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Hot stops, cool looks: Aesthetic solutions for thermal comfort at transit stops

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ABSTRACT

Increased urban heat intensifies thermal discomfort, particularly in critical public spaces such as transit stops. This study investigated the predictors of transit users' thermal perceptions in Denver, Colorado—a semi-arid city. Sixty bus stops spanning a gradient of land cover compositions were selected for study. Micrometeorological data, including thermal comfort indices, were collected alongside survey responses from 77 users at 31 unique stops. Survey responses captured thermal sensation votes (TSV) and thermal comfort votes (TCV) as well as aesthetic preference votes (APV) of bus stop structure. Ordinal forest analysis revealed that for both TSV and TCV, aesthetic preferences and thermal comfort indices were the most influential predictors of transit user thermal perception. Multiple ordered logistic regression further demonstrated that, for TSV, higher APV was associated with lower odds of rating a thermal environment as hot (OR = 0.664, $p < 0.002$) while increased Physiological Equivalent Temperature (PET) raised these odds (OR = 1.101, $p < 0.006$). An interaction analysis demonstrated that APV significantly moderated the effect of PET on TCV (interaction OR = 1.040, $p < 0.041$), suggesting that aesthetic preferences are significantly correlated with an alleviation of thermal discomfort under high heat stress. Bivariate analyses further indicated that bus stops with greater tree canopy cover (OR = 1.032, $p < 0.025$) and higher visible vegetation view factors (OR = 10.350, $p < 0.022$) were more likely to be rated as aesthetically pleasing. These findings underscore the importance of aesthetic preferences in transit stop planning for urban heat resiliency.

Abbreviations: APV, Aesthetic Preference Vote; BSID, Bus Stop ID; BVF, Building View Factor; CI, Confidence Interval; DRCOG, Denver Regional Council of Governments; PET, Physiological Equivalent Temperature; RPS, Ranked Probability Score; RTD, Regional Transportation District of Denver; SVF, Sky View Factor; T_{Air}, Air Temperature; TCV, Thermal Comfort Vote; T_{Globe}, Globe Temperature; T_{MRT}, Mean Radiant Temperature; TSV, Thermal Sensation Vote; UTCI, Universal Thermal Climate Index; Va, Wind Velocity VVF: Vegetation View Factor; WBGT, Wet Bulb Globe Temperature.

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1. Introduction & background

1.1. Urban heat and transit user thermal comfort

Increased urban heat is often a function of dynamic spatial and social heterogeneity of urban ecosystems (Mokhtari et al., 2022; Pickett et al., 2017), whereby human activity, land cover, and radiant heat fluxes interact to drive thermal dynamics (Akbari et al., 2001; Ibsen et al., 2022; Lu et al., 2020; Ogashawara and Bastos, 2012). The effects of urban heat intensify during extreme heat events, compounding heat stress and leading to higher rates of weather-related mortality (Li and Bou-Zeid, 2013). Furthermore, disproportionate exposure to increased urban heat leads to worse health outcomes for low-income communities and communities of color in most major U.S. cities (Hsu et al., 2021). As cities grapple with rising temperatures, the design and function of urban infrastructure—particularly public transit—play a crucial role in shaping how individuals experience and adapt to heat exposure (Turner et al., 2022).

Public transit systems are widely touted for enhancing mobility and reducing greenhouse gas emissions, congestion, and air pollution (Anderson, 2014; Beaudoin et al., 2015; Giuliano, 2005; Hodges, 2010), making transit use a key strategy in sustainability, urban planning, and public health initiatives (Nieuwenhuijsen and Khreis, 2016). However, public transit use in urban heat contexts may increase exposure to heat, exacerbating thermal stress and associated health risks for users, especially those without alternative transportation options (Fraser and Chester, 2017; Karner et al., 2015). Transit agencies are now increasingly interested in integrating heat resilience and thermal comfort into transit stop design (Keith and Meerow, 2022). Increased access to shade is often promoted as a way to mitigate pedestrian heat exposure (Middel et al., 2016), but the effectiveness of different types of shade on thermal comfort can often vary (Middel et al., 2021).

Incorporating shade through bus shelters can improve the thermal comfort of transit users in certain climatic contexts, however this depends on their materials and design, with aesthetically pleasing bus stops being perceived as cooler (Dzyuban et al., 2022b). This is further demonstrated in the case of "La Sombrita", a recent pilot program that cast built structural shade at bus stops in Los Angeles. This particular initiative sparked debate regarding the design and effectiveness of this intervention, further highlighting the social and aesthetic dimensions of bus stops (Jiménez and Albeck-Ripka, 2023; Miranda, 2023). Furthermore, bus shelters alone are often not effective at mitigating thermal discomfort (Pan et al., 2024), with trees and vegetation outperforming shade structures in reducing heat stress for transit users (Lanza et al., 2025). Lastly, extreme heat events typically reduce public transit use—even when built shade structures are available—suggesting that only the most transit-dependent individuals continue riding (Jain and Singh, 2021); however, stops with greater tree canopy cover experience a less pronounced decline in ridership (Lanza and Durand, 2021).

Therefore, designing bus stops that are thermally comfortable remains a critical task for many cities, with shade infrastructure from vegetation and built structures sometimes displaying dynamic and synergistic effects (Gai et al., 2025). However, defining thermal comfort for transit users is complex. According to the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE, 1992), thermal comfort is 'the condition of the mind that expresses satisfaction with the thermal environment.' It is often quantified through modeling, using biometric and meteorological data to calculate thermal comfort indices such as the Physiological Equivalent Temperature (PET) (Höppe, 1999) and the Universal Thermal Climate Index (UTCI) (Błażejczyk et al., 2013). Under UTCI, heat stress is typically defined as temperatures above 26 °C, and cold stress as below 9.1 °C, while for PET, thermal comfort is defined between 18.1 °C to 23.0 °C (Basarin et al., 2020). However, to add further complexity to this issue, personal factors such as an individual's biological base, level of physical activity, clothing insulation, exposure time, and preferences also influence the human response to the thermal environment, with these psychological and physical attributes forming the basis for subjective thermal perception (Knez et al., 2009; Lenzholzer and de Vries, 2020). These thermal perceptions vary significantly between cities, even when the type of outdoor space and environmental conditions are held close to constant (Knez and Thorsson, 2006, 2008).

Additionally, thermal perceptions intersect with other environmental perceptions, particularly visual perception (Mayes et al., 2023) and the aesthetic qualities of outdoor spaces (Du et al., 2023; Lau and Choi, 2021), thus further illustrating the complexity of outdoor thermal perception. When subjective responses are coupled with in-situ micrometeorological measurements, aesthetic perceptions are sometimes more influential in predicting thermal perceptions than the conditions of the thermal environment (Wang et al., 2017), and are more strongly associated with thermal comfort in summer seasons rather than in winter or the other transitional seasons (Chen et al., 2022). Environmental perceptions can also reveal distinct aesthetic preferences in their relation to outdoor thermal comfort, though this relationship is not causal. Color composition of the built environment has an effect on thermal perception in indoor settings (Wang et al., 2018), and in outdoor settings such as public squares, surface materials can be perceived as cold if they are blue or made of glass, while bricks and red colors are often perceived as warmer (Lenzholzer and van der Wulp, 2010). Dense, green vegetation is often associated with thermal comfort (Klemm et al., 2015; Louafi et al., 2017), though this effect is sometimes displays seasonal differences (Zhang et al., 2022). Moreover, the positive aesthetic perception of outdoor spaces is strongly correlated with the amount of vegetation (Xie et al., 2024), which can lead to emotional wellbeing (Aghabozorgi et al., 2025; Wang et al., 2019). Both these environmental perceptions of landscapes and emotional responses therein are recognized as contributing factors to thermal comfort (Yan et al., 2023).

Therefore, there is a clear need for spatial components, micrometeorological measurements, and physiological conditions to be paired with psychological assessments of the thermal environment and its associated aesthetic qualities for a wholistic understanding of urban heat impacts and its implications for outdoor thermal comfort (Du et al., 2023; Dzyuban et al., 2022a; Klemm et al., 2015; Kuras et al., 2017; Lau and Choi, 2021; Lenzholzer and de Vries, 2020). In addition, much like the differing effects of shade on reducing transit user heat stress, context matters when understanding subjective thermal perceptions. These perceptions vary not only between individuals, but also across different cities and outdoor environments (Aghamolaei et al., 2023), making it critical to examine thermal comfort solutions within the specific climatic and land use conditions in which they are situated.

In this study, we focus on Denver, Colorado—a semi-arid city. Within this context, bus stops, being heterogenous in structure, present a unique opportunity for exploring urban heat's thermal dynamics, transit user experience, and potential landscape interventions for heat mitigation and improved rider comfort. As increased urban heat continues to affect transit users and planners alike, a thorough analysis of the predictors of subjective transit user thermal perception is crucial for informing the development of thermally comfortable transit stops.

1.2. Research objectives, questions, and hypotheses

We aim to investigate the complex factors that shape transit users' thermal perceptions to inform thermally comfortable bus stop design in a semi-arid system. Specifically, our objectives are to (1) identify the main predictors of transit users' thermal perceptions in the Denver metropolitan area, (2) assess whether Denver's transit users' aesthetic preferences moderate the relationship between modeled thermal comfort indices and their thermal perceptions, and (3) determine which urban structural variables best predict the aesthetic preferences of Denver's transit users.

To achieve these objectives, we ask the following three questions. (1) Which factors—among urban structure, thermal dynamics, thermal comfort indices, personal factors, and aesthetic preferences—most strongly predict transit users' thermal perceptions? (2) When temperatures are high, are transit users more likely to indicate that they feel thermally comfortable and/or cooler at bus stops that they find aesthetically pleasant? (3) What elements of bus stop structure are associated with higher aesthetic ratings among transit users?

Building on prior studies highlighting the significant influence of urban structure—such as the various shade interventions that reduce bus stop temperatures and shape thermal dynamics—we hypothesize that urban structure will be the strongest predictor of thermal perceptions. Additionally, we expect that aesthetically pleasing bus stops will moderate thermal discomfort, and that bus stops with more green infrastructure will be rated as more aesthetically pleasing by the users of Denver's semi-arid transit system.

2. Methods

2.1. Methodological overview

The study took place within the Denver Front Range region of Colorado, USA. Denver is a semi-arid city (Köppen Climate Classification: BSk) located at about 1600 m above sea level. The Regional Transportation District of Denver (RTD) serves a population of approximately 3.08 million residents, with over 41 million bus boardings in 2023 (RTD, 2024). A flowchart outlines the methodology for this study (Fig. 1). The following subsections will further detail these processes.

