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E-bikes enhance climate resilient urban mobility through heat adaptation as revealed by mediation analysis

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Climate change intensifies urban heat stress, creating urgent challenges for sustainable mobility. Here we analyzed 4068 individuals' heat adaptation behaviors across different transportation modes in Beijing. Our findings, derived from a causal mediation framework, suggest that e-bikes offer superior climate resilience compared to traditional cycling and walking. E-bike users demonstrated strong overall adaptation and adopted significant protective measures, contrasting with pedestrians and cyclists who both showed significant reductions in mobility. Demographic analysis revealed female users exhibited particularly strong adaptation responses, while the elderly showed concerning gaps in adaptation capacity across all transportation modes. Urban design features further influenced adaptation, with green spaces helping to sustain mobility. These findings, while context-specific to the Beijing study area, suggest that supporting e-bike infrastructure represents a promising strategy for maintaining urban mobility while enabling effective heat adaptation behaviors under increasing climate stress.

Climate change has intensified heat-related health risks globally, with increasing frequency, duration, and intensity of heat waves posing substantial challenges to urban populations¹. According to recent assessments, heat-related mortality in urban areas has increased by over 50% in the past two decades, with particularly severe impacts in rapidly urbanizing regions². Given that greenhouse gas emissions in the atmosphere will continue driving temperature increases in the coming decades³, adaptation to higher temperatures has become an unavoidable necessity in urban areas^{4–6}. These impacts are experienced unequally across populations due to individual, demographic, geographical, and social factors that determine vulnerability and adaptation capacity^{7,8}.

Recent studies have demonstrated the urgency of tracking and enhancing urban climate adaptation capabilities⁹. While cities worldwide are increasingly integrating climate adaptation into their sustainable development strategies, these efforts must address multiple interconnected urban systems. Among these, transportation systems warrant particular attention due to their dual role in shaping both climate vulnerability and adaptation options¹⁰. Despite this critical importance, considerable gaps remain in understanding how urban residents modify their mobility behaviors in response to climate stress¹¹. This is particularly true for the ubiquitous first- and last-mile (FM/LM) segments of multimodal journeys, where trips to and from public transit hubs are often necessary, time-constrained, and involve direct exposure to the elements.

Users of urban transportation systems face particular challenges. Studies have shown that cyclists and pedestrians exposed to temperatures above 35 °C show a 40% higher risk of heat exhaustion compared to those in air-conditioned environments¹². Hospital admissions for heat-related conditions can increase by 20–30% during heat waves, with outdoor workers and active commuters showing elevated risk¹³. These health impacts underscore the particular vulnerability of transportation system users to heat stress.

Research on heat adaptation has traditionally relied heavily on health outcome-based indicators, particularly mortality and morbidity rates, to assess population-level adaptation capacity. This approach has generated crucial insights into heat vulnerability and adaptation patterns¹⁴, revealing marked variations in heat-related mortality across different populations¹⁵. However, while these ex-post adaptation indicators effectively capture long-term health outcomes, they provide limited insight into the immediate behavioral mechanisms through which adaptation occurs, particularly in urban mobility contexts where exposure to heat stress is often unavoidable.

Within this context, individual protective behaviors represent a critical and immediately accessible adaptation strategy. Unlike longer-term institutional or infrastructural adaptations, these behaviors can be implemented rapidly and modified based on changing conditions. Studies have shown that effective behavioral adaptation can reduce heat-related mortality by 15–20% in urban populations¹⁶. These protective behaviors work through multiple physiological mechanisms: umbrellas and hats reduce direct solar

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radiation exposure, which can lower skin temperature by 3–4 °C¹⁷; proper hydration helps maintain blood volume and sweating capacity; while lightweight, breathable clothing enhances evaporative cooling¹⁸. The effectiveness of adaptation strategies varies significantly across different population groups. Recent studies have identified substantial differences in adaptation capacity based on age, gender, and socioeconomic status¹⁹. Transportation mode choice significantly influences both heat exposure and adaptation options. Studies have shown that cycling trips decrease significantly at high temperatures above 31 °C²⁰, with traditional cyclists particularly vulnerable to heat stress due to physical exertion²¹. Meanwhile, pedestrians exhibit complex adaptation patterns influenced by multiple environmental factors such as shade availability and rest areas²².

