

Article

Winter Thermal Environments and Adaptive Thermal Responses in Three Rural Courtyard Dwellings: A Field Study in Qingcheng Ancient Town, Northwest China

Benteng Liu ^{1,2}, Yifan Wu ^{1,2}, Haiyan Tong ^{1,2,*}, Yanting Wang ^{1,2} and Wenjuan Cai ^{1,2}

¹ School of Architecture and Art Design, Lanzhou University of Technology, Lanzhou 730030, China; liubt@lut.edu.cn (B.L.); 242081300022@lut.edu.cn (Y.W.); 20250090@lut.edu.cn (Y.W.); 20240004@lut.edu.cn (W.C.)

² Key Laboratory of Urban and Architectural Heritage Conservation of the Ministry of Education, China (Northwest Center), Lanzhou 730050, China

* Correspondence: 2022041004@chd.edu.cn

Abstract

Rural courtyard dwellings in cold regions are commonly characterized by low winter indoor temperatures, intermittent heating, solar heat gain, pronounced thermal fluctuations, and strong occupant adaptation. This study aimed to compare short-term winter indoor thermal conditions among three rural courtyard dwelling cases in Qingcheng Ancient Town, Gansu Province, Northwest China, and to examine the associations between operative temperature and multidimensional subjective thermal responses under the monitored conditions. Synchronized indoor–outdoor environmental measurements and 216 paired questionnaire records were collected during two winter survey days. To account for shared environmental exposure, the questionnaire records were organized into 66 dwelling–time clusters. The results showed that: (1) outdoor air temperature ranged from $-13.34\text{ }^{\circ}\text{C}$ to $13.24\text{ }^{\circ}\text{C}$, with a mean of $-3.91\text{ }^{\circ}\text{C}$, while the mean operative temperature during the questionnaire periods was $11.31\text{ }^{\circ}\text{C}$ and the mean thermal sensation vote (TSV) was -0.97 , indicating an overall sensation close to slightly cool; (2) the dwelling with an added sunspace had the highest mean operative temperature, the ordinary brick–concrete dwelling exhibited the greatest temperature fluctuation, and the earth–wood dwelling remained cooler but relatively stable; (3) each $1\text{ }^{\circ}\text{C}$ increase in operative temperature was associated with 75% higher odds of reporting a warmer TSV category ($\text{OR} = 1.75$, 95% CI: 1.53–2.00), while the two-way fixed-effects model estimated a 0.176-unit increase in mean TSV; and (4) higher operative temperature was associated with greater broad and clear thermal acceptability and a lower likelihood of preferring warmer conditions, with the study-specific neutral operative temperature estimated at $16.75\text{ }^{\circ}\text{C}$ and a block-bootstrap 95% confidence interval of $15.66\text{--}18.40\text{ }^{\circ}\text{C}$. These findings provide field-based evidence of the associations between operative temperature and multidimensional winter thermal responses and offer an empirical basis for climate-responsive and heritage-sensitive thermal improvement strategies for rural courtyard dwellings.



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Keywords: rural courtyard dwelling; winter thermal environment; adaptive thermal response; thermal sensation; thermal acceptability; operative temperature; Northwest China

1. Introduction

1.1. Winter Thermal Environments and Adaptive Responses in Rural Dwellings

Rural dwellings constitute an important component of China's residential building stock, but their winter indoor thermal conditions vary considerably because many houses are self-built, incrementally modified, and operated through household-level environmental control. In northern and northwestern China, rural households commonly rely on locally operated and intermittent heating systems, while envelope insulation, airtightness, heating schedules, and room-use patterns differ substantially among dwellings. Previous field studies have reported low indoor temperatures, pronounced temporal fluctuations, marked room-to-room differences, and strong associations between indoor conditions and household operation [1–5]. Winter thermal performance in rural dwellings should therefore be evaluated in terms of both mean indoor temperature and the spatial and temporal variability actually experienced by occupants.

Cold-dry climatic conditions create additional challenges for rural housing. Low outdoor temperatures and large diurnal temperature ranges increase heat loss through roofs, walls, doors, and windows, whereas relatively abundant daytime solar radiation provides opportunities for passive heat gain in south-facing rooms, courtyards, and attached sunspaces. Winter indoor conditions are consequently shaped by the combined effects of envelope performance, thermal mass, solar access, local heating, and occupant behaviour. Unlike continuously conditioned urban buildings, rural dwellings may contain heated and unheated rooms, semi-open transitional spaces, and locally warmed areas within the same household. Occupants may therefore experience substantial spatial and short-term thermal variations even when the whole-dwelling average temperature remains low. Abrupt temperature changes and prolonged cool exposure are particularly relevant to older adults and occupants with limited mobility, highlighting the importance of characterizing the spatial and temporal variability of winter indoor conditions [6–9].

The predicted mean vote–predicted percentage dissatisfied model remains a widely used framework for thermal comfort assessment [10–12]. In spatially non-uniform, naturally ventilated, or intermittently heated rural dwellings, however, field responses are also shaped by behavioural, physiological, and psychological adaptation [13–22]. Field-based assessment should therefore combine synchronized physical measurements with multiple dimensions of subjective thermal response. Thermal sensation vote describes the perceived thermal state, thermal preference vote indicates the desired direction of change, and thermal acceptability vote reflects whether the existing condition is regarded as tolerable or acceptable. These dimensions are related but distinct: occupants may accept a cool environment while preferring warmer conditions, and high acceptability may coexist with thermal sensations below neutrality.

Recent occupant-centric studies have further demonstrated the value of repeated, context-rich thermal feedback and personal comfort models for representing individual and temporal variations in thermal preference [23,24]. Such developments reinforce the importance of preserving the categorical structure of subjective votes and linking each response to its corresponding environmental exposure.

Adaptive practices reported in cold residential environments include adding clothing, using local heating devices, remaining close to heat sources, concentrating activities in selected rooms, and moving between indoor, courtyard, and sun-exposed spaces [1,2,4,5,8,9,25,26]. Long-term experience with low indoor temperatures may also shape thermal expectations. These established adaptation pathways provide a literature-informed framework for interpreting the associations between measured indoor conditions and multidimensional subjective responses in Qingcheng Ancient Town.

1.2. Passive Thermal Regulation in Rural Courtyard Dwellings

The spatial and constructional characteristics of vernacular and courtyard dwellings can substantially influence winter indoor thermal conditions [27–45]. Courtyard enclosure, south-facing orientation, thick walls, earthen materials, eaves, semi-open spaces, and attached sunspaces can reduce climatic exposure, provide thermal buffering, store solar heat, and create transitional zones between indoor and outdoor environments [35,37,46–52].

Studies of traditional earthen and courtyard dwellings have shown that high thermal mass can attenuate short-term temperature fluctuations and improve thermal stability [28–33,39,41,42,45]. The thermal performance of these dwellings can be further enhanced through improvements to roofs, doors, windows, and construction joints [34,52–54]. Ordinary brick–concrete dwellings can respond relatively quickly to local heating, while coordinated improvements in insulation, airtightness, and heating schedules can strengthen heat retention [53,54]. Attached sunspaces can enhance daytime solar gain and buffer occupied rooms from cold outdoor conditions, with their performance shaped by orientation, heat transfer, thermal storage, opening schedules, and night-time insulation [35,37,46–51].

These studies indicate that spatial form, construction materials, solar access, and household operation jointly determine the combination of indoor temperature level and thermal stability. Comparative monitoring of dwellings with contrasting configurations can therefore characterize how these factors are reflected in indoor thermal conditions under a shared regional climate. Such comparative field evidence supports the formulation of configuration-sensitive improvement priorities and transferable design hypotheses for cold–dry rural courtyard dwellings.

1.3. Research Context and Knowledge Gaps

Field investigations in northern, northwestern, coastal, and high-altitude regions of China have provided substantial evidence of low winter indoor temperatures, intermittent heating, locally adapted thermal responses, and differences between field thermal votes and conventional PMV predictions in rural residences [1–5,13,28–34,53,55–58]. Research on Kang-heated houses, earthen dwellings, attached sunspaces, and other vernacular building forms has also emphasized the integration of thermal comfort, energy demand, construction cost, passive climatic response, and the conservation of traditional building characteristics [1,27–35,37,39,41,46,52,54].

Rural courtyard dwellings in the Longzhong Yellow River valley provide a distinctive context for extending this body of knowledge. Qingcheng Ancient Town, located in Gansu Province, Northwest China, contains traditional earth–wood courtyard dwellings, ordinary self-built brick–concrete dwellings, and brick–concrete dwellings modified with attached sunspaces. The coexistence of these configurations creates a natural comparative setting for examining winter thermal conditions under different spatial, material, and operational contexts.

The present study monitors three contrasting rural courtyard dwellings: a brick–concrete dwelling with an added sunspace, an ordinary brick–concrete dwelling, and a traditional earth–wood dwelling. By examining the three configurations under the same regional winter context, the study establishes a focused comparative field design that links building characteristics, indoor thermal dynamics, and subjective thermal responses. The resulting evidence can inform the thermal improvement of comparable rural courtyard dwellings while retaining sensitivity to local construction and heritage characteristics.

Three research needs are particularly relevant. First, synchronized winter evidence combining indoor environmental measurements with thermal sensation, thermal acceptability, and thermal preference remains limited for rural courtyard dwellings in the Longzhong Yellow River valley. Second, closer integration is needed between the analysis of phys-

ical building performance and the examination of multiple subjective thermal-response dimensions within the same field investigation. Third, synchronized surveys may produce multiple questionnaire records sharing the same dwelling–time environmental exposure, making it important to account for within-cluster correlation in statistical modelling.

From a statistical perspective, TSV is an ordered categorical response. Cumulative ordinal regression preserves the ordering of response categories without assuming equal numerical distances between adjacent categories [59]. For observations linked by shared or repeated exposure, generalized estimating equations extend generalized linear models to correlated outcomes and provide marginal effect estimates using specified working correlation structures and robust variance estimation [60]. Extensions of the GEE framework also support correlated ordinal and multinomial responses [61]. These methodological developments provide a direct basis for analysing synchronized thermal-comfort records at both the questionnaire and dwelling–time levels.

1.4. Research Questions and Contributions

Accordingly, this study addresses the following research questions:

1. How did winter indoor thermal conditions and multidimensional subjective thermal responses differ among the three monitored rural courtyard dwelling cases?
2. How was operative temperature associated with thermal sensation, thermal acceptability, and thermal preference under the monitored conditions?
3. What study-specific neutral operative temperature could be estimated, and what differentiated thermal improvement priorities could be identified from the combined environmental and subjective evidence?

The study aims to characterize the short-term winter thermal environments and multidimensional subjective thermal responses of three rural courtyard dwellings in Qingcheng Ancient Town and to quantify the associations between operative temperature and thermal sensation, thermal acceptability, and thermal preference.