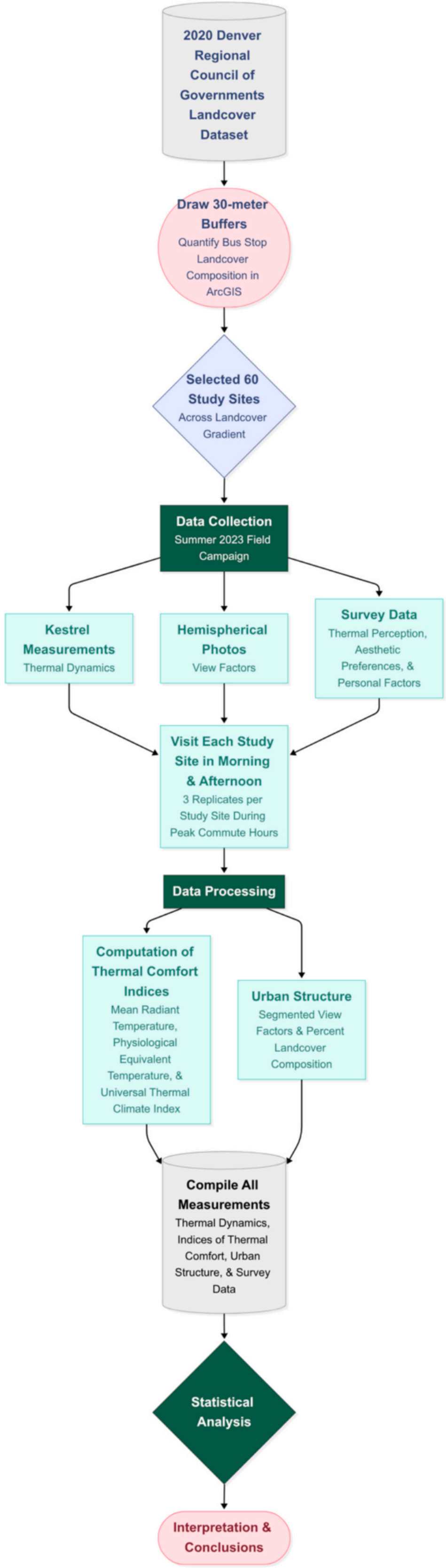
2.2. Study site selection and initial urban structure quantification

To understand urban heat and its effects on the perceptions of transit users, study sites were selected across a gradient of land cover compositions among bus stops above mean daily ridership. To examine the biophysical processes underpinning thermal and environmental perception, 30-m buffers were drawn around each bus stop to estimate the transit users' experience of urban structure while waiting for the bus. 30-m buffers were chosen to represent Satellite Derived-Land Surface Temperature (SD-LST) variation from the image resolution of the Landsat 8 satellite; the Landsat program forming the largest contribution to science out of all Earth orbital programs (Wulder et al., 2022). From these buffers, 60 study bus stops were selected across a gradient of land cover composition from the 2020 one-square-meter land cover data set from the Denver Regional Council of Governments (DRCOG) (Fig. 2). Variables from these data were percentages of land cover composition around a 30-m buffer at each bus stop, calculated via the Tabulate Area tool in ArcGIS Pro. These tabulations included the compositional percentages of vegetation (%Veg), impervious surfaces (%Imper), buildings (%Bldg), and tree canopy cover (%Tree). Sites ranged from Denver's downtown core to its surrounding suburbs (Fig. 2).

2.3. Field data collection overview

All field measurements were taken over an extensive summer field campaign, a five-week period from July and August of 2023, months that are historically the hottest in Denver. Inspired by Middel and Krayenhoff (2019) and Dzyuban et al. (2022b), these field measurements took place at the select study sites and consisted of three components: (1) upper-hemispherical photos that further quantified bus stop structure, (2) thermal micrometeorological sensors that recorded the thermal dynamics of the bus stop, and (3) a survey that was administered to willing transit users, documenting thermal perceptions, aesthetic preferences, and personal factors (Fig. 3).

Each bus stop was surveyed six times (three mornings, three afternoons) during peak commute hours (07:30–10:30; 14:00–18:00). Measurements were collected concurrently, except for the upper-hemispherical photo, which was taken once for the 2023 season. That summer, Denver experienced below-average temperatures with no extreme heat events (Appendix B, Fig. 1). Data collection was suspended during occasional afternoon rain to avoid confounding results.



(caption on next page)

Fig. 1. Flowchart of methods. The starting and ending points are depicted as rose ovals, major processes are depicted as forest green rectangles, subprocesses are depicted as aqua rectangles, decisions are depicted as light blue diamonds, and data are depicted as gray cylinders. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

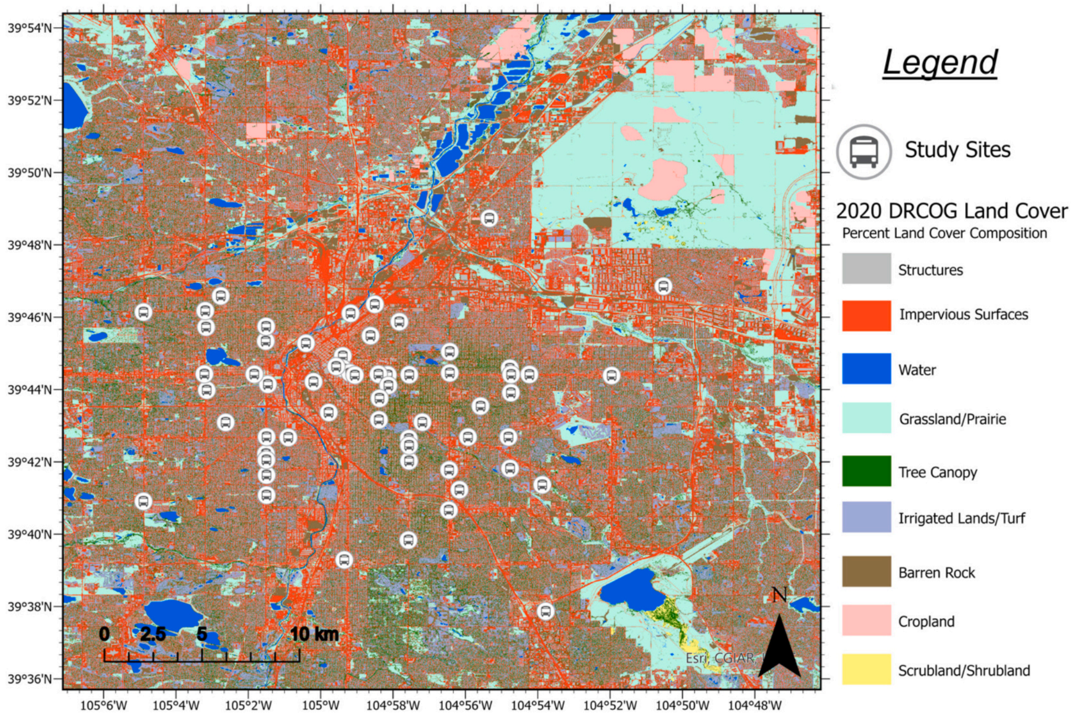


Fig. 2. 60 bus stops in the Denver metropolitan area were chosen as study sites across a gradient of one-meter-squared land cover composition.

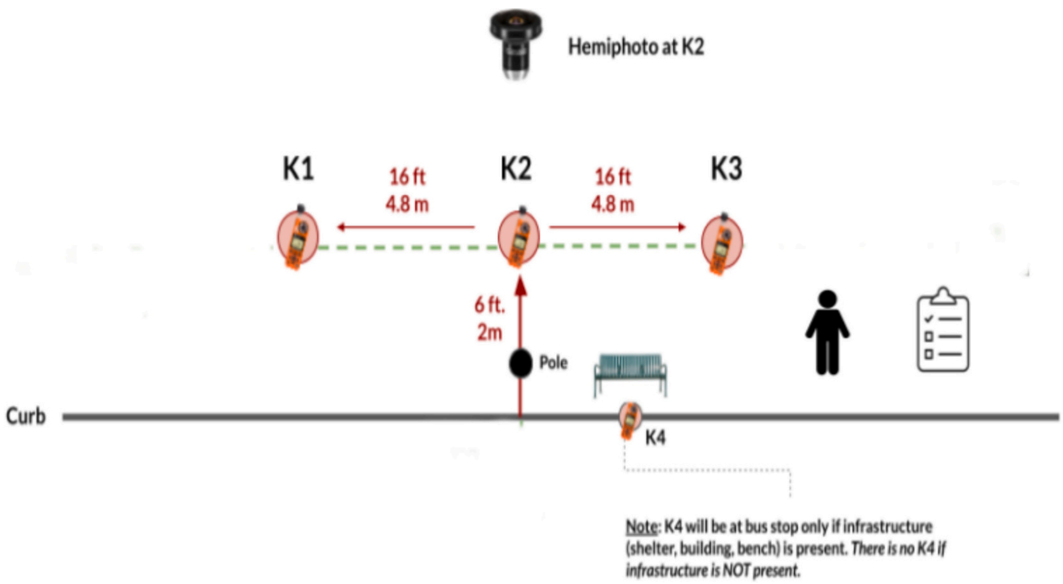


Fig. 3. Sampling method for the summer field campaign. Sensor placement and spacing is depicted, along with icons symbolizing survey data collection.

2.4. Thermal dynamic measurements

Thermal dynamic data were recorded to account for the micrometeorological variation at each bus stop. Measurements were taken with a Kestrel® 5400 Globe Thermometer, and included air temperature (T_{Air}), wind speed (V_a), relative humidity (RelHum), and Wet Bulb Globe Temperature (WBGT). Three sensors were positioned 4.8 m apart on tripods at 1.1 m above ground level at each site, following a similar methods designed by Dzyuban et al. (2022b). Bus stops that had amenities, i.e. a shelter or bench, were given an additional sensor that was placed inside or next to the amenity (Fig. 3). Sensors were set up to acclimate for five minutes prior to recording. Sensors recorded for two minutes, with their measurements averaged.

2.5. Further urban structure quantification: View factors

To further quantify urban structure at bus stops, upper-hemispherical photos were taken from the center point at each bus stop using a Nikon CoolPix™ 4500 camera with a mounted fish-eye lens. Using modified methods derived from Steyn (1980) and Middel and Krayenhoff (2019), these photographs were then segmented into three classes, and pixels counted for the following ratios: 180 degree visible Sky View Factor (SVF), Building View Factor (BVF), and Vegetation View Factor (VVF). This approach quantified the amount and type of obstruction at the center point within each study site (Fig. 4). A complete table of these urban structure quantification metrics, including land cover composition, can be found in the supplemental data section (Appendix B).

2.6. Survey design & implementation

A survey was designed and implemented to document the subjective thermal and environmental perceptions of transit users. Coinciding with the thermal dynamic measurements, the survey was administered to transit users who were waiting at the bus stop during the summer field campaign. Selection criteria for participants included adults aged 18 and over, who were using public transit at the time of administration, and who had not participated in the survey prior. Participants who had not been exposed to the outdoor thermal environment for at least 15 min were excluded from selection to meet ASHRAE (1992) standards and to reduce the confounding effects of thermal alliesthesia, the phenomenon in which sudden changes in the thermal environment result in rapid hedonic shifts in thermal perception (Dzyuban et al., 2022c). Once participants were selected, they self-administered the survey by either scanning a QR code or participating with pen and paper. Participants were asked to complete the survey as soon as possible. Participants who submitted in excess of 30 min were excluded from analysis. The survey took an average of ten minutes to complete.

Participants were asked to rate their thermal and aesthetic perception of the bus stop and its associated field of view. For thermal perception, participants were asked to rate the thermal environment along an ordinal seven-point scale. Two such scales were used and inspired from Dzyuban et al. (2022a): a descriptive scale assessing the Thermal Sensation Vote (TSV) ranging from Very Cold (1) to Very Hot (7), and an affective scale assessing the Thermal Comfort Vote (TCV) ranging from Very Uncomfortable (1) to Very Comfortable (7). For aesthetic perception, participants were asked to visually assess the aesthetics of the bus stop and its associated area along an ordinal seven-point scale ranging from Very Unpleasant (1) to Very Pleasant (7), a descriptive scale resulting in the Aesthetic Preference Vote (APV). Participants were also asked to describe what clothes they were wearing, and their level of physical exertion before arriving at the bus stop. Optional questions included biometrics: gender, age, height, and weight, and sociodemographic data such as mean annual household income, and racial identity. The time at which the survey was completed was recorded, and participants were further categorized by the time they took the survey, either in the morning (AM) or in the afternoon (PM). A full list of survey questions can be found in Appendix A. Ethics for research conducted with human participants were reviewed and approved by the University of British Columbia's Behavioral Research Ethics Board under study ID H23–01399.