However, three critical knowledge gaps remain: First, while extensive research has documented adaptation outcomes through mortality and morbidity indicators, there remains limited empirical evidence on how urban residents implement proactive behavioral adaptations under different temperature conditions. Second, while correlational relationships between temperature and health outcomes are well documented, there is a notable lack of rigorous causal inference regarding how temperature directly influences adaptation behaviors²³. Third, although research has shown that demographic factors like age and gender significantly influence heat vulnerability¹⁵, few studies have systematically examined how these characteristics moderate the relationship between temperature and adaptation behaviors within our proposed framework.

This study addresses these gaps by developing a methodological framework combining mobile monitoring with deep learning technology to investigate heat adaptation behaviors in urban settings. Through constructing a Climate-Mobility-Adaptation (CMA) framework, we analyzed 4068 individuals' adaptation behaviors across different transportation modes, demographic characteristics, and built environment contexts. Our analysis specifically focuses on active and semi-active mobility modes (walking, cycling, and e-biking) where users are continuously exposed to ambient weather conditions. This group represents a particularly vulnerable population whose travel is essential for short-distance and "last-mile" urban connectivity. The methodological innovations include: (1) the integration of panoramic cameras with deep learning for automatic adaptation behavior recognition; (2) establishment of a systematic causal inference framework for evaluating temperature's behavioral impact mechanisms; (3) comprehensive integration of built environment variables into the adaptation behavior analysis framework, allowing for quantification of how urban design features influence heat adaptation across different demographic groups and transportation modes. This methodological framework offers a replicable approach that can be applied to cities globally, facilitating context-specific investigations for understanding and promoting urban heat adaptation.

Results

Climate-Mobility-Adaptation framework

Our analysis develops a CMA framework to examine how temperature influences urban residents' adaptation behaviors through multiple pathways (Fig. 1). This framework distinguishes between three key relationships: temperature's effect on transportation modes (path A), the influence of mobility decisions on adaptation behaviors (path B), and temperature's direct effect on adaptation behaviors. This approach allows us to quantify both direct and indirect (Mediated) effects of temperature on adaptation behaviors across different population segments and transportation modes. When temperature reduces mobility (negative path A), this represents an avoidance strategy—people adjust travel patterns to reduce heat exposure. Conversely, a positive path B indicates that those who do travel implement more adaptation behaviors. The direct effect captures how temperature influences adaptation behaviors beyond its impact on mobility decisions. By analyzing these pathways, we can determine which transportation modes and demographic groups exhibit the most effective adaptation strategies and under what conditions.

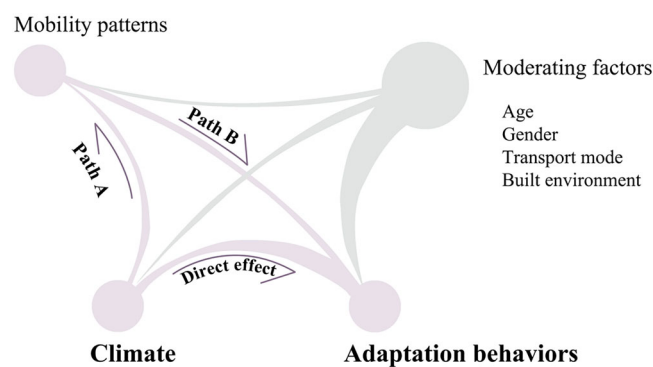


Fig. 1 | Climate-Mobility-Adaptation (CMA) framework. The diagram illustrates the direct and mediated pathways between temperature, transportation modes, and adaptation behaviors. Path A represents temperature's effect on mobility choices, Path B represents the influence of mobility decisions on adaptation, and the direct arrow captures temperature's immediate impact on behaviour.

Table 1 | Weather conditions during the observation period

Date	Temperature (°C)	Humidity (%)	UV	Weather
5.26	26 °C	39	6	Sunny
5.28 (weekend)	26 °C	53	5	Few clouds
5.31	22 °C	44	5	Cloudy
6.02	27 °C	22	7	Sunny
6.05	32 °C	17	7	Sunny
7.19	34 °C	29	8	Sunny
7.26	29 °C	65	6	Few clouds
7.27	31 °C	66	6	Few clouds
8.13 (weekend)	32 °C	75	7	Few clouds
8.14 (weekend)	32 °C	57	7	Sunny

Overview of observation samples

During the research period (5.26–8.14, 2023), 10 days of observation data were recorded, with temperatures ranging from 22 to 34 °C, humidity 17 to 75%, UV index 5 to 8, and weather conditions including sunny, few clouds, and cloudy days. A total of 4068 individuals were observed, including 2805 electric bicycle (e-bike) users (68.9%), 375 cyclists (9.2%), and 888 pedestrians (21.9%). The observation data covered both weekdays and weekends, as well as different weather conditions, ensuring the representativeness of the sample. The specific daily observation data is shown in Table 1.