The study makes three main contributions. First, it provides synchronized environmental measurements and multidimensional subjective thermal-response evidence for rural courtyard dwellings in the Longzhong Yellow River valley, enriching winter field research in a cold–dry regional context. Second, its comparative field design connects contrasting dwelling configurations with measured temperature levels, thermal stability, humidity conditions, and subjective responses, thereby supporting configuration-sensitive and heritage-responsive improvement strategies. Third, it introduces a cluster-aware analytical framework that combines ordinal and binary GEE models, dwelling–time fixed-effects analysis, and block-bootstrap uncertainty estimation to examine thermal sensation, acceptability, preference, and neutral operative temperature.

Together, these contributions provide an empirical and methodological basis for understanding winter thermal responses and informing climate-responsive and heritage-sensitive thermal improvement in rural courtyard dwellings in the Longzhong Yellow River valley and comparable cold–dry settings.

2. Materials and Methods

As shown in Figure 1, the study procedure comprised dwelling-case selection, indoor and outdoor environmental monitoring, synchronized questionnaire surveys, environmental–questionnaire data pairing, organization of the records into dwelling–time clusters, statistical modelling, and sensitivity analysis.

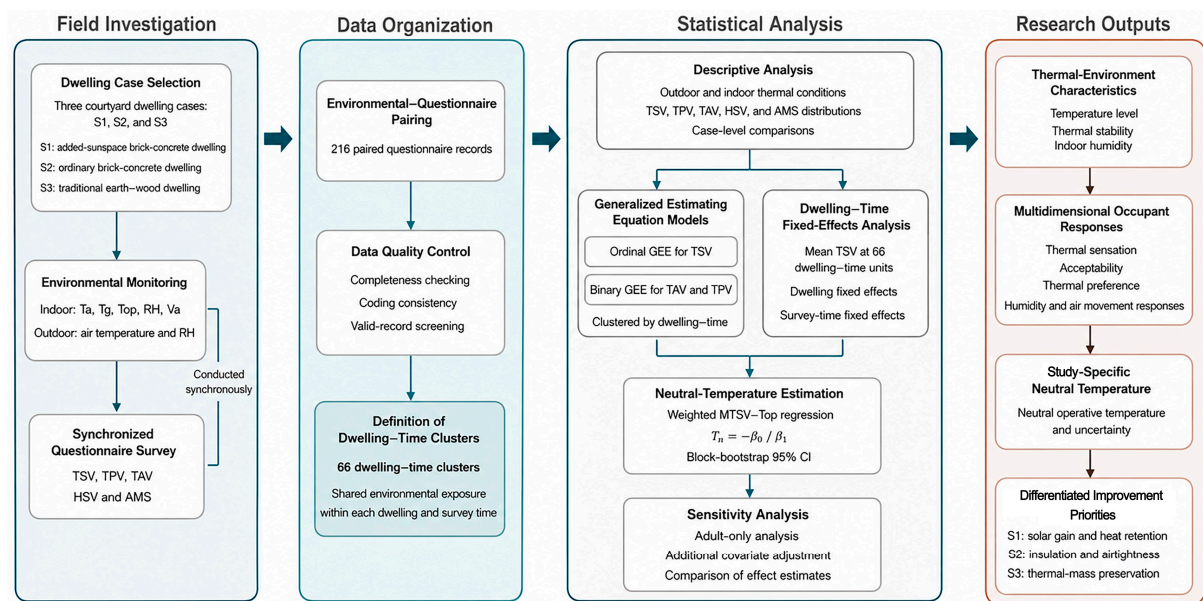


Figure 1. Research framework and analytical workflow.

2.1. Study Area and Dwelling Cases

Qingcheng Ancient Town is located in northern Yuzhong County, Lanzhou, Gansu Province, Northwest China. The town lies between the Yellow River valley terrace and the surrounding loess hills and has a cold-dry winter climate. Winters are characterized by low temperatures, dry air, and pronounced diurnal temperature variation. Daytime solar radiation may influence south-facing rooms, courtyards, and attached sunspaces. As shown in Figure 2, the study area is located within the cold climatic zone of China. Figure 2 also presents the monthly climatic background and the locations of the three monitored dwelling cases within Qingcheng Ancient Town. Three dwelling cases with contrasting construction and spatial configurations were selected through field reconnaissance to support a focused comparative analysis of winter thermal conditions and occupant responses. Accordingly, S1–S3 were analyzed as monitored dwelling cases rather than as statistically replicated dwelling types. Their main characteristics are summarized in Table 1.

Table 1. Characteristics of the Three Monitored Dwelling Cases.

Code	Image	Dwelling Configuration	Main Characteristics
S1		Brick-concrete courtyard dwelling with an added sunspace	South-facing glass sunspace adjoining the principal occupied rooms
S2		Ordinary brick-concrete courtyard dwelling	No attached sunspace; limited systematic insulation and airtightness; intermittent heating
S3		Traditional earth-wood courtyard dwelling	Thick earth-wood walls and relatively high thermal mass

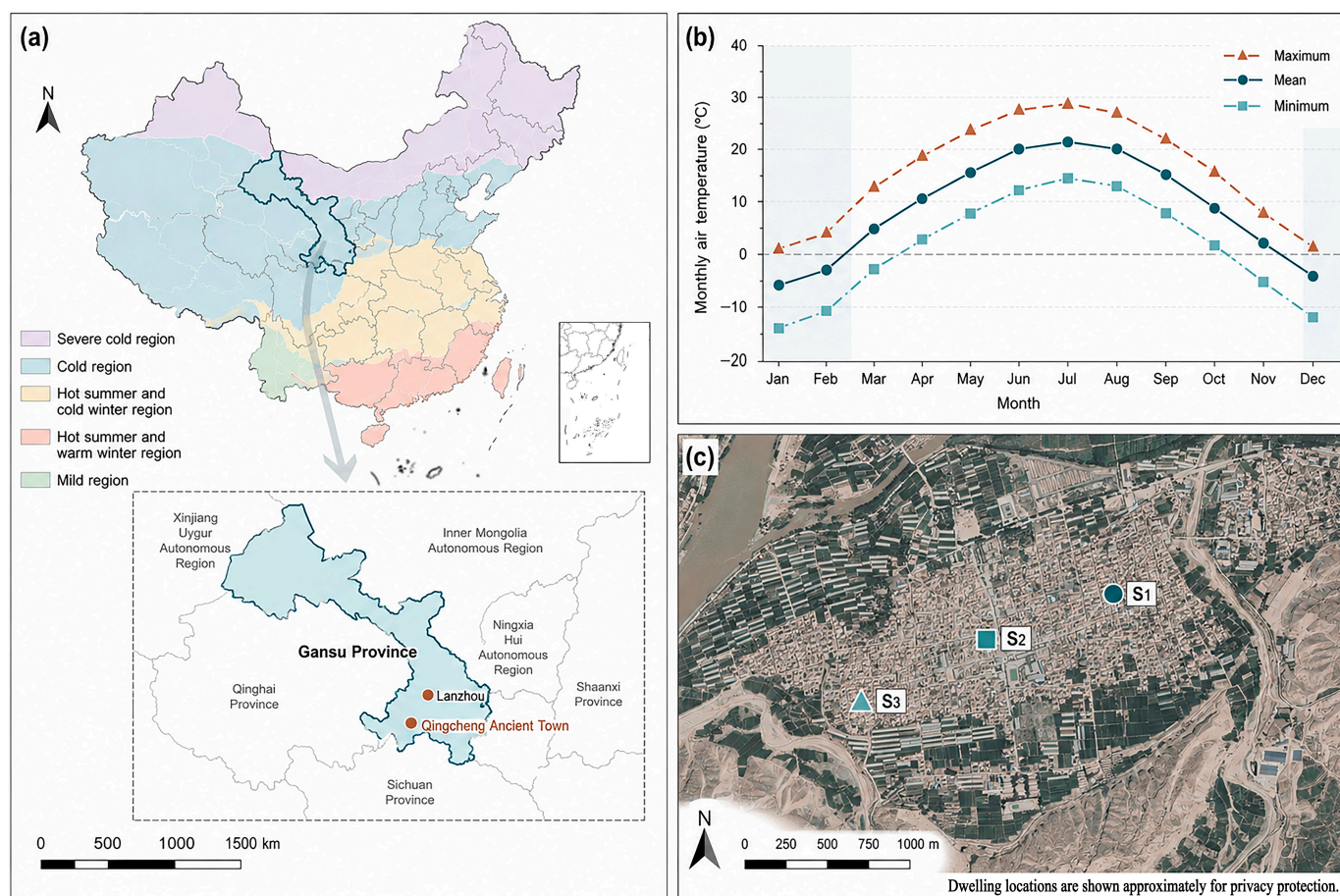


Figure 2. Study area and monitored dwelling locations: (a) China's building climate zones and Qingcheng Ancient Town; (b) monthly maximum, minimum, and mean air temperatures; and (c) locations of S1, S2, and S3. The shaded areas in panel (b) indicate the winter survey months.

The layouts and environmental measurement points of the three dwelling cases are shown in Figure 3.

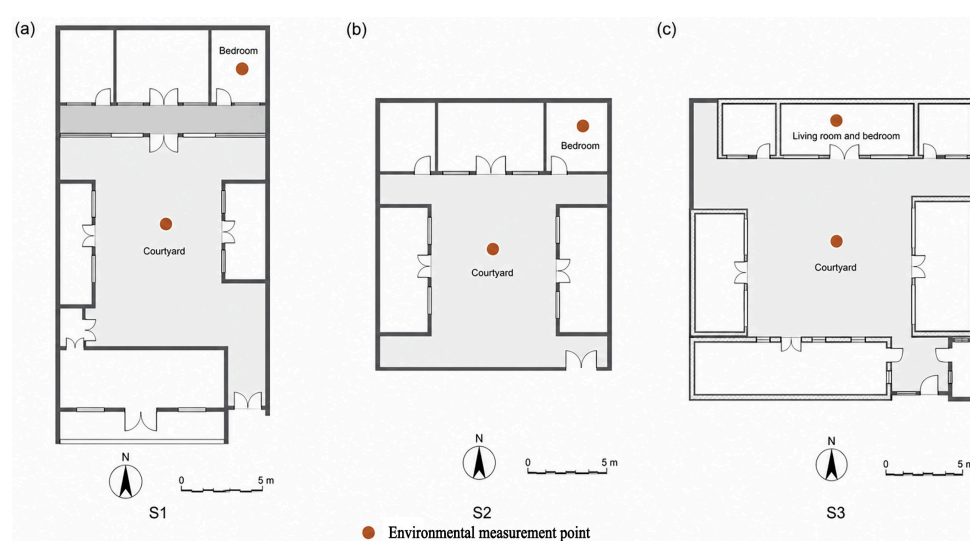


Figure 3. Plan layouts and environmental measurement points of the three monitored dwelling cases: (a) S1; (b) S2; and (c) S3.

