cold season	average	7.83	27.9	428.1	0.92
	maximum	17.70	39.8	931.0	3.26
	minimum	−9.80	19.4	10.0	0.00
transition season	average	19.70	26.6	304.2	0.61
	maximum	26.80	45.6	789.0	2.93
	minimum	15.40	14.2	33.0	0.00
hot season	average	29.62	50.4	457.1	0.32
	maximum	34.70	63.1	997.0	1.20
	minimum	24.00	29.9	22.0	0.02



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

Figure 1. (**a**) Percentage of actual thermal sensation vote (ATSV) in different seasons; (**b**) ATSV percentage of seven-point scale.

At the same time people feel 'neutral', they don't necessarily feel 'comfortable'. As shown in Figure 2a, there is a big difference between ATSV and OCV. In the transition season, the percentage of 'neutral' is the highest at 33.6%, and there are only a few 'hot' (7.5%) and 'cold' (0%) votes, as shown in Figure 1a. As shown in Figure 2a, 'comfortable' voting rates are also the highest in the transition season. The result shows that people feel the most comfortable in the transition season. In the hot and cold seasons, the 'neutral' votes are very close to that of the transition season, but 'comfortable' votes are fewer. There are more 'extremely uncomfortable' votes (13%) in the hot season than in other seasons. These votes are mainly concentrated on samples with a temperature above 30 °C.

In the 'comfortable' sample of four seasons, many people think that the thermal sensation is not 'neutral', but rather 'slightly warm' or 'slightly cool'. In the cold season and severe cold season, the 'extremely uncomfortable' and 'very uncomfortable' votes can be considered as the consequence of 'cool' and 'cold' votes. However, fewer volunteers felt 'very uncomfortable' or 'extremely uncomfortable'. This is because that the people living in severe cold areas are better adapted to the cold climate in comparison to the people living in the other regions. This adaptation is a physiological adaptation achieved by behavioral regulation.

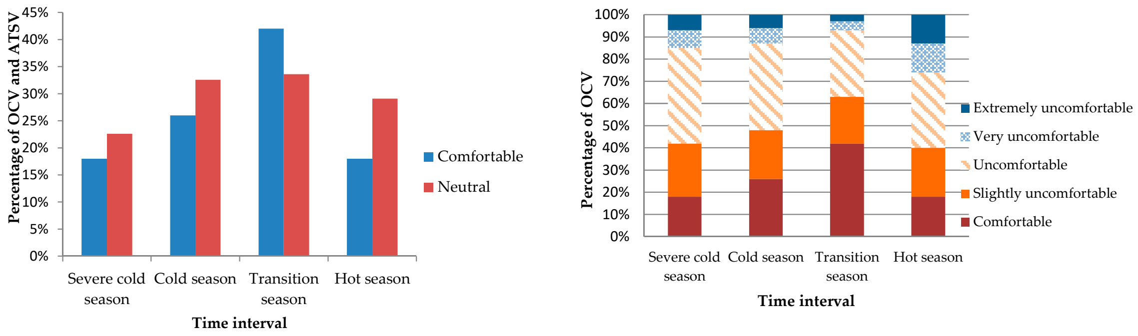


Figure 2. (**a**) Compare the percentage of 'comfortable' and 'neutral'; (**b**) Percentage of overall comfort vote (OCV) in different seasons.

3.3. The Relationship between Outdoor Thermal Sensation and Microclimatic Parameters

In practice, we can get the microclimate data of the design scheme by measuring or simulating. If the actual thermal sensation in various places can be evaluated at the beginning of design, will help to identify the potential constraints and to adjust or optimize the plan based on the quantitative evidence. Instead of choosing to correlate microclimate parameters with most common heat stress indices including cold stress when using required clothing insulation (IREQ) [29] and wet bulb globe temperature (WBGT) [30,31], the survey focused on the relationship between the subjective investigation results and microclimatic parameters in public spaces severe cold cities. Taking the voting sample as the analysis object, the microclimate parameters as the independent variable, and the thermal sensation voting value as the dependent variable, the formula of the annual influence relation is obtained by the multivariate linear regression fitting, as shown by the Equations (1)–(4).