Based on the 3D visualization analysis (Fig. 2), the heat adaptation behavior patterns across different transportation modes (e-bikes, cyclists, and pedestrians) are displayed. The figure presents three key indicators: the adoption rate of any heat adaptation behavior (ratio), the adoption rate of multiple heat adaptation behaviors (1+beh), and the overall intensity of heat adaptation behaviors (behratio). Throughout the observation period from May 26 to August 14, e-bike users demonstrated the highest heat adaptation capacity across all indicators. Bicycle users showed moderate levels of adaptation, while pedestrians generally exhibited the lowest adaptation levels.

Data analysis indicates that as temperatures increased (especially when exceeding 30 °C), heat adaptation behaviors increased across all transportation modes, though to varying degrees. E-bike users not only showed the highest adoption rate of single heat adaptation behaviors but also demonstrated a stronger capacity for behavior combinations, particularly under high-temperature conditions.

Analysis of adaptation behavior diversity across observation dates revealed distinct patterns related to both temperature variations and transportation modes (Fig. 3). Overall, e-bike users consistently

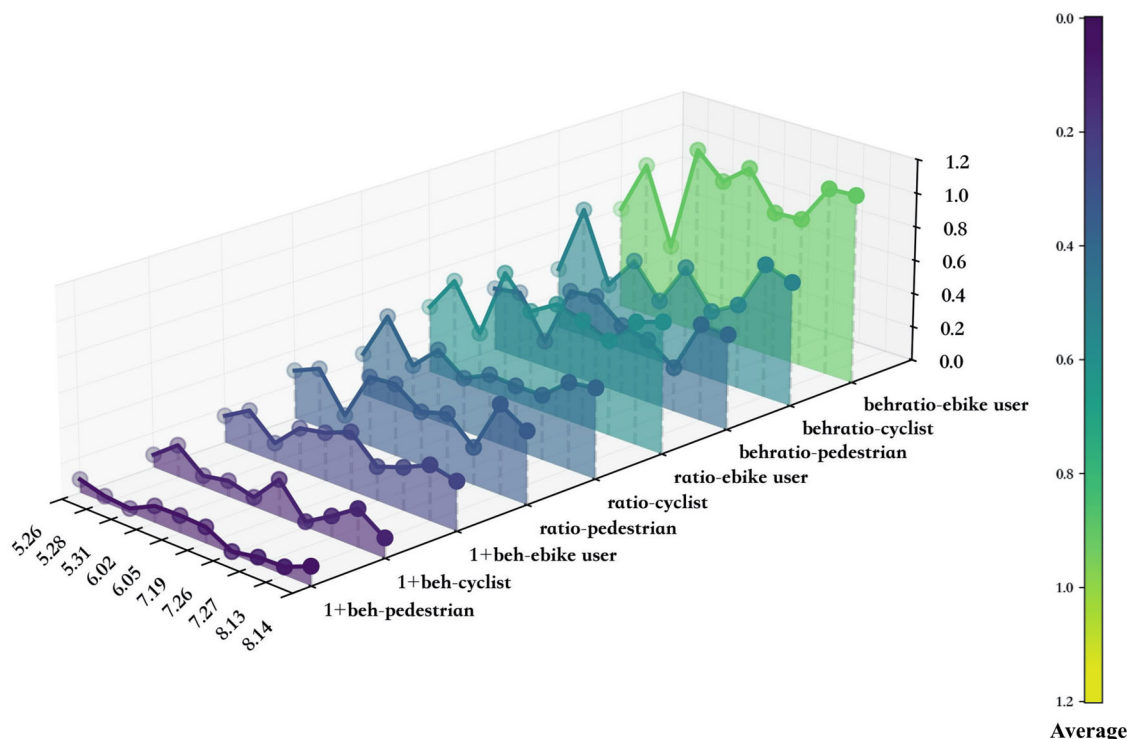


Fig. 2 | Descriptive statistics of heat adaptation behaviors across transportation modes. The chart presents three key indicators: the adoption rate of any heat adaptation behavior (ratio), the adoption rate of multiple heat adaptation behaviors

