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Main effects and interactions of multiple key factors related to thermal perception

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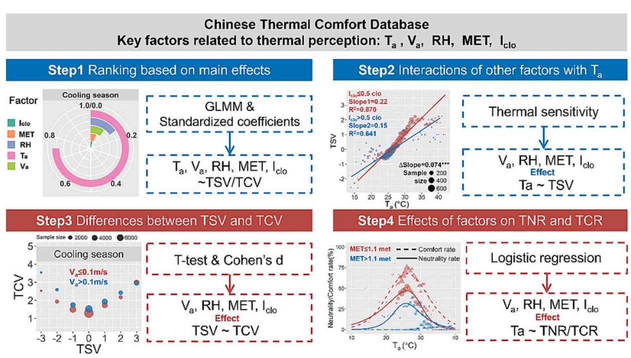
HIGHLIGHTS

- Air temperature is the primary factor affecting thermal sensation and comfort.
- Interaction effects between other factors and air temperature are significant.
- Find certain reasons for thermal discomfort in thermal neutrality state
- New evidence for distinction between thermal sensation and thermal comfort

GRAPHICAL ABSTRACT



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ABSTRACT

The real indoor environment involves the comprehensive interaction of multiple factors, and human subjective responses to different factors are influenced by various aspects such as physics, physiology, and psychology. The relative significance of various factors influencing different types of human subjective thermal perception, as

Abbreviations: T_a, air temperature, °C; T_r, mean radiant temperature, °C; RH, relative humidity, %; V_a, air speed, m/s; I_{clo}, clothing insulation, clo; MET, metabolic rate, met; TSV, thermal sensation vote; TCV, thermal comfort vote; TAV, thermal acceptability vote; TPV, thermal preference vote; PMV, predicted mean vote; PPD, predicted percentage of dissatisfied; TNR, thermal neutrality rate; TCR, thermal comfort rate; SET, standard effective temperature, °C; GLMM, generalized linear mixed model; HSWW, hot summer warm winter region; COLD, cold region; HSCW, hot summer cold winter region; SC, severe cold region.

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well as the extent of their interactions, remains somewhat unclear. This investigation, leveraging the "Chinese Thermal Comfort Dataset," analyzed the integrated impact of basic thermal perception factors—temperature, humidity, air speed, as well as clothing insulation and metabolic rate—on subjective thermal perception. The findings underscored the definitive role of air temperature as the primary determinant of thermal sensation, with the impact of other factors generally remaining below 15 % of temperature. Nonetheless, the sensitivity of thermal sensation to temperature is significantly affected by other factors, demonstrating a significant interaction between temperature and different factors in influencing temperature sensation. Additionally, it was observed that significant differences ($p < 0.001$) in thermal comfort levels existed even at the same thermal sensation. For instance, in the state of thermal neutrality, occupants with relatively higher clothing insulation reported higher thermal comfort level ($d = 0.40$, $p < 0.001$) during the cooling season but lower thermal comfort level ($d = 0.54$, $P < 0.001$) during the heating season. Consequently, it can be deduced that when comprehensively considering the impact of multiple factors, evaluating the environment solely based on thermal sensation or thermal neutrality may prove insufficient.

1. Introduction

One of the principal goals of the indoor environment is to provide a comfortable setting that simultaneously safeguards the well-being of occupants and does not impair their performance (de Dear, 2004). In order to accurately assess thermal perception, it is crucial to employ appropriate methodologies for quantifying this subjective experience (Kim et al., 2018; Lian, 2024; Wang et al., 2020). Simultaneously, it is essential to identify which factors within the indoor environment influence thermal perception and to quantify these effects accurately.

1.1. Thermal perception metrics

There are many types of voting for subjective evaluation of thermal perception, including thermal sensation vote (TSV), thermal comfort vote (TCV), thermal preference vote (TPV), and thermal acceptability vote (TAV). The most commonly used of these is the Thermal Sensation Vote (TSV), which generally utilizes questions and scales consistent with the recommendations of ASHRAE-55. It has been pointed out that the TSV description reflects a person's subjective evaluation of the state of the body's thermal receptors (Parsons, 2014), a perceptive sensation scale, while the thermal comfort scale is an Affective Sensation Scale (Schweiker et al., 2017). ASHRAE-55 defines thermal comfort as "a psychological state that expresses satisfaction with the thermal environment and is assessed through subjective evaluations" (ASHRAE, 2020), and unlike perceptual categories such as TSV, thermal comfort involves a cognitive judgment of satisfaction (Berglund, 1998). This leads to the fact that even in the same state of thermal sensation, people's feelings such as comfort and satisfaction can be affected by many factors and thus differ.

The differences in various evaluation metrics are evident in many studies, and these discrepancies can be categorized into two main types. The first type involves the fact that thermal neutrality (based on thermal sensation) does not align entirely with the most ideal thermal environment (based on thermal comfort, thermal preference, etc.) (Liu et al., 2020). In other words, the optimal points or recommended ranges calculated by different metrics are not identical. Albadra et al. compared thermal sensation votes and thermal preference votes in refugee camps, revealing that during the summer, the preferred temperature was lower than the neutral temperature, while in the winter, the preferred temperature was higher than the neutral temperature, with the disparity being approximately 4 K. The authors also suggested that these differences could not be solely attributed to semantic variations in questionnaire (Albadra et al., 2017). The similar seasonal drift between TSV and the percentage of acceptability was observed by Kim et al. in their study investigating the differences between Korean and English TSV scales (Kim et al., 2022). The second manifestation is that people often find comfort outside of non-neutral environments or feel uncomfortable in neutral environments. Liu et al. conducted a comparative analysis of indoor and outdoor thermal comfort rate and thermal neutral rate. They asserted that thermal comfort could not be simplistically equated with thermal neutrality. While thermal neutrality was a sufficient condition for thermal comfort, it was not a necessary one (Liu et al., 2022). Additionally, thermal neutrality may not necessarily signify ideal thermal conditions, as individuals typically prefer non-neutral thermal sensations (van Hoof, 2008). There are many researches and evidences related to the separation of thermal sensation and thermal comfort in non-uniform and dynamic environments (Zhang and Zhao, 2009, 2008) as well as outdoor environments (Liu et al., 2022, 2020), but the gap between the two in general indoor environments and the reasons for it need to be further discussed.

1.2. Multiple factors related to thermal perception

Numerous factors influence thermal perception, including air temperature (T_a), mean radiant temperature (T_r), air velocity (V_a), relative humidity (RH), metabolic rate (MET), and clothing insulation (I_{clo}). These six factors are widely acknowledged as major variables influencing thermal sensation, and there is substantial research available on the study of these factors. Two highly representative models in this context are the Predicted Mean Vote (PMV) model (Fanger, 1970) and the Standard Effective Temperature (SET) model (Gagge et al., 1971). The PMV model, grounded in the heat balance equation, offers a predictive method for thermal sensation. Conversely, the SET model provides a calculation method for equivalent temperature by comprehensively considering six factors. Subsequent research has delved into various modifications based on these two models to explore more accurate approaches in addressing the impact of individual factors.

According to the principles of the above models, the six main factors affect thermal sensation mainly by influencing the heat exchange between the human body and the environment. But there's also a lot of research that points to them influencing people's judgment of comfort or satisfaction in other ways. Xie et al. pointed out that wind comfort evaluation emphasized the importance of tactile stimulation rather than heat exchange in comparing natural and different types of mechanical winds (Xie et al., 2023). An investigation studying the influence of clothing on comfort pointed out that the phenomenon of physiological comfort is intricate, encompassing not just thermal aspects but also the sensory experience arising from the feel of the fabric (Matusiak, 2010). Humidity affects heat loss, thus influencing heat balance and thermal sensation, but also affects perception of air quality and the aspect of comfort and satisfaction. It has also been noted that the effect on humidity sensation and sweating sensation (Kong et al., 2019; Li et al., 2018). At the same time, the regulation of air speed and the adjustment of the thermal resistance of clothing are important adaptive behaviors (Liu et al., 2017), and the availability of control over them will further affect people's satisfaction with the environment by influencing their mental activity (Brager and de Dear, 1998). However, studies have mainly analyzed the simultaneous effects of each factor on thermal sensation and thermal comfort, and have not further analyzed whether these factors have an independent effect on thermal comfort after excluding the effects of thermal sensation. In other words, few studies have analyzed whether these factors lead to differences in thermal comfort at the same level of thermal sensation.

In addition, human perception is intricate, and the effects of different factors on both physiological and psychological aspects are comprehensive, featuring interactive and coupled influences (Sansaniwal et al., 2020; Yan et al., 2020). Particularly in real-world settings, where there is a wide range of factors that vary across settings, the methods used in analyzing the interaction of different factors on subjective responses vary widely across studies and generally rarely involve simultaneous analyses of all of the major factors mentioned above.