$$\text{Severe cold season: ATSV} = 0.274\text{Tair} - 0.46\text{Swind} - 0.014\text{Rhum} + 0.003\text{Rsolar} + 2.701, \quad R^2 = 0.788\ p < 0.05 \tag{1}$$

$$\text{Cold season: ATSV} = 0.151\text{Tair} - 0.185\text{Swind} - 0.023\text{Rhum} + 0.001\text{Rsolar} - 1.499, \quad R^2 = 0.718\ p < 0.05 \tag{2}$$

$$\text{Transition season: ATSV} = 0.12\text{Tair} - 0.286\text{Swind} - 0.013\text{Rhum} + 0.004\text{Rsolar} - 2.117, \quad R^2 = 0.772\ p < 0.01 \tag{3}$$

$$\text{Hot season: ATSV} = 0.157\text{Tair} - 0.577\text{Swind} + 0.014\text{Rhum} + 0.003\text{Rsolar} - 4.456, \quad R^2 = 0.688\ p < 0.01 \tag{4}$$

ATSV is actual thermal sensation voting; Tair is air temperature (°C); Swind is wind speed (m/s); Rhum is humidity (%); Rsolar is solar radiation (W/m^2). From the statistical analysis, the P values of the above fitting equations are all less than 0.05, which indicates that the prediction of a thermal sensation by using the above equations can obtain reliable results.

The monomial coefficient in the prediction equation represents the relationship between the microclimate parameter and the thermal sensation. In different seasons, the effect of each parameter on thermal sensation is different. As shown in the Equations (1)–(4), air temperature has the most significant effect on the thermal sensation in the severe cold season. The thermal sensation increases by 0.274 when the temperature increases by 1 °C. The increase is the lowest in the transition season, at only 0.12. The thermal sensation increases roughly the same during the hot season and the cold season, at 0.157 and 0.151, respectively. Similarly, solar radiation has the most significant effect on the thermal sensation of the transition season. The thermal sensation increases by 0.004 when solar radiation increases by 1 W/m^2, while the effect on the thermal sensation in the cold season was the lowest, with an increase of merely 0.001. The wind speed has the most apparent effect on the hot season. The increase in the wind speed of 1 m/s can cause a 0.577 decrease in thermal sensation. While the effect on the cold season was the least, only decreasing by 0.185. Humidity is the most discrete variable in the prediction formula of each season. In the hot season, humidity is positively correlated with thermal sensation, while it is negatively correlated in the severe cold season, cold season and transition season.

To compare the relative impact of independent variables on ATSV, we took the voting sample as the analysis object, the microclimate parameters as the independent variable, and the thermal sensation voting value as the dependent variable, the standardization coefficients of the microclimate parameters are obtained by the multivariate linear regression fitting, as shown in Table 6. Among the four parameters, temperature has the greatest effect on ATSV in cold season (0.81) and severe cold season (0.697). Solar radiation has the greatest effect on ATSV in transition season and hot season. In the severe cold season and hot season, the wind speed also has a significant effect on ATSV (−0.17, −0.167), but in the transition season and cold season, the effect becomes less (−0.077, −0.099). The effect of hot air on thermal sensation has not been demonstrated in this study. Climatic conditions also have an effect on humidity, resulting in a very small coefficient of humidity. These issues need to be further studied.

Table 6. Standardization coefficient of microclimatic parameters in different seasons.

Time Interval	Temperature	Wind Speed	Humidity	Solar Radiation
severe cold season	0.697	−0.170	−0.110	0.271
cold season	0.810	−0.077	−0.085	0.184
transition season	0.360	−0.099	−0.080	0.618
hot season	0.272	−0.167	0.125	0.528

4. Discussion

The above results reveal the effect of outdoor microclimate parameters on the actual thermal sensation in severe cold cities. Throughout the year, the increase in outdoor air temperature and solar radiation caused the rise of outdoor thermal sensation, while the effect on wind speed was the opposite. At the same time, there are seasonal and regional differences in the effect of microclimate parameters on the outdoor actual thermal sensation, which are mainly reflected in neutral air temperature (NAT).