(1+beh), and the overall intensity of heat adaptation behaviors (behratio). Comparisons are shown for e-bike users, cyclists, and pedestrians.

demonstrated the greatest diversity of adaptation behaviors across all weather conditions. UV-protective clothing emerged as the most frequently adopted measure across all transportation modes (20–38%), followed by wide-brimmed hats and baseball caps.

Temperature significantly influenced adaptation behavior diversity. On the hottest observation day (July 19, 34 °C), all transportation modes showed increased adaptation measure adoption, with e-bike users exhibiting particularly high rates of cooling sleeves (21.1%) and UV-protective clothing (24.1%). During high humidity conditions (July 26–27, 65–66% humidity), adaptation strategies shifted toward increased use of UV-protective clothing across all transportation modes.

Transportation-specific adaptation patterns were evident. E-bike users favored UV-protective clothing, cooling sleeves, sun shields, and wide-brimmed hats. Cyclists predominantly adopted UV-protective clothing, baseball caps, and wide-brimmed hats. Pedestrians uniquely showed high adoption of sun umbrellas (13–35%) alongside UV-protective clothing and wide-brimmed hats. During high UV index days (7–8), face protection measures and sunglasses usage increased notably among all transportation users, particularly e-bike riders.

Main causal effect analysis

As indicated in Fig. 4, the overall analysis demonstrates a significant positive total effect of temperature on adaptation behaviors (0.720), characterized by complex underlying pathways. The significant negative path A coefficient (−0.209**) suggests that higher temperatures tend to reduce pedestrian flow, representing an avoidance strategy. Concurrently, the highly significant positive path B coefficient (0.408***) indicates that individuals who do travel in the heat are more likely to adopt protective measures. The analysis reveals a significant positive direct effect (Average Direct Effect (ADE)) of 1.028** and a significant negative indirect effect (Average Causal Mediation Effect (ACME)) of −0.308***, suggesting that while temperature directly prompts adaptation, this effect is partially counteracted by the reduction in pedestrian flow. This interplay confirms a partial mediation,

where temperature influences behavior both directly and indirectly through its impact on mobility decisions.

Gender analysis reveals distinct patterns. Females show a strong, positive total effect (1.685*) with a significant positive direct effect (2.296***), indicating a robust adaptive response to rising temperatures. Their adaptation is partially mediated, with temperature significantly reducing their mobility (Path A: −0.354**) while simultaneously increasing protective behaviors among those who remain active (Path B: 0.484**). In contrast, males exhibit no significant total effect and show a weaker, though still significant, adoption of protective measures (Path B: 0.074*) when their mobility decreases (Path A: −0.216*).

Age-based analysis highlights significant disparities in adaptation capacity. Middle-aged individuals demonstrate the most effective adaptation, with a significant positive total effect (0.743). They effectively balance mobility reduction (Path A: −0.266***) with a strong adoption of protective measures (Path B: 0.430***), resulting in a significant positive direct effect (1.152*). The youth and elderly groups, however, show no significant total effect in their adaptation responses. This is particularly concerning for the elderly, who are known to be more vulnerable to heat stress. The lack of significant adaptation patterns in these groups points to potential barriers, such as lower risk perception or physical limitations, highlighting a critical need for targeted interventions.

Transportation mode analysis reveals that e-bike users are the most resilient. They show a significant positive total effect (1.320*) on adaptation, maintaining their mobility with a non-significant reduction in traffic (Path A: −0.136) while significantly increasing protective behaviors (Path B: 0.265**). Pedestrians, while showing a significant decrease in mobility (Path A: −0.387**), still adopt protective measures effectively (Path B: 0.130***). Cyclists present a unique case; although higher temperatures significantly reduce their numbers (Path A: −0.511*), those who continue to cycle adopt adaptive behaviors at a very high rate (Path B: 0.710***), suggesting that only the most prepared cyclists venture out in the heat.