2.2. Environmental Monitoring

The measured environmental parameters included indoor and outdoor air temperature (T_a), relative humidity (RH), globe temperature (T_g), and air velocity (V_a). Indoor instruments were placed in the main occupied rooms, avoiding external walls, doors, windows, direct solar radiation, and local heating sources as far as practicable. The measurement height was approximately 1.1 m above the floor, corresponding to the occupied level of seated or light-activity residents.

Outdoor instruments were installed in a ventilated location near the dwellings to record the simultaneous climatic boundary conditions. The instruments, measurement ranges, and stated accuracies are listed in Table 2.

Table 2. Environmental Measurement Instruments and Technical Specifications.

Instrument		Parameter	Measurement Range	Accuracy
JT2180		Air temperature	−20~85 °C	±0.5 °C
JT2180		Globe temperature	−20~85 °C	±0.5 °C
JT2180		Relative humidity	10~90%RH	±3% RH
JT2180		Air velocity	0.05~2.0 m/s	±(0.05 m/s + 2%)
TA622B		Air-temperature check	−40~80 °C	±0.5 °C
TA622B		Relative-humidity check	10~90%RH	±3% RH
GR-2019		Globe temperature	0~120 °C	±0.5 °C
Testo 405i		Air velocity	0~30 m/s	±(0.1 m/s + 5% of the measured value)

Environmental parameters were sampled and logged at 5-min intervals. Before formal monitoring, the instruments were cross-checked under the same indoor conditions using the TA622B for air temperature and RH, the GR-2019 for globe temperature, and the Testo 405i for air velocity, followed by a 30-min stabilization period after deployment. For questionnaire analyses, the 5-min measurements within each hourly survey interval were averaged and paired with questionnaire records from the same dwelling and period.

2.3. Questionnaire Survey and Data Organization

The questionnaire survey was conducted on 20 and 21 January 2026 from 08:00 to 18:00 at hourly intervals, resulting in 22 survey periods. Each questionnaire record was paired with the environmental measurements obtained in the same dwelling, on the same date, and during the same survey period. The paired records were then organized by dwelling and survey period according to their corresponding environmental exposure.

The questionnaire recorded thermal sensation vote (TSV), thermal preference vote (TPV), thermal acceptability vote (TAV), humidity sensation vote (HSV), air-movement sensation (AMS), activity state, sex, and age. The survey design and characteristics of the questionnaire records are summarized in Table 3. For sensitivity analysis, reported

activity states were coded as 1.0 met for seated activity, 1.4 met for standing, and 1.7 met for walking/housework.

Table 3. Survey Design and Characteristics of the Questionnaire Records.

Item	Category	Result
Paired questionnaire records	—	216
Survey dates	—	20–21 January 2026
Survey period	—	08:00–18:00, hourly
Sex	Female	113 (52.31%)
	Male	103 (47.69%)
Age group	<60 years	111 (51.39%)
	≥60 years	105 (48.61%)
Activity state	Seated	133 (61.57%)
	Standing	45 (20.83%)
	Walking/housework	38 (17.59%)

The subjective response scales and analytical coding are presented in Table 4. Two thermal-acceptability outcomes were defined. Broad acceptability was coded as $TAV \geq 0$, whereas clear acceptability was coded as $TAV \geq 1$. A preference for warmer conditions was defined as $TPV = 1$.

Table 4. Subjective Response Scales and Analytical Coding.

Variable	Meaning	Response Scale	Analytical Coding
TSV	Thermal sensation	−3 cold; −2 cool; −1 slightly cool; 0 neutral; +1 slightly warm; +2 warm; +3 hot	Ordinal thermal-sensation outcome
TPV	Thermal preference	−1 prefer cooler; 0 no change; +1 prefer warmer	TPV = +1 defined preference for warmer conditions
TAV	Thermal acceptability	−3 clearly unacceptable to +3 clearly acceptable	$TAV \geq 0$ defined broad acceptability; $TAV \geq 1$ defined clear acceptability
HSV	Humidity sensation	−3 very dry to +3 very humid	Descriptive analysis
AMS	Air movement sensation	−3 very still to +3 strong air movement	Descriptive analysis

2.4. Statistical Analysis

2.4.1. Descriptive Analysis

Operative temperature was calculated because air velocity was generally low and the convective and radiative heat-exchange contributions were assumed to be comparable:

$$T_{OP,dt} = \frac{T_{a,dt} + T_{g,dt}}{2} \quad (1)$$

where $T_{OP,dt}$, $T_{a,dt}$, and $T_{g,dt}$ are the operative, air, and globe temperatures, respectively, for dwelling d at time t .

Continuous variables were summarized using the mean, standard deviation, minimum, and maximum, as appropriate. Categorical questionnaire variables were summarized using counts and percentages. Indoor thermal conditions were compared descriptively among S1, S2, and S3.

For descriptive visualization only, the questionnaire records were grouped into 2 °C operative-temperature intervals of 5–7, 7–9, 9–11, 11–13, 13–15, 15–17, and 17–19 °C. These

intervals were used to display the distributions of TSV, TPV, and TAV and were not used to fit the primary regression models.

TSV distributions by adult age group and sex were examined as exploratory descriptive analyses. For dwelling–time analyses, mean TSV was calculated as:

$$\overline{TSV}_{dt} = \frac{1}{n_{dt}} \sum_{i=1}^{n_{dt}} TSV_{idt} \quad (2)$$

where $\overline{TSV}_{dt}$ is the mean TSV in dwelling d at survey time t , TSV_{idt} is the vote of record i , and n_{dt} is the number of questionnaire records in the corresponding dwelling–time unit.

2.4.2. Ordinal GEE Model for Thermal Sensation

Because TSV is an ordered categorical outcome, an ordinal generalized estimating equation model with a cumulative-logit link was fitted, with dwelling–time units specified as clusters to account for shared environmental exposure among questionnaire records collected within the same dwelling and survey period:

$$\log \left[\frac{P(TSV_{ic} > k)}{P(TSV_{ic} \leq k)} \right] = \alpha_k + \beta_1 T_{OP,c} + \beta_2 S2_c + \beta_3 S3_c + \beta_4 D_c \quad (3)$$

where TSV_{ic} is the thermal sensation response of record i in dwelling–time cluster c ; α_k is the threshold parameter for category k ; $T_{OP,c}$ is operative temperature; $S2_c$ and $S3_c$ are dwelling indicators, with $S1$ as the reference; and D_c is an indicator for the second survey day. An exchangeable working correlation structure and robust standard errors were used.

2.4.3. Binary GEE Models for Thermal Acceptability and Preference

Separate binary GEE models with logit links were fitted for broad thermal acceptability, clear thermal acceptability, and preference for warmer conditions:

$$\log \left[\frac{P(Y_{ic} = 1)}{P(Y_{ic} = 0)} \right] = \beta_0 + \beta_1 T_{OP,c} + \beta_2 S2_c + \beta_3 S3_c + \beta_4 D_c \quad (4)$$

where Y_{ic} is the binary outcome of questionnaire record i in dwelling–time cluster c ; β_0 is the model intercept; β_1 is the coefficient for operative temperature; $T_{OP,c}$ is the operative temperature of cluster c ; $S2_c$ and $S3_c$ are dwelling indicators, with $S1$ as the reference; and D_c is the survey-day indicator, with the first survey day as the reference.

The three binary outcomes were defined as follows:

$$\begin{aligned} Y_{ic}^{Broad} &= \begin{cases} 1, & TAV_{ic} \geq 0, \\ 0, & TAV_{ic} < 0, \end{cases} \\ Y_{ic}^{Clear} &= \begin{cases} 1, & TAV_{ic} \geq 1 \\ 0, & TAV_{ic} < 1, \end{cases} \\ Y_{ic}^{Warmer} &= \begin{cases} 1, & TPV_{ic} = 1, \\ 0, & TPV_{ic} \neq 1. \end{cases} \end{aligned} \quad (5)$$

Here, Y_{ic}^{Broad} denotes broad thermal acceptability, Y_{ic}^{Clear} denotes clear thermal acceptability, and Y_{ic}^{Warmer} denotes a preference for warmer conditions.

The binary models used the same dwelling–time clustering, exchangeable working correlation structure, and robust standard errors as the ordinal GEE model. For both the ordinal and binary GEE models, the effect of a 1 °C increase in operative temperature was expressed as an odds ratio:

$$OR = \exp(\beta_1) \quad (6)$$

where OR represents the multiplicative change in the odds of the modeled outcome associated with a 1 °C increase in operative temperature. For the ordinal GEE model, $OR > 1$ indicates higher odds of reporting a higher TSV category; for the binary GEE models, $OR > 1$ indicates higher odds of the outcome coded as $Y_{ic} = 1$.

2.4.4. Dwelling–Time Fixed-Effects Model

A weighted two-way fixed-effects model was fitted using the 66 dwelling–time observations:

$$\overline{TSV}_{ht} = \beta T_{OP,ht} + \mu h + \tau t + \varepsilon_{ht} \quad (7)$$

where $\overline{TSV}_{ht}$ is the mean thermal sensation vote in dwelling h during survey period t ; $T_{OP,ht}$ is the corresponding operative temperature; β is the operative-temperature coefficient; μh and τt represent dwelling and survey-period fixed effects, respectively; and ε_{ht} is the error term.

2.4.5. Neutral Operative Temperature

A separate weighted linear regression was fitted using the 66 dwelling–time observations:

$$\overline{TSV}_{ht} = \beta_0 + \beta_1 T_{OP,ht} + \varepsilon_{ht} \quad (8)$$

The neutral operative temperature was defined as the value at which the predicted mean TSV equalled zero:

$$T_n = -\frac{\beta_0}{\beta_1} \quad (9)$$

where T_n is the study-specific neutral operative temperature. Its 95% confidence interval was estimated using 5000 block-bootstrap resamples. The 22 survey periods were treated as resampling blocks, and observations from all three dwellings within each selected period were retained together.

2.4.6. Sensitivity Analysis Procedure

An adult-only sensitivity analysis was conducted after excluding 11 records with reported age below 18 years, leaving 205 records. The ordinal TSV model and the three binary GEE models were re-estimated using the adult-only dataset, followed by additional adjustment for sex, age, and metabolic rate. Age was centred at 60 years and expressed per 10-year increase. All statistical tests were two-sided, and $p < 0.05$ was considered statistically significant. Analyses were conducted using Python 3.13.5 and statsmodels 0.14.6.

3. Results

3.1. Outdoor Climatic Conditions During the Monitoring Periods

As shown in Figure 4a, during the monitoring period, the outdoor air temperature ranged from -13.34 °C to 13.24 °C, with a mean of -3.91 °C and a standard deviation of 6.98 °C. Outdoor relative humidity ranged from 19.57% to 57.43%, with a mean of 38.03%. Outdoor air temperature was generally lowest in the morning and increased during the daytime, whereas relative humidity tended to decrease as outdoor temperature increased. The monitoring period therefore included both pronounced cold exposure and substantial daytime variation in the outdoor climatic boundary. As shown in Figure 4b,c, the interval distributions further indicated that the outdoor environment was dominated by low-temperature and low-to-moderate-humidity conditions.