Outdoor neutral air temperature (NAT) refers to the outdoor air temperature when the average thermal sensation vote of the target group equals to 0 (neutral). The NAT can be calculated according to the Equations (1)–(4). The values of outdoor humidity, wind speed, and solar radiation need to be set according to the standard thermal conditions [5]:

- The outdoor air humidity is set to 50%;
- The outdoor wind speed is set to 0.1 m/s;
- The solar radiation is 0 (close to 0 thermal radiation).

The results are as follows: NAT reaches the highest value in summer (24.3 °C) and the lowest value (−7.1 °C) in winter. The NAT of spring and autumn (including the cold and transition seasons mentioned above) are between 17.7 °C and 23.3 °C.

Given the regional and seasonal differences between outdoor thermal sensation and neutral air temperature, the neutral air temperature in Harbin is compared with that in cities in southern China, Changsha, and Taipei [15,26], as shown in Table 7. It is found that the NAT in Harbin is lower and of a higher difference in winter and summer than that of other two cities. These differences are related to the climatic conditions of the city. The difference between the average temperature in summer and winter in Harbin is approximately 40 °C, which is the reason why the residents in a city of this kind of severe cold are more adaptable to seasonal climate change.

Table 7. Comparison of outdoor air temperature range and neutral air temperature (NAT) between north and south cities in China.

City	Outdoor Mean Temperature (°C)		Outdoor Neutral Temperature (°C)	
	Severe Cold Season (Winter)	Hot Season (Summer)	Severe Cold Season (Winter)	Hot Season (Summer)
Harbin	−15	24	−7.1	24.3
Taipei	19	25	21.3	28.5
Changsha	8.3	30.2	16.7	24.5

Existing research suggests the people living in severe cold areas are better adapted to the cold climate in comparison to the people living in the other regions. This study also verifies this conclusion, but this adaptation is a physiological adaptation achieved by behavioral regulation. People generally choose the right clothes according to the season to enhance their cold resistance. In addition to physical cold tolerance, mental and behavioral adjustments are also important reasons, that people can reach the thermal neutral state in the range of air temperature from −7.1–24.3 °C in severe cold cities. As shown in Table 8, the comparison between NAT and NPET [16] in Harbin shows that the difference between NAT and NPET is greater in severe cold season. This difference is not only affected by the increase or decrease in clothing and exercise levels, but also by the individual behavior based on their perception of each microclimate parameter in outdoor.

Table 8. Comparison between neutral physiological equivalent temperature (NPET) and NAT in Harbin.

	Severe Cold Season (Winter)	Hot Season (Summer)
NAT (°C)	−7.1	24.3
NPET(°C)	18.0	20.0

Although volunteers can't vote explicitly for thermal radiation levels, in addition to solar radiation, infrared radiation also has an impact on thermal sensation. The average radiation temperature can be used to represent the intensity of outdoor thermal radiation (including solar and infrared radiation). In this study, the partial correlation analysis was used to capture the relationship between solar radiation and thermal sensation, mean radiant temperature and thermal sensation. In the partial correlation analysis, the other variables were controlled. Therefore, their influences were eliminated. As shown in Table 9, the effects of solar radiation and average radiation temperature on ATSV are significant ($p < 0.01$). The correlation between solar radiation and ATSV is 0.477 (control variables are air temperature, humidity and wind speed), and this value is higher than the R^2 value of the average radiation temperature. The results show that both solar radiation and average radiation temperature have significant effects on ATSV of public space population. But if the solar radiation parameter (Rsolar) is replaced with the average radiation temperature, the influence coefficients of Tair, Rhum and Swind may be increased.

Table 9. Partial correlation coefficient of solar radiation and mean radiation temperature between ATSV.