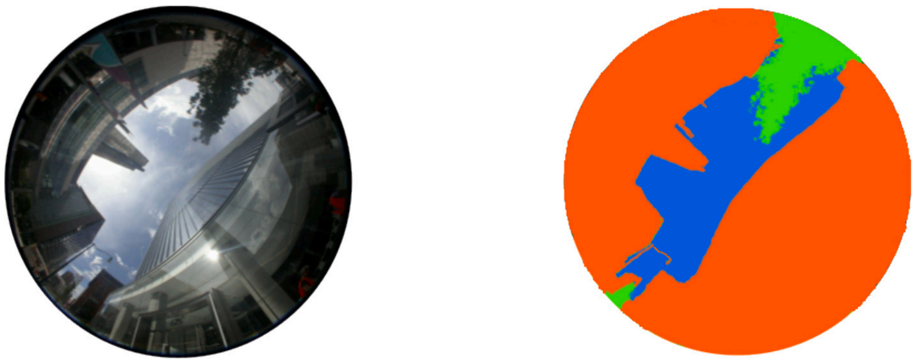


Fig. 4. Example of an upper hemispherical photo (left) and its corresponding classification into view factors (right). Colors of the photo on the right correspond to the following view factors: visible SVF (blue), visible VVF (green), and visible BVF (red). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

2.7. Calculation of mean radiant temperature and thermal comfort indices

Mean Radiant Temperature (T_{MRT}), an important metric for human thermal comfort and heat stress, was calculated using a modified method from the ISO black globe thermometer equation (Ouyang et al., 2022). This modified method is specifically calibrated for the Kestrel sensor and has the following equation:

$$T_{\mathrm{MRT}} = \left((T_{\mathrm{Globe}} + 273.15)^4 + \frac{(0.678 \times 10^8 \cdot V_a^{0.019})}{(0.95 \cdot 150^{0.4})} \cdot (T_{\mathrm{Globe}} - T_{\mathrm{Air}}) \right)^{0.25} - 273.15$$

where T_{Globe} and T_{Air} are the globe temperature and air temperature in Celsius, respectively, and v_a is the wind velocity in meters per second. The thermal comfort index Physiological Equivalent Temperature (PET) was calculated using RayMan Pro (Matzarakis et al., 2007, 2010), and another thermal comfort index, the Universal Thermal Climate Index (UTCI) was calculated using the R package 'comf' (Schweiker et al., 2024). Wet Bulb Globe Temperature (WBGT) was computed via the Kestrel sensors.

2.8. Statistical analysis

To identify significant main predictors of TCV and TSV along transit corridors in Denver, two ordinal forest models were generated using the 'ordinalForest' package in R (Hornung, 2022). The ordinal forest proposed by Hornung (2020) is a modification of the random forest predictive method. Like a traditional random forest, an ordinal forest model ranks predictors by their variable importance but is better suited for ordinal response variables. Variable importance is measured by a Ranked Probability Score (RPS). Independent predictors for both models were classified into the following five subcategories: (1) urban structure, representing the percentage of one-meter-squared land cover composition, classified view factor (SVF, VVF, BVF), and the presence of a bus stop shelter; (2) thermal dynamics, representing micrometeorological measurements (T_{Air}, RelHum, V_a); (3) indices of thermal comfort, which include computed metrics associated with human thermal stress and discomfort (T_{MRT}, PET, UTCI, WBGT); (4) aesthetic preferences, which capture how aesthetically pleasing transit users rated a stop (APV); and finally, (5) personal factors, including exposure time (Exposure), level of physical activity (Activity), time of survey completion (AM/PM), and clothing insulation, quantified via the clo metric, a unit of measure that describes the amount of thermal insulation provided by clothing on a human body.

All variables of urban structure, thermal dynamics, thermal comfort indices, personal factors, and aesthetic preference were put into the ordinal forest models to find the influential predictors of TCV and TSV. APV was transformed into an interval variable, while TCV and TSV retained their ordinal structure. This approach was taken for general congruence with other interval predictors, and since the survey question for APV assigned numbers next to each response option, it could be assumed to be an interval variable (Harpe, 2015). Features were scaled as a percentage, where the associated RPS value for each predictor from the output was converted to a percentage value to visualize variable importance. From these percentages, a cutoff threshold of 5 % was established, and variables below this threshold were discarded from model building and predictor selection.

After ranking the predictors by their variable importance, a series of multiple ordered logistic regression models were developed to identify significant predictors of thermal perceptions among transit users, and to select models of best fit, with the ordinal forest serving as a first pass for predictor selection. Models were fitted with R package 'MASS' (Ripley et al., 2024). Predictors with an RPS percentage greater five were placed into multiple ordered logistic regression models, and then iteratively removed in a backward elimination via a series of likelihood ratio tests between nested models. Predictors were examined for elimination based on their RPS percentage: variables with lowest score were assessed for removal first. This was done to avoid the pitfalls of stepwise regression, and was inspired by similar techniques from Lin et al. (2021) that combined machine learning techniques and regression models to select influential predictors and model forest ecosystem processes. The proportional odds assumption for these models was evaluated using visual inspection and Brant tests (Brant, 1990). Multicollinearity was assessed using variance inflation factors. After two final models for TCV and TSV were selected, the main effects in the best fitted models were given interaction terms to examine moderating effects. Likelihood ratio tests between the nested models were run to determine if interaction terms were needed. Pseudo-R squared values were calculated for the final models using the 'pscl' package (Jackman, 2005).

To examine the urban structural predictors of APV, a series of bivariate ordered logistic regression models were fitted. Percent land cover composition, the presence or absence of a bus shelter, and view factors were considered. While we sought to build a multivariate model, this could not be done due to the issues of multicollinearity between these predictors.

Model parameters were reported, and log-odds were exponentiated into odds ratios for interpretability. Independent variables were considered significant if their 95 % confidence intervals did not include an odds ratio of 1.0, indicating a clear directional effect. Both the ordinal forest models and ordinal logistic regression models were validated against null models. Ordinal forest models were validated by generating 100 null models with the dependent variable randomly permutated. Average variable importance (the RPS metric) for these null models was then compared to the RPS for observed values. Validation for influential predictors were based on whether the observed RPS value fell outside the mean null RPS value's confidence interval. Validation for the final ordinal logistic regression models was assessed via likelihood between a null model with the intercept as a sole predictor, and the final ordinal logistic regression models. Statistical significance was assessed using p-values at a 0.05 threshold ($\alpha = 0.05$).

3. Results

3.1. Descriptive statistics

Within the parameters for qualification, the selective sample of survey participants was $n = 77$ at 31 unique bus stops, with 32 responses occurring in the morning and 45 responses occurring in the afternoon. Descriptive statistics for all variables of urban structure, thermal dynamics, and transit users' perceptions are demonstrated below (Figs. 5, 6).

Survey participants overwhelmingly did not often find the thermal environment cold, with TSV categories "Slightly Cold", "Cold", and "Very Cold" seeing minimal votes. Participants also did not find the thermal environment "Slightly Comfortable" or "Very Comfortable", demonstrating that for TCV, most participants found the thermal environment "Neutral" to "Very Uncomfortable", indicating some extremes on the Likert response ends of the thermal perception votes. APVs demonstrated more of a normal distribution with the highest number of votes assigned to the category of "Neutral" (Fig. 5).

For measurements of the thermal environment, the indices of thermal comfort UTCI, PET, and T_{MRT} showed wider interquartile ranges (IQR) compared to T_{Air} and WBGT, indicating greater variability in measurements that are traditionally associated with shortwave and longwave radiation. UTCI ranged from 17.9 °C to 37.3 °C, with the IQR spanning 26.5–33.5 °C, indicating that most conditions fell within the moderate to strong heat stress categories. PET values showed a wider spread, ranging from 15.0 °C to 42.4 °C, with the IQR between 26.5 and 35.9 °C, suggesting similar transit user exposure to heat stress. T_{MRT} exhibited the widest variability, ranging from 8.9 °C to 51.1 °C (IQR: 28.7–41.7 °C), emphasizing the strong variability of radiant heat across study sites. WBGT, a thermal comfort index accounting for humidity, varied from 16.2 °C to 28.6 °C, with an IQR of 20.7–24.7 °C, a lower range than the other indices of thermal comfort. T_{Air} ranged from 20.0 °C to 36.8 °C, with most observations between 27.1 and 32.1 °C. (Fig. 6, top panel).

Urban structure measurements demonstrated variation in land cover composition and view factors across bus stops SVF ranged from 0.1 to 0.7, with most values falling between 0.3 and 0.6, suggesting substantial variation in overall obstruction or sky exposure between study sites. VVF showed a broader distribution (0.0–0.8), but most values were concentrated between 0.1 and 0.4. Tree canopy cover (%Tree) exhibited similar variation, with values spanning from 0 to 0.6 but concentrated between 0 and 0.2. This aligns

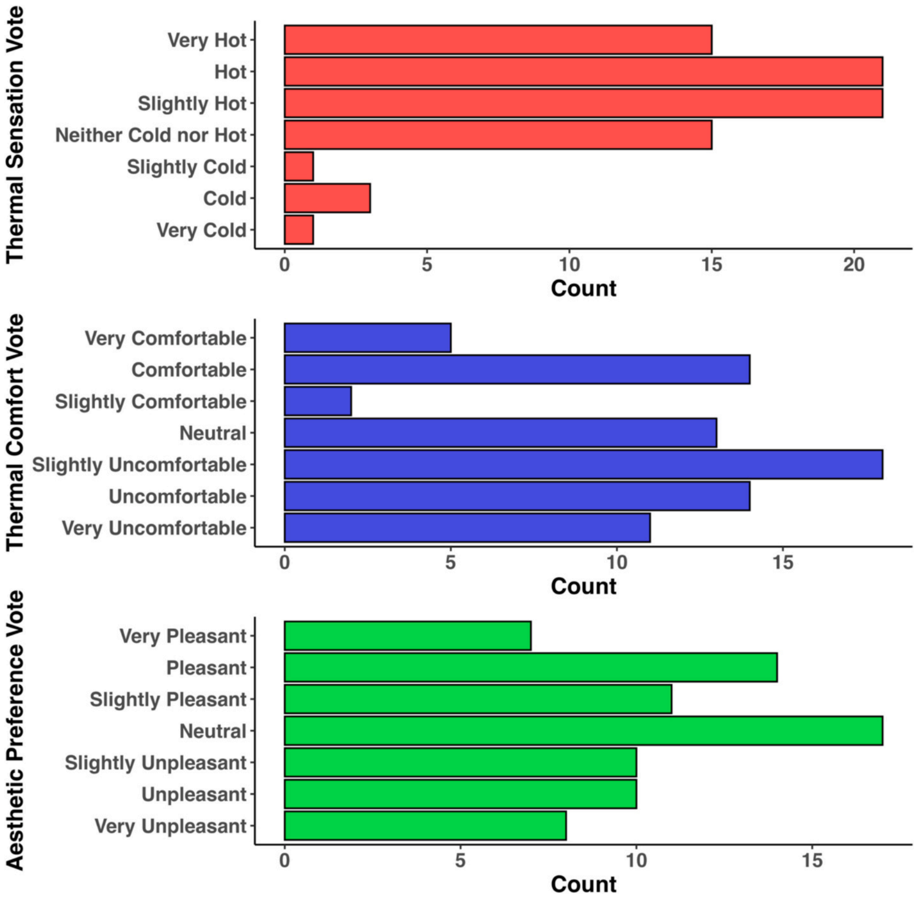


Fig. 5. Total counts of Thermal Sensation Vote (top), Thermal Comfort Vote (middle), and Aesthetic Preference Vote (bottom) among the survey participants.