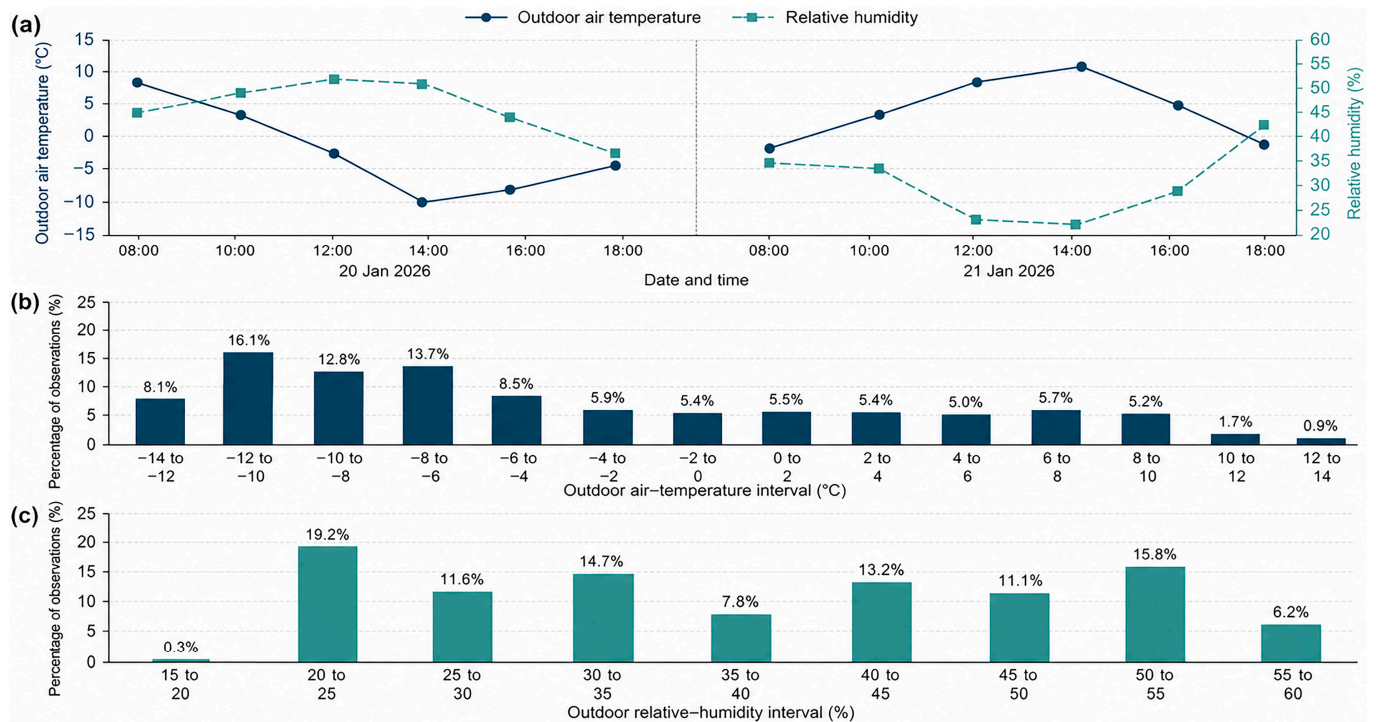


Figure 4. Outdoor climatic conditions during the monitoring period: (a) continuous variations in outdoor air temperature and relative humidity; (b) percentage distribution of outdoor air-temperature intervals; and (c) percentage distribution of outdoor relative-humidity intervals.

3.2. Indoor Thermal Conditions of the Three Dwelling Cases

Across all 216 questionnaire records, the mean operative temperature during the synchronized survey periods was 11.31 °C, with an observed range of 5.23–17.40 °C. The corresponding mean indoor relative humidity was 34.05%. As summarized in Table 5, the three dwelling cases differed in temperature level, thermal fluctuation, relative humidity, and mean thermal sensation.

Table 5. Indoor Thermal Conditions and Mean Thermal Sensation during the Questionnaire Periods.

Dwelling Case	Dwelling Description	Questionnaire Records, n	Mean TOP (°C)	TOP Range (°C)	Mean RH (%)	Mean TSV
S1	Brick-concrete dwelling with an added sunspace	72	12.99	9.93–15.07	38.41	−0.69
S2	Ordinary brick-concrete dwelling	72	11.41	5.23–17.40	24.58	−0.94
S3	Traditional earth-wood dwelling	72	9.54	5.50–11.77	39.16	−1.28
Overall	Three monitored dwelling cases	216	11.31	5.23–17.40	34.05	−0.97

S1 had the highest mean operative temperature, at 12.99 °C, and the mean TSV closest to neutrality, at −0.69. Its operative-temperature range was 9.93–15.07 °C, corresponding to a span of 5.14 °C. S2 had a mean operative temperature of 11.41 °C but showed the largest variation, ranging from 5.23 °C to 17.40 °C, with a span of 12.17 °C. S3 had the lowest mean operative temperature, at 9.54 °C, and the lowest mean TSV, at −1.28. Its operative-temperature range was 5.50–11.77 °C, substantially narrower than that observed in S2.

As shown in Figure 5, continuous monitoring further illustrated the dynamic differences among the three cases. S1 generally maintained a relatively high indoor temperature level during the monitored period. S2 exhibited the largest short-term temperature changes, whereas S3 remained cooler but showed comparatively smoother variation. Indoor humidity also differed substantially: the mean RH of S2 was 24.58%, compared with 38.41% in S1 and 39.16% in S3.

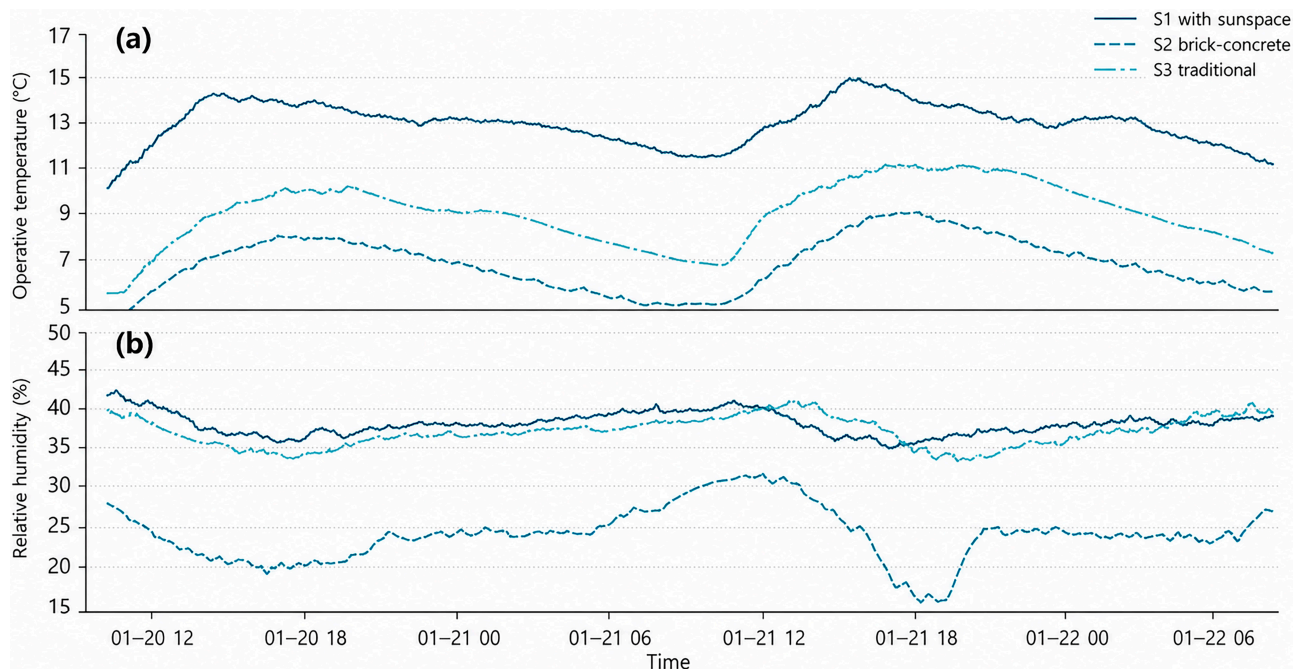


Figure 5. Continuous indoor thermal conditions of the three dwelling cases: (a) operative-temperature variations in S1, S2, and S3; (b) relative-humidity variations in S1, S2, and S3.

3.3. Subjective Thermal, Humidity, and Air-Movement Responses

The overall TSV distribution was concentrated in the slightly cool, cool, and neutral categories. Of the 216 questionnaire records, 45.8% had a TSV of -1 , 23.6% had a TSV of -2 , and 25.5% had a TSV of 0 . Only 2.3% of the records were classified as cold (TSV = -3), while 2.8% were classified as slightly warm (TSV = $+1$). No records had TSV values of $+2$ or $+3$. The mean TSV was -0.97 , indicating a slightly cool overall thermal state.

Thermal preference and acceptability did not follow identical distributions. A warmer environment was preferred in 54.6% of the questionnaire records, whereas 41.2% indicated no change and 4.2% preferred cooler conditions. For thermal acceptability, 93.98% of the records met the broad acceptability criterion ($TAV \geq 0$), and 75.93% met the clear acceptability criterion ($TAV \geq 1$). Thus, a high proportion of acceptable votes coexisted with a substantial preference for warmer conditions.

As shown in Figure 6, the temperature-interval distributions indicated a systematic shift in the composition of subjective thermal responses as operative temperature increased. In the $5\text{--}7\text{ }^{\circ}\text{C}$ interval, 75.0% of the records reported TSV = -2 and 15.0% reported TSV = -3 , while 90.0% preferred warmer conditions, indicating pronounced cold sensation and a strong demand for additional warmth at the lower end of the observed temperature range. In the $13\text{--}15\text{ }^{\circ}\text{C}$ interval, the proportion of neutral TSV records increased to 46.0%, 54.0% indicated no change in thermal preference, and clear acceptability reached 95.2%. These changes suggest that thermal conditions became substantially more acceptable and closer to occupants' preferred state, although sensation, preference, and acceptability did not change at exactly the same rate. At the highest observed interval of $17\text{--}19\text{ }^{\circ}\text{C}$, 50.0% of the records reported TSV = $+1$ and 50.0% preferred cooler conditions, showing that

subjective responses had begun to shift from cold-related demand toward mild warmth and cooling preference. Overall, the interval distributions reveal a gradual transition from cold sensation and warmer preference to neutral or slightly warm sensation and greater thermal acceptance.

