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Research article

Enhancing the effectiveness of heat adaptation strategies through citizen science-based outdoor thermal comfort

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A R T I C L E I N F O

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Living lab

A B S T R A C T

Urbanization and intensifying climate change expose populations in cities to escalating heat stress and associated health risks. Mitigating these challenges require comprehensive assessments that combine quantitative and qualitative data to develop effective heat wave response strategies and policies. Previous research has primarily focused on thermal sensation measured by individual biometrics within specific locations. However, limitations in data collection across large areas often lead to the neglect of the influence of diverse urban environments. This may disregard the importance of regional variations and citizen engagement in formulating effective heat wave mitigation strategies. This study explored the impact of heat wave frequency and intensity across various urban spatial types and assessed thermal sensation vote (TSV) among residents of Suwon City using a citizen science approach. Temperature measurements and subjective heat sensations were collected over a three-year period using homemade temperature sensors. The analysis investigated thermal sensation differences across spatial types—open high rise, open low rise, compact mid-rise, urban park, and lake park—utilizing boxplots, and examined TSV variations by age using the R program localized smoothing methodology. Results indicate significant variations in TSV across different urban areas, particularly when temperatures exceeded 32 °C. The TSV was highest in the lake park areas (average thermal sensation vote +3.5) and was comparatively lower in the open high-rise and open low-rise areas (average thermal sensation vote +2.0). A significant age-related trend was observed, with the highest TSV reported by the 19–30 age group. Heat sensitivity appeared to decrease among participants aged 41 and over. These findings highlight the limitations of traditional top-down heatwave response strategies, which may not adequately account for spatial variations and individual experiences. Conversely, a bottom-up approach that leverages citizen science can inform the development of tailored and proactive strategies that consider a region's specific conditions.

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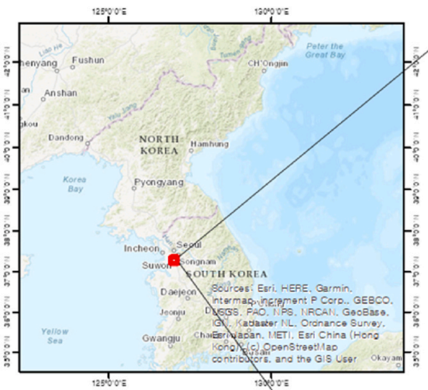
1. Introduction

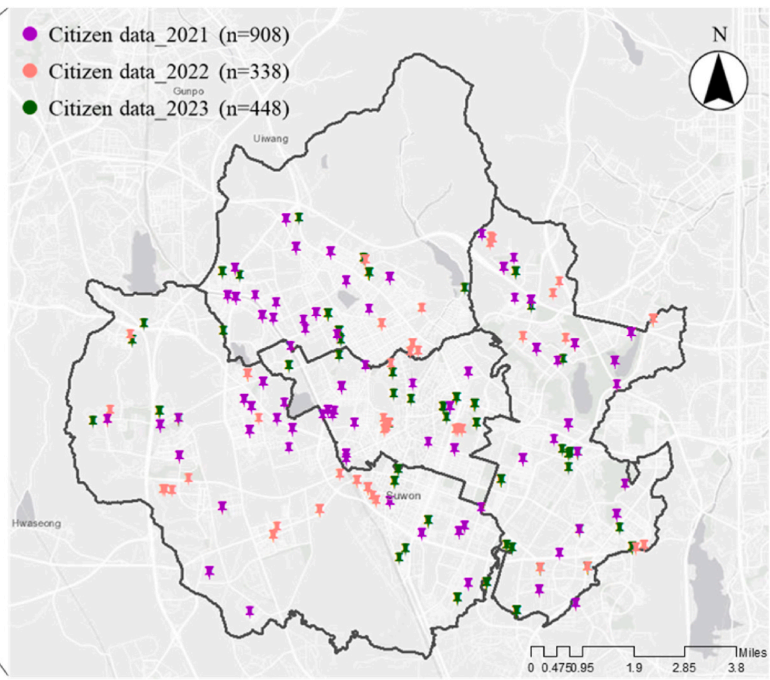
Climate change is no longer breaking news, as the frequency and intensity of heatwaves are increasing globally, with exacerbated effects in urban areas [1]. Urbanization, characterized by the urban heat island (UHI) phenomenon, aggravates existing natural climate variability, leading to elevated urban air temperatures and a subsequent negative impact on human health [2]. The UHI effect is intensified in rapidly developing cities owing to the prevalence of dense urban structures and asphalt surfaces. These materials absorb solar radiation and impede nocturnal radiative cooling, consequently amplifying heat stress [3,4]. This leads to health issues such as heatstroke and exacerbates chronic health conditions. The development and implementation of evidence-based adaptation strategies are critical for effectively addressing the escalating health risks associated with intensifying heat waves, particularly in rapidly urbanizing environments [5,6].