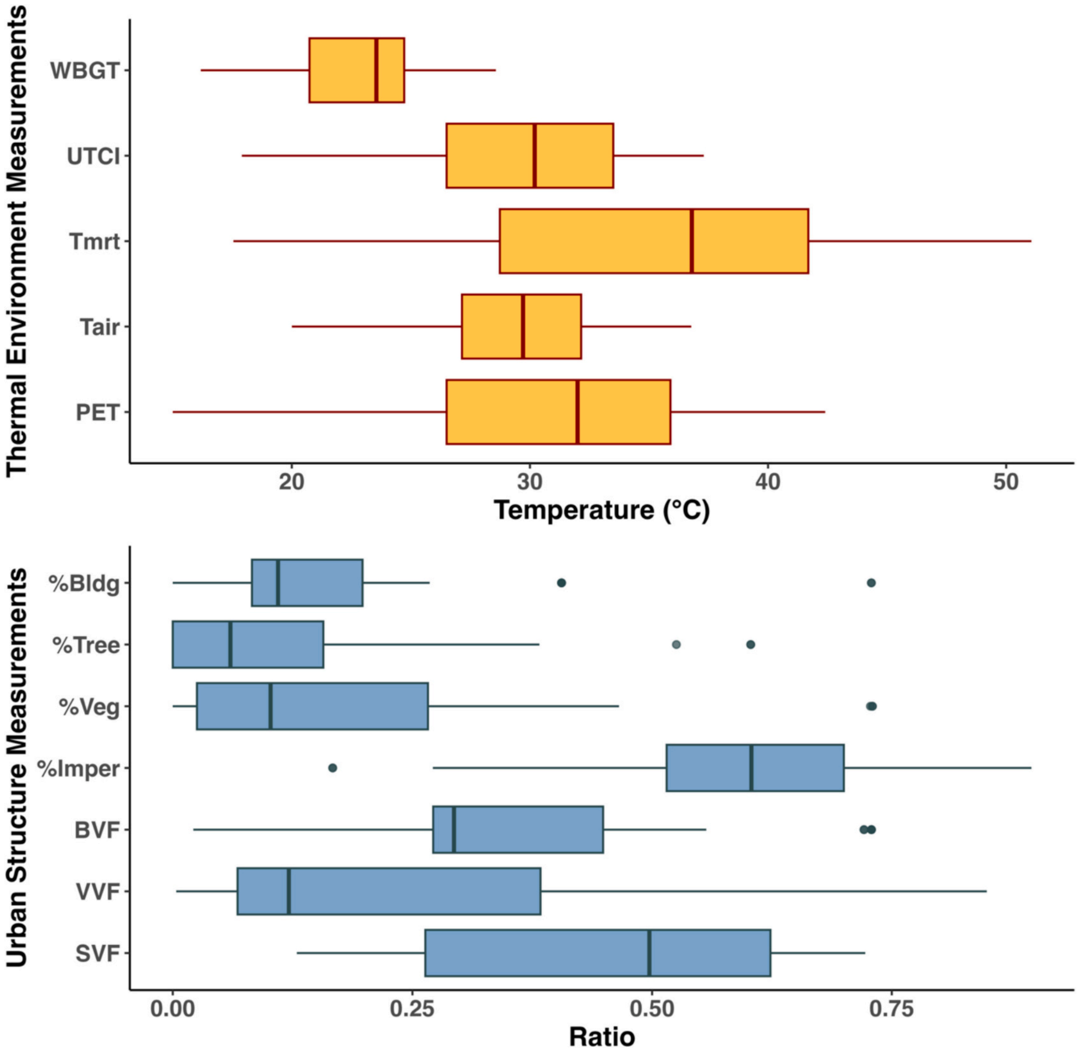


Fig. 6. The box-and-whisker plots demonstrate the distribution of two types of variables: (1) thermal measurements, including Kestrel measurement air temperature (top panel, T_{Air}) and indices of thermal comfort, including Wet Bulb Globe Temperature, Universal Thermal Climate Index, Mean Radiant Temperature, and Physiological Equivalent Temperature (top panel, WBGT, UTCI, $T_{MRT,}$ PET, respectively) and (2) urban structure measurements, both land cover composition, including percent building, tree canopy, vegetation, and impervious surfaces (bottom panel, %Bldg, %Tree, %Veg, %Imper, respectively), and the view factors, including, building, vegetation, and sky (bottom panel, BVF, VVF, SVF, respectively). Each box plot represents the spread of values for a specific variable, with the central box indicating the interquartile range (IQR), the horizontal line within the box showing the median, and the "whiskers" extending to the minimum and maximum values within 1.5 times the IQR. Data points outside this range are displayed as outliers.

more broadly with Denver's city-wide tree canopy cover metric of 15 % (Parks, 2025). BVF ranged from 0.0 to 0.7, with an IQR of 0.3–0.4. Percent building composition (%Bldg) ranged from 0 to 0.7, though most values clustered between 0.1 and 0.2, indicating study sites were more often obstructed by buildings than trees. In terms of surface composition, percent impervious surface (%Imper) was generally high across sites, ranging from 0.2 to 0.9, with a central IQR of 0.5–0.7, indicating that most stops were composed of paved surfaces. Percent of vegetated surfaces (%Veg) ranged from 0 to 0.7, but with a typical spread between 0 and 0.3, reflecting some presence of soft landscaping (Fig. 6, bottom panel).

Sociodemographic variables, including gender, age, income, and racial identity were optional on the survey, and were not a focus of this study. Nevertheless, a summary of these statistics demonstrated the following percentages out of the 77 survey participants. For age, a slight majority of participants fell between the ages of 36–64, comprising 40.26 % of the sample. 37.66 % of survey participants were between the ages of 18–35, while the elderly, those who were 65 and older, represented 5.19 % of survey participants. 16.88 % of respondents did not provide an age.

Regarding gender identity, participants showed clear male representation, who accounted for 62.34 % of the sample. In comparison, participants identifying as female made up 23.38 %, while 14.29 % of participants did not specify their gender. Though given the option to self-identify, no survey participants specified a gender outside of the traditional binary. When examining income distribution, the largest income group consisted of those earning less than $25,000 annually, representing 33.77 % of respondents. The $25,000–$49,999 income range followed closely with 16.88 %. Other income groups included those earning between $75,000–$99,999 at 10.39 %, and $50,000–$74,999 at 6.49 %. Smaller proportions of respondents fell within the $100,000–$149,999 range at 5.19 %, and $150,000 or more at 2.60 % of identified income brackets. Additionally, a large portion of survey respondents, 24.68 %, did not report their income.

Lastly, racial identity among survey respondents represented a diverse range of racial backgrounds. The largest group consisted of White respondents, who made up 33.77 % of the sample. Black or African American respondents accounted for 10.39 % of the sample, while those who identified as American Indian/Alaska Native and those reporting more than one racial identity each made up 7.79 %. A smaller proportion of respondents identified as Native Hawaiian or Other Pacific Islander, 2.60 %, or Asian, 1.30 %. While it is important to note that Hispanic and/or Latino are ethnic identities rather than racial identities, 16.88 % of survey respondents self-identified within this group. 19.48 % of respondents declined to disclose their racial identity.

3.2. Predictors of thermal perceptions

Results from the ordinal forest model highlight influential predictors of the Thermal Comfort Vote (TCV), a rating of thermal satisfaction, and the Thermal Sensation Vote (TSV), which measured sensations of the thermal environment. (Fig. 7).

For TCV, APV was the most influential predictor of TCV (> 20 % RPS), followed by the thermal comfort indices PET and UTCI (> 10 % RPS). The other thermal comfort indices, WBGT and T_{MRT} had a moderate amount of influence, along with thermal dynamics, namely T_{Air}. (> 5 % RPS). Remaining predictors of urban structure and personal factors had the least amount of influence (< 5 % RPS). RPS percentage totals by group included 21.8 % for aesthetic preference, 44.3 % for the thermal comfort indices, 12.3 % for thermal dynamics, 16.3 % for urban structure, and 5.2 % for personal factors (Fig. 7).

For TSV, the thermal comfort indices T_{MRT} was the most influential predictor (> 15 % RPS), followed by WBGT, PET, UTCI, and APV (> 10 % RPS). $T_{Air,}$ and relative humidity were moderately influential (> 5 % RPS). Similarly to TCV, personal factors and urban structural predictors demonstrated minimal to no influence (< 5 % RPS). RPS percentage totals by group included 51.8 % for thermal comfort indices, 10.0 % for aesthetic preference, 16.5 % for thermal dynamics, 7.4 % for personal factors, and 14.6 % for urban structure (Fig. 7). We conclude from both these ordinal forest models that APV, thermal comfort indices, and thermal dynamics were all influential predictors of TCV and TSV, while personal factors and urban structure displayed minimal influence for the thermal perceptions of transit users in a semi-arid system.

These ordinal forests models were then validated against null models, where TCV and TSV were randomly permuted. 100 hundred

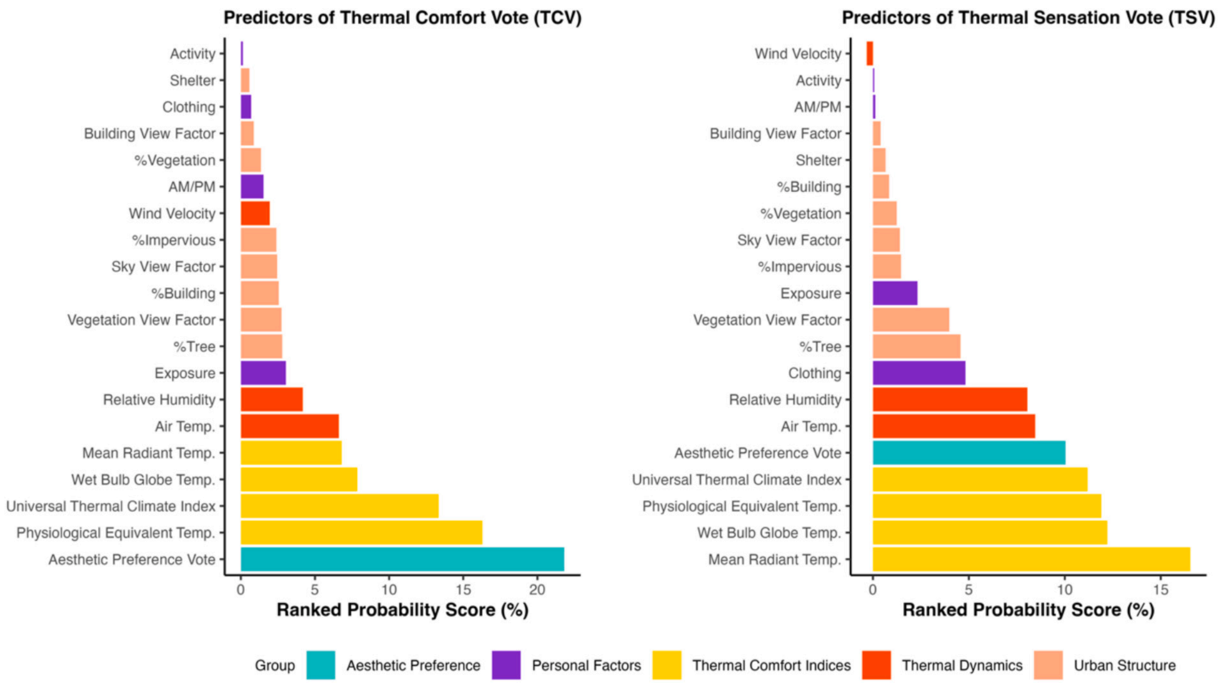


Fig. 7. Predictors of Thermal Comfort Vote (TCV) and Thermal Sensation Vote (TSV) ranked by Ranked Probability Score (RPS, y-axis) from the ordinal forest models. RPS denotes the accuracy of probabilistic predictions by measuring alignment with observed outcomes, thus providing a variable importance metric. Aesthetic Preference Vote (APV) and thermal comfort indices have the highest RPS, followed by thermal dynamics for TCV. Most thermal comfort indices followed by APV have the highest RPS for TSV. Urban structure, including shelter presence, percent land cover composition and view factors, as well as the personal factors of transit users all generally demonstrate lower RPS than thermal dynamic measurements for both TCV and TSV metrics.

Table 1
Thermal Comfort Vote (TCV) and Thermal Sensation Vote (TSV) predicted by Aesthetic Preference Vote (APV) and the Physiological Equivalent Temperature (PET). Asterisks denote significance at *p*-values less than 0.05.

Predictor	Odds-ratio (exp(β))	95 % Confidence Interval	t-value	Std. Error	p-value
			TCV		
APV	1.954	[1.491, 2.607]	4.717	0.142	0.000***
PET	0.889	[0.826, 0.954]	−3.228	0.036	0.001***
			TSV		
APV	0.664	[0.508, 0.855]	−3.103	0.132	0.002***
PET	1.101	[1.029, 1.180]	2.768	0.035	0.006**

Table 2
Thermal Comfort Vote (TCV) and Thermal Sensation Vote (TSV) moderated by Aesthetic Preference Vote (APV) and the Physiological Equivalent Temperature (PET). Asterisks denote significance at *p*-values less than 0.05. Moderation effects are significant for TCV but not TSV.