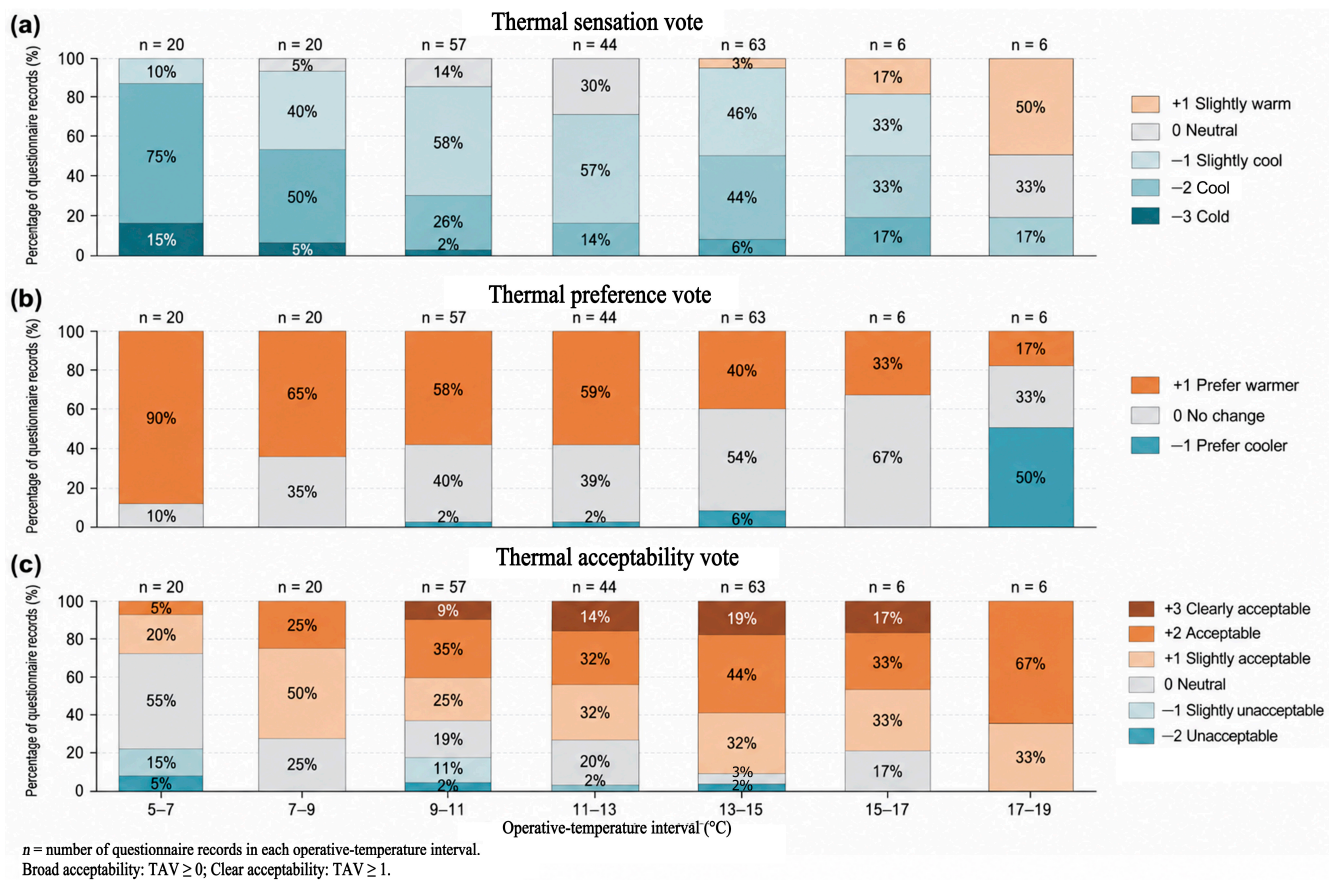


Figure 6. Distributions of subjective thermal responses across operative-temperature intervals: (a) thermal sensation vote; (b) thermal preference vote; and (c) thermal acceptability vote. The values above the bars indicate the number of questionnaire records in each interval.

As shown in Figure 7a, the exploratory age-group distributions were based on adult questionnaire records only. Both the 18–59-year group ($n = 100$) and the ≥ 60 -year group ($n = 105$) were concentrated at TSV = -1 . The proportion reporting TSV = -1 was 42.0% in the 18–59-year group and 49.5% in the ≥ 60 -year group. TSV = -2 accounted for 28.0% and 18.1% of the respective groups. As shown in Figure 7b, the distributions by sex were also broadly similar. TSV = -1 accounted for 42.7% of male records and 48.7% of female records, while neutral votes accounted for 26.2% and 24.8%, respectively.

As shown in Figure 8a, the mean humidity sensation vote was -0.97 . Negative HSV categories accounted for 65.3% of the questionnaire records, including 40.3% at HSV = -1 , 16.7% at HSV = -2 , and 8.3% at HSV = -3 . A neutral humidity sensation was reported in 32.9% of the records, whereas only 1.9% reported HSV = $+1$. These distributions indicate that perceived dryness was common during the survey.

The measured relative humidity corresponding to the questionnaire records had a mean of 34.05%. As shown in Figure 8c, the RH distributions across HSV categories showed a clear descriptive gradient. Median RH was 21.4% for HSV = -3 , 24.4% for HSV = -2 , 37.7% for HSV = -1 , 38.8% for HSV = 0 , and 44.0% for HSV = $+1$. Although the ranges overlapped between adjacent categories, progressively less-negative humidity sensations were generally associated with higher measured RH.

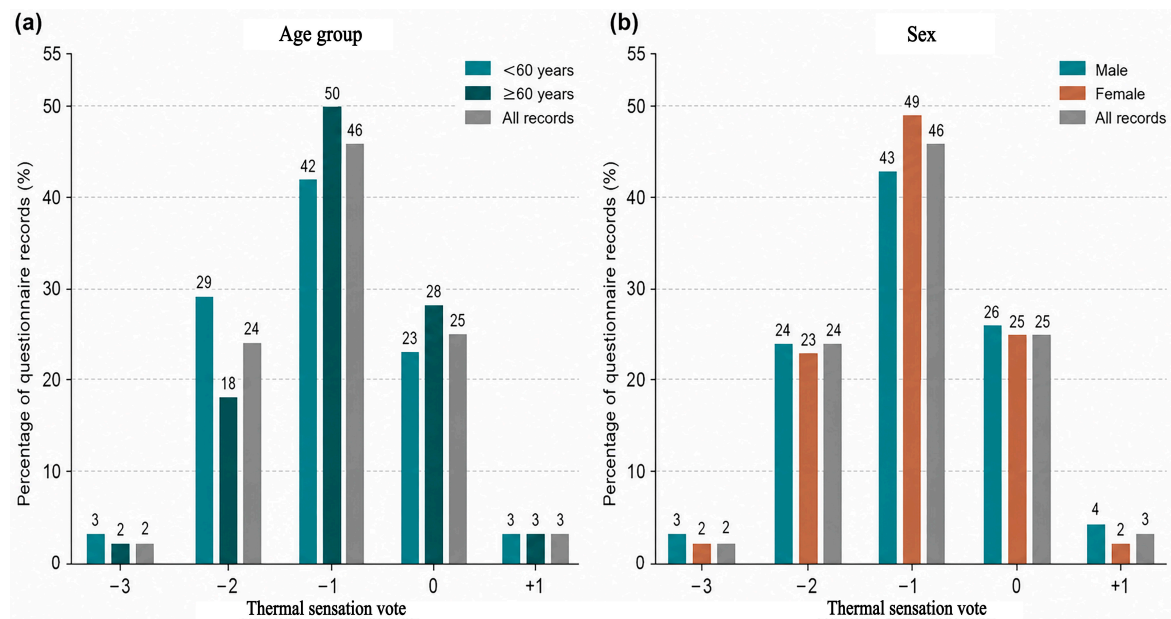


Figure 7. Exploratory distributions of thermal sensation votes by (a) adult age group and (b) sex.

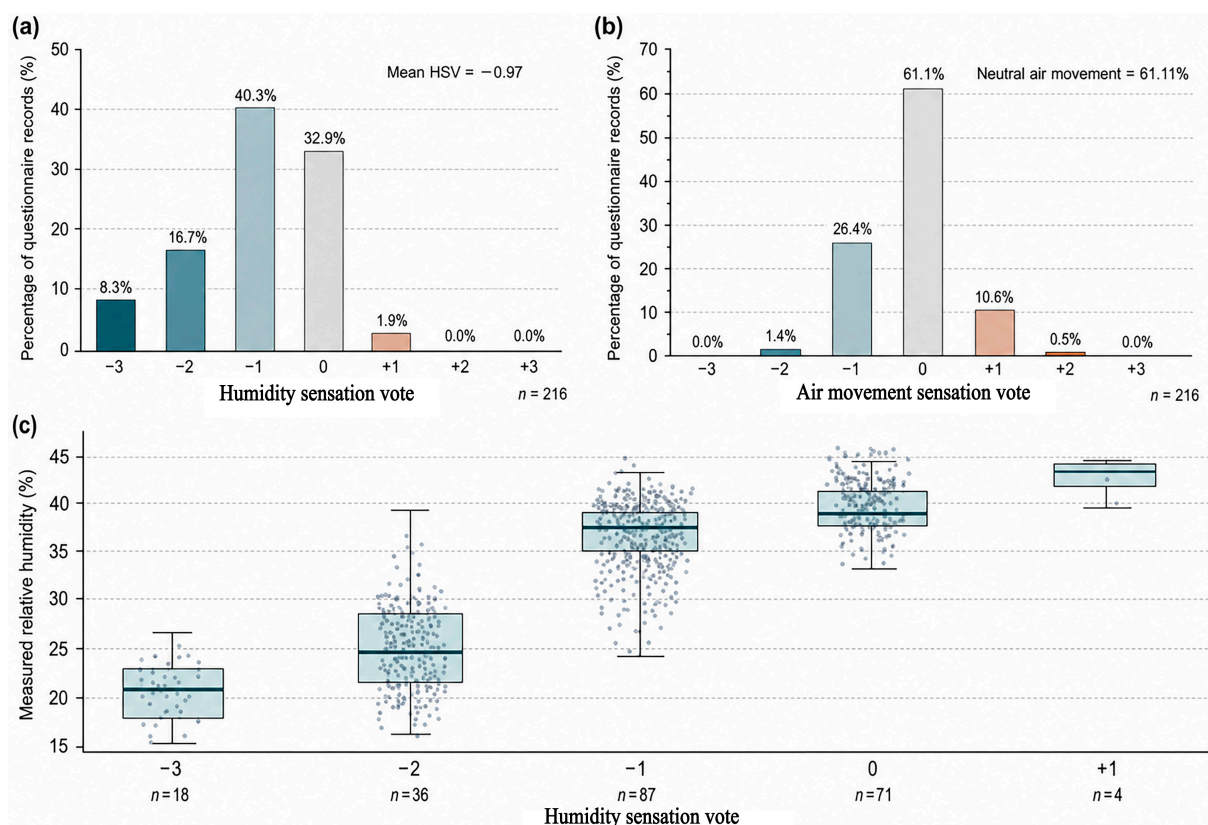


Figure 8. Humidity and air-movement responses: (a) distribution of humidity sensation votes; (b) distribution of air-movement sensation votes; and (c) relationship between measured relative humidity and humidity sensation.