The effectiveness of traditional top-down policy approaches in mitigating the health consequences of climate-related phenomena such as heatwaves has been increasingly questioned [7]. These approaches frequently prioritize centralized decision-making and standardized solutions, potentially neglecting the unique socioecological contexts and diverse needs of local communities [8]. Owing to the significant spatial variability in heatwave impacts, top-down policy approaches that prioritize standardized solutions for risks do not accord due consideration to local communities' unique vulnerabilities and capacities [9]. Citizen science initiatives are gaining traction as potential solutions to address the limitations of top-down approaches. By facilitating data collection and analysis through citizen participation, these initiatives can provide a more nuanced understanding of the spatial variations in heat perception and the differential impacts of heatwaves on local communities [10]. By tailoring heatwave response strategies to specific local conditions, citizen science, which incorporates qualitative assessments through citizens' active involvement, can empower communities to adapt more effectively to heatwaves. Furthermore, these initiatives can generate vital data to inform the development of heatwave-related policies and design guidelines [11]. Citizen science can further contribute by fostering community awareness of heatwaves. By disseminating information on preventive measures and response strategies, these initiatives can promote proactive heatwave mitigation efforts within participating communities [12].

Previous research has examined TSV in various landscape types within specific spaces, such as vegetation types [13], building types on university campuses [14], radiation energy on university campuses [15], landscape configurations in schools [16], and TSV based on the sky view factor [17]. Although these studies provide valuable insights into the relationship between spatial structure (e.g., sky view factor and sunlight/shaded areas) and heat perception, they are limited by the need for surveys and data collection within specific spaces. Citizen science offers a significant advantage by enabling the simultaneous investigation of heat perception across diverse spatial types. This comprehensive understanding can facilitate more effective and sustainable heatwave response strategies tailored to spatial, age, and even individual differences [18,19]. Thus, citizen science reaffirms the value of a bottom-up approach in policy and practice for heatwave responses and plays a pivotal role in addressing community heatwave challenges [3,20,21].

This study aimed to improve our understanding of heatwaves and develop effective response strategies for rapidly developing urban areas. We investigated variations in heat perception across different spatial types and age groups within the City. Citizen science





year	Number of data
~12	231
13~18	491
19~30	227
31~40	244
41~50	212
51~	289
Sum	1694

Fig. 1. Study area and number of data recordings by year.

was employed for data collection, leveraging the R programming language for advanced data visualization techniques. This approach enabled the quantitative analysis of spatial and age-related differences in heat perception. Analyzing these variations is crucial for developing heatwave response policies and urban planning strategies that reflect communities' diverse needs. By integrating citizen participation through citizen science, this study contributes to a new paradigm that values citizens' voices in scientific research and policymaking. This approach promotes sustainable urban development and fosters healthy communities.

2. Methods

2.1. Study area

Suwon City, a rapidly developing urban area in South Korea's Gyeonggi Province (area: 121.01 km^2, population: >1 million), has experienced significant land-cover changes owing to numerous development projects since the 2010s, such as Gwanggyo New Town, Homae-sil District [22] (Fig. 1). This rapid urbanization coincided with increased heatwave days, with 2018 recording the highest number (38 days) [23,24]. The urban heat island phenomenon is expected to intensify as urban development continues. However, with only two Automated Weather Stations (AWS) in the city, obtaining accurate and spatially detailed information on heat waves remains challenging [25]. These limited data hinder effective strategies for addressing the growing issue of heat waves in Suwon City.

2.2. Citizen-driven framework and study design

Suwon City benefits from the collaborative efforts of environmental and civic organizations. The "Suwon Climate Change Experience Center Dodream" [26] has promoted public engagement in climate action. The Center fosters a collaborative system in which the community plans, implements, and evaluates local environmental initiatives. A key project, the "Suwon Heat Map Drawing" initiative, directly engages citizens in temperature monitoring. This project served three purposes: enhancing citizens' understanding of the local climate, increasing public participation in climate action, and contributing valuable data to identify annual temperature trends in Suwon City [26].

A diverse group of citizen scientists were recruited to facilitate urban temperature monitoring. Prior to data collection, workshops were held to familiarize participants with the research objectives and appropriate data acquisition methods. During the workshops, participants were instructed on correctly using the temperature sensors, including maintaining consistent measurement conditions with the CADA application. To ensure data quality, participants were instructed to conduct measurements in unshaded areas within five distinct spatial types identified using Suwon City's Local Climate Zone (LCZ) classification: open high-rise (HHD), open low-rise (LHD), compact mid-rise (MHD), urban park (PAK), and lake park (RIV) [27,28]. These LCZ categories correspond to open high-rise, open low-rise, compact mid-rise, dense tree, and water (Fig. 2). In this study, the survey was conducted in unshaded areas to assess thermal discomfort under direct solar radiation accurately. This allowed for establishing a baseline of thermal stress, as unshaded environments represent conditions where individuals experience the most intense heat exposure. These data served as a benchmark to compare thermal sensation across different urban settings.