	R^2	p
solar radiation	0.477	$p < 0.01$
mean radiation temperature	0.258	$p < 0.01$

In outdoor, people are free to choose their space and location based on their perception of each microclimate parameter, such as walking in the shade in summer. The microclimate perception votes shows that more than 50% of the volunteers considered the air temperature and solar radiation to be 'neutral' in each season, indicated that they could effectively enhance their comfort through individual behavior. 80% of the volunteers thought that the humidity was 'neutral', indicating that the change in humidity was within the acceptable range. The wind environment becomes much more complex due to the occlusion of the buildings in the city. Moreover, the wind speed may vary significantly in different places in the same day, which often makes the negative impact of wind speed on thermal sensation more serious. In the cold season, 55% of the volunteers thought that the wind speed was 'strong' or 'very strong', which indicated that high wind speed is an essential reason for the discomfort of outdoor activity. However, it was the opposite in the hot season, where the wind speed was low, and people were feeling muggy. These problems are difficult to adjust through personal behavior. So from the perspective of urban planning, the negative effects of unstable wind speed are more critical than the persistent low temperature in winter, especially in severe cold cities.

The survey focused on the relationship between actual thermal sensation voting and microclimatic parameters in severe cold cities. In this survey, volunteers were randomly selected to vote in urban public space. This kind of investigation pays attention to the practice, makes the research result more accord with the city situation. However, the sample collected in the survey was not evenly distributed, such as different age structures, sex ratios and behavior types did not have the same number of questions. The study also did not collect microclimate data and votes in extreme weather (such as rain and snow). We have obtained the thermal sensing equation for practical engineering, but the variation trend of regression coefficient needs to be further studied. At the same time, the concrete practice method has not been explained in detail in this paper. In the future, we will further study these problems.

5. Conclusions

The effects of microclimate on outdoor thermal sensation in severe cold cities were analyzed, and the following conclusions can be drawn:

1. The actual thermal sensation varies greatly from the seasons. In the severe cold and cold seasons, and the thermal sensation votes were mainly distributed over the 'neutral' and 'slightly cool'. During the transitional season and hot season, the voting is mainly in the range of 'neutral' and 'slightly warm'. Although the microclimate varies greatly from the seasons, 'neutral' voting accounts for a large proportion. This phenomenon is consistent with the stress reaction mentioned in microclimate perception theory. The microclimate perception of the volunteers is relatively accurate. Therefore, improving the microclimate environment can efficiently improve the activity quality.
2. People feel the most comfortable in the transition season. In the transition season, the percentage of 'neutral' is the highest at 33.6%, and there are only a few 'hot' (7.5%) and 'cold' (0%) votes, and 'comfortable' voting rates are also the highest. In the hot and cold seasons, the 'neutral' votes are very close to that of the transition season, but 'comfortable' votes are fewer. There are more 'extremely uncomfortable' votes (13%) in the hot season than in other seasons.
3. Microclimate parameters play an essential role in outdoor thermal sensation. From a year-round perspective, the increase in the air temperature and the solar radiation lead to the rise of outdoor thermal sensation, while the influence of wind speed and relative humidity is the opposite. Outdoor volunteers in severe cold cities are usually not sensitive to humidity. Among the four parameters, temperature has the greatest effect on ATSV in cold season (0.81) and severe cold season (0.697). Solar radiation has the greatest effect on ATSV in transition season and hot season. In the severe cold season and hot season, the wind speed also has a significant effect on ATSV (−0.17, −0.167), but in the transition season and cold season, the effect becomes less (−0.077, −0.099).
4. The NAT of Harbin is 24.3 °C in summer, −7.1 °C in winter, and between 17.7 °C and 23.3 °C in spring and autumn.

5. People's perception of each microclimate parameter has an impact on comfort. More than 50% of the volunteers considered the air temperature and solar radiation to be 'neutral' in each season, and 80% of the volunteers thought that the humidity was 'neutral', indicating that they can effectively enhance their comfort through individual behavior. In the cold season, 55% of the volunteers thought the wind speed was 'strong' or 'very strong', which indicates that high wind speed is an essential reason for the discomfort of outdoor activity. However, it is the opposite in the hot season, where the wind speed is low, and the activists feel muggy. These problems are difficult to adjust through personal behavior. So from the perspective of urban planning, the negative effects of unstable wind speed are more critical than the persistent low temperature in winter, especially in severe cold cities.