As shown in Figure 8b, the mean air-movement sensation vote was -0.18 . Neutral air movement accounted for 61.1% of the records, while 26.4% reported AMS = -1 . The remaining records were distributed across AMS = -2 (1.4%), AMS = $+1$ (10.6%), and AMS = $+2$ (0.5%). Air movement was therefore perceived as neutral in most records, with a secondary concentration on the low-air-movement side of the scale.

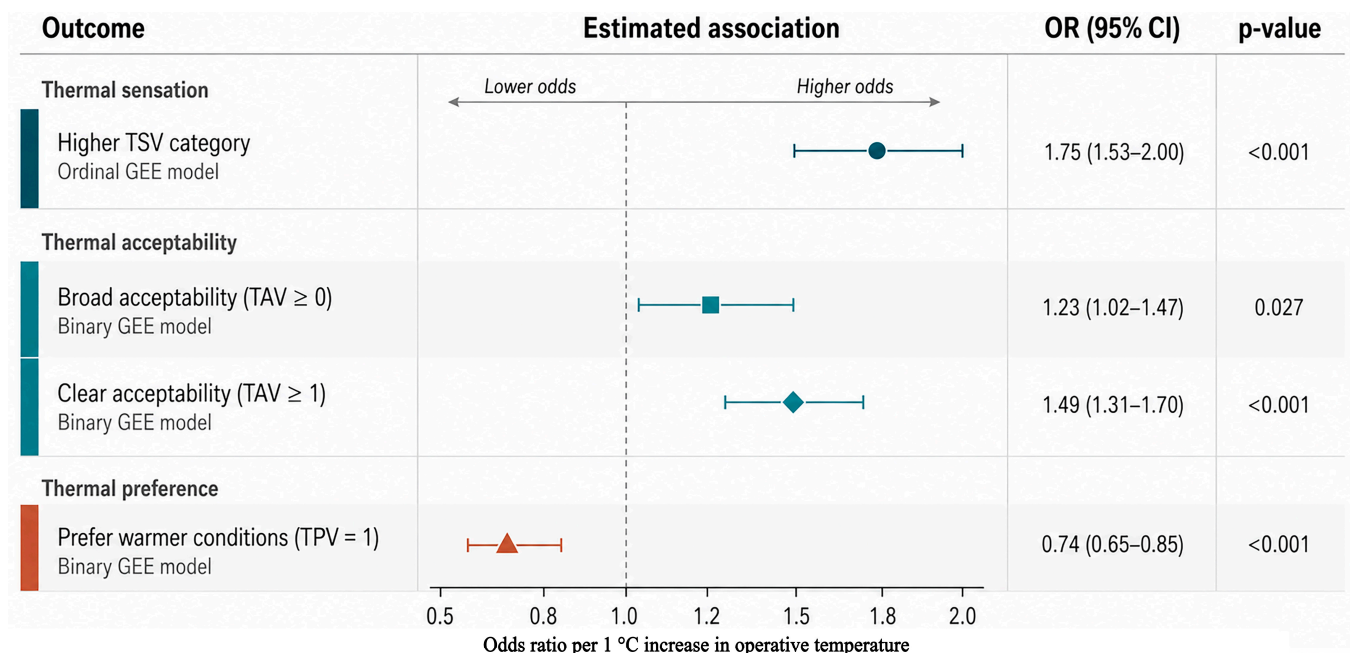
3.4. Associations Between Operative Temperature and Subjective Thermal Responses

The ordinal GEE model showed a positive association between operative temperature and TSV after adjustment for dwelling case and survey day. For each 1 °C increase in operative temperature, the odds of reporting a higher TSV category increased by 75.0% (OR = 1.75, 95% CI: 1.53–2.00, $p < 0.001$). The binary GEE models showed consistent associations across the two thermal-acceptability definitions. Each 1 °C increase in operative temperature increased the odds of broad acceptability by 22.8% (OR = 1.23, 95% CI: 1.02–1.47, $p = 0.027$) and increased the odds of clear acceptability by 49.0% (OR = 1.49, 95% CI: 1.31–1.70, $p < 0.001$).

The direction of the thermal-preference association was reversed. Each 1 °C increase in operative temperature reduced the odds of preferring warmer conditions by approximately 25.9% (OR = 0.74, 95% CI: 0.65–0.85, $p < 0.001$). As summarized in Table 6 and visualized in Figure 9, the four models consistently indicated that warmer operative conditions were associated with less-cold thermal sensation, greater acceptability, and a lower probability of requesting additional warmth.

Table 6. Generalized Estimating Equation Model Results for Subjective Thermal Responses.

Outcome	Model	Coefficient, β	Robust SE	OR per 1 °C Increase in TOP	95% CI for OR	p -Value
Higher TSV category	Ordinal GEE	0.56	0.067	1.75	1.53–2.00	<0.001
Broad acceptability (TAV ≥ 0)	Binary GEE	0.205	0.092	1.23	1.02–1.47	0.027
Clear acceptability (TAV ≥ 1)	Binary GEE	0.399	0.066	1.49	1.31–1.70	<0.001
Prefer warmer conditions (TPV = 1)	Binary GEE	−0.299	0.068	0.74	0.65–0.85	<0.001



Estimates represent the association of a 1 °C increase in operative temperature with each outcome, adjusted for dwelling case and survey day. GEE models used dwelling-time clusters with robust standard errors.

Figure 9. GEE-estimated associations between operative temperature and subjective thermal responses. The dashed line represents the reference value of OR = 1.

As shown in Figure 10, the model-predicted curves provided a continuous representation of these associations across the observed operative-temperature range. The predicted probabilities of both broad and clear acceptability increased with operative temperature. The increase was more pronounced for clear acceptability because broad acceptability was already relatively common at the lower end of the observed range. Conversely, the predicted probability of preferring warmer conditions declined continuously as operative temperature increased. The curves were restricted to the observed overall temperature range of 5.23–17.40 °C.

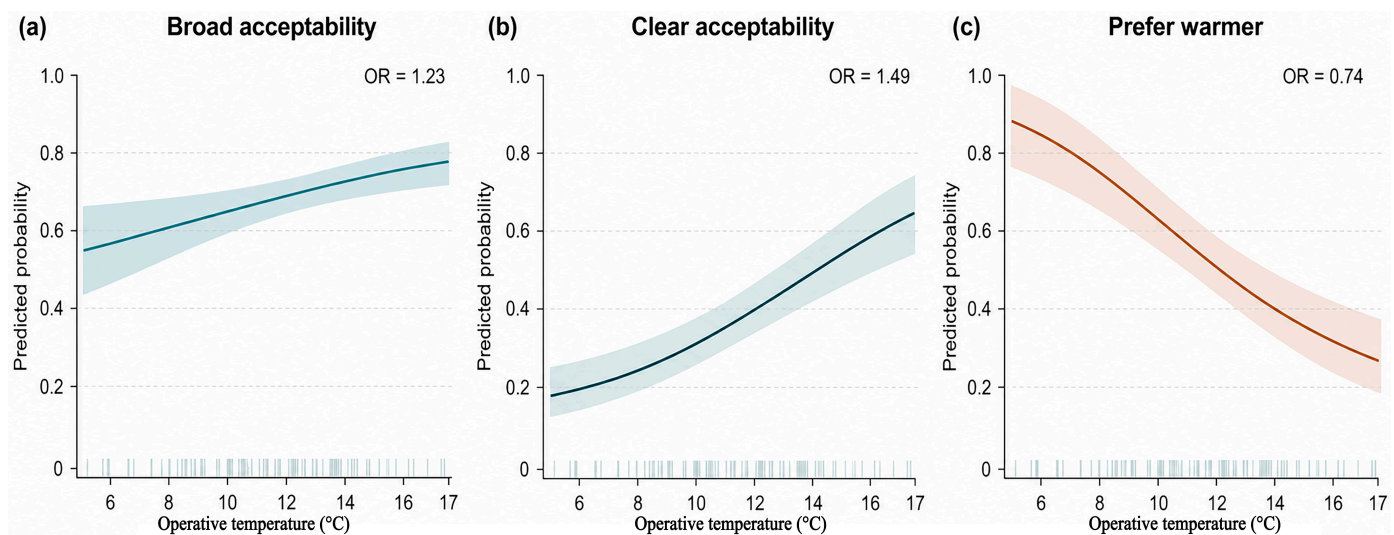


Figure 10. Model-predicted probabilities of thermal acceptability and preference across operative temperature: (a) broad acceptability ($TAV \geq 0$); (b) clear acceptability ($TAV \geq 1$); and (c) preference for warmer conditions ($TPV = 1$). The shaded areas represent the 95% confidence intervals of the predicted probabilities.

3.5. Dwelling–Time Analysis and Neutral Operative Temperature

The questionnaire data were aggregated into 66 dwelling–time units, each representing records collected within the same dwelling, on the same date, and at the same survey time. Each unit contained three or four questionnaire records sharing the same environmental measurements.

In the two-way fixed-effects model, the dwelling–time mean TSV was regressed on operative temperature while controlling for dwelling fixed effects and 22 survey-time fixed effects. Units were weighted by their number of questionnaire records. After these controls, each 1 °C increase in operative temperature was associated with a 0.176-unit increase in dwelling–time mean TSV ($\beta = 0.176$, 95% CI: 0.089–0.262, $p < 0.001$). A separate weighted dwelling–time regression was used to estimate the neutral operative temperature:

$$MTSV = -2.993 + 0.179 T_{Op} \quad (10)$$

The regression slope was 0.179 TSV units per 1 °C (95% CI: 0.150–0.207, $p < 0.001$). Setting the predicted MTSV to zero yielded a study-specific neutral operative temperature of 16.75 °C, which lies within the observed operative-temperature range of 5.23–17.40 °C. A block bootstrap was conducted by resampling the 22 survey timestamps, thereby retaining the shared short-term climatic background of the three dwelling cases within each timestamp. Based on 5000 bootstrap repetitions, the 95% confidence interval of the neutral operative temperature was 15.66–18.40 °C.

As shown in Figure 11, the dwelling–time mean TSV increased with operative temperature, and the fitted regression crossed the neutral-sensation line at approximately 16.75 °C.

The fixed-effects estimate and weighted neutral-temperature regression are summarized together with the sensitivity analyses in Table 7.