Considering the aforementioned issues, this study aims to address the following research objectives: (1) to compare the extent of influence exerted by various factors on thermal sensation and thermal comfort within real-world environments, (2) to concurrently analyze and compare the interactions among different factors impacting thermal sensation using temperature sensitivity, and (3) to examine variations in thermal comfort based on thermal sensation, while further investigating the underlying causes for the reduction in comfort levels within the same thermally neutral state.

2. Method

2.1. Dataset

The Chinese Thermal Comfort Dataset (Yang et al., 2023) collected a total of 41,977 data sets from various climate regions across China. It encompasses the six major factors related to thermal perception required for this study, as well as TSV and TCV. The database records information including the time, location, and source institution of the data collection. The data underwent rigorous quality checks (Sun, 2022), ensuring comprehensive and accurate characteristics, and many published work could ensure it (Du et al., 2022a, 2022b, 2021), which guarantees the representativeness of the analysis results. TSV are set on a scale from −3 (Cold) to 3 (Hot), while TCV are set on a scale from 1 (Comfortable) to 5 (Extremely Uncomfortable), with details in Appendix A1.1. The data cleansing process can be referred to in Appendix A1.2, where only data with missing values was removed. In the end, 35,160 data sets were used for analyses involving TSV and 33,235 data sets were used for analyses involving TCV. The distribution of the six factors in the database and their correlation with TSV and TCV indicators is illustrated in Appendix A1.3. This study did not include the contribution of radiant temperature, because the limitations of common statistical methods in handling covariance (the Pearson correlation coefficients of T_a and T_r ranging from 0.92 to 0.94). The detailed relationship between T_a and T_r and the influence of T_r on thermal comfort could be referenced in Appendix A1.3 and A3.1.

2.2. Variable processing

Five independent variables were included in this study: T_a, RH, V_a, I_{clo}, MET, along with two dependent variables, TSV and TCV. The factors were categorized to examine subjective thermal perception differences at different levels. RH was classified based on established standards and studies. Generally, research suggests that significant effects on thermal sensation, thermal comfort, sweating, etc., are observed when humidity exceeds 60 %–80 %(Berglund, 1998; Hayakawa et al., 1989; Kong et al., 2019; Li et al., 2018). Recommended RH values in common standards typically range from 30 % to 70 % (Amaripadath et al., 2023). Based on this, RH was divided into three levels. The classification of V_a is referenced from ASHRAE 55–2020 (ASHRAE, 2020), where V_a below 0.1 m/s are considered still air. V_a exceeding 0.1 m/s may involve the introduction of mechanical or natural ventilation. Therefore, the division at 0.1 m/s was used to discern the presence or absence of air movement effects.

The distribution range of MET in the database is relatively narrow, with a maximum value not exceeding 2.0 met. The data was segmented at a value of 1.1 met, representing the MET for seated typing. Values exceeding this threshold are generally considered to involve standing or higher levels of activity. The classification of I_{clo} took into account seasonal variations. For the cooling season, it was divided using the typical summer indoor clothing of 0.5 clo, while for the heating season, the division was based on 1.0 clo for winter. The transitional seasons were assigned based on the mean value in the dataset (refer to Appendix A1.3), which was 0.7 clo. Specific classification levels can be found in Table 1.

2.3. Statistical analysis

2.3.1. Ranking method

The Generalized Linear Mixed Model (GLMM) was employed to compare the importance of different factors (Hoffman, 2020). In contrast to the multiple linear regression, one of the advantages of GLMM is its ability to handle random effects. Due to the diverse sources of data in the database, originating from different institutions and time periods, and encompassing various cities and building types, these contextual factors may introduce random influences into the results. However, as these are not the focus of the study, random intercepts were incorporated into the regression equation to eliminate the impact of such random effects on the regression coefficients.

The specific calculation equations are given by Eqs. (1) and (2), where the regression coefficients for T_a, RH, V_a, MET, and I_{clo} represent the change in TSV or TCV for a one-unit change in each parameter. A higher value indicates a greater impact of the corresponding parameter on TSV or TCV. However, the magnitude of this value is also influenced by the unit of the corresponding parameters. Therefore, to eliminate the influence of unit, all coefficients were standardized (Hoffman, 2020). The standardized coefficients were then used for the comparative ranking of all factors. The final results reflect the impact of each parameter on subjective perception after eliminating the influence of unit. Its significance lies in reflecting which factors in the real environment have the most significant impact on human thermal sensation and thermal comfort. This impact may originate from two aspects: first, the degree to which human thermal sensation is influenced by the factor, and second, the magnitude of fluctuations in the parameter itself.

$$TSV \sim a_1 Ta + a_2 RH + a_3 Va + a_4 Met + a_5 Iclo + intercept(randomeffect) \tag{1}$$

$$TCV \sim b_1 Ta + b_2 RH + b_3 Va + b_4 Met + b_5 Iclo + intercept\ (random\ effect) \tag{2}$$

where, a_1 to a_5 are the regression coefficients of each factor for TSV, b_1 to b_5 represent the regression coefficients of each factor for TCV.

2.3.2. Temperature Sensitivity, significance, and effect size

In addition to the main effects mentioned above, there may also be interaction effects between different factors affecting thermal sensation. The interaction between T_a and other factors was explored using Eqs. (3)–(5). Here, the sensitivity of thermal sensation to temperature is defined as temperature sensitivity, which can be reflected by the

Table 1
Factors category details.

Factor	Level	Cooling season	Transitional seasons	Heating season
RH (%)	Level-1	[15,30]	[8,30]	[6,30]
	Level-2	(30,70]	(30,70]	(30,70]
	Level-3	(70,100]	(70,100]	(70,84]
V_a (m/s)	Level-1	[0,0.1]	[0,0.1]	[0,0.1]
	Level-2	(0.1,3.0)	(0.1,3.0)	(0.1,1.9]
MET (met)	Level-1	[0.7,1.1]	[0.7,1.1]	[0.04,1.1]
	Level-2	(1.1,2.0]	(1.1,2.0]	(1.1,2.0]
I_{clo} (clo)	Level-1	[0.04,0.50]	[0.11,0.70]	[0.17,1.00]
	Level-2	(0.50,2.00]	(0.70,2.75]	(1.00,2.87]

regression slope of T_a in Eqs. (3)–(5). Eq. (3) is the basic mathematical equation for interaction effect (Du et al., 2023), which introduces interaction terms (T_a * Factor), aiming to identify whether there is a significant interaction between T_a and the specific Factor being considered. To enhance comprehension, Eqs. (4) and (5), derived from Eq. (3), were introduced. They are equivalent to Eq. (3) but present a more intuitive representation of the relationship.

It is noteworthy that a significant interaction term (Ta * Factor) in Eq. (3) suggests the presence of an interaction between T_a and the Factor. In simpler terms, the thermal sensation response to T_a varies across different Factor levels. Eq. (4) is entirely the same as Eq. (3) and offers a more intuitive representation of the relationship between temperature sensitivity ($k_1 + k_3$ * Factor) and the Factor. Additionally, by employing Eq. (5) to calculate temperature sensitivity at various levels of each Factor, the extent of the interaction can be assessed based on the differences in temperature sensitivity at different levels and their significance. Generally, a larger and more significant difference in temperature sensitivity indicates a greater impact of the interaction.

$$TSV \sim k_1 Ta + k_2 Factor + k_3 Ta^* Factor + intercept \tag{3}$$

$$TSV \sim (k_1 + k_3 Factor) Ta + k_2 Factor + intercept \tag{4}$$

$$TSV \sim k_4 Ta + intercept(in\ different\ levels) \tag{5}$$

where k_1 to k_4 are the regression coefficients based on the data, Factor represents RH, V_a, I_{clo} or MET.

In addition, the impact of different levels of factors on comfort levels under the same thermal sensation was analyzed using *t*-test and Cohen's d. The t-test was employed to assess the significance of differences in TCV between different levels of factors, while Cohen's d was used to quantify the effect size of these differences. The *p*-values are indicated by '***' for $p < 0.001$, '**' for $p < 0.01$, '*' for $p < 0.05$, and '.' for $p < 0.1$. The significance symbols in other calculation results convey the same meaning. Furthermore, reference values for small, medium, and large effect sizes are 0.2, 0.5, and 0.8, respectively (Cohen, 1988; Lan et al., 2009).

2.3.3. *Thermal neutrality rate, and thermal comfort rate*

To quantitatively explore the effects of various factors on thermal sensation and comfort, the concepts of thermal comfort rate (TCR) and thermal neutrality rate (TNR) are introduced (Liu et al., 2022). In the study, thermal neutrality was defined as TSV between −0.5 and 0.5, while thermal comfort was defined as TCV < 2 (slightly uncomfortable). The thermal neutrality rate was determined by the proportion of votes meeting the specified thermal neutrality condition per unit temperature to the total votes. Similarly, the thermal comfort rate was calculated based on the proportion of votes meeting the specified thermal comfort condition per unit temperature to the total votes. Given that the relationship between thermal comfort and T_a is not unidirectional, using TSV = 0 as the boundary, Discomfort was categorized into cool discomfort and warm discomfort. For discomfort data with TSV = 0, it is classified as cool discomfort in the heating season and transitional seasons, and as warm discomfort in the cooling season. This processing method is discussed in detail in Appendix A2.