Predictors	Odds-ratio (exp(β))	95 % Confidence Interval	t-value	Std. Error	p-value
			TCV		
APV	0.640	[0.206, 1.896]	−0.780	0.559	0.424
PET	0.747	[0.615, 0.893]	−3.083	0.094	0.002**
APV:PET	1.040	[1.002, 1.081]	2.043	0.019	0.041*
			TSV		
APV	0.961	[0.311, 2.844]	0.182	0.839	0.943
PET	1.167	[0.971, 1.405]	1.771	0.143	0.098
APV:PET	0.987	[0.951, 1.025]	−0.724	0.030	0.500

such models were run, with the mean RPS and a corresponding 95 % confidence interval of the null models calculated. Validation indicated agreement for APV, thermal dynamics, and thermal comfort indices as strong predictors of both TCV and TSV, with observed RPS values falling outside the null models' confidence intervals (Appendix B, Tables 1, 2, and Fig. 2).

Results from the validated ordinal forest models were then used in the model building process.

All predictors with an RPS percentage greater than or equal to five were placed in multiple ordinal logistic regression models predicting TCV and TSV respectively. For TCV, predictors included, PET, UTCI, WBGT, T_{MRT}, and T_{Air}. For TSV, predictors included T_{MRT}, PET, WBGT, APV, UTCI, T_{Air}, and relative humidity. Predictors were iteratively eliminated through a series of likelihood ratio tests between nested models.

APV and the thermal comfort index PET were ultimately selected as the final main effects for TCV and TSV from the backward elimination process, largely mirroring validated ordinal forest results. For TSV, T_{MRT} indicated a better fit over PET, however PET was ultimately selected as the model with T_{MRT} did not display proportional odds, an assumption of ordinal logistic regression. Other variables representing urban structure and personal factors for both models were not selected due to the poor influence demonstrated in the previous analysis process, and issues of multicollinearity. From this variable selection process, two final multiple ordered logistic regression models were fitted, each predicting TCV and TSV, respectively. Significant predictors are denoted with asterisks (Table 1).

For TCV, both APV and PET were both significant predictors of the thermal comfort of transit users in a semi-arid system. The odds-ratio of 1.954 for APV indicated that for each unit increase in the pleasantness of a bus stop, the odds that a transit user finds the bus stop thermally comfortable increased by approximately 0.95. Conversely, the odds-ratio of 0.889 for PET showed that for each unit increase in PET (which signifies increasing thermal stress), the likelihood of an individual finding the bus stop thermally comfortable decreased by about 0.11 (Table 1).

For TSV, APV and PET were statistically significant predictors of the thermal sensation of transit users in a semi-arid system. The odds-ratio of 0.664 for APV demonstrated that for each unit increase in bus stop pleasantness, the odds an individual found the bus stop hot decreased by approximately 0.34. That is to say, bus stops that were aesthetically pleasing were more likely to be rated as cooler. Conversely, a per unit increase in PET was associated with about a 0.10 increase in the odds that a transit user rated their thermal sensation as hot (Table 1).

3.3. Aesthetic preference moderating outcomes of thermal perception

Our next goal was to analyze whether APV moderated transit users' thermal perceptions (TCV and TSV). In other words, when temperatures were high, were transit users more likely to indicate that they felt comfortable and/or cooler at bus stops that they found aesthetically pleasant. Interaction terms were added to the two models found in the previous section for TCV and TSV, respectively (Table 2).

When predicting TCV, APV were significant in models without interaction terms but became insignificant when the interaction terms were added. However, the interaction term (APV: PET) remains significant, indicating that APV significantly moderated the effect of PET on TCV (Table 2, p-value). The odds-ratio of 0.747 for PET indicated that for each unit increase in PET (increasing thermal stress), the odds that an individual finds the bus stop thermally comfortable decreased by approximately 0.25 (Table 2, Odds-ratio). While the odds of this decrease are more drastic than in the previous model (Table 1), the significant interaction term's odds-ratio of

1.040 (Table 2) suggested that the effect of PET on TCV is moderated by APV, meaning that the pleasantness of a bus stop influenced how thermal stress affected thermal comfort. The odds ratio of the interaction term also suggests that when PET and APV are high (high thermal stress coupled with a more pleasant bus stop), the odds that a bus stop is perceived to be thermally comfortable were decreased by APV. For each unit increase in PET, the odds of heat stress were increased by 1.040, but reduced by APV at a constant 0.64. (Table 2).

When predicting TSV (thermal sensation of transit users), APV was significant only in the models without interaction terms ($p < 0.002$, Table 1) and APV's interaction with PET was not significant ($p < 0.943$, Table 2). This insignificance of the interaction indicated that the pleasantness of a bus stop is not dependent on PET: when temperatures are hot, APV does not affect the odds that a bus stop will be rated as cooler.

Lastly, a likelihood ratio test between nested the two TCV models and a null model was run. Maximum Likelihood Pseudo R-squared values were also calculated (Table 3). The significant p-value (0.00372) from the likelihood ratio test showed that the model with the interaction term explained the variability in TCV better than the model without it. The pseudo-R-squared values (pseudo-r^2ML) were indicative measures of model fit. The TCV model with APV and PET alone has a pseudo-r^2ML of 0.389, suggesting it explained a substantial part of the data relative to a null model. Including the interaction term increased this measure to 0.434 and indicated an improvement in model fit. Both models display better fit compared to the null model.

For TSV, the insignificance of the interaction effect did not warrant a likelihood ratio test. We found that increases in PET raised the odds that a transit user rates a bus stop as hot, while more aesthetically pleasing bus stops reduced the odds that a transit user rates a bus stop as hot. These effects remained independent: when PET was high and a bus stop was aesthetically pleasing, the odds remained unchanged.

3.4. Urban structural predictors of aesthetic preferences

With aesthetic preferences being an influential predictor for thermal perceptions, we then wanted to see what elements of bus stop urban structure were influencing transit users' Aesthetic Preference Vote (APV). To examine this, DRCOG one-meter-squared land cover composition within 30-m bus stop buffers, in-situ view factor measurements, and the presence or absence of a bus shelter were considered in a series of bivariate ordered logistic regression models.

A bivariate analysis for APV and all predictors representing urban structure was conducted via a series of ordinal logistic regression models (Table 4). Results indicated that increases in large stature vegetation, such as the percentage of tree canopy land cover (%Tree) and visible vegetation view factor (VVF), were associated with a significant higher likelihood of a bus stop being perceived as pleasant. The presence of a bus shelter was a significant predictor of APV, indicating that shelters decreased the odds a bus stop is perceived as pleasant. Other variables representing urban structure, including SVF, and metrics of gray infrastructure including BVF and %Bldg, were statistically insignificant predictors of APV (*p*-values, Table 4).

For each percent increase in canopy cover, the odds of a bus stop being rated as pleasant increased by 1.03. For each unit increase in VVF, the odds a bus top is perceived as pleasant increased by 10.35 (Odds-ratio, Table 4). Additionally, the presence of a shelter decreased the odds of a bus stop being rated as pleasant by 0.67 (Odds-ratio, Table 4).

With an increase in bus stop canopy cover (%Tree), the odds that a transit user finds the bus stop pleasant increased (increasing APV). Conversely, with an increase in tree canopy cover, the odds that transit users found a stop unpleasant decreased (Fig. 8). A similar figure for VVF was generated and is largely identical to this figure (Appendix B, Fig. 3). We conclude that transit users in a semi-arid system were more likely to find bus stops with higher amounts of large stature vegetation as aesthetically pleasing, and that bus stops with shelters were less likely to be aesthetically pleasing.

4. Discussion and future directions

4.1. Aesthetics preferences: Key predictors of the thermal perceptions of transit users

This study sought to examine the main predictors of transit user thermal perception at bus stops within a semi-arid system. Out of all sets of predictors, including the structure of bus stops, measurements of the thermal environment, thermal comfort indices, aesthetic preferences, and personal factors, our results demonstrated that aesthetic preferences (APV) and the thermal comfort index Physiological Equivalent Temperature (PET) were the most significant predictors of thermal comfort and thermal sensation (TCV and TSV). Bus stops were more likely to be rated as cooler or more thermally comfortable when they were rated as aesthetically pleasing

Table 3
Likelihood ratio test for Aesthetic Preference Vote (APV) Physiological Equivalent Temperature (PET), and interaction terms predicting Thermal Comfort Vote (TCV). Asterisks denote significance at *p*-values less than 0.05.

Model	Residual Degrees of Freedom	Residual Deviance	Test	Degrees of Freedom	Likelihood Ratio Stat.	p-value	AIC	Pseudo-r^2ML
Null	71	278.796	NA	NA	NA	NA	290.761	NA
APV + PET	69	240.852	1 vs 2	NA	37.944	< 0.000001***	256.851	0.389
APV: PET	68	236.510	2 vs 3	1	4.342	0.00372**	254.510	0.434

Table 4
Aesthetic Preference Vote (APV) bivariate ordered logistic regression model parameters. Asterisks denote significance at p-values less than 0.05. The amount of large stature vegetation a bus stop had, and the presence of a shelter were significant predictors of APV.

Predictor	Odds-ratio (exp(β))	95 % Confidence Interval	t-value	Std. Error	p-value
SVF	0.170	[0.021, 1.310]	−1.687	1.050	0.092
%Tree	1.032	[1.004, 1.060]	2.245	0.014	0.025*
%Veg	1.019	[0.998, 1.041]	1.739	0.011	0.082
%Bldg	0.985	[0.957, 1.016]	−1.014	0.015	0.311
%Imper	0.985	[0.959, 1.011]	−1.16	0.013	0.246
VVF	10.350	[1.427, 80.852]	2.284	1.023	0.022*
BVF	0.388	[0.036, 4.126]	−0.786	1.204	0.432
Shelter	0.334	[0.126, 0.864]	−2.243	0.489	0.025*

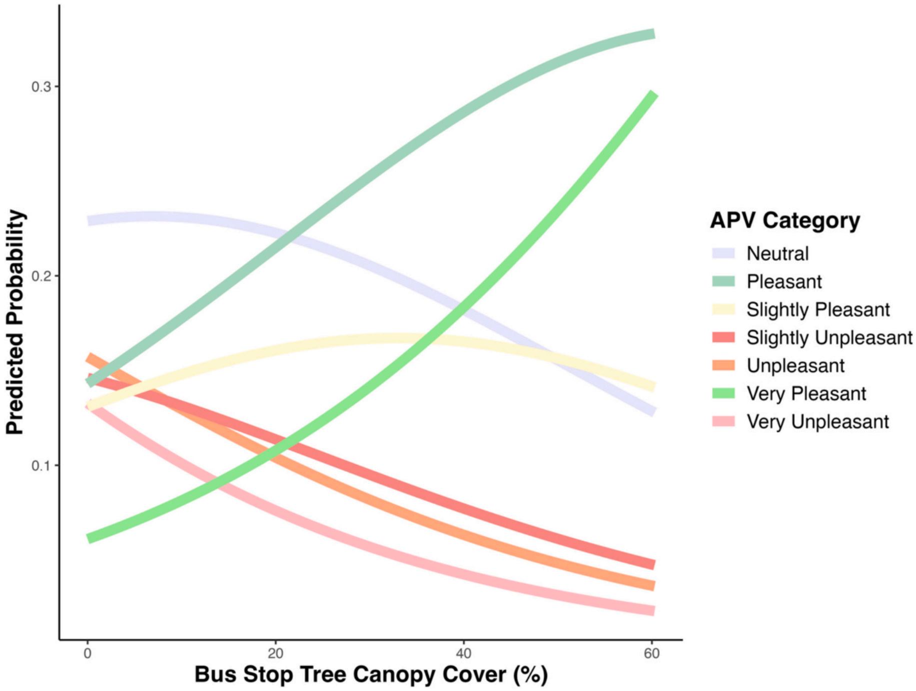


Fig. 8. Increases in percent tree canopy cover at bus stops were associated with the likelihood that a bus stop was rated as aesthetically pleasing. Aesthetic Preference Vote (APV) categories are depicted on the right.