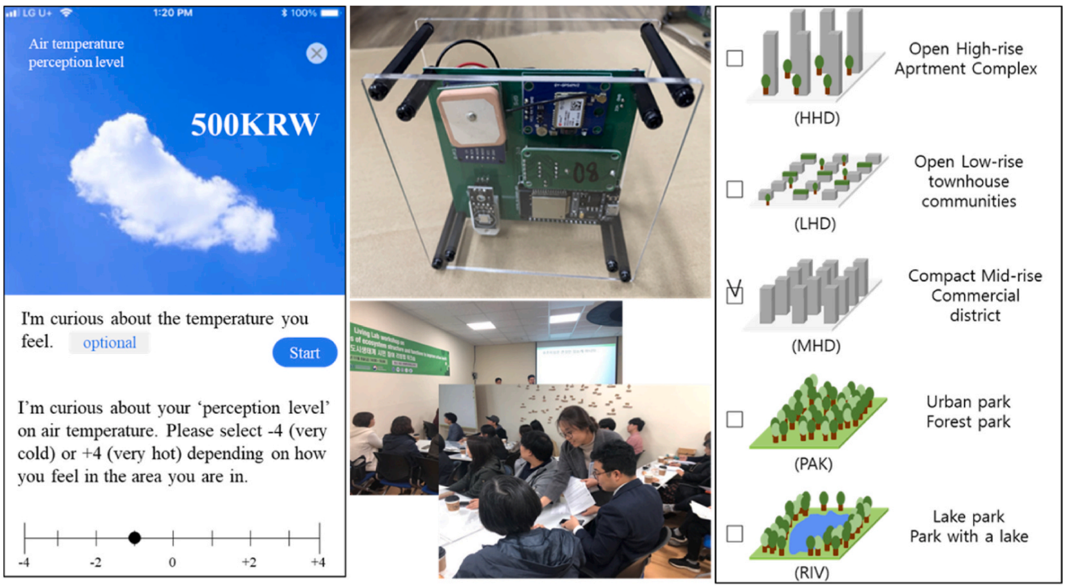


Fig. 2. Citizen data collection using the CADA app.

2.3. Temperature and thermal sensation vote data collection

Data collection was conducted over a three-year period (2021–2023), resulting in 908 entries in 2021, 338 entries in 2022, and 448 entries in 2023. Both objective and subjective data were gathered throughout the study. Temperature measurements were acquired using Arduino units equipped with temperature sensors, GPS modules, and a data storage card for logging the data (Table 1). Measurements were conducted at 2:00 p.m. and 9:00 p.m. every Saturday between July 1st and August 30th for all three years. Air temperature measurements were performed at chest height in unshaded outdoor areas within each spatial type to ensure uniform exposure to direct solar radiation and maintain consistency in the measurement conditions. In addition, citizens' TSV were captured using the CADA smartphone application [29], where the thermal sensation was recorded using the Thermal Sensation Vote (TSV) scale, a 9-point Likert scale defined by ISO 10551 (1995) for thermal comfort studies [30,31]. The TSV scale ranges from very cold (−4) to very hot (+4), with 0 representing a neutral or comfortable thermal state.

The CADA app was designed to allow citizens to easily record their TSV by selecting from predefined options based on their current sensations. When a user submits their response, the app automatically logs the time and GPS location to provide contextual data. The interface is intuitive, requiring minimal input, which encourages consistent participation. The app also includes a feature to ensure data accuracy by limiting submissions to once per hour and flagging potential duplicates. This method enabled collecting reliable, large-scale data on TSV across different urban areas. Finally, outliers were identified and removed using box plots to ensure data quality, with data points outside the whisker range considered anomalous (Table S1). Additionally, a kernel density plot (Fig. S1) was used to assess the distribution of air temperature measurements across different age groups, confirming that most readings clustered around 30 °C. This central tendency suggests that, despite slight variations, the citizen-collected data are consistent and reliable for further analysis.

2.4. Analysis of differences in TSV by spatial and age

Following the completion of the data collection process, the analysis workflow was structured as depicted in Fig. 3. The flowchart outlines the key steps in the data acquisition, measurement, and analytical procedures used in this study.

To investigate variations in outdoor TSV across different age groups and spatial types, data visualization was conducted using the R programming language, with the ggplot2 package. Smooth curves were generated to represent the relationships between atmospheric temperature, preferred comfort levels across age groups, and the various spatial types. These curves were created using the geom_smooth function, which applies the locally estimated scatterplot smoothing (LOESS) method to the thermal sensation data for each age group and spatial category. This visualization technique facilitated a clear understanding of how cognitive responses to atmospheric temperature vary by age, providing valuable insights into the impact of temperature on human comfort across diverse environments [32]. Additionally, to assess the severity of heatwaves, we analyzed differences in thermal sensation during periods when temperatures exceeded 33 °C compared to cooler periods.