This study employed logistic regression to calculate the variations of thermal neutrality rate and thermal comfort rate with T_a, as it demonstrates good performance in predicting the distribution of thermal comfort (Du et al., 2021). Since both the intercept and slope of the regression were required when calculating thermal neutrality and comfort rate, random effects could not be included. Additionally, there are typically regional differences in the neutral or comfortable temperature ranges. Therefore, representative regions were specifically analyzed.

Fig. 1 illustrates the data divisions based on TSV and TCV, along with the corresponding probability values, which are used to explain the logistic regression procedure. (a) represents the classification of thermal sensation, where the probability of thermal neutrality is Y, the probability of Cool Biased is P1, and the probability of Warm Biased is P2. (b) represents the classification of thermal comfort, with probabilities for Thermal Comfort, Cool Discomfort, and Warm Discomfort as Y, P1, and P2, respectively.

Both the thermal neutrality rate and thermal comfort rate were obtained through two logistic regressions, and the specific method for logistic regression are as Eqs. (7) and (8) (Du et al., 2021; Liu et al., 2023).

$$\begin{cases} P1 + Y + P2 = 100\% \\ ln\dfrac{P1}{Y} = c_1 + d_1{}^* T_a \\ ln\dfrac{P2}{Y} = c_2 + d_2{}^* T_a \end{cases} \tag{7}$$

where c_1, d_1, c_2, d_2 are the regression coefficients based on the data.

According to the three relations in Eq. (7), the calculated values for Y can be obtained as shown in Eq. (8). The Y values represent the logistic regression-calculated values for thermal neutrality rate or thermal

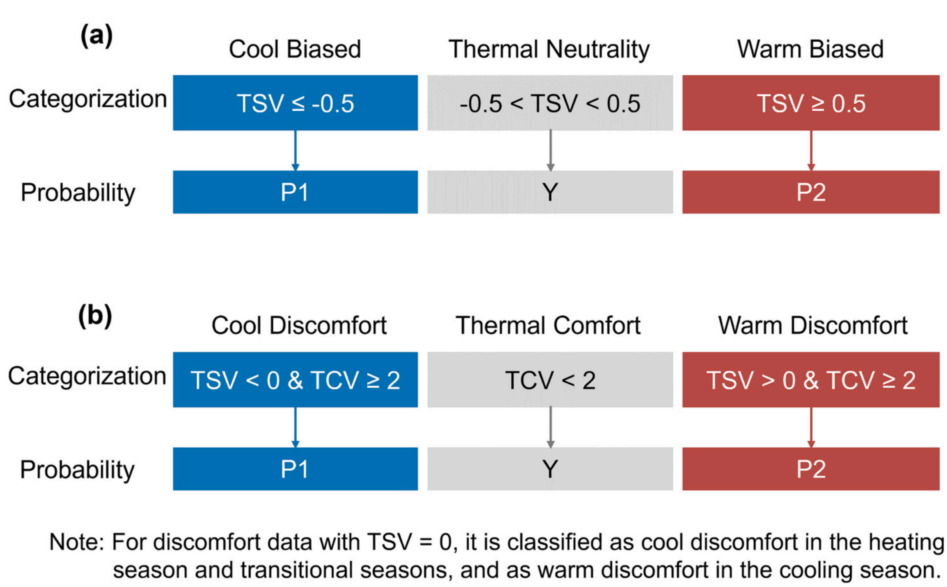


Fig. 1. The categorization and probability representation of thermal neutrality and thermal comfort.

comfort rate at different T_a

$$Y = 1/\left(1 + e^{c_1 + d_1 * Ta} + e^{c_2 + d_2 * Ta}\right) \tag{8}$$

where c_1, d_1, c_2, d_2 are the regression coefficients obtained through Eq. (7).

Statistical analysis was performed using R version 4.3.2 (R Core Team, 2023) and R studio (Posit team, 2023).

3. Results

3.1. Factor rankings

Rankings were based on the standardized regression coefficients of various parameters obtained using GLMM. The results for TSV as the dependent variable are shown in Fig. 2, where each ring represents the relative importance ranking of the five factors. Each ring displays the standardized coefficients for a parameter, sorted from outer to inner based on coefficient magnitudes, and non-significant terms were not depicted in the figure.

According to Fig. 2, T_a is the primary factor influencing TSV, with standardized coefficients ranging from 0.6 to 0.75. RH and V_a also have a significant impact on TSV, with standardized coefficients exceeding 0.1 during the cooling season, while the influences of other factors are below 0.1. In different seasons, the ranking of factors, except for T_a, varies slightly, but their impact does not exceed 15 % of T_a. Based on the database analysis, the importance of temperature is mainly attributed to two factors: firstly, thermal sensation is highly sensitive to temperature, and secondly, indoor air temperature generally experiences substantial fluctuations. While RH also exhibits large fluctuations, its impact is much smaller than that of T_a, possibly due to the lower sensitivity of thermal sensation to relative humidity within the fluctuation range. In everyday life, individuals' thermal sensation predominantly centers around the thermal neutral state, with occurrences of sweating being infrequent. Therefore, humidity primarily influences thermal sensation through its impact on latent heat exchange, resulting in a relatively minor effect on thermal perception in such circumstances.

However, the impact of each factor on thermal comfort is not unidirectional. Thermal comfort levels are highest when thermal sensation approaches neutrality. Moving towards either side will result in cool discomfort or warm discomfort, as illustrated in Fig. A3. Therefore, in the ranking process of thermal comfort, the data were divided into two intervals: TSV $\geq$ 0 (Warm Biased) and TSV $\leq$ 0 (Cool Biased), and rankings were conducted separately for each interval. The results are depicted in Fig. 3. Due to the close relationship between temperature and thermal sensation, compared to the results without dividing into warm and cold sides, even when both rankings use TSV as an indicator (Fig. 3(b)), the influence of T_a will decrease. Hence, the comparison between the two indicators relied on the results obtained from interval divisions.

Fig. 3(a) illustrates that T_a is also a primary factor influencing thermal comfort. Comparing Fig. 3(a) and (b) for the same season and the same warm and cold sides, it can be observed that the impact of T_a on TCV is generally smaller than its impact on TSV and the influence of other factors is more significant. In the transitional and heating seasons, the second-ranked factors' impact on TCV can reach 27 % to 30 %, while the impact of other factors on TSV is smaller, approximately 12 % to 27 % of the impact of T_a. In the cooling season, the second-ranked factor has a substantial impact on both thermal sensation and thermal comfort. On the Cool Biased, the impact of V_a on thermal comfort can reach 58 % of the impact of T_a, and V_a also has a significant impact on thermal sensation, up to 60 %. On the Warm Biased, the impact of RH can reach 38 % of the temperature's impact, affecting thermal sensation by 21 %. It is noteworthy that RH has a significant impact on TCV, ranking in the top three in all intervals, with standardized coefficients ranging from 0.05 to 0.2.

These two rationales could elucidate the minimal impact of V_a in the heating season and I_{clo} in the cooling season. The initial rationale is grounded in the inherent connection between Va and Iclo with adaptive behaviors, fostering individuals' proximity to thermal neutrality and comfort. The subsequent rationale pertains to the relatively smaller standard deviation observed in V_a during the heating season and I_{clo} during the cooling season.

3.2. The interaction effects between T_a and other factors

In indoor environments, T_a, as the primary factor influencing TSV, generally plays a decisive role in thermal sensation. Therefore, in the further analysis in this section, with TSV as the dependent variable, the interaction effects between other factors and T_a were examined. Each factor was categorized based on the levels shown in Table 1, and for each level, the regression slope (temperature sensitivity) was calculated using Eq. (5). The regression lines were plotted in Figs. 4 and 5, and the slope, R^2, p-values, as well as the differences and significance of slopes between different levels were indicated in the graphs. ΔSlope was obtained by subtracting the slope of higher level from the slope of lower level. Due to limited data for RH below 30 % in the cooling season and above 70 % in the heating season, these data were excluded from the comparative analysis.