Author Contributions: Conceptualization, M.L. and T.H.; Methodology, M.L. and T.H.; Data curation, T.H. and Y.W.; Formal analysis, T.H.; Investigation, T.H., J.F. and Y.W.; Resources, M.L.; Supervision, M.L.; Project administration, M.L.; Funding acquisition, M.L.; Writing—original draft preparation, T.H.; Writing—review and editing, M.L., T.H. and J.F.

Funding: This research was funded by National Natural Science Foundation of China for the major project "Research on Adjustment Principle and Design Method of the City Microclimate for Severe Cold Areas", grant number "No. 51438005".

Acknowledgments: Thanks to the team (National Natural Science Foundation of China for the major project, No. 51438005) for its technical support. The authors would like to acknowledge the subjects who volunteered for the outdoor field investigation.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Gaitani, N. On the use of bioclimatic architecture principles in order to improve thermal comfort conditions in outdoor spaces. *Build. Environ.* **2007**, *1*, 317–324. [CrossRef]
2. Givoni, B.; Noguchi, M.; Saroni, H.; Pochter, O.; Yaacov, Y.; Feller, N.; Becker, S. Outdoor comfort research issues. *Energy Build.* **2003**, *35*, 77–86. [CrossRef]
3. Stathopoulos, T.; Wu, H.; Zacharias, J. Outdoor human comfort in an urban climate. *Build. Environ.* **2004**, *39*, 297–305. [CrossRef]
4. Nikolopoulou, M.; Lykoudis, S. Use of outdoor spaces and microclimate in a Mediterranean urban area. *Build. Environ.* **2007**, *42*, 3691–3707. [CrossRef]
5. Höppe, P. Different aspects of assessing indoor and outdoor thermal comfort. *Energy Build.* **2002**, *34*, 661–665. [CrossRef]
6. Andrade, H.; Alcoforado, M.; Oliveira, S. Perception of temperature and wind by users of public outdoor spaces: Relationships with weather parameters and personal characteristics. *Int. J. Biometeorol.* **2011**, *55*, 665–680. [CrossRef] [PubMed]
7. Krüger, E.; Rossi, F. Effect of personal and microclimatic variables on observed thermal sensation from a field study in southern Brazil. *Build. Environ.* **2011**, *46*, 690–697. [CrossRef]
8. Matzarakis, A.; Rutz, F.; Mayer, H. Modelling radiation fluxes in simple and complex environments application of the Rayman model. *Int. J. Biometeorol.* **2007**, *51*, 323–334. [CrossRef]
9. Ahmed, K.S. Comfort in urban spaces: Defining the boundaries of outdoor thermal comfort for the tropical urban environment. *Energy Build.* **2003**, *35*, 103–110. [CrossRef]
10. Thorsson, S. Thermal comfort and outdoor activity in Japanese urban public places. *Environ. Behav.* **2007**, *39*, 660–684. [CrossRef]
11. Hou, T.; Lu, M.; Fu, J. Microclimate perception features of commercial street in severe cold cities. *Energy Procedia* **2017**, *134*, 528–535. [CrossRef]
12. Lenzholzer, S.; Koh, J. Immersed in microclimatic space: Microclimate experience and perception of spatial configurations in Dutch squares. *Landsc. Urban Plan.* **2010**, *11*, 1–15. [CrossRef]
13. Wei, Y. Research of Thermal Comfort of Microclimate on Harbin Urban Park Based on Behavior Activity. Master's Thesis, Harbin Institute of Technology, Harbin, China, 2015.