3. Results

3.1. Comparison of TSV among spatial environments

This study examined the influence of temperature variations between five urban spatial types (HHD, LHD, MHD, PAK, and RIV) on TSV (Fig. 4). We focused on temperatures ranging from 24 °C to 34 °C. To analyze the distribution of the TSV across this range, we employed boxplots as a statistical tool. Data collected from URP and PKL at temperatures exceeding 34 °C were excluded owing to insufficient sample size (fewer than 20 observations).

Our analysis revealed variations in the influence of temperature increases on the TSV across the five spatial types. Within the 24 °C–28 °C range, RIV exhibited the lowest TSV (−2 to −1), indicating a cooler perception compared to other types (−1 to 0). At 30 °C, MHD areas had the lowest thermal sensation, while PAK had a relatively high perception of heat. Interestingly, above 32 °C, RIV demonstrated an increase in thermal perception, suggesting that areas with water features may provide some cooling effect compared with areas with less permeable surfaces. Additionally, at 30 °C, HHD areas had a higher perception of heat compared to LHD ones. However, this trend reversed at 32 °C, with LHD exhibiting higher levels than HHD areas, experiencing a greater increase in thermal perception. These findings highlight the complex interplay between the structural and environmental characteristics of each spatial type and their impacts on human thermal perception.

Table 1
Measurement equipment.

Category	Measure	Sensor	Unit	Accuracy
Air temperature	Temperature	DHT22	°C	±0.5
GPS	Location	NEO-6M	m	±2.5
Time attack	Time	DS3231	s	±0.3024
Data storage	Data communication	SD card	GB	8
Main board		PCB	cm	4 cm * 6

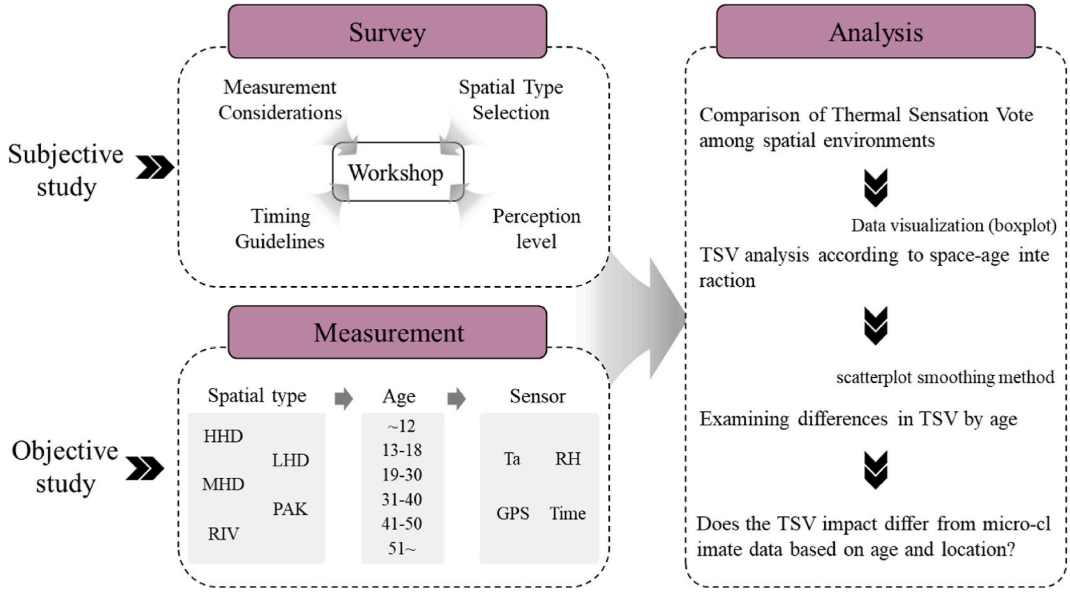


Fig. 3. Data collection and research analysis process.

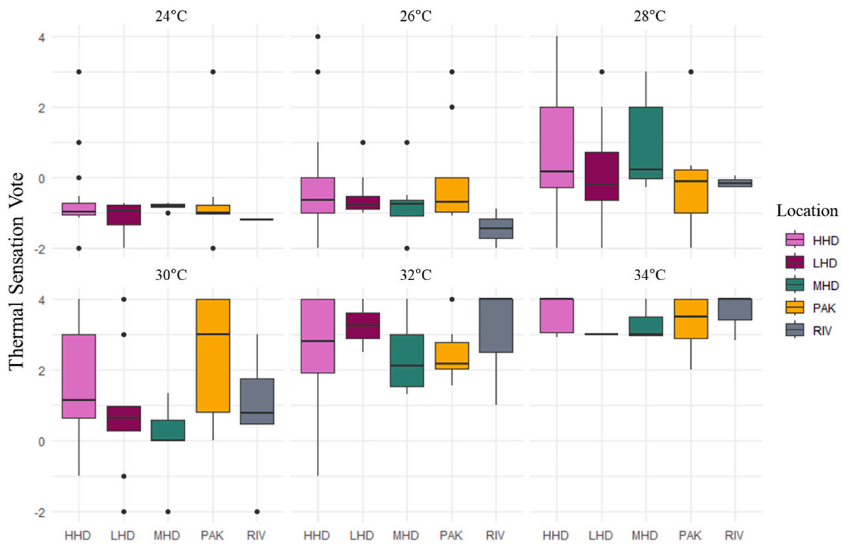


Fig. 4. Boxplots of TSV through space-age interaction analysis.