Fig. 4 illustrates the impact of RH and V_a on temperature sensitivity. Overall, the trend of temperature sensitivity is observed as cooling season > transitional seasons > heating season. Fig. 4(a) depicts the impact of RH. In the cooling season, the temperature sensitivity is higher by 0.029/°C when the RH is above 70 % compared to Level-2 (RH between 30 % and 70 %). In the transitional seasons, higher RH leads to an increase in temperature sensitivity by approximately 0.020/°C compared to the middle RH level, while lower RH results in a decrease of 0.019/°C. In the heating season, the influence of RH shows a different

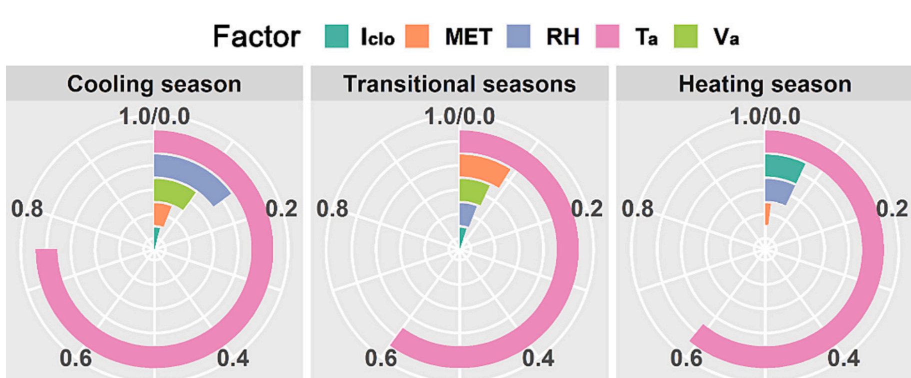


Fig. 2. Factor rankings based on TSV.

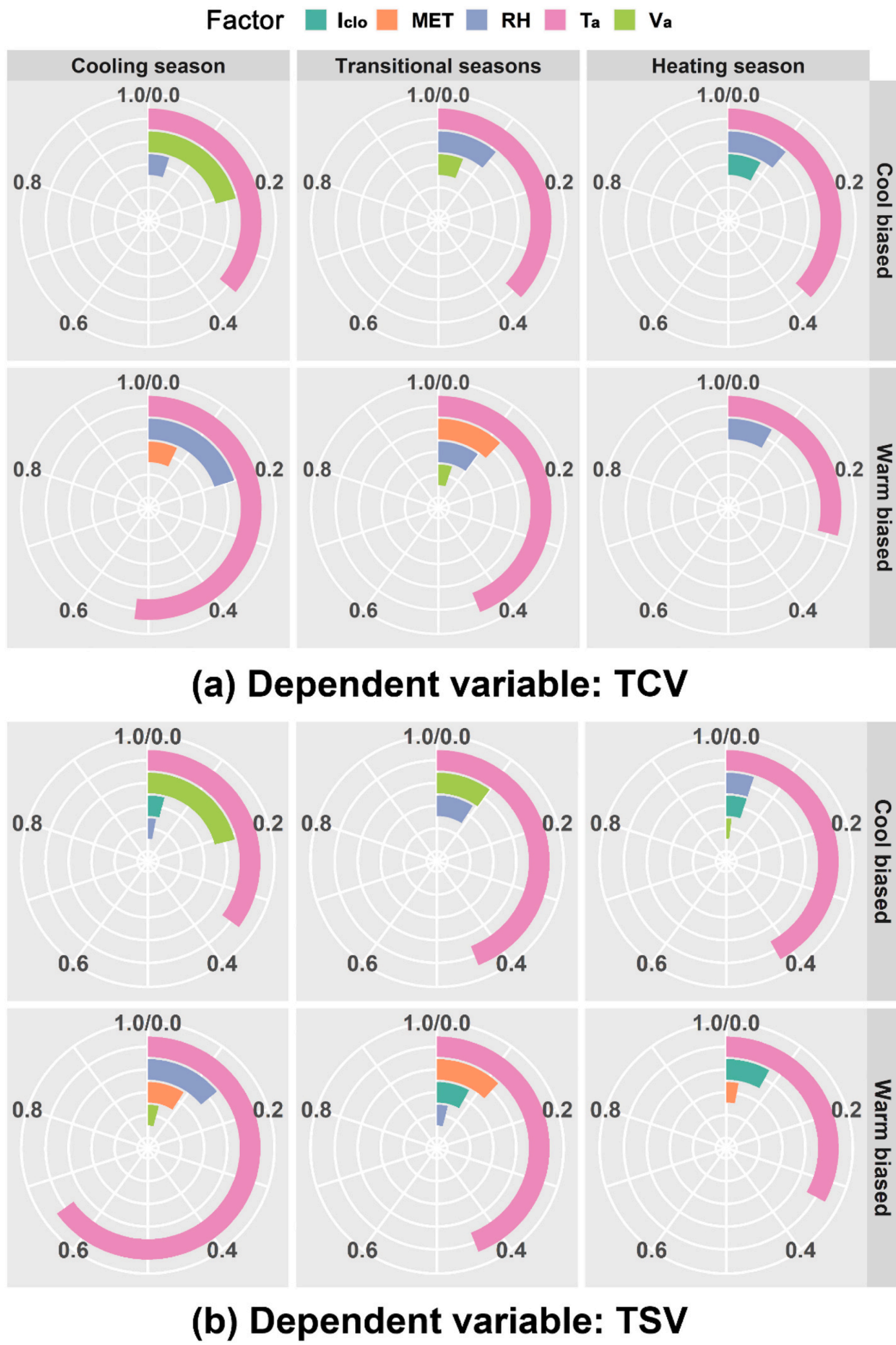


Fig. 3. Factor rankings for Warm and Cool Biased.

direction, with lower RH level increasing temperature sensitivity by 0.049/°C. The impact of V_a is similar across different seasons. When the V_a exceeds 0.1 m/s, temperature sensitivity is higher by 0.030–0.042/°C compared to a still air environment, with a greater effect in the heating season.

The impact of I_{clo} and MET on temperature sensitivity is illustrated in Fig. 5. In the cooling season, temperature sensitivity significantly decreases (by 0.074/°C) when I_{clo} exceeds 0.5 clo. Conversely, in the heating season, temperature sensitivity increases by approximately 0.023/°C when I_{clo} exceeds 1.0 clo. In the transitional seasons, I_{clo} does not have a significant impact on temperature sensitivity. An increase in MET leads to higher temperature sensitivity, with the most significant impact in the cooling season (an increase of approximately 0.047/°C), followed by the transitional season (0.038/°C), and the smallest impact in the heating season (a change of approximately 0.025/°C).

3.3. The relationship between environmental factors and TCV

This section primarily analyzes the impact of four factors: RH, V_a, I_{clo}, and MET on TCV. The assessment calculates the significance of differences and their magnitudes in thermal comfort levels influenced by different factors under the same thermal sensation vote.

Fig. 6 illustrates the influence of RH on thermal comfort levels. The graph depicts the average TCV at different RH levels under the same TSV. To enhance the visualization of data patterns, TSV data were rounded, followed by the averaging of TCV data under each TSV. In the cooling and transitional seasons, TCV values are noticeably higher at the high RH level (Level-3). This indicates that even with the same thermal