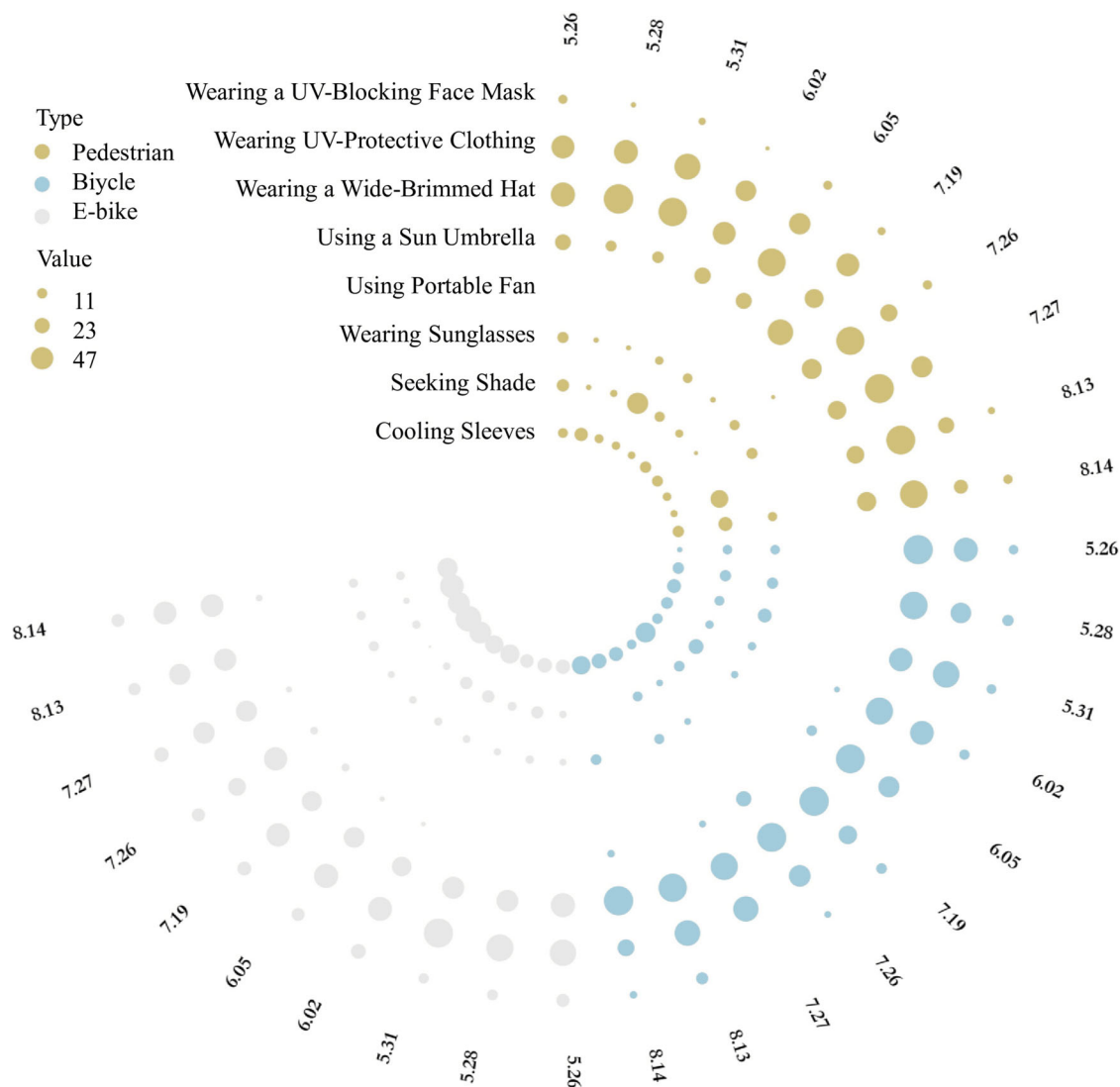


Fig. 3 | Diversity and patterns of heat adaptation behaviors across transportation modes. The visualization displays the variation in adaptation behavior diversity across different observation dates and weather conditions. It details the adoption

frequency of specific measures (e.g., UV-protective clothing, hats) across e-bike users, cyclists, and pedestrians.

Specific adaptation behaviors effectiveness analysis

An analysis of specific adaptation behaviors reveals varying effectiveness and adoption patterns. The most effective measures show strong, significant positive total effects, including wearing sunglasses (2.235***) and wide-brimmed hats (0.757**). These measures offer direct UV protection and thermal comfort with minimal physical burden. Seeking shade (1.392) and using a sun umbrella (0.539*) are also effective strategies.