(Table 1). Measurements of the thermal environment and bus stop structure, as well as the personal factors of transit users, were less influential in predicting thermal perception (Fig. 7). Furthermore, APV significantly moderated PET in high thermal stress scenarios, increasing the likelihood that transit riders felt slightly more thermally comfortable at bus stops that were aesthetically pleasing. However, APV did not appear to moderate PET in relation to thermal sensation outcomes (Table 2).

Past studies have demonstrated that the aesthetics of outdoor spaces affect thermal perception (Lenzholzer and van der Wulp, 2010), with many of these studies taking place in a diverse range of outdoors spaces, populations, and climates (Aghamolaei et al., 2023). Environmental quality, defined as both the visual and acoustic properties of outdoors spaces, namely streets, parks, and private estates, can moderate outdoor thermal comfort (Du et al., 2023; Lau and Choi, 2021). Nevertheless, while pedestrians often appreciate the aesthetics of specific landscape features, such as street greenery, the moderating effect of the visual perception of these features is not significant, with shade cast from vegetation displaying the direct effect (Klemm et al., 2015). Instead, the effects of visual perception on thermal comfort are often the result of glare and sun sensation, among other sensory inputs (Lam et al., 2024).

Research analyzing transit user thermal perception and aesthetic preferences of the bus stop are limited. Instead, studies of transit user thermal perception often focus on the specific shade features at bus stops (Lanza et al., 2025; Pan et al., 2024), or the effects of these bus stop features transit user behavior during extreme heat (Lanza and Durand, 2021). In perhaps the most similar study to this one, Dzyuban et al. (2022b) found that transit users in an arid system are more likely to rate cooler bus stops as more beautiful and pleasant, however aesthetic elements also included bus stop shelters and the artistic design present at the study sites. Therefore, this study, while similar in scope, took a more direct approach, directly examining the effects of aesthetic preferences on transit user thermal perception. In contrast, it analyzed a semi-arid transit system and ultimately revealed that aesthetic perception moderates thermal comfort during scenarios of increased thermal stress (Table 2).

Since thermal dynamics largely constitute the thermal environment, it is not surprising that these variables predicted thermal perceptions. However, the finding that APV had a greater influence on TCV and TSV than urban structure was unexpected. After all, thermal dynamics are largely determined by the biophysical interactions between the built environment and urban heat fluxes. We therefore posit that the aesthetic preferences of transit users should be measured alongside subjective thermal perception, as they appear to significantly predict thermal perception outcomes and can even moderate these outcomes on a hedonic scale.

4.2. Bus stop structure and aesthetic preferences

While we expected urban structure and the heterogeneity of bus stops to have a stronger influence on thermal perceptions, we still believe that it is an important set of variables to consider when predicting thermal perceptions. Indeed, through aesthetic perceptions, we can begin to see the linkages between urban structure and thermal perception: APV mediates the relationship between the built environment and thermal perception. Preliminarily, bus stops with greater amounts of large stature vegetation are more likely to be rated as aesthetically pleasing (Table 4, Fig. 8).

It is not uncommon for transit users to find bus stops with more vegetation aesthetically appealing (Dzyuban et al., 2022b; Klemm et al., 2015), and for other pedestrians, tree canopy morphology, amount of greenness, and seasonal color variation to be correlated with aesthetic perception of streetscapes and urban parks (Hu et al., 2022; Wang et al., 2020). However, for thermal perception, this relationship changes with seasonality, as the illumination resulting from the phenological cycles of trees influences visual perceptions of brightness, and therefore thermal perception (Zhang et al., 2022). While this study examined vegetation from two metrics, an object-oriented one-meter-squared percent canopy cover metric, and the ground-based VVF metric, the study was nevertheless conducted during summer months and therefore may not be generalizable to other seasons and points on a phenological cycle.

The presence of a bus stop shelter appears to significantly decrease the odds that a transit user finds a bus stop aesthetically pleasing ($p < 0.025$, Table 4). However, with most study sites having shelters, and a disproportionate representation for each level of APV and non-sheltered stops, there remains some ambiguity if shelters alone are considered unpleasant (Appendix B, Table 3). While a similar study examining thermal perception found transit users are more likely to rate bus stops as beautiful if they have artistic designs (Dzyuban et al., 2022b), we conclude that whether transit users find bus shelters aesthetically pleasing is a point for future inquiry. Continuing studies would be helpful to examine the aesthetic appeal of bus stop shelters to inform decisions about their design and efficacy.

The results of this study point to a more nuanced understanding of urban structure and thermal perception: they are linked indirectly through aesthetic preferences. We still believe that understanding structural heterogeneity in semi-arid systems remains key to understanding urban ecosystem function (Mokhtari et al., 2022; Pickett et al., 2017), and is necessary knowledge needed to make landscape decisions for urban heat mitigation and thermally comfortable bus stop design.

We conclude that transit systems in semi-arid climates may benefit by adopting measures to increase the aesthetic appeal of their bus stops to increase the thermal comfort of their users. Preliminarily, large stature vegetation appears to be aesthetically pleasing, which in turn can positively moderate transit user thermal comfort in thermal stress scenarios. While these results then do contribute to the growing body of literature on the need for vegetation in transit corridors, we still believe that more research is needed to understand what exactly is driving aesthetic preferences, as aesthetic perception is likely driven by factors beyond vegetation. Lastly, research in semi-arid systems would avail to monitoring use patterns in conjunction with weather events and the structural composition of their bus stops. Therefore, we abstain from making concrete latter recommendations until these aspects are further addressed.

4.3. Directions for future research

Thes results of this study point towards future directions for public transit research and landscape design along transit corridors in semi-arid systems. Points of departure for further inquiry include focusing on transit use patterns and behaviors, the quality of transit experience, and landscape preferences of transit users. Given the importance of aesthetic preferences in predicting the outcomes of transit user thermal perception, we hope to elaborate on discourses surrounding heat resilient public transit design further.

Future inquiry could concentrate on green infrastructure interventions at bus stops and their relationship to transit use behavior during heat events. Street greenery is known to promote active travel, whereby residents are more likely to walk, bike, or otherwise physically exert themselves on streets with higher amounts of vegetation (Wu et al., 2020; Yu et al., 2024). Lanza and Durand (2021) found that during the warm weather events in a humid subtropical city, bus stops with more vegetation were slightly less likely to see declines in ridership than bus stops with shelters alone. Shi et al. (2021) found that improvements to bus stop amenities, such as shelter and bike hoops, are also known to increase transit ridership, however this study did not consider vegetation as a variable. Future studies could examine ridership patterns in conjunction with warm weather events in a semi-arid city to examine if transit stops with greater amounts of vegetation see smaller reductions in ridership than bus stops with shelters only.

Future research could also help determine if aesthetic design of bus stops influence other adaptive behaviors of transit users in semi-arid systems. For example, public transit amenities such as buses with air conditioning mediate perceived risk in transit decisions in subtropical systems (Ban et al., 2019). While we do not wish to promote transit user exposure to extreme heat for the sake of transit ridership, we do seek higher quality experiences for transit users, especially for those who are transit dependent. Specifically, this study further points to the benefits of green infrastructure over shade cast from built structures, differing from what was found in arid systems (Middel et al., 2021). While shade from built structures still carries its benefits, the aesthetic appreciation of green infrastructure moderates thermal comfort in a semi-arid system and has the potential to carry future behavioral benefits beyond moderating thermal comfort.

Therefore, this research outlines a valuable foundation for studying landscape preferences, expanding the conversation on how bus stop design shapes transit users' thermal perceptions. While sociodemographic factors reveal complex adaptive behaviors in response to heat (Guardaro et al., 2022), and aesthetic preferences vary widely across cultures and individuals (Palmer et al., 2013), these values and behaviors can be examined in conjunction with outdoor thermal perception, potentially offering new insights into heat resilient transit design.

Our results demonstrating significant correlations between aesthetically pleasing bus stops and large stature vegetation encourages further inquiry into the specific landscape features driving such preferences. Future research in semi-arid systems could ask transit users what specific elements of transit corridor infrastructure have aesthetic appeal and suggest landscape interventions based on those findings. These landscape preferences could include the type, amount, and configuration of vegetation at bus stops. For example, controlled studies could see if small interventions, such as the placement of flower beds, improves the aesthetic appeal of bus stops, and if those interventions are at all associated with an increased likelihood that a transit user finds a stop thermally comfortable. In addition, past studies have indicated that aesthetic and thermal perception are influenced by multi-sensory inputs, including sound (Du et al., 2023; Lam et al., 2024; Lau and Choi, 2021). Future research could incorporate acoustic monitoring or other measurements of soundscapes alongside thermal perception to better understand how these aspects of bus stops and transit corridors affect users' thermal comfort. While further research is necessary to fully understand use patterns, adaptive behaviors, and heat-related vulnerabilities within these systems, examining aesthetic preferences offers a promising pathway for designing public transit spaces that balance functionality with user experience.

4.4. Limitations

This study has a few limitations regarding data collection and analysis. The first limitation regards the modeling of physiological thermal comfort. Thermal comfort indices, such as PET, are often derived from T_{MRT} and other thermal dynamic measurements and remain a significant group of predictors for the thermal perceptions of transit users in a semi-arid system (Fig. 6, Table 1). However, T_{MRT}, an essential measurement for understanding human thermal comfort, is also one that is extremely difficult to measure (Kántor and Unger, 2011). Past studies have indicated that the structure of the black globe thermometer, a component of the instrument used in this study, including its spherical shape, color, material, and diameter, have resulted in inconsistencies in T_{MRT} estimation (Johansson et al., 2014; Kántor and Unger, 2011; Khrit et al., 2017; Thorsson et al., 2007; Vanos et al., 2021). While we hope that using the recalibrated method from Ouyang et al. (2022) corrected for many of these issues, it should be noted that T_{MRT} measurements, and therefore UTCI and PET calculations, were reliant on black globe thermometers and equations, and did not measure shortwave and longwave radiation directly.

Our methodological approach for the survey introduces some potential forms of bias. We did not count the number of participants who declined to take part in the survey, nor did we account for group sampling effects, introducing non-response bias and group bias. While most survey respondents were solo riders, a few responses could be biased based on a group interpretation of the survey. Furthermore, questions were not randomized within the survey, leading to potential question-order bias. Nevertheless, with the survey taking an average of less than ten minutes to complete, we believe these biases are minimal.

The study carries some statistical limitations. Namely, the study's small sample size ($n = 77$) and the use of ordered logistic regression, which is more robust when used for larger samples. Nevertheless, some authors stress the importance of respecting the ordinal nature of thermal perception data by utilizing ordered logistic regression (Favero et al., 2023), especially when survey responses skew to the extreme ends of Likert response scales (Pantavou and Lykoudis, 2014). Notwithstanding, small sample sizes result in large standard errors. Therefore, that while we contend that ordered logistic regression approach is valid, and our significance legitimate (Norman, 2010), the small sample size in our study necessitates cautious interpretation of the effect sizes, and future research with larger samples would be helpful to continue to validate these findings.

While the results indicate that APV moderates PET and outcomes of TCV, this is not a causal relationship. Causal inferences cannot be made in this study, as controlled treatments were not applied to participants: it remains an observational study. Indeed, this study does not differentiate between the causal mechanisms between environmental perceptions and thermal perceptions. Moreover, APV could be driven by thermal perceptions, and vice versa. Similar models to the ones found in the last section were fitted to predict APV. No significant interaction effects were found between APV, TCV, and TSV, however we still cannot make conclusions about causality due to the nature of the study. Moreover, this was not a question posed by the original design of this study: we sought to examine the effects of APV on thermal comfort outcomes. We suggest that future studies triangulate these findings further with qualitative methods, such as transit user interviews.