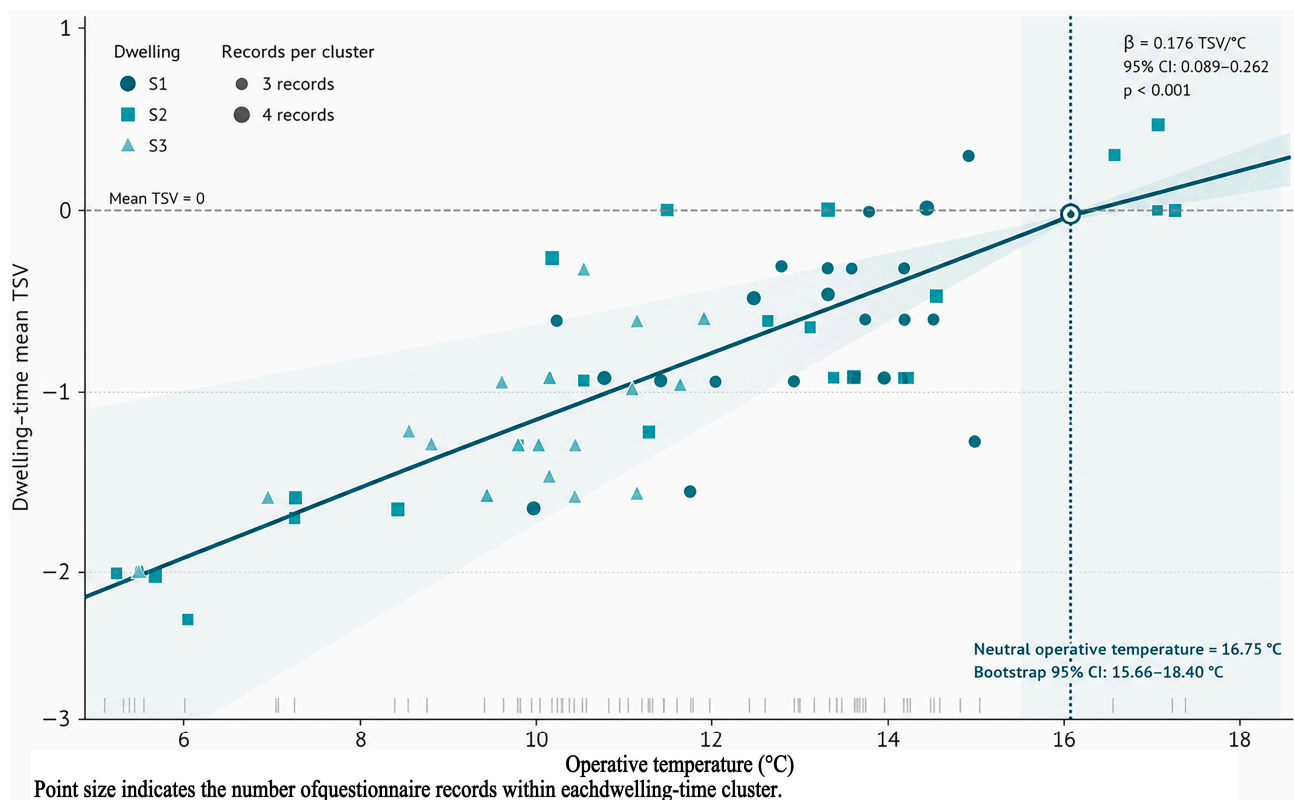


Figure 11. Relationship between dwelling-time mean thermal sensation vote and operative temperature. The shaded area around the regression line represents the 95% confidence interval, while the vertical shaded area indicates the bootstrap 95% confidence interval of the estimated neutral operative temperature.

Table 7. Dwelling-Time Analysis, Neutral-Temperature Estimation, and Sensitivity Analyses.

Analysis	Outcome	Effect Measure	Estimate	95% CI	<i>p</i> -Value
Primary dwelling-time analysis	Mean TSV	Change per 1 °C increase in TOP	0.176	0.089–0.262	<0.001
Weighted neutral-temperature regression	Mean TSV	Regression slope per 1 °C	0.179	0.150–0.207	<0.001
Weighted neutral-temperature regression	Neutral TOP	Temperature estimate (°C)	16.75	15.66–18.40	—
Adult-only ordinal GEE	Higher TSV category	OR per 1 °C	1.76	1.53–2.01	<0.001
Adult GEE adjusted for sex, age, and met	Higher TSV category	OR per 1 °C	1.78	1.54–2.05	<0.001
Adult-only binary GEE	Broad acceptability (TAV ≥ 0)	OR per 1 °C	1.23	1.02–1.47	0.028
Adult GEE adjusted for sex, age, and met	Broad acceptability (TAV ≥ 0)	OR per 1 °C	1.23	1.03–1.46	0.02
Adult-only binary GEE	Clear acceptability (TAV ≥ 1)	OR per 1 °C	1.51	1.32–1.73	<0.001
Adult GEE adjusted for sex, age, and met	Clear acceptability (TAV ≥ 1)	OR per 1 °C	1.51	1.32–1.72	<0.001

Table 7. *Cont.*

Analysis	Outcome	Effect Measure	Estimate	95% CI	p-Value
Adult-only binary GEE	Prefer warmer conditions (TPV = 1)	OR per 1 °C	0.73	0.64–0.84	<0.001
Adult GEE adjusted for sex, age, and met	Prefer warmer conditions (TPV = 1)	OR per 1 °C	0.73	0.63–0.84	<0.001

The primary fixed-effects analysis used 66 dwelling–time units and controlled for dwelling and 22 survey timestamps. The neutral-temperature confidence interval was obtained from 5000 block-bootstrap repetitions at the survey-timestamp level. Adult sensitivity analyses included 205 questionnaire records. Covariate-adjusted models additionally included sex, age centred at 60 years and expressed per 10-year increase, and metabolic rate. The covariate-adjusted models were used as sensitivity analyses rather than primary models.

3.6. Sensitivity Analysis Results

Sensitivity analyses were conducted using the 205 adult questionnaire records. The operative-temperature effects remained close to the primary estimates after the 11 records with reported age below 18 years were excluded. For the adult-only ordinal TSV model, the OR for entering a higher TSV category was 1.76 per 1 °C increase in operative temperature (95% CI: 1.53–2.01, $p < 0.001$). After additional adjustment for sex, age, and metabolic rate, the corresponding OR was 1.78 (95% CI: 1.54–2.05, $p < 0.001$).

The adult-only ORs were 1.23 for broad acceptability, 1.51 for clear acceptability, and 0.73 for preferring warmer conditions. Additional covariate adjustment produced nearly identical estimates of 1.23, 1.51, and 0.73, respectively. As shown in Table 7, the direction and magnitude of the operative-temperature associations remained stable across the sensitivity specifications.

4. Discussion

4.1. Case-Level Thermal Environmental Differences and Building Interpretation

The three monitored dwelling cases exhibited different combinations of indoor temperature level, thermal fluctuation, and relative humidity. S1 had the highest mean operative temperature, S2 showed the greatest temperature fluctuation and lowest humidity, and S3 remained cooler but comparatively stable. These findings indicate that mean temperature alone does not fully characterize the winter indoor environment; temporal stability and moisture conditions are also relevant to occupants' actual exposure.

The relatively high temperature observed in S1 is consistent with the potential buffering function of an added sunspace. A transparent enclosure can intercept daytime solar radiation, reduce direct wind exposure, and moderate the boundary conditions of adjacent rooms [35,37,46–51]. Because solar exposure, heating operation, occupancy, and envelope characteristics differed among cases, the higher temperature in S1 should be interpreted as a case-level outcome rather than an isolated effect of the sunspace.

The wide temperature range in S2 is compatible with intermittent local heating combined with limited envelope insulation and airtightness. A room may warm rapidly while heating is operating but cool quickly after it stops. Such variation is relevant because occupants experience not only average temperature but also repeated transitions between warmer and cooler conditions. Winter temperature steps have been associated with health discomfort, particularly among vulnerable occupants [6].

The smoother temperature variation observed in S3 is consistent with the thermal inertia commonly associated with heavy earth–wood construction [27,30–33,39,52–54]. Maintaining this thermal-mass advantage while improving roof insulation, openings, and construction joints may therefore help raise winter indoor temperatures without losing the stabilizing characteristics of the existing structure.

The particularly low RH in S2 also shows that warming and humidity cannot be considered separately. Increasing air temperature through local heating can reduce relative humidity and intensify perceived dryness. Winter improvement should consequently address temperature, thermal stability, humidity, ventilation, and indoor air quality together.

4.2. Operative Temperature, Multidimensional Thermal Responses, and Adaptation

The observed operative-temperature range of 5.23–17.40 °C represents the naturally occurring winter exposure of the three monitored dwellings and therefore defines the empirical domain of the present temperature–response analysis. Across the analyses, operative temperature was consistently associated with winter thermal responses. Both the ordinal GEE and dwelling–time fixed-effects analyses showed that warmer operative conditions were associated with higher thermal sensation votes. The consistency between the two analytical levels supports the robustness of the observed temperature–sensation relationship.

The acceptability models further showed that broad and clear acceptability represent different levels of evaluation. Broad acceptability was already common at relatively low temperatures, whereas clear acceptability increased more strongly with operative temperature. Reporting both thresholds therefore distinguishes merely tolerable conditions from conditions evaluated more positively.

A central finding was the coexistence of high acceptability and a frequent preference for warmer conditions. Although 93.98% of the questionnaire records met the broad acceptability criterion, 54.63% still indicated a preference for greater warmth. Acceptability should therefore not be equated with neutrality or full satisfaction. Residents may regard a cool environment as tolerable under local economic and heating conditions while still desiring a warmer indoor environment.

The combined use of TSV, TPV, and TAV is consequently important. TSV describes the perceived thermal state, TPV indicates the desired direction of change, and TAV reflects whether the existing condition can be accepted. Their different response patterns show that no single scale fully represents winter thermal experience.

The humidity results similarly showed that subjective response was multidimensional. Perceived dryness was common, and less-negative HSV values generally occurred at higher RH. However, the overlap between HSV categories indicates that humidity sensation was also influenced by other environmental and individual factors. Most AMS records were neutral, but a notable proportion indicated weak air movement. Reduced draught can be beneficial in winter, although excessively restricted ventilation may create indoor-air-quality concerns.

Potential adaptation may help explain why cool sensations coexist with high acceptability. Clothing adjustment, localized heating, movement toward warmer rooms, changes in activity, and reduced thermal expectations are frequently observed in weakly controlled rural residences [1,2,4,8,17,25,26,36,56,58]. These literature-informed mechanisms are therefore interpreted as plausible adaptive pathways for understanding the observed response patterns.

4.3. Comparison with Previous Studies and Retrofit Implications

The estimated neutral operative temperature of 16.75 °C represents a study-specific neutral point under the climatic, heating, clothing, activity, and spatial-use conditions of the investigation. Its lower value relative to conventional winter setpoints commonly adopted in fully heated urban residences highlights the distinct thermal context of the monitored rural dwellings.

A winter field investigation in a coastal village of Qingdao reported a neutral temperature of 13.7 °C [2], approximately 3.05 °C below the present estimate. The difference may reflect variations in cold–humid and cold–dry climates, dwelling form, heating mode, humidity, clothing, participant composition, monitoring duration, and analytical approach. It should not be attributed to climate alone.