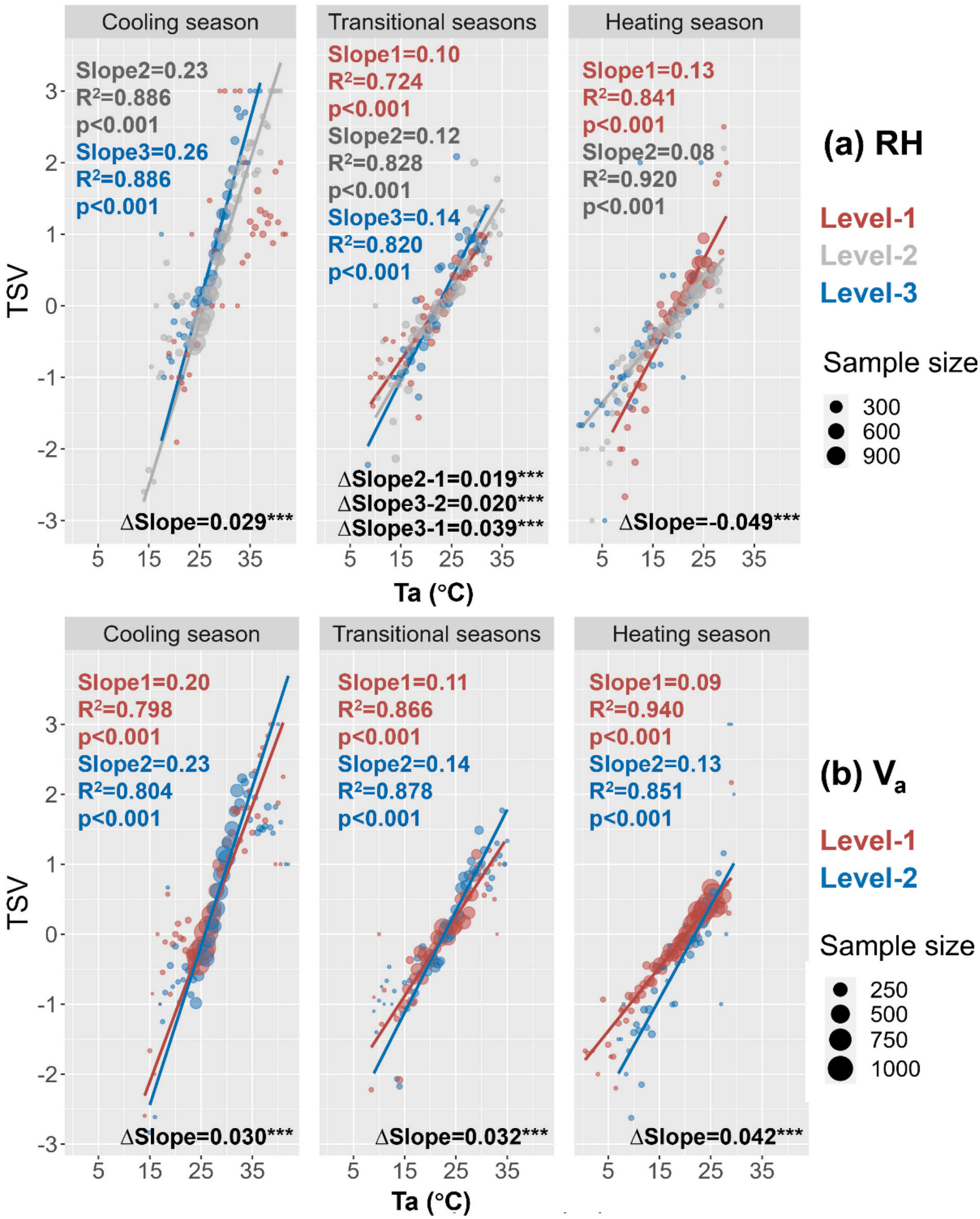


Fig. 4. The interaction effects between T_a and RH (a), V_a (b).

sensation, higher humidity can lead to a decrease in thermal comfort levels. This also indirectly suggests that, besides influencing thermal sensation through its impact on heat exchange, humidity may affect comfort through its influence on individuals' perceptions of air quality, skin moisture, or the tactile sensation of clothing. In the heating season, where data with relative humidity exceeding 70 % is limited, the difference is less significant, and the effect size is negligible.

The influence of V_a is illustrated in Fig. 7(a). In the cooling season, except for TSV = 3, the average TCV values for Level-2 ($V_a > 0.1$ m/s) are significantly higher than Level-1 (still air), especially when TSV ≤ 0, with a minimum effect size of 0.37. This indicates that, under the same thermal sensation, environments with higher air speed may be less comfortable.

As shown in Fig. 7(b), in the cooling season, the average TCV values for a higher MET (Level-2) are significantly higher than the lower level (Level-1), indicating that an increase in MET significantly lowers

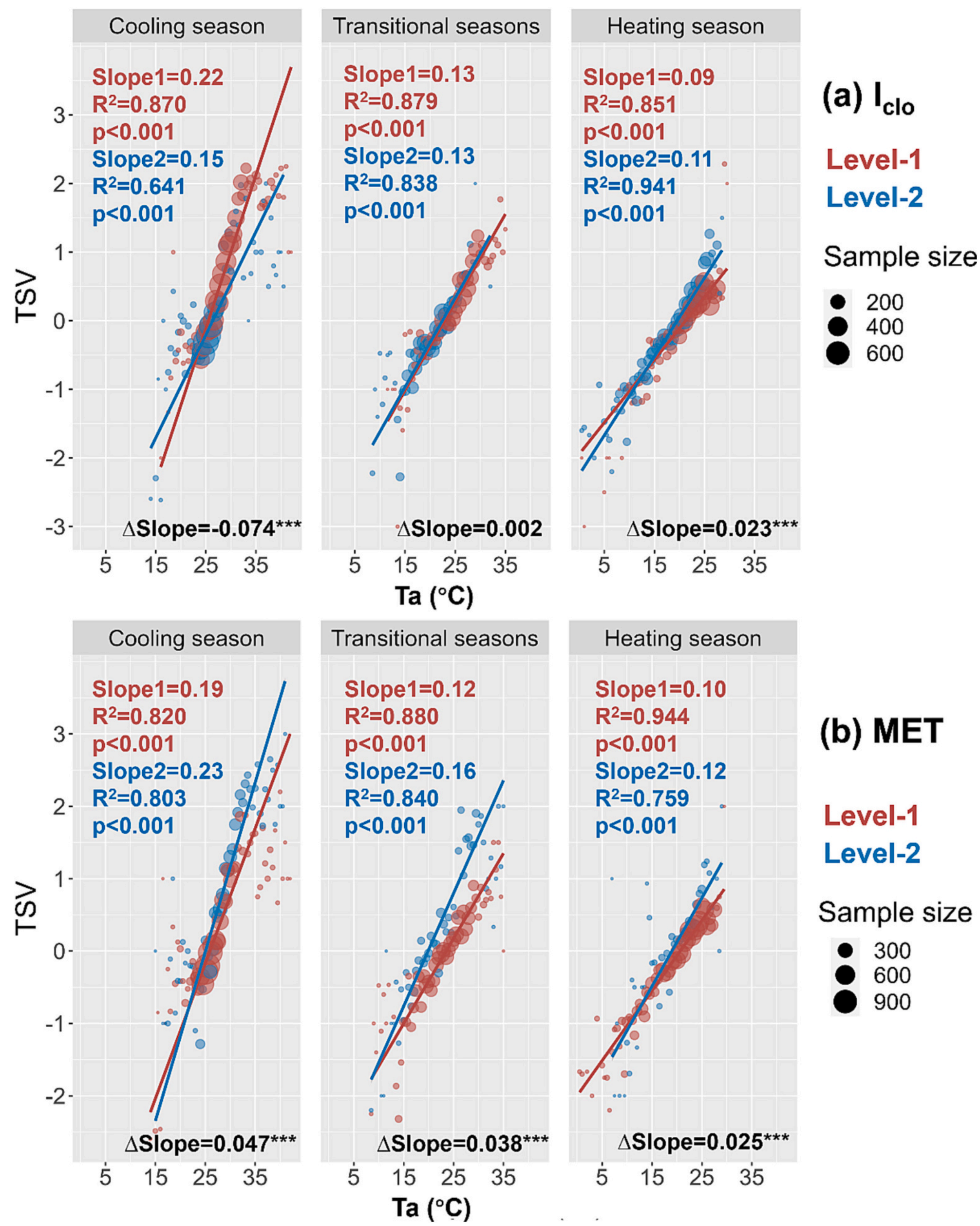


Fig. 5. The interaction effects between T_a and I_{clo} (a), MET (b).

thermal comfort levels, with effect sizes all above 0.37. However, the impact in the other two seasons is relatively smaller.

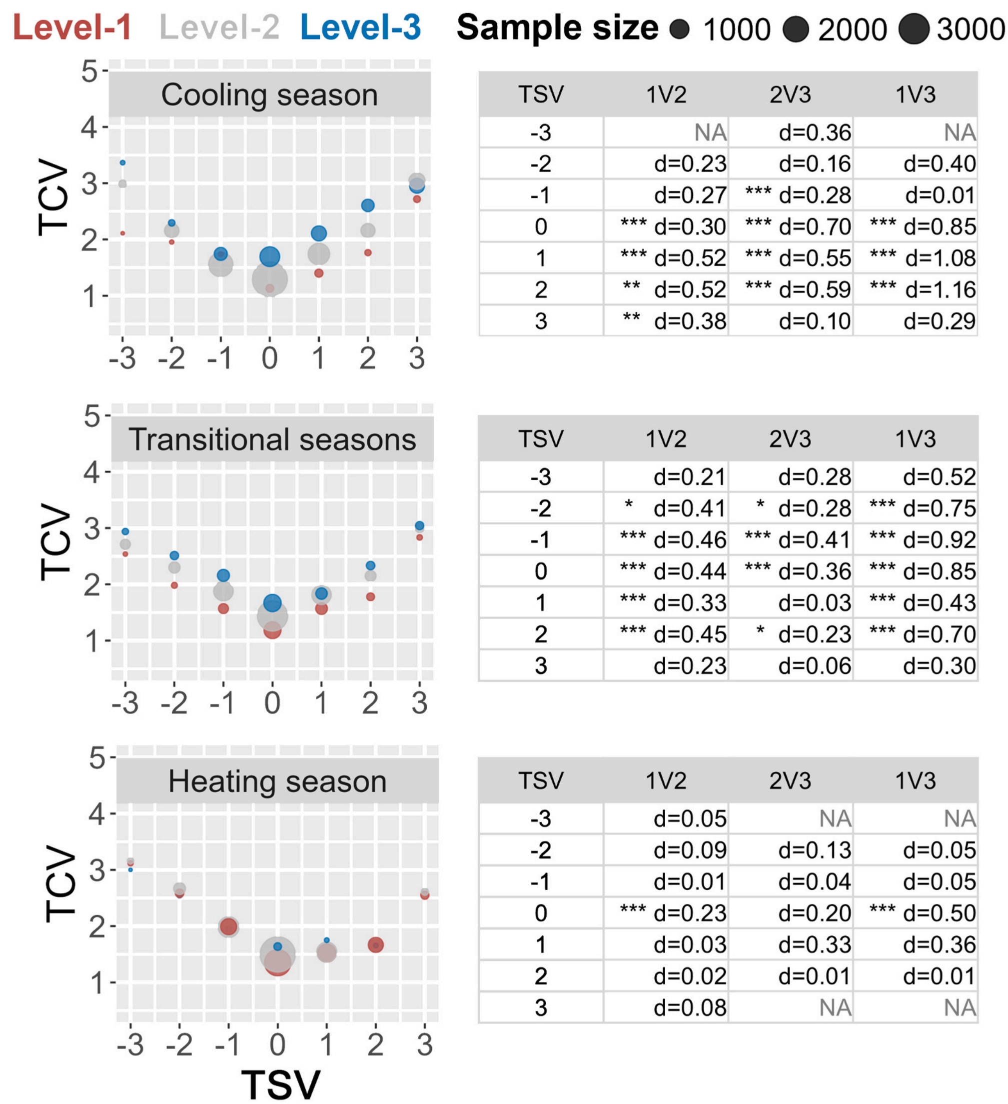
As shown in Fig. 7(c), the impact of I_{clo} varies in the cooling and heating seasons. In the cooling season, the TCV values for Level-2 ($I_{clo} >$ 0.5 clo) are smaller, indicating greater comfort. However, in the heating season, Level-1 ($I_{clo} <$ 1.0 clo) has smaller TCV values, suggesting greater comfort. In the transitional season, although there are significant differences, the effect sizes are small or negligible, except for TSV = −2, where the effect size is >0.5, while the others are below 0.5.