3.2. Analysis of perceived emotions according to space-age interaction

This study investigated variations in the TSV across different urban spaces throughout the day, focusing on age-related differences (Fig. 5). All age groups exhibited consistently high TSVs during the daytime. Notably, individuals aged 12–30 years demonstrated a more pronounced increase in TSV throughout both day and night compared to other age groups. These findings suggest potentially higher heat sensitivity among younger populations, whereas the decrease in TSV observed beyond the age of 30 years may indicate age-related changes in thermal perception.

For participants under 18 years of age, higher TSVs were observed in PAK and RIV, suggesting that natural environments may play a significant role in shaping thermal perceptions in younger age groups. Conversely, MHD exhibited high TSVs during the day, potentially owing to factors such as heat accumulation. However, the TSVs in these areas were relatively low at night, possibly owing to reduced heat retention or lower activity levels.

The 19–30-year age group consistently reported high TSVs across all times of the day, potentially reflecting their higher activity levels during this period of peak social and economic engagement. Individuals over 41 years of age exhibited higher TSVs during the day in areas with less permeable surfaces (HHD and LHD) than in areas with permeable surfaces (PAK and RIV). This difference may be

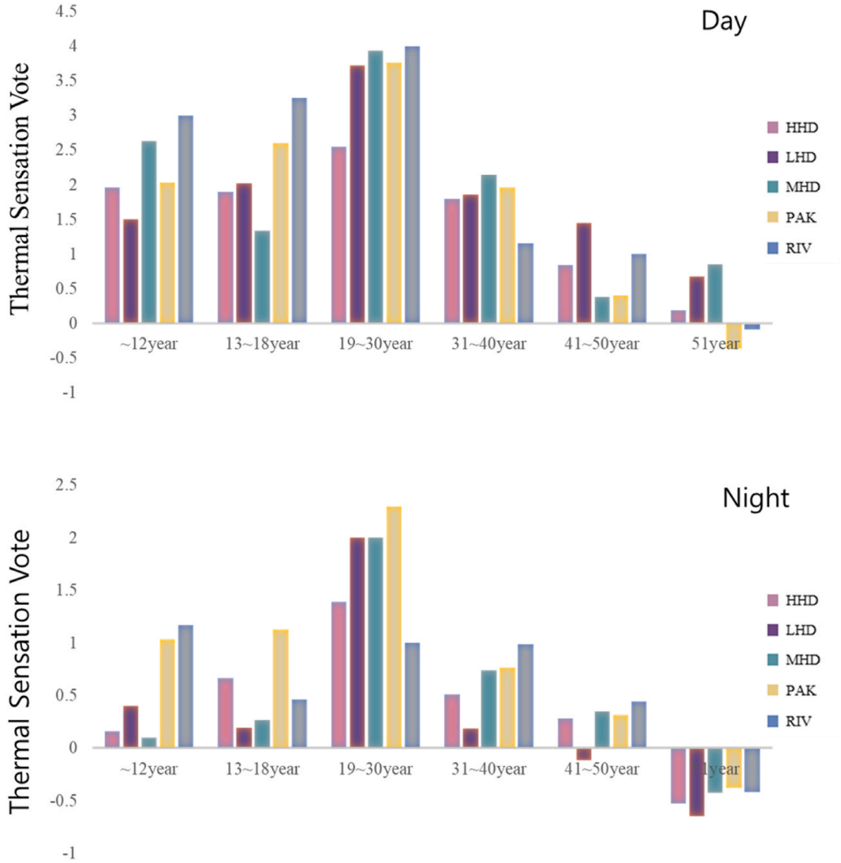


Fig. 5. Comparison of TSV by age group.

attributed to the increased heat absorption and retention properties of impermeable surfaces, potentially affecting thermal perception in this age group. Interestingly, participants over 51 years of age reported negative TSVs, suggesting a perception of coolness even at lower temperatures, or a generally lower sensitivity to heat.