Other Chinese residential studies have similarly demonstrated that thermal responses vary with climate region, season, heating stage, settlement type, and building context [3,12,13,15,25,42,43]. Direct numerical comparison across studies should therefore account for differences in temperature metrics and estimation methods, including the use of air, globe, or operative temperature.

As summarized in Table 8, the closest contextual comparison is the Qingdao rural winter study, whereas investigations in Beijing, Xi’an, the Tibetan Plateau, and different arid settlement types provide broader evidence of regional and contextual heterogeneity.

Table 8. Contextual Comparison with Selected Chinese Residential Thermal-Comfort Field Studies.

Study and Reference	Residential and Climatic Context	Main Relevance to the Present Study	Interpretation
Qingcheng Ancient Town, present study	Three rural courtyard dwelling cases; cold–dry winter; intermittent or localized heating	Operative-temperature relationships, multidimensional responses, and study-specific neutral temperature	Neutral TOP = 16.75 °C, with a 95% CI of 15.66–18.40 °C
Qingdao coastal village [2]	Rural coastal dwellings under cold–humid winter conditions	Closest rural winter field comparison	Reported neutral temperature of 13.7 °C; climate, humidity, dwellings, and methods differ
Beijing residences [3,13]	Urban residences during transition, heating, summer, and winter periods	Seasonal and heating-stage variation in thermal responses	Supports the influence of season and heating context
Bedrooms in different Chinese climate regions [12]	Residential bedrooms across multiple climatic regions	Regional variation in thermal environment and adaptive behaviour	Supports climate-dependent residential adaptation
Xi’an residential and elderly-care environments [15,43]	Residential buildings and nursing homes investigated seasonally	Seasonal adaptation and the thermal responses of older occupants	Relevant to seasonal and demographic heterogeneity
Tibetan Plateau residences [25]	High-altitude residential buildings	Cold-region thermal adaptation under distinctive climatic and building conditions	Shows the importance of altitude, construction, and heating availability
Urban, town, and rural residences in arid China [42]	Arid-region residences at different settlement levels	Differences in clothing, expectations, and acceptable conditions	Supports urban–rural and settlement-level variation

As illustrated in Figure 12, the findings are organized into four linked stages: winter thermal exposure, observed occupant responses, potential adaptive mechanisms, and differentiated improvement priorities. Solid pathways indicate observed associations, whereas dashed pathways indicate literature-informed interpretive pathways.

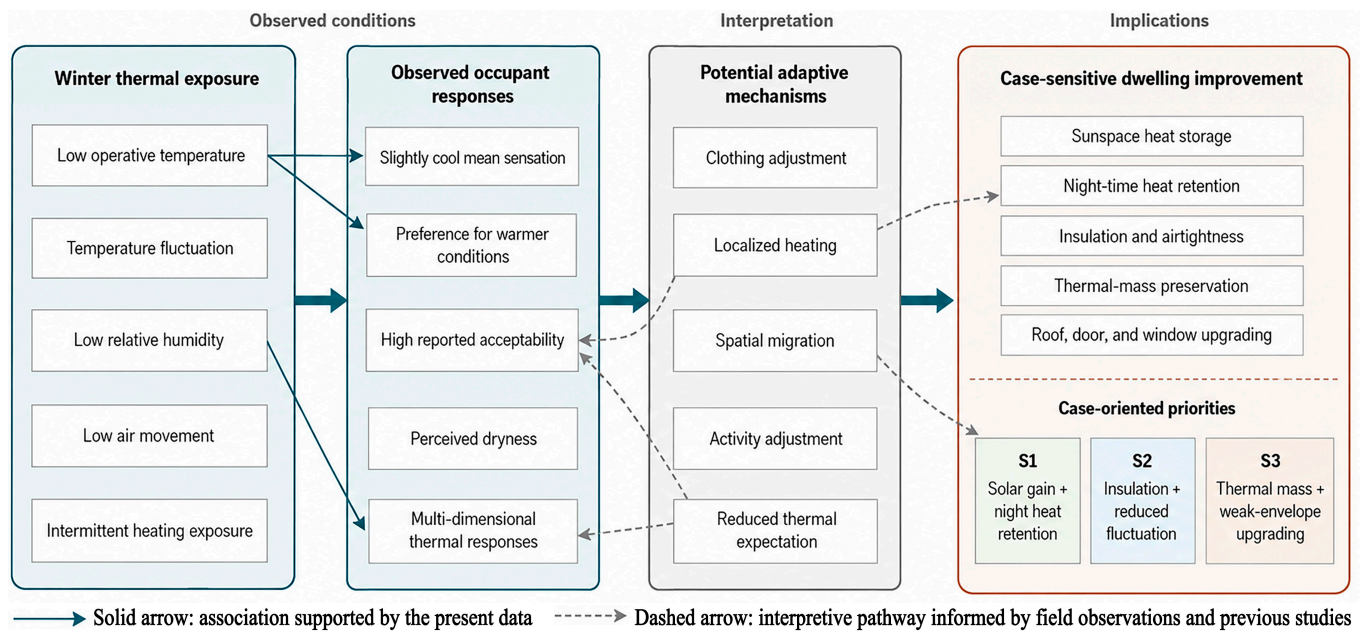


Figure 12. Conceptual pathways linking winter thermal exposure, occupant responses, potential adaptive mechanisms, and differentiated thermal improvement priorities.

For S1, a potential improvement priority is to strengthen the sequence of daytime solar collection, heat transfer, heat storage, and night-time retention. Candidate measures include controllable openings between the sunspace and occupied rooms, thermal-storage surfaces, insulated curtains, and improved sealing.

For S2, a potential improvement priority is to reduce heat loss and temperature fluctuation rather than simply increasing heating power. Candidate measures include roof and wall insulation, door and window sealing, insulated curtains, and improved heating schedules to reduce rapid cooling. Because S2 also showed low RH, temperature improvement could be coordinated with humidity and ventilation management.

For S3, a potential improvement priority is to preserve the thermal inertia and heritage value of the heavy earth–wood structure while upgrading weak envelope components. Candidate measures include roof insulation, door and window sealing, ground heat-loss control, and efficient localized heating, rather than wholesale replacement with lightweight construction.

At the courtyard scale, courtyards, sunspaces, south-facing rooms, walls, doors, and windows should be treated as an integrated thermal system. Previous studies on passive building systems, envelope improvement, and rural residential retrofits indicate that measures such as insulation, airtightness, thermal storage, and passive solar utilization can improve indoor thermal conditions while reducing heating demand; their application should therefore balance thermal comfort with energy efficiency, cost, carbon emissions, and heritage conservation [50,52–54]. Behavioural adaptation can complement physical improvements by providing additional flexibility in responding to short-term winter thermal variation.

4.4. Limitations and Future Work

This study was designed as a short-term comparative field investigation of three rural courtyard dwellings during two winter survey days. Accordingly, the findings characterize temperature–response relationships under the monitored climatic, building, and heating conditions. The consistent results obtained from the GEE models, dwelling–

time fixed-effects analysis, and adult sensitivity analyses support the internal robustness of the principal findings.

Because participant identifiers were unavailable, the GEE clustering accounted for shared environmental exposure within dwelling–time units rather than within-person repeated responses.

Future studies can extend the present framework by including multiple dwellings within each configuration, monitoring across the heating season, and collecting participant-linked repeated surveys together with detailed records of heating operation, clothing insulation, occupant location, solar exposure, and recent thermal history. Controlled or crossover comparisons including conventionally heated conditions (e.g., 20–22 °C) could further examine the influence of recent thermal history and preceding exposure on subsequent thermal evaluations.

5. Conclusions

This study investigated short-term winter thermal environments and adaptive thermal responses in three rural courtyard dwellings in Qingcheng Ancient Town, Northwest China. Indoor and outdoor environmental measurements were combined with 216 synchronized questionnaire records, which were organized into 66 dwelling–time clusters to account for shared environmental exposure. The main conclusions are as follows.

1. The monitored dwellings provided different combinations of indoor temperature level, thermal stability, and humidity under a cold–dry winter climate. The mean outdoor air temperature during the monitoring period was -3.91 °C, whereas the overall mean indoor operative temperature during the questionnaire periods was 11.31 °C. S1 had the highest mean operative temperature, S2 exhibited the greatest temperature fluctuation and the lowest relative humidity, and S3 was cooler but comparatively stable.
2. Operative temperature was consistently associated with multiple dimensions of subjective thermal response. Each 1 °C increase in operative temperature increased the odds of reporting a higher TSV category by 75%, increased the odds of broad and clear thermal acceptability, and reduced the likelihood of preferring warmer conditions. The dwelling–time fixed-effects analysis similarly showed that mean TSV increased by 0.176 units per 1 °C increase in operative temperature.
3. High thermal acceptability did not indicate thermal neutrality or the absence of demand for improvement. Although 93.98% of the questionnaire records met the broad acceptability criterion, 54.63% still indicated a preference for warmer conditions. The mean TSV was -0.97 , and perceived dryness was also common. These findings support a multidimensional approach to winter thermal evaluation that considers sensation, preference, acceptability, humidity sensation, and air-movement sensation together rather than relying on a single indicator.
4. The study-specific neutral operative temperature was estimated at 16.75 °C, with a block-bootstrap 95% confidence interval of 15.66 – 18.40 °C. This estimate provides a contextual reference for interpreting winter thermal responses under the monitored conditions. The observed case differences suggest differentiated improvement priorities: strengthening solar heat storage and night-time retention in S1, reducing envelope heat loss and temperature fluctuation in S2, and preserving thermal mass while upgrading weak envelope components in S3.

Overall, the study provides field-based evidence that operative temperature is systematically associated with multidimensional winter thermal responses, while differences in temperature stability and humidity further distinguish the thermal environments of the three monitored dwellings. These findings provide an empirical basis

for climate-responsive and heritage-sensitive thermal improvement in comparable rural courtyard settings.

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Institutional Review Board Statement: Full ethical review was not required for this non-interventional, minimal-risk study involving environmental monitoring and an anonymous questionnaire survey, as determined by the School of Architecture and Art Design, Lanzhou University of Technology.

Informed Consent Statement: Verbal informed consent was obtained from all participants prior to participation. Participants were informed of the study purpose, voluntary nature of participation, right to withdraw, and the anonymous use of the collected data.

Data Availability Statement: The data presented in this study are available on request from the corresponding author. The data are not publicly available due to ownership rights.

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

Abbreviations

The following abbreviations are used in this manuscript:

Abbreviation	Definition
AMS	Air movement sensation
CI	Confidence interval
GEE	Generalized estimating equations
HSV	Humidity sensation vote
MTSV	Mean thermal sensation vote
OR	Odds ratio
PMV	Predicted mean vote
RH	Relative humidity
TAV	Thermal acceptability vote
TPV	Thermal preference vote
TSV	Thermal sensation vote

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