3.4. Thermal comfort rate and thermal neutrality rate

Many studies have indicated that due to regional adaptability (Du et al., 2021; Liu et al., 2022), individuals in different regions may have different thermal neutrality or comfort ranges. Therefore, this section categorizes the analysis based on regions. However, regional differences and adaptability are not the main focus of this research. This section specifically discusses representative regions for different seasons. Taking the hot summer warm winter region (HSWW) as an example for the cooling season and the cold region (COLD) for the heating season, due to the abundance of existing data in these two regions (see Appendix A1.2). Since the delineation of the different climate regions mainly considers data from the coldest and hottest months, it is useful for differentiating between winter and summer (or cooling and heating seasons) but does not consider data from the transitional seasons, and therefore the calculation of the transitional season did not relate to the delineation of the regions.

In the cooling season, without considering the influence of various factors (Fig. 8(a)), the optimal temperature for thermal comfort rate (thermal comfort temperature) is 24.9 °C, corresponding to a maximum comfort rate of 59.6 %. The optimal temperature for thermal neutrality rate (thermal neutrality temperature) is 25.9 °C, 1 °C higher than the thermal comfort temperature, while the maximum thermal neutrality rate is 45.7 %, 13.8 % lower than the maximum comfort rate.

Fig. 8(b) illustrates the impact of RH. An increase in RH causes the maximum thermal comfort rate to decrease from 66.1 % (Level-2) to



Cooling season

TSV	1V2	2V3	1V3
-3	NA	d=0.36	NA
-2	d=0.23	d=0.16	d=0.40
-1	d=0.27	*** d=0.28	d=0.01
0	*** d=0.30	*** d=0.70	*** d=0.85
1	*** d=0.52	*** d=0.55	*** d=1.08
2	** d=0.52	*** d=0.59	*** d=1.16
3	** d=0.38	d=0.10	d=0.29

Transitional seasons

TSV	1V2	2V3	1V3
-3	d=0.21	d=0.28	d=0.52
-2	* d=0.41	* d=0.28	*** d=0.75
-1	*** d=0.46	*** d=0.41	*** d=0.92
0	*** d=0.44	*** d=0.36	*** d=0.85
1	*** d=0.33	d=0.03	*** d=0.43
2	*** d=0.45	* d=0.23	*** d=0.70
3	d=0.23	d=0.06	d=0.30

Heating season

TSV	1V2	2V3	1V3
-3	d=0.05	NA	NA
-2	d=0.09	d=0.13	d=0.05
-1	d=0.01	d=0.04	d=0.05
0	*** d=0.23	d=0.20	*** d=0.50
1	d=0.03	d=0.33	d=0.36
2	d=0.02	d=0.01	d=0.01
3	d=0.08	NA	NA

Fig. 6. Impact of RH on thermal comfort under the same thermal sensation.

20.6 % (Level-3), while the impact on the thermal neutrality rate is relatively small, with the maximum thermal neutrality rate decreasing only from 47.5 % to 34.6 %. Moreover, when RH exceeds 70 %, the thermal comfort rate is lower than the thermal neutrality rate. The results indicate that excessively high RH leads to a reduction in both thermal neutrality and thermal comfort rates, with the effect on thermal comfort rate being greater than that on thermal neutrality rate.

Fig. 8(c) illustrates the impact of V_a. Compared to the Level-1 still air, when V_a exceeds 0.1 m/s, both the maximum thermal comfort rate (decreasing from 61.2 % to 49.1 %) and maximum thermal neutrality rate (decreasing from 48.5 % to 33.5 %) show declines, with respective reductions of 12.1 % and 15.0 %. Additionally, the thermal comfort temperature (shifting right from 24.7 °C to 25.7 °C) and thermal neutrality temperature (shifting right from 26.2 °C to 27.0 °C) exhibit a certain degree of rightward movement. The results indicate that higher V_a leads to a simultaneous decrease in thermal comfort and thermal neutrality rates, along with an increase of 1.0 °C and 0.8 °C in thermal comfort and thermal neutrality temperatures, respectively.

The impact of MET (Fig. 8(d)) on thermal comfort rate is substantial. When the metabolic rate is at Level-2 (Met >1.1 met), the thermal comfort rate is primarily concentrated below 10 %, whereas at Level-1 (Met ≤1.1 met), the maximum thermal comfort rate can reach up to 67.6 %. The increase in MET only results in a decline in the maximum thermal neutrality rate from 47.2 % to 32.0 %. This indicates that the influence of MET on thermal comfort rate is more pronounced than its effect on thermal neutrality rate.

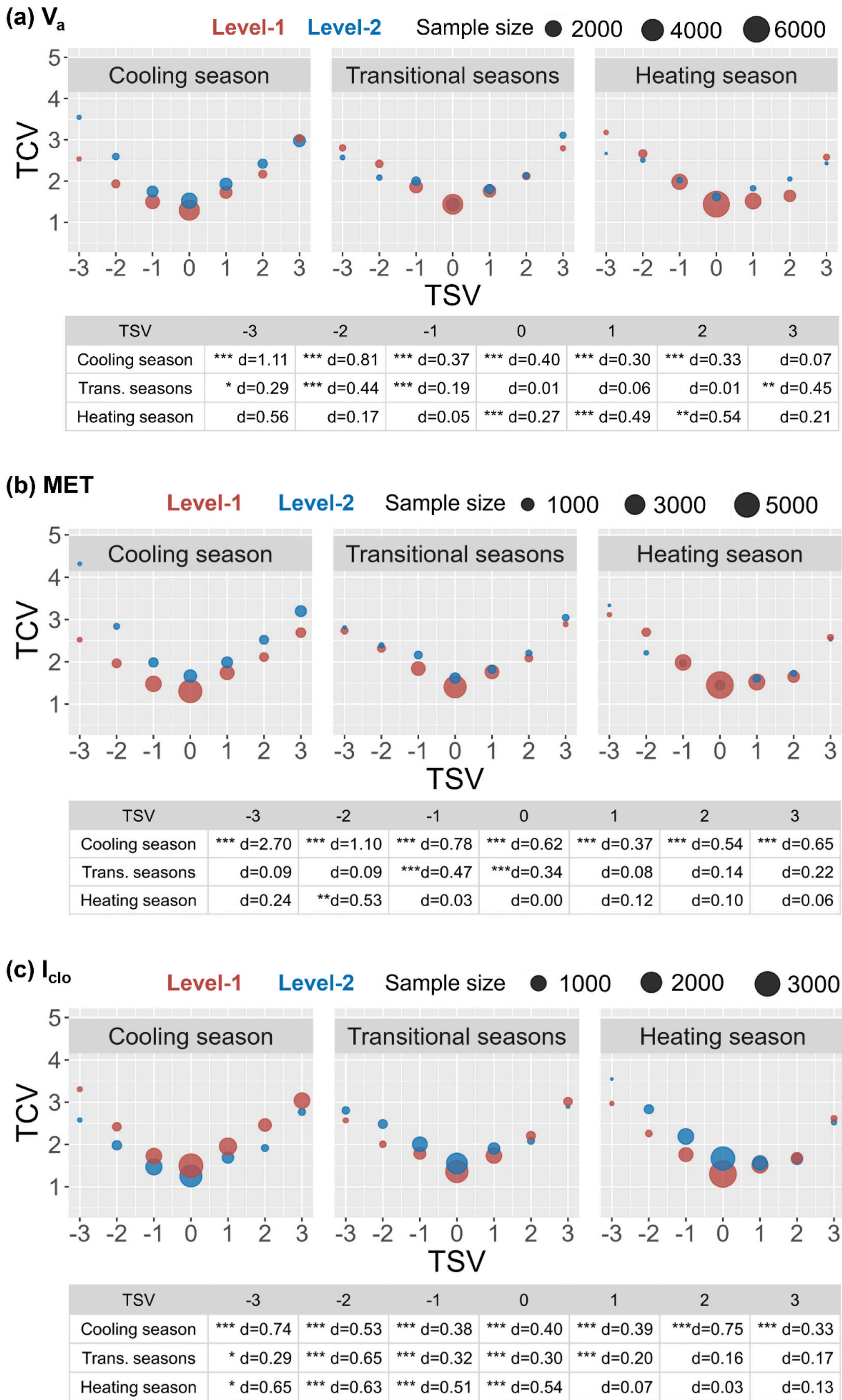
Fig. 8(e) depicts the results for I_{clo}. The maximum thermal neutrality rate in Level-1 (Iclo ≤1 clo) is only slightly lower (42.9 %) than in Level-2 (47.1 %). However, an increase in clothing thermal resistance raises the maximum thermal comfort rate from 50.0 % to 67.7 %.