APV was transformed from an ordinal variable to an interval variable for analysis. While this remains a point of contention, we propose that such a method for a predictor is appropriate as numbers were placed next to the survey response choices, demonstrating equal intervals (Harpe, 2015). A model with APV treated as an ordinal variable was also generated, indicating similar results but was ultimately not included in the main study for general parsimony with reporting model parameters.

5. Conclusions

This study sought to examine the primary predictors of transit users' thermal perceptions at bus stops in a semi-arid system. 60 bus stops within the Denver metropolitan area were selected along a gradient of one-meter-squared land cover compositions. Data were collected during a summer field campaign and included micrometeorological measurements, upper-hemispherical photographs to calculate view factors, transit user surveys, and calculations of thermal comfort indices. This resulted in 77 survey participants across

31 unique bus stops.

Through an ordinal forest analysis, we demonstrated the strong influence of aesthetic preferences and indices of thermal comfort on transit users' thermal perceptions, with these two categories of predictors accounting for over 60 % of predictor importance (RPS). Personal factors, such as clothing insulation and exposure time, as well as elements of bus stop structure, displayed less influence, accounting for less than 25 % RPS. Followed by ordered logistic regression, we demonstrated that these aesthetic preferences and PET are strong predictors of both thermal sensation (APV: OR = 0.664, $p < 0.002$ & PET: OR = 1.101, $p < 0.006$) and thermal comfort (APV: OR = 1.954, $p < 0.000$ & PET: OR = 0.889, $p < 0.001$) and can even moderate thermal comfort in scenarios of thermal stress, with aesthetically pleasing bus stops slightly increasing the likelihood a transit user finds the thermal environment of a bus stop comfortable (OR = 1.040, $p < 0.041$). A bivariate analysis preliminary found that increases in large stature vegetation increased the likelihood that a bus stop was perceived as pleasant, including one-meter-squared percent canopy cover composition (OR = 1.032, $p < 0.025$), and vegetation view factor (OR = 10.350, $p < 0.022$). These insights highlight the potential of integrating green infrastructure into bus stop design to create more thermally comfortable and heat resilient transit systems.

Importantly, this research highlighted the potential for enhancing user experience through landscape design that prioritizes both structural and functional considerations. Our results support a multi-dimensional approach to future public transit planning and research, where bus stop design, including green infrastructure such as trees, provide aesthetic benefits that may alleviate thermal discomfort during hot weather. This aligns with broader urban heat mitigation goals, emphasizing the need to reimagine public spaces, particularly transit stops, as spaces that prioritize thermal comfort and user experience.

While this study establishes these insights, further research is needed to refine our understanding of how specific elements of transit stop design—such as vegetation type and arrangement—impact both the thermal perceptions and aesthetic preferences of transit users. Additionally, exploring these dynamics with a larger sample, including one of diverse sociodemographic groups and cultural backgrounds, will be essential to designing transit systems that are both resilient to heat and inclusive of varied user experiences. These results can serve the needs of cities for sustainable transit design.

CRediT authorship contribution statement

Logan Steinharter: Writing – original draft, Visualization, Methodology, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Peter C. Ibsen:** Writing – review & editing, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization. **Tzeng Yih Lam:** Writing – review & editing, Validation, Formal analysis. **Lorien Nesbitt:** Writing – review & editing, Methodology, Funding acquisition. **Keunhyun Park:** Writing – review & editing, Methodology. **Melissa R. McHale:** Writing – review & editing, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization.

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Declaration of competing interest

The authors declare no financial/personal interests which may be considered as competing interests in this study.

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Appendix A. Transit Corridor Thermal Perception Survey and Letter of Informed Consent

Thermal perceptions of transit riders in Denver, Colorado.
Letter of Informed Consent — *Transit Corridor Thermal Perception Survey.*
Ethics ID#: H23–01399.

A.1. Purpose

This study aims to help us learn more about urban heat and hot weather affects the thermal comfort of Denver's public transit riders. As someone using public transit today, your insight will be valuable in helping the research team understand and connect to the various ways in which the urban environment influences our perceptions of heat, comfort, and pleasantness. The following questions will ask you how the weather is making you feel in the present moment, how pleasing you find this environment, how you utilize public transit, and some questions about your individual characteristics. We estimate that this survey will take 5–10 min to complete.

A.2. Who can take this survey?

Any adult over 18 years of age who is riding the bus today, has been outside for at least 15 min, and has not completed the survey before.

A.3. Confidentiality

The results of this study may be published via peer-reviewed journal articles and book chapters, and may also be presented at academic conferences. All personally identifiable data will be kept confidential and anonymized in any publications resulting from this research. Data recorded through this survey will be stored in a password-protected and encrypted file only accessible to the study team. Data will be stored at the University of British Columbia for five years after the end of study.

If you have any concerns or complaints about your rights as a research participant and/or your experiences while participating in this study, contact the Research Participant Complaint Line in the UBC Office of Research Ethics at 604–822-8598 or if long distance, e-mail RSIL@ors.ubc.ca or call toll free 1–877–822-8598.

If you wish to be informed of the research results or have any additional questions, please contact the research team via the contact emails listed below.

A.4. Research team contacts

Melissa McHale (Principal Investigator) – email: melissa.mchale@ubc.ca
Logan Steinharter (Primary Contact) – email: lms94@student.ubc.ca

A.5. Consent

Participation in this survey is voluntary. You may withdraw from the survey at any point while completing it. The survey concludes with the final submission of your responses. Once submitted, those responses cannot be withdrawn.

Do you consent to participate in this survey? By agreeing with "Yes" you are also confirming you have not participated in this survey before, are over 18 years of age, and have been outside for at least 15 min.

o Yes (1).
o No (2).

This first set of questions will ask about your location and recent behavior. This is in order to understand your activity level before asking questions about how the weather is making you feel. It is best if you answer these questions while at the bus stop.

Please locate the red sign associated with the bus stop where you are currently. Please enter the 5 digit number within the white rectangle.

Which of these choices would best categorize your behavior within the past 15 min?

o Sitting (1).
o Standing (2).
o Walking (3).
o Biking (4).
o Running (5).

Approximately how many minutes did it take you to get to this bus stop from an indoor setting? Write your answer in the box at the bottom right.

0	15	30	45	60	75	90	105	120
Minutes								

A.6. What clothes are you currently wearing? Select all that apply.

- T-Shirt (0.09).
- Sleeveless Shirt (0.06).
- Long-Sleeved Shirt (0.25).
- Long-Sleeved Blouse (0.15).
- Thin Sweater (0.20).

- Thick Sweater (0.35).
- Jacket (0.25).
- Shorts (0.06).
- Jeans (Thin Fabric) (0.20).
- Trousers (Thick Fabric) (0.25).
- Light Skirt (0.01).
- Heavy-Knee Length Skirt (0.25).
- Light Sleeveless Dress (0.25).
- Long Sleeved Dress (0.4).
- Socks (0.02).
- Sandals (0.02).
- Shoes (0.02).
- Boots (0.1).

This set of questions asks how you are experiencing the thermal environment at this bus stop. The thermal environment is defined as the weather from where you are currently positioned. It is best if you answer these questions while at the bus stop. Please select the option that best completes the prompt given.

At present, the thermal environment of this bus stop feels…

o Very Cold (1).
o Cold (2).
o Slightly Cold (3).
o Neither Cold nor Hot (4).
o Slightly Hot (5).
o Hot (6).
o Very Hot (7).

A.7. I find the thermal environment of this bus stop to be…

o Very Uncomfortable (1).
o Uncomfortable (2).
o Slightly Uncomfortable (3).
o Neutral (4).
o Slightly Comfortable (5).
o Comfortable (6).
o Very Comfortable (7).

A.8. I would prefer the thermal environment of this bus stop to be…

o Much Cooler (1).
o Cooler (2).
o Slightly Cooler (3).
o No Change (4).
o Slightly Warmer (5).
o Warmer (6).
o Much Warmer (7).

This next question will ask for your opinion on the aesthetic qualities of this bus stop and your surroundings. Please consider these questions as the area around your field of vision, out to about 15–20 ft from where you are currently positioned at the bus stop.

A.9. Compared to other bus stops in Denver, I find this bus stop to be…

o Very Unpleasant (1).
o Unpleasant (2).
o Slightly Unpleasant (3).
o Neither Pleasant nor Unpleasant (4).
o Slightly Pleasant (5).
o Pleasant (6).
o Very Pleasant (7).

This final set of questions asks some questions about socio-demographics. The purpose of this section is not to stereotype people, but to better understand and inform issues surrounding equity within Denver's public transit system, as well as model heat as it pertains to human physiology. If you do not wish to answer any number of these questions, you may leave them blank.

How do you describe yourself?

o Male.
o Female.
o Non-binary / third gender.
o Prefer to self-describe ________________________________.
o Prefer not to say.

A.10. Do you identify as? Select any that apply.

- White.
- Black or African American.
- American Indian/Native American or Alaska Native.
- Asian.
- Native Hawaiian or Other Pacific Islander.
- Other (Please Specify) ________________________________.
- Prefer not to say.

A.11. What was your total household income before taxes during the past 12 months?

o Less than $25,000.
o $25,000–$49,999.
o $50,000–$74,999.
o $75,000–$99,999.
o $100,000–$149,999.
o $150,000 or more.
o Prefer not to say.

A.12. How many years old are you? Write age in box to the right.

18	28	37	47	57	67	76	86	96	105	115
Age										

A.13. What is your approximate height, in feet and inches? Write answers in boxes on the right.

0	1	2	4	5	6	7	8	10	11	12
Feet										
Inches										

A.14. What is your approximate weight, in pounds? Write answer in box below.

0	50	100	150	200	250	300	350	400	450	500
Pounds										

A.15. Are you interested in seeing the results of this study?

o Yes, please contact me about the results of this study.
o No, I am not interested.

A.16. ANSWER IF YES TO THE ABOVE QUESTION.

Thank you for your interest! Please enter some contact details below. We will be in touch shortly.
o Email ________________________________.
o Phone Number ________________________________.
Thank you for your time, this survey has concluded.

Appendix B. Supplementary Tables and Figures, and Data

Table B.1
Thermal Comfort Vote (TCV) ordinal forest validation. 100 ordinal forests were generated by randomly permuting TCV to create null models. Variable importance was assessed using the Ranked Probability Score (RPS). The "Observed RPS" column shows unscaled values from the original model (also visualized in Fig. 7, scaled as a percent), while the "Null RPS" represents the mean importance scores across the 100 null models. Lower and upper bounds correspond to the 95 % confidence intervals of the null distribution. RPS values are presented unscaled, as the null distributions include a range of negative values.

Predictor	Observed RPS	Mean Null RPS	Null RPS Lower Bound	Null RPS Upper Bound
%Impervious	0.00289684	0.000673455	−0.001566212	0.005250583
%Tree	0.002677905	0.000920537	−0.001271541	0.004297891
%Vegetation	0.003228051	0.00077257	−0.001577811	0.004649676
%Building	0.003261051	0.000483588	−0.002044858	0.004036463
SVF	0.003223671	0.000256031	−0.001704126	0.003149828
VVF	0.003557286	0.000625141	−0.001654286	0.004659549
BVF	0.001127518	0.000769713	−0.002162048	0.005765252
T_{Air}	0.007358659	0.001924132	−0.001013343	0.006176346
WBGT	0.008851338	0.001629814	−0.00161022	0.008020854
T_{MRT}	0.007126156	0.000852172	−0.001908636	0.005045445
UTCI	0.012996046	0.001904744	−0.000718157	0.005913543
PET	0.019592611	0.002125427	−0.00049742	0.007040227
APV	0.024961319	0.00046057	−0.001785132	0.005639905
Wind Velocity	0.001860713	0.000406831	−0.002544454	0.005928276
Rel. Humidity	0.004425104	0.001249549	−0.001516717	0.005187514
Clothing	0.000388196	−0.000252172	−0.002811243	0.003619887
Exposure	0.004263625	0.000186258	−0.002425803	0.004995365
Activity	0.000185853	0.00027578	−0.0014399	0.004340309
Shelter	0.000746793	0.000123838	−0.000521769	0.001488226
AM/PM	0.001239404	0.000197222	−0.000674255	0.002742059

Table B.2
Thermal Sensation Vote (TSV) ordinal forest validation. 100 ordinal forests were generated by randomly permuting TSV to create null models. Variable importance was assessed using the Ranked Probability Score (RPS). The "Observed RPS" column shows unscaled values from the original model (also visualized in Fig. 7, scaled as a percent), while the "Null RPS" represents the mean importance scores across the 100 null models. Lower and upper bounds correspond to the 95 % confidence intervals of the null distribution. RPS values are presented unscaled, as the null distributions include a range of negative values.