However, some behaviors show non-significant or even negative effects. Wearing cooling sleeves (−0.116) and using e-bike sunshade attachments (−0.244*) were associated with a slight negative total effect, though the effect for cooling sleeves was not statistically significant. This suggests these items might impose a thermal burden or restrict airflow during physical activity, potentially increasing discomfort. Similarly, wearing UV-protective clothing (0.200) and face masks (−0.188) did not show a significant positive effect on the overall adaptation count, indicating that while these are common, their effectiveness in the context of this study’s overall behavioral metric is less pronounced than items like sunglasses or hats.

Built environment pathway analysis

The built environment analysis reveals complex relationships between urban design features and heat adaptation behaviors, acting as crucial

moderators in our causal framework (Fig. 5). While specific coefficients for environmental variables were analyzed as controls in our models, their influence is best understood through their interaction with different demographic and transport groups.

The analysis indicates that green spaces (green view index (GVI)) play a protective role. For the general population, and particularly for males and middle-aged individuals, higher GVI values appear to mitigate the temperature-driven reduction in mobility, encouraging continued travel even in the heat. This finding aligns with the known cooling benefits of urban vegetation, suggesting that green corridors can sustain urban mobility during heat events.

Sky view factor (SVF) demonstrates divergent effects across transport modes. Pedestrians actively avoid areas with high sky exposure, as reflected in their reduced presence in such locations. In contrast, cyclists and e-bike users seem less deterred by open, sun-exposed routes, likely because their faster travel speed allows them to traverse these areas more quickly. This highlights how urban morphology interacts with travel mode to create different constraints and opportunities for heat avoidance.

Road width also appears to amplify heat exposure, with wider roads potentially discouraging travel more than the baseline effect of temperature alone. This suggests a compound effect where urban design can either buffer



Fig. 4 | CMA framework pathway analysis results. Path coefficients showing temperature’s direct and indirect effects on adaptation behaviors, with asterisks indicating significance levels (* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$).

or intensify the impacts of heat stress, influencing both the decision to travel and the selection of adaptive strategies. These findings underscore the importance of designing cool pathways with ample shade and green infrastructure to support safe and active mobility for all urban residents.

Discussion

Theoretical and methodological contributions

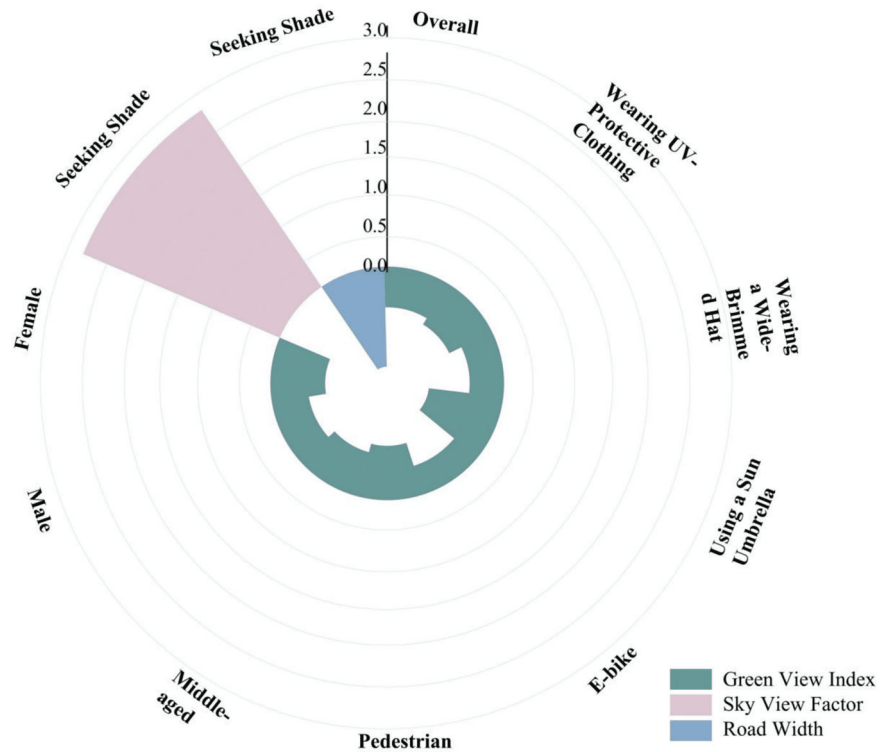
In the context of accelerating global warming, our study systematically examined urban residents’ heat adaptation behaviors using the CMA framework. By employing a modern causal mediation analysis based on the counterfactual framework, we advance the theoretical understanding of urban heat adaptation. This approach moves beyond traditional associative methods to quantify both the direct behavioral responses to temperature (ADE) and the strategic mobility adjustments that mediate this relationship (ACME). Unlike frameworks that treat demographic factors as static vulnerability indicators, our analysis reveals how these characteristics dynamically shape adaptation strategies through distinct causal pathways, offering a more nuanced view of adaptation as a complex behavioral process.