In summary, except for V_a, the impact of other factors on thermal comfort rate is more significant than their effects on thermal neutrality rate, while V_a has a comparable influence on both. The results for the transitional seasons and heating season can be found in the appendix A4.

4. Discussion

4.1. Composite Indicator SET and PMV

In this study, several crucial relationships were investigated, including the relationship between air temperature and thermal sensation, the relationship between thermal sensation and thermal comfort, and the relationship between air temperature and thermal comfort rate as well as thermal neutrality rate. The study found that key factors related to thermal perception had an impact on these relationships. However, can the commonly used composite indicators, SET and PMV,



TSV	-3	-2	-1	0	1	2	3
Cooling season	*** d=1.11	*** d=0.81	*** d=0.37	*** d=0.40	*** d=0.30	*** d=0.33	d=0.07
Trans. seasons	* d=0.29	*** d=0.44	*** d=0.19	d=0.01	d=0.06	d=0.01	** d=0.45
Heating season	d=0.56	d=0.17	d=0.05	*** d=0.27	*** d=0.49	**d=0.54	d=0.21

TSV	-3	-2	-1	0	1	2	3
Cooling season	*** d=2.70	*** d=1.10	*** d=0.78	*** d=0.62	*** d=0.37	*** d=0.54	*** d=0.65
Trans. seasons	d=0.09	d=0.09	***d=0.47	***d=0.34	d=0.08	d=0.14	d=0.22
Heating season	d=0.24	**d=0.53	d=0.03	d=0.00	d=0.12	d=0.10	d=0.06

TSV	-3	-2	-1	0	1	2	3
Cooling season	*** d=0.74	*** d=0.53	*** d=0.38	*** d=0.40	*** d=0.39	***d=0.75	*** d=0.33
Trans. seasons	* d=0.29	*** d=0.65	*** d=0.32	*** d=0.30	*** d=0.20	d=0.16	d=0.17
Heating season	* d=0.65	*** d=0.63	*** d=0.51	*** d=0.54	d=0.07	d=0.03	d=0.13

Fig. 7. Impact of V_a (a), MET (b), I_{clo} (c) on thermal comfort.

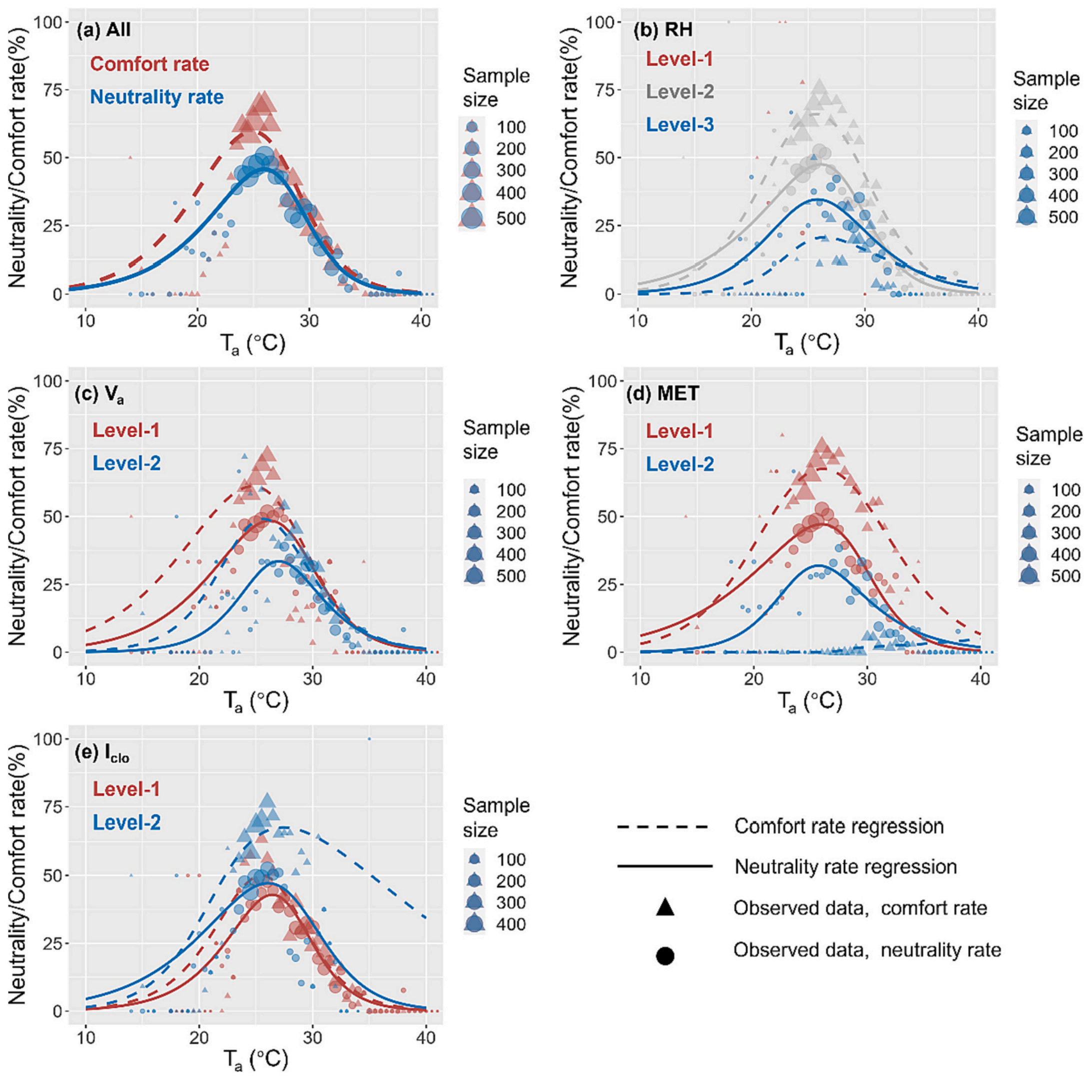


Fig. 8. HSWW, cooling season, thermal neutrality rate and thermal comfort rate.

address the aforementioned issues? Fig. 9 provides an analysis using the cooling season as an example with RH levels at Level-2 and Level-3. The analysis in (a) followed the same approach as Fig. 4(a), but replaced T_a with SET. The slopes of the regression lines also vary at different RH levels, and contrary to the results in Fig. 4(a), the slope of the regression line decreases when RH exceeds 70 %. This suggests that the SET indicator may overestimate the impact of humidity on thermal sensation, a result consistent with existing research (Li et al., 2018).

For the relationship between thermal sensation and thermal comfort, the analysis in Fig. 9(b) followed the same method as Fig. 6(a), but replaced actual thermal sensation votes with calculated PMV. Even within the same PMV values, higher RH leads to a decrease in comfort level. This reflects the inherent inaccuracies when using thermal sensation or PMV values to predict thermal comfort. Additional investigation into the relationship between PMV-PPD and the actual TSV-PPD based on this dataset may find support in another study (Du et al., 2022b). When using SET instead of T_a to calculate thermal comfort rate and thermal neutrality rate (Fig. 9(c) follows the same method as Fig. 8 (b)), the thermal neutrality rates at two RH levels are closer. However, the difference in the maximum thermal comfort rates is still 30.8 %, a reduction compared to the difference using T_a regression (45.5 %), but still comparatively large. This indicates that even in environments with the same SET, differences in RH can lead to variations in subjective thermal perception, especially in the dimension of thermal comfort.