Predictor	Observed RPS	Mean Null RPS	Null RPS Lower Bound	Null RPS Upper Bound
%Impervious	0.001549032	0.000673455	−0.001566212	0.005250583
%Tree	0.003658734	0.000920537	−0.001271541	0.004297891
%Vegetation	0.001420568	0.00077257	−0.001577811	0.004649676
%Building	0.000942433	0.000483588	−0.002044858	0.004036463
SVF	0.001231	0.000256031	−0.001704126	0.003149828
VVF	0.002804922	0.000625141	−0.001654286	0.004659549
BVF	0.001171875	0.000769713	−0.002162048	0.005765252
T_{Air}	0.006422084	0.001924132	−0.001013343	0.006176346
WBGT	0.008987455	0.001629814	−0.00161022	0.008020854
T_{MRT}	0.013983999	0.000852172	−0.001908636	0.005045445
UTCI	0.009545436	0.001904744	−0.000718157	0.005913543
PET	0.009205817	0.002125427	−0.00049742	0.007040227
APV	0.008294668	0.00046057	−0.001785132	0.005639905
Wind Velocity	−0.0000625	0.000406831	−0.002544454	0.005928276
Rel. Humidity	0.006227641	0.001249549	−0.001516717	0.005187514
Clothing	0.00358564	−0.000252172	−0.002811243	0.003619887
Exposure	0.002119619	0.000186258	−0.002425803	0.004995365
Activity	0.0000589752	0.00027578	−0.0014399	0.004340309
Shelter	0.000554676	0.000123838	−0.000521769	0.001488226
AM/PM	0.000100494	0.000197222	−0.000674255	0.002742059

Table B.3
Aesthetic Preference Vote (APV) and bus shelter presence contingency table.

APV Category	Bus Shelter Absent (count)	Bus Shelter Present (count)
Very Unpleasant	0	8
Unpleasant	0	10
Slightly Unpleasant	1	9
Neutral	4	13
Slightly Pleasant	5	6
Pleasant	3	11
Very Pleasant	2	5

B.1. *Land Cover Composition and View Factor Metrics for all Sixty Study Sites*

See attached spreadsheet.

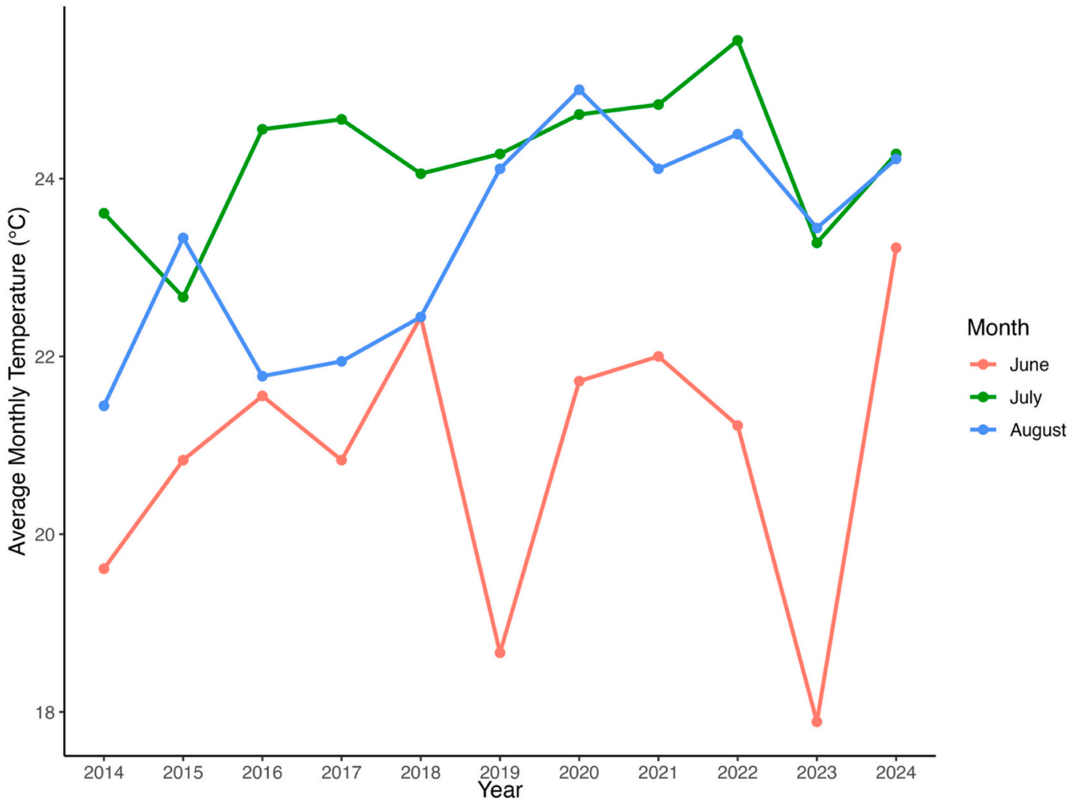

Fig. B.1. Historic average air temperatures for summer months (June – August) in Denver between 2014 and 2024. The year of the study, 2023, demonstrates lower than average air temperatures, particularly since 2019 for all months. Historic data acquired from weather.gov.

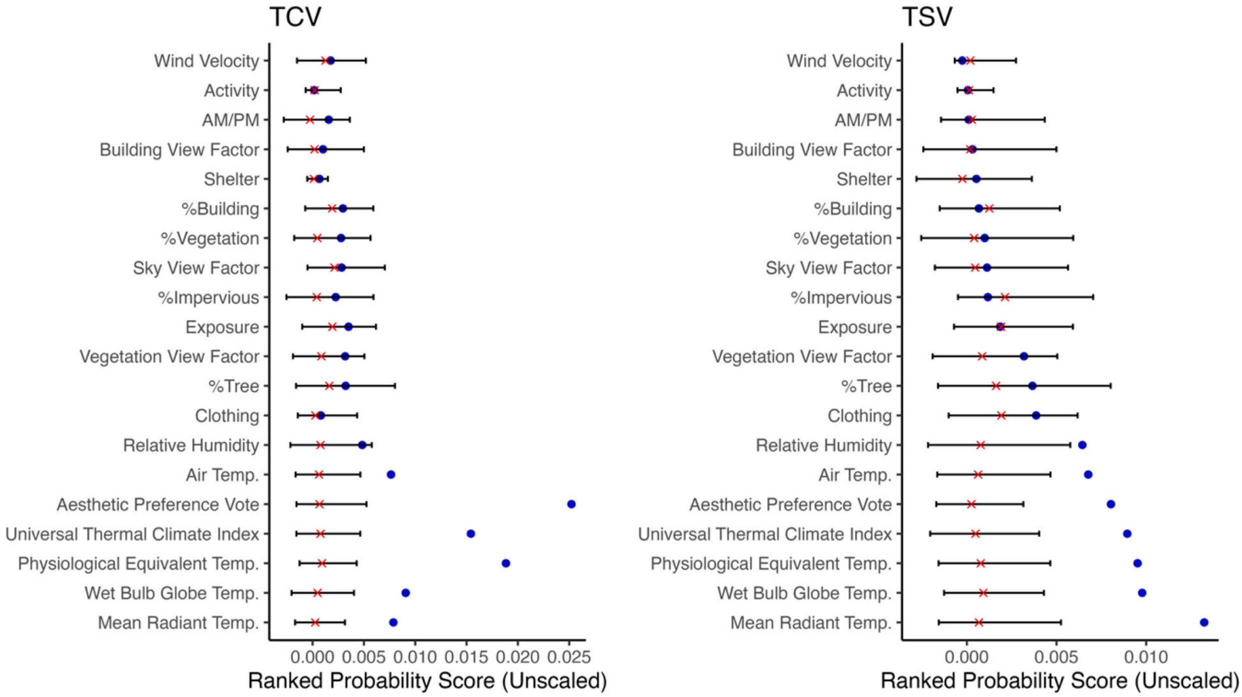

Fig. B.2. Ordinal forest validation for Thermal Comfort Vote (TCV) and Thermal Sensation Vote (TSV). Blue dots represent the observed variable importance (unscaled Ranked Probability Score) from the ordinal forest models found in Section 3.2. Red crosses indicate the mean unsacled RPS values from 100 null models, generated by randomly permuting the TCV and TSV responses. Gray lines show the 95 % confidence intervals of the RPS under the null distributions. Predictors whose observed importance falls outside the null confidence intervals are likely to be genuinely informative, supporting the validity of their role as main predictors of transit users' thermal perceptions. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

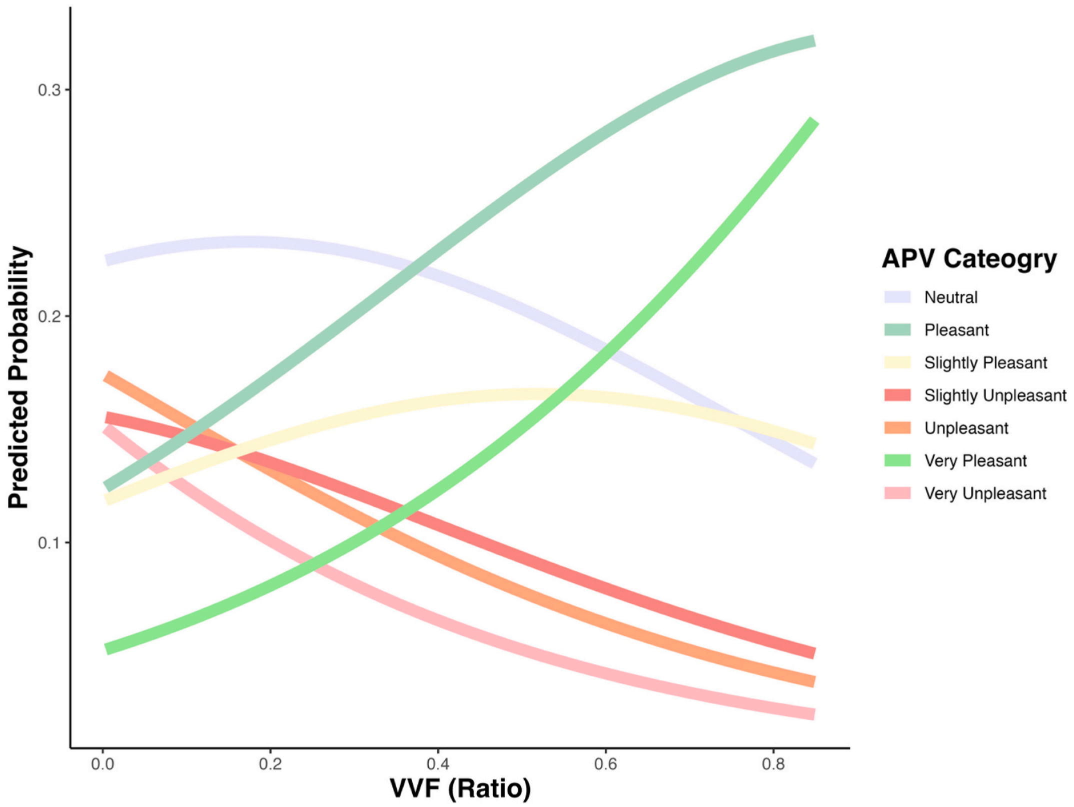

Fig. B.3. Increases in Vegetation View Factor (VVF) at bus stops are associated with the likelihood that a bus stop is rated as aesthetically pleasing.

Appendix C. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.uclim.2025.102606.

Data availability

Data will be made available upon request.

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