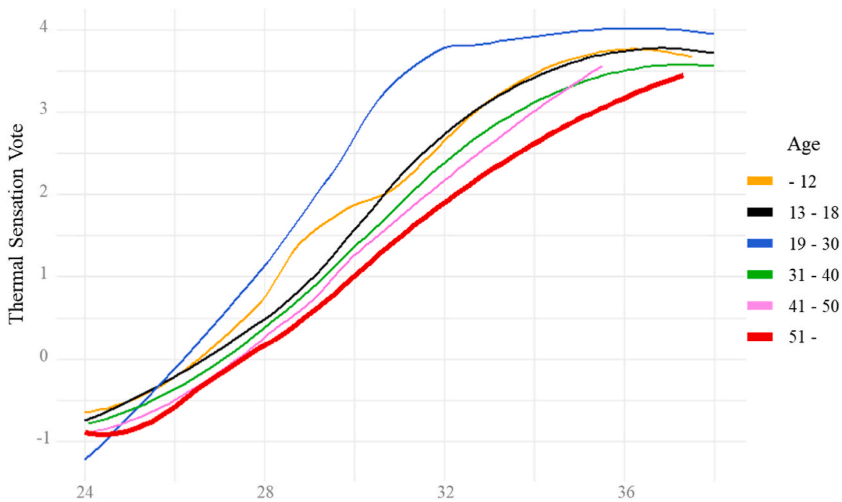


Fig. 6. Thermal sensation vote (TSV) across age groups based on air temperature.

3.3. Examining differences in TSV by age

This study investigated age-related variations in thermal perception. Participants were categorized into six age groups (up to 12 years, 13–18 years, 19–30 years, 31–40 years, 41–50 years, and over 51 years) to examine their sensitivity differences (Fig. 6). Overall, the average perception of temperature increased sharply above a baseline of 28 °C. Notably, individuals under 18 years (up to 12 and 13–18 years) exhibited a steeper rise in perceived temperature, starting at 26 °C. While all age groups reported the highest thermal perception at 36 °C, the 19–30-year-olds uniquely displayed a rapid convergence towards a "+4 (very hot)" perception as temperatures surpassed 32 °C. Considering a neutral (0) rating as the optimal thermal comfort range, individuals under 18 and those aged 19–30 years preferred a cooler temperature of 26.1 °C, while the over-41 group favored a slightly warmer temperature of 27.6 °C (approximately 1.5 °C higher).

The rate of change in perceived temperature across age groups was also analyzed (Table S2). This analysis revealed a decreasing trend in sensitivity with increasing age. The 19-30- year-olds exhibited the fastest rate of change in perceived temperature, followed by individuals under 18 years (the up to 12 and 13–18 years old groups). The rate of change progressively slowed down in the 31–40, 41–50, and over 51 age groups, with the slowest rate observed in the over-51 group. For example, at 34 °C, all other age groups reported a perceived temperature of at least 3.4, whereas the over-51 group perceived the temperature as cooler (TSV: 2.5). This finding is congruent with previous research suggesting a diminished perception of heatwave intensity among older adults.

4. Discussion

4.1. Review of spatial experience analysis through interviews

Consistent with existing research, this study confirms that the physical characteristics of urban spaces significantly influence thermal perception. Impermeable areas, such as HHD, experience greater thermal stress owing to the urban heat island effect [33,34]. This aligns with our findings of high TSV in HHD areas. Conversely, spaces with high permeability, such as PAK and RIV, effectively dissipate heat and offer cooling benefits, resulting in a lower TSV [35,36]. However, the interview data suggest that even in PAK and RIV, temperatures exceeding 30 °C were perceived as very hot. This can be attributed to several factors such as direct sunlight exposure, high humidity, and variations in wind speed and activity levels.

1. Impact of direct sunlight: Open spaces in RIV areas may expose individuals to more direct sunlight, making them feel hotter despite the actual air temperatures being lower.
2. Humidity effects: The presence of water in RIVs can increase relative humidity, reducing sweat evaporation, and increasing perceived temperature.
3. Wind speed differences: Parks with dense trees may have impeded airflow, leading to heat accumulation and increased perceived temperatures.

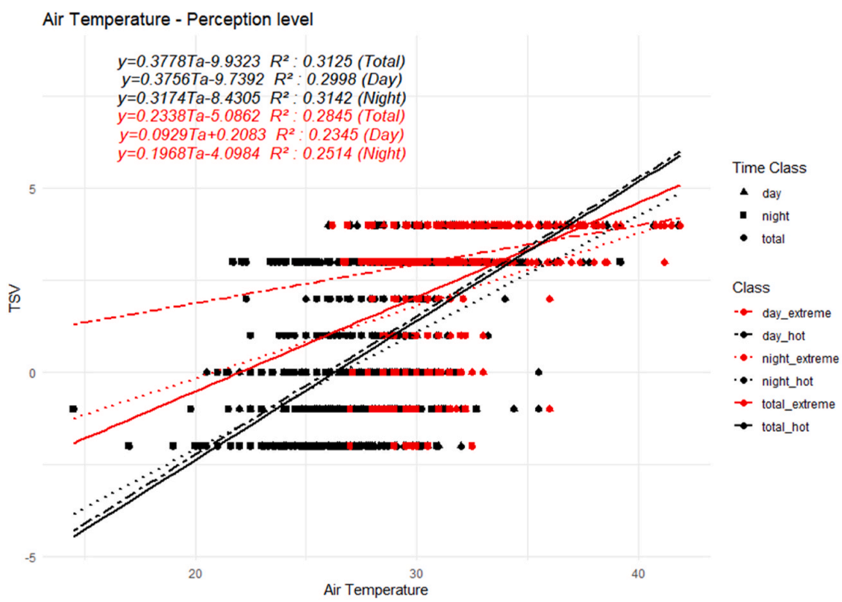


Fig. 7. Analysis of perceived differences between extreme heat days and regular days.