Transportation mode differences reveal crucial adaptation mechanisms. The superior adaptation of e-bike users is strongly supported, as they demonstrate a significant positive total effect (1.320*) while their travel

volume is not significantly reduced (Path A: -0.136). This suggests e-bikes enhance climate resilience by lowering the physical barrier to adopting protective measures, a finding that extends beyond prior research merely documenting activity reduction. In stark contrast, our analysis uncovers a “filtering effect” for cyclists. The significant decrease in their numbers in high heat (Path A: -0.511^*), combined with the strong positive adaptation behaviors among those who remain (Path B: 0.710^{***}), indicates that high temperatures deter all but the most prepared individuals. This finding revises the simplistic notion of negative adaptation, revealing a more complex behavioral selection process. Pedestrians employ a dual strategy of reducing mobility (Path A: -0.387^{**}) and adopting protective gear (Path B: 0.130^{***}), showcasing a classic combination of avoidance and protection.

Demographic factors critically moderate adaptation pathways. We find pronounced gender differences, with females exhibiting a strong and direct adaptive response to temperature (Total Effect: 1.685^* ; ADE: 2.296^{***}), suggesting a higher risk perception or stronger ingrained protective habits. Men, conversely, show no significant overall adaptation response. Age-based variations highlight a critical vulnerability gap. Middle-aged individuals effectively balance mobility reduction with protective measures, showing a significant positive adaptation effect (0.743). However, the lack of any significant adaptation pattern among the elderly is a major concern. This inertia, failing to either reduce exposure or increase protection, points

Fig. 5 | Coefficients of built environment's influence on mobility patterns across different groups. The plot illustrates the moderating effects of urban design features, including Green View Index, Sky View Factor, and Road Width. It displays how these factors influence mobility decisions across different demographic (gender, age) and transportation mode groups.



to major barriers—be it physical, informational, or perceptual—that demand urgent policy attention.

The built environment shapes adaptation opportunities. Our findings confirm that urban design operates through complex mechanisms to either facilitate or hinder adaptation. The protective effect of the GVI against mobility reduction suggests that green spaces provide both physical (shade) and psychological comfort, sustaining activity levels during heat. Conversely, the varying effects of SVF across transport modes reveal how spatial characteristics interact with mobility constraints. Pedestrians actively avoid open, exposed areas, whereas faster-moving e-bike and bicycle users are less constrained, demonstrating that urban morphology creates differentiated adaptation landscapes for different users. This complex interaction between built form and human behavior provides new insights into how urban design can be leveraged to enhance climate resilience beyond just direct thermal mitigation.

Policy implications and recommendations

These findings have crucial implications for urban climate adaptation policy and practice, particularly in rapidly urbanizing regions facing increasing heat stress. The development of targeted population support strategies should consider both physiological vulnerability and behavioral adaptation barriers. Following previous work¹⁴, we recommend establishing community support networks to promote social learning of adaptation behaviors. The observed stronger adaptation capacity among middle-aged groups suggests potential for peer education programs, leveraging their successful adaptation strategies to benefit more vulnerable populations.

Built environment optimization requires a multi-faceted approach considering both direct thermal benefits and behavioral facilitation effects. The development of “cool pathway” networks emerges as a critical priority, requiring continuous shade corridors with comprehensive tree canopy coverage. These networks should prioritize routes connecting elderly residential areas to key destinations, integrating building shade and green infrastructure to maintain optimal SVFs. The installation of heat-resistant permeable pavements on high-traffic pedestrian routes further enhances these corridors’ effectiveness in reducing thermal stress.