4.2. Differences and similarities between TSV and TCV

Zhang and Zhao indicated significant differences between thermal sensation and thermal comfort in dynamic environments (Zhang and Zhao, 2009). de Dear provided a detailed explanation for this difference using the Alliesthesia hypothesis (de Dear, 2011). However, Zhang et al. also pointed out that in steady and uniform conditions, thermal sensation and thermal comfort were consistent. This may be because their study only involved data from neutral and warm environments, and the highest point of thermal comfort in summer may fall on the cool side of thermal sensation, a difference not reflected in their research. Additionally, Zhang et al. did not consider the impact of multiple factors, leading to a strong linear relationship between average TSV and average TCV. However, through the analysis in our study, it is found that even in steady and uniform conditions, there are certain differences in the correspondence between thermal sensation and thermal comfort at different factor levels. Particularly in summer, the influence of RH, MET, Va, and Iclo on thermal comfort shows clear patterns. Under the same thermal sensation, higher RH and MET generally correspond to lower comfort levels, consistent with common knowledge.

However, the impact of air speed and clothing insulation is worth further discussion. The research results indicate that during the cooling season, higher comfort levels generally correspond to lower air speed. It's important to note that most studies on air speed often focus on

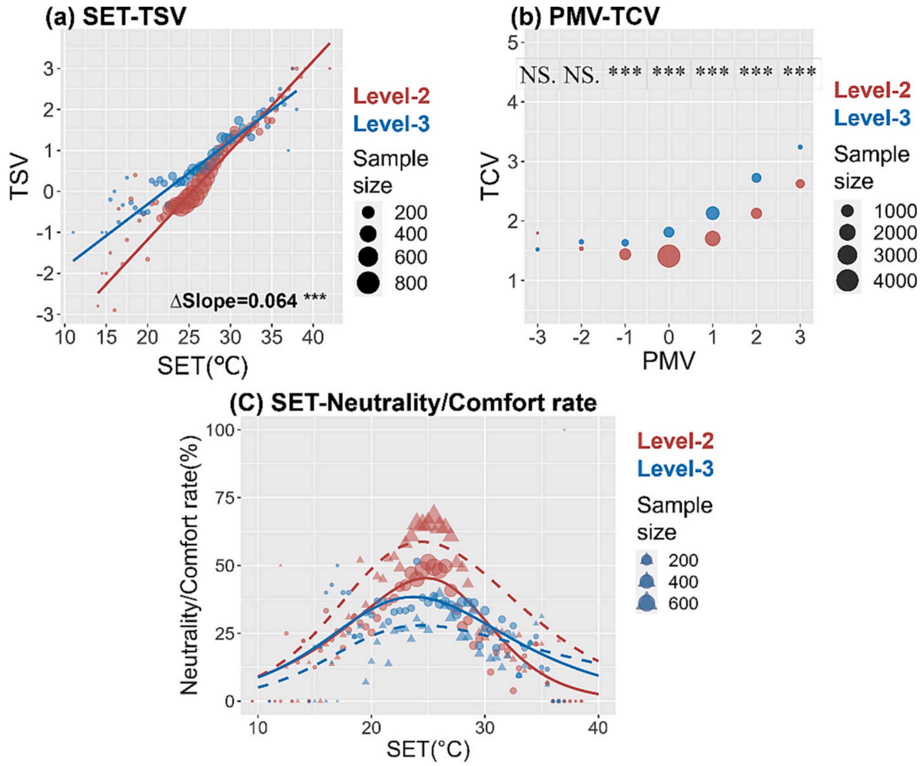


Fig. 9. Performance of indicators in handling relative humidity.

comparisons in environments with the same temperature, such as comparing environments at 30 °C with no wind to those at 30 °C with 2 m/s air speed, where the latter may be more comfortable. In this discussion, we compared an environment with 30 °C and 1 m/s air speed to an environment with 26 °C and no wind. In both scenarios, the body may reach thermal neutrality, but the latter might be more comfortable due to the potential higher risk of draft sensation in the former. Similarly, for data in field studies reflecting real-world conditions, higher air speeds during the summer might be caused by air conditioning airflow. The draft sensation induced by air conditioning airflow might potentially lead to a decrease in comfort perception. This result could be supported by further analysis in Appendix A3.3 which shows that only in Air-Conditioned environment the TCV was influenced by air speed under same thermal sensation, but it is not significant in Free-running environment.

The impact of clothing insulation during the cooling season reveals a characteristic where higher clothing insulation corresponds to higher comfort levels across all thermal sensations. The same result is obtained using The ASHRAE Global Thermal Comfort Database II (Parkinson et al., 2018), but it is only significant when TSV no smaller than −1 (see Appendix A3.2). This could be attributed to several factors. Firstly, the adjustment of clothing is a crucial adaptive behavior for individuals to enhance comfort levels in response to the environment. Combined with the potential for additional I_{clo} reduction influencing psychological expectations, akin to having control over the environment (Zhou et al., 2014), it is more likely to lead to an elevated perception of comfort. For individuals feeling warm but with I_{clo} already below 0.5 clo, they may have lost the opportunity to further adjust thermal sensations by lowering I_{clo}, potentially resulting in more uncomfortable votes.

Moreover, higher I_{clo} is typically associated with lower indoor (refer to Appendix A3.2) and outdoor temperatures (ASHRAE, 2020; Brager and de Dear, 1998). Therefore, the conclusion drawn from this result is that, in cooling season, the combination of high clothing thermal resistance with low temperatures, as well as low clothing thermal resistance with high temperatures, might both achieve similar thermal sensations, but the former tends to provide a more comfortable experience.

Based on the results and discussions, it is evident that there are differences between thermal sensation and thermal comfort in various scenarios within actual indoor environments. Therefore, relying solely on thermal sensation and thermal neutrality to evaluate thermal environments might be insufficient, especially in comfort-oriented settings such as residential spaces where indicators like TCV should not be overlooked.

4.3. *Limitation*

Due to the limited range of air speeds (up to 3.0 m/s) and metabolic rates (up to 2.0 met) in the database, the results reflect patterns in common indoor environments and do not address the impact of high air speeds and metabolic rates on subjective perception. Additionally, the high correlation between radiant temperature and air temperature in the database led to the omission of a separate discussion on the influence of radiant temperature in this study. Some studies suggest that the correspondence between votes and perceptions may vary in different semantic environments (Kim et al., 2022). However, this research utilizes survey data in a Chinese context, and as such, semantic effects are not considered, warranting further comparative analysis. Moreover, thermal discomfort may arise from factors not adequately included in the dataset, such as air turbulence and asymmetric radiation. However, more detailed investigations are required to understand how these factors influence thermal comfort, especially in the same state of thermal sensation.

5. Conclusions

Based on the Chinese thermal comfort database, an evaluation was conducted on the impact of key fundamental factors related to thermal perception —air temperature, air speed, relative humidity, metabolic rate, and clothing insulation—on human subjective responses. By comparing the influence and interactions of each factor on thermal sensation and comfort, the main conclusions are as follows:

(1) In real indoor environments, air temperature is the primary factor affecting thermal sensation and thermal comfort. The impact of other factors on thermal sensation is generally <15 % compared to temperature, and the influence on thermal comfort may be slightly larger but generally does not exceed 30 %.
(2) Temperature sensitivity was employed to assess the interaction between various factors and air temperature. The results reveal significant interaction effects between different factors and air temperature. Both increased air velocity and metabolic rate are associated with higher temperature sensitivity, with temperature sensitivity in Level-2 approximately 0.025–0.047/°C higher than that in Level-1. The impact of clothing insulation and relative humidity varies across different seasons.
(3) Under the influence of different factors, there are significant differences in thermal comfort even at the same thermal sensation. The impact of these factors is more pronounced during the cooling season, with higher air velocity, humidity, and metabolic rate, as well as lower clothing insulation, contribute to a reduction in comfort levels, even within the thermal neutrality. Therefore, when considering the combined effects of multiple factors, relying solely on thermal sensation or thermal neutrality to evaluate thermal environments may be insufficient.
(4) As temperature changes, both thermal comfort rates and thermal neutrality rates are influenced by various factors. Notably, during the cooling season and transitional seasons, thermal comfort rates experience a more significant decrease compared to thermal neutrality rates, particularly due to excessive relative humidity and higher metabolic rates.

CRediT authorship contribution statement

Yuxin Yang: Writing – review & editing, Writing – original draft, Methodology, Investigation, Data curation. **Junmeng Lyu:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Data curation. **Heng Du:** Methodology, Investigation, Data curation. **Zhiwei Lian:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Funding acquisition. **Weiwei Liu:** Investigation, Data curation. **Lin Duanmu:** Investigation, Data curation. **Yongchao Zhai:** Investigation, Data curation. **Bin Cao:** Investigation, Data curation. **Yufeng Zhang:** Investigation, Data curation. **Xiang Zhou:** Investigation, Data curation. **Zhaojun Wang:** Investigation, Data curation. **Xiaojing Zhang:** Investigation, Data curation. **Fang Wang:** Investigation, Data curation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2024.170683.

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