4. Activity levels: PAKs and RIVs often host outdoor activities, such as walking, jogging, and other sports, which can raise body temperature and enhance the sensation of heat. Additionally, the discrepancy between the expectation of a cooler natural environment and the actual perception contributes to a higher perceived temperature [37].

This study suggests a link between age and thermal perception sensitivity. The higher TSV observed in younger individuals (particularly those aged 19–30 years) might be attributed to their active lifestyles and frequent outdoor activities during the day (work, school, and social events). Nighttime TSV may also remain elevated in this age group owing to continued social activities. Contrastingly, middle-aged individuals exhibited a higher TSV within impermeable areas during the day, possibly reflecting the influence of workplace environments on thermal perception.

Building on prior research on age-related variations in physiological and psychological adaptations to thermal conditions, this study observed a decrease in the rate of perceived temperature change and lower sensitivity to heat waves among older adults (over 51 years of age) [38,39]. This finding is congruent with previous literature demonstrating that thermal acceptance increases with age and that older populations exhibit lower sensitivity to temperature fluctuations [40–42]. While the interviews suggest that younger generations spend more time indoors owing to technology use, they may still report a higher thermal sensitivity. This could be attributed to experiencing more extreme heat events or a heightened awareness of heat. Conversely, the lower TSV observed in older adults might be owing to an increased adaptability to heat or a behavioral tendency to avoid hot environments during daily activities.

4.2. Improved ability to adapt to heat during heatwaves

This study investigated the variations in thermal discomfort perception across different heatwave risk levels (Fig. 7). Daily maximum temperatures exceeding the South Korean heatwave threshold of 33 °C were classified as "extreme heat" days, whereas temperatures below that threshold were categorized as "hot" days. Data visualization employed long dashes for daytime, short dashes for nighttime, and solid lines for the combined data. Red indicated extreme heat days and black represented typical days. Consistent with prior research, the neutral thermal sensation vote (TSV = 0) on typical days was found to be 26.3 °C [43–45]. Interestingly, discomfort owing to perceived heat begins at lower temperatures on extreme heat days than on hot days. Notably, at 35 °C, participants reported higher discomfort on hot days compared to extreme heat days. This suggests that psychological factors or heat adaptation mechanisms may influence perceived discomfort levels.

On days with heatwave warnings, people may adopt proactive responses or experience heightened heat awareness, potentially leading to a logarithmic increase in discomfort owing to rising temperatures. This pattern aligns with the daytime discomfort perception on extreme heat days, exhibiting the most gradual rise with temperature ($y = 0.0929Ta + 0.2083$), indicating a less pronounced increase in discomfort compared with hot days.

4.3. Differences between quantitative and qualitative evaluations by spatial area

This study investigated outdoor thermal comfort in South Korean urban spaces characterized by a temperate climate. Our findings both align with and diverge from previous domestic and international studies. Consistent with existing literature, the neutral temperature in open spaces like parks fell within the 22°C-28 °C range typically reported as comfortable for urban residents.

A key finding was the significant discrepancy between objectively measured temperatures and citizen-perceived thermal comfort in the HHD and RIV areas. In HHD areas, although recorded temperatures were high, participants reported feeling cooler due to the reduced radiative heat emitted from building surfaces shaded by the high-rise structures [46]. The shadow area by these high-rise buildings lowered surface temperatures and diminished heat release from building facades, which likely contributed to a reduced thermal perception compared to open-space areas. This reduction in surface heat, combined with potential airflow through wind corridors, created a more comfortable thermal environment for individuals in these urban spaces [47]. Conversely, citizen-reported thermal discomfort in the RIV areas exceeded the measured temperatures, likely owing to factors such as increased humidity and sunlight reflection from water surfaces amplifying the perceived heat [48,49].

This study revealed a novel finding: younger individuals reported higher thermal discomfort in lake parks than older adults. This contrasts with existing research that suggests higher heat sensitivity in older populations. One potential explanation is that younger individuals with higher metabolic rates and activity levels may be more susceptible to the combined effects of high humidity and direct sunlight, which are prevalent in the RIV areas.

Supporting this notion, Zhang et al. [50] reported that under certain climatic conditions (e.g., humidity and wind), young adults experience greater discomfort than older adults in urban areas. This aligns with the possibility that younger individuals may experience greater thermal perception under specific conditions owing to their higher metabolic rates and active lifestyles. These findings underscore the importance of age-sensitive planning in the development of heatwave response strategies. Furthermore, our study assessed thermal comfort across various urban space types by integrating both scientific and citizen-reported data. Similar to previous research, we observed elevated thermal stress in multi-use spaces, such as commercial areas, probably owing to high population density and artificial heat sources [51,52]. However, the citizen science approach revealed that the perceived thermal stress in these areas could be higher than scientific measurements, particularly among younger individuals at night.