14. Yang, W.; Wong, N.H.; Jusuf, S.K. Thermal comfort in outdoor urban spaces in Singapore. *Build. Environ.* **2013**, *59*, 426–435. [CrossRef]
15. Liu, W.; Zhang, Y.; Deng, Q. The effects of urban microclimate on outdoor thermal sensation and neutral temperature in hot-summer and cold-winter climate. *Energy Build.* **2016**, *128*, 190–197. [CrossRef]
16. Chen, X.; Xue, P.; Liu, L.; Gao, L.; Liu, J. Outdoor thermal comfort and adaptation in severe cold area: A longitudinal survey in Harbin. *Build. Environ.* **2018**, *143*, 548–560. [CrossRef]
17. Lai, D.; Guo, D.; Hou, Y.; Lin, C.; Chen, Q. Studies of outdoor thermal comfort in northern China. *Build. Environ.* **2014**, *77*, 110–118. [CrossRef]
18. Zhang, A.; Bokel, R.; Dobbelsteen, A.; Sun, Y.; Huang, Q.; Zhang, Q. An integrated school and schoolyard design method for summer thermal comfort and energy efficiency in northern China. *Build. Environ.* **2017**, *124*, 369–387. [CrossRef]
19. Hedquist, B.C.; Brazel, A. Seasonal variability of temperatures and outdoor human comfort in Phoenix. *Build. Environ.* **2014**, *72*, 377–388. [CrossRef]
20. Limor, S.; Loannis, X.T.; Milo, H. Passive cooling design options to ameliorate thermal comfort in urban streets of a Mediterranean climate (Athens) under hot summer conditions. *Build. Environ.* **2012**, *3*, 110–119. [CrossRef]
21. Gruchy, G.F.D. Some environmental relationships between topography, built form, landscape and microclimate in Brisbane's city centre. *Urban Ecol.* **1978**, *57*, 155–170. [CrossRef]
22. Taleghani, M.; Kleerekoper, L.; Tenpierik, M.; Dobbelsteen, A. Outdoor thermal comfort within five different urban forms in the Netherlands. *Build. Environ.* **2015**, *83*, 65–78. [CrossRef]
23. Salata, F.; Golasi, I.; Vollaro, R.; Vollaro, A. Urban microclimate and outdoor thermal comfort: A proper procedure to fit ENVI-met simulation outputs to experimental data. *Cities Soc.* **2016**, *26*, 318–343. [CrossRef]
24. Middel, A.; Hab, K.; Brazel, A.J.; Martin, C.A.; Guhathakurta, S. Impact of urban form and design on mid-afternoon microclimate in Phoenix local climate zones. *Urban Plan.* **2014**, *122*, 16–28. [CrossRef]
25. Jin, H.; Kang, J.; Jin, Y.; Shao, T. A study on the construction technics of strawbale walls in severe cold rural areas of northeast China. *Sci. Sin. Technol.* **2016**, *46*, 1079–1085. [CrossRef]
26. Lin, T.; Matzarakis, A. Tourism climate and thermal comfort in Sun Moon Lake, Taiwan. *Int. J. Biometeorol.* **2008**, *52*, 281–290. [CrossRef]
27. Shui, T.; Liu, J.; Zhang, P.; Liu, S.; Zhao, Z. Development of an urban canopy model for the evaluation of urban thermal climate with snow cover in severe cold regions. *Build. Environ.* **2016**, *96*, 160–170. [CrossRef]
28. International Organization for Standardization. *ISO 10551 Ergonomics of the Thermal Environment—Assessment of the Influence of the Thermal Environment Using Subjective Judgement Scales*; ISO Stand; ISO 10551:2001 (E); ISO: London, UK, 2002.
29. International Organization for Standardization. *ISO 11079 Ergonomics of the Thermal Environment—Determination and Interpretation of Cold Stress When Using Required Clothing Insulation (IREQ) and Local Cooling Effects*; ISO Stand; ISO 11079:2007 (E); ISO: Geneva, Switzerland, 2007.
30. International Organization for Standardization. *ISO 7243 Ergonomics of the Thermal Environment—Assessment of Heat Stress Using the WBGT (Wet Bulb Globe Temperature) Index*; ISO Stand; ISO 7243:2017 (E); ISO: Geneva, Switzerland, 2017.
31. D'Ambrosio Alfano, F.R.; Malchaire, J.; Palella, B.I.; Riccio, G. The WBGT index revisited after 60 years of use. *Ann. Occup. Hyg.* **2014**, *58*, 955–970. [CrossRef] [PubMed]