4.4. Avoiding maladaptation planning using citizen science

The integration of citizen science data in this study provides valuable insights for the development of climate change adaptation plans. These findings highlight the importance of considering user demographics when designing adaptive strategies for urban environments [53]. For example, enhancing access to water for younger individuals during heatwaves, installing temporary shade structures during peak usage times, and incorporating cooling benches can improve comfort for park users. Based on the findings of this study, incorporating user age and spatial context into the design and placement of climate adaptation facilities could significantly enhance their effectiveness.

Our results showed that younger individuals reported feeling hotter in high-density urban areas (HHD, LHD, MHD) at night. This highlights the need to reevaluate nighttime heatwave response strategies. Potential solutions include installing cooling facilities in public spaces for nighttime use, expanding access to green spaces during nighttime hours, and implementing measures to mitigate heat during nighttime events. By incorporating spatial and temporal variations in thermal perception, such as the heightened nighttime discomfort reported by younger individuals in dense urban areas, climate adaptation strategies can be made more flexible and diversified [54,55]. This may involve adjusting the operating hours of heat-reduction facilities or revising building heating and cooling policies.

4.5. Limitations of the study

While this study provides valuable insights into thermal perception across various age groups and spatial environments, several limitations should be acknowledged. First, the dataset primarily consisted of citizen-collected data, which, despite efforts to standardize and ensure accuracy through workshops and training, may still contain biases or inconsistencies. Specific personal attributes such as occupation, exact age, residence, and gender were not collected, limiting our ability to examine more detailed demographic factors. Additionally, data collection was restricted to specific times and days (Saturdays at 2:00 p.m. and 9:00 p.m.), which may not capture the full range of thermal perceptions across different times and conditions. The study was also limited by the exclusion of certain contextual factors, such as the influence of wind, humidity, and activity levels, which could affect thermal sensation but were not directly measured. While the data showed a strong central tendency around 30 °C, slight variations between age groups were observed, which could be attributed to differences in measurement times and locations. These limitations highlight the need for further studies that incorporate more detailed demographic and environmental data to enhance the generalizability of the findings.

Despite its limitations, this study makes a meaningful contribution to the understanding of thermal perception across different age groups and spatial environments. The utilization of citizen science enabled the collection of a large-scale dataset while actively engaging local communities in climate research. By incorporating spatial and demographic diversity into the analysis of thermal comfort, this study offers valuable insights that can inform the development of more tailored and adaptable urban planning strategies. Furthermore, the findings highlight the potential of citizen-driven data collection to address critical gaps in urban climate research, particularly in areas where formal monitoring systems may be insufficient. By presenting a more inclusive and participatory model for climate adaptation, this research provides a solid foundation for future studies and policy interventions aimed at enhancing urban resilience to heatwaves.

5. Conclusion

This study examined the increasing impact of heatwaves on the health of urban residents in the context of climate change and rapid urbanization, employing Suwon City as a case study. We investigated TSV across diverse spatial types and age groups to enhance understanding of effective policy responses to heatwaves and the valuable role of citizen science.

The results revealed that citizen science can significantly enhance data collection by involving local residents, offering more detailed insights into urban heat exposure. Specifically, this study found that natural environments, particularly lake parks, were areas where thermal discomfort was most pronounced. This indicates that although these spaces may offer cooling effects under temperature conditions, they can intensify discomfort during extreme heat events.

A marked difference in heat sensitivity was observed across age groups, with younger individuals, particularly those aged 19–30, reporting significantly higher levels of thermal discomfort than older participants. This highlights the need for age-sensitive urban planning that can effectively address different demographic groups' specific heat adaptation needs. Furthermore, the study emphasized the limitations of traditional top-down heatwave response strategies, which often fail to account for local variations in heat perception, both spatially and demographically. By contrast, the citizen science approach proved valuable for informing more tailored and proactive urban heat adaptation strategies.

In conclusion, this study underscores the critical role of citizen science in addressing climate change challenges such as heatwaves. It proposes a novel paradigm incorporating citizen perspectives into scientific research and policy formulation, paving the way for contributions to sustainable urban development and healthier communities. Future research should expand citizen participation studies to encompass a wider range of geographic areas and environmental conditions, ultimately leading to more effective heatwave response strategies.

CRediT authorship contribution statement

Eun Sub Kim: Writing – original draft, Data curation, Conceptualization. **Chaeyoung Bae:** Writing – review & editing, Methodology. **Se Yean Ko:** Writing – review & editing, Methodology, Conceptualization. **Ji Eun Won:** Investigation. **Jae Hong Lee:** Writing – review & editing. **Yong Paio:** Writing – review & editing. **Dong Kun Lee:** Writing – review & editing, Supervision, Project administration, Funding acquisition.

Data availability

Data will be made available upon reasonable request.

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.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.heliyon.2024.e39413.

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