For high-density cities like Beijing, priority should be given to establishing comprehensive e-bike lane networks that connect residential areas

with major commercial and employment centers, accompanied by shaded charging stations integrated with public transit nodes. In the contexts with strong existing cycling cultures, policies should focus on e-bike subsidies and conversion programs to transition traditional cyclists to e-bikes during the summer months, supported by education on effective heat adaptation behaviors. For cities with car-dependent infrastructure, implementing protected e-bike corridors along major transit routes with dedicated traffic signal priority would enhance the feasibility as an alternative mobility option. In all contexts, particular attention should be paid to connecting elderly residential areas to essential services through shaded e-bike corridors, addressing the concerning adaptation gaps identified in this demographic group.

Our findings advance multiple Sustainable Development Goals through concrete, measurable impacts. For Sustainable Cities (SDG 11), our work provides quantitative metrics for heat-adaptive urban design and demonstrates the effectiveness of integrated mobility-adaptation approaches. In terms of Climate Action (SDG 13), we develop evidence-based adaptation strategies and quantify the effectiveness of various measures, creating a framework for monitoring adaptation progress and identifying specific intervention points for maximum impact. Our contribution to Good Health (SDG 3) is equally substantial, mapping heat vulnerability patterns and identifying effective protective behaviors that can be implemented at both individual and community levels.

Limitations and future research directions

While this study introduces a framework and provides compelling findings, we acknowledge several limitations, particularly concerning the establishment of definitive causality.

First and foremost, the study’s observational design is its primary limitation. Although we employed a rigorous counterfactual-based mediation analysis to test our hypothesized causal pathways, this statistical approach cannot replace a true experimental or quasi-experimental design. Therefore, our findings should be interpreted as strong, theory-consistent evidence rather than definitive causal proof.

This observational design leads to a key challenge: the potential for unobserved confounding variables. There may be unmeasured factors that

correlate with both temperature and adaptation behaviors, which could bias our estimates. For instance, an individual's underlying health consciousness or socioeconomic status could simultaneously influence their choice of transportation mode (e.g., preferring an e-bike), their sensitivity to heat, and their propensity to adopt protective behaviors. Similarly, other micro-environmental factors that co-vary with temperature, such as localized air pollution or noise levels, might also influence travel decisions independently.

This omission of individual-level data stems from an inherent trade-off in our research design. Our study lacks individual-level socioeconomic and situational covariates. The analysis is limited to demographic characteristics (age and gender) that could be visually inferred, while critical variables like income, education, occupation, and specific trip purpose were not collected. We chose a large-scale observational methodology to objectively capture the real-time, spontaneous behaviors of over 4000 individuals, a scale difficult to achieve with surveys. However, this non-intrusive approach precludes the collection of sensitive personal data that would be necessary for a more granular analysis. Doing so would have been logistically impractical and ethically complex. Consequently, while our study benefits from a large sample of naturalistic behavior, its findings should be interpreted with the understanding that socioeconomic variables play a crucial role in shaping adaptation capacity. Furthermore, the analysis did not include formal robustness checks, such as sensitivity analyses, to quantify how strong an unobserved confounder would need to be to alter our conclusions. This constitutes an important avenue for future work.

Beyond the issue of causality, the study's generalizability is constrained by its temporal and spatial scope. The study's temporal scope is a primary limitation. Our analysis is based on 10 observation days, which is insufficient to capture long-term adaptation processes such as behavioral habituation over a full season or responses to prolonged, multi-day heatwave events. However, the selection of these days was deliberate to enable a comparative analysis. The sampling period was designed to establish a behavioral baseline on cooler, comfortable days in late May (22–26 °C) and contrast it with behavior on hotter summer days, including one of the hottest days of the year in the area (34 °C). Therefore, while our results may reflect shorter-term behavioral adjustments rather than sustained adaptation patterns, they provide a valuable, comparative snapshot of how behaviors change across a significant temperature gradient.

Spatially, the geographic representativeness is limited. The study was conducted in a single 2 × 2 km district in Beijing that is modern, redeveloped, and green-rich, which is not representative of all urban contexts. However, this choice of a high-quality urban environment was intentional, as it allowed us to study a high volume of active travel and the associated adaptation behaviors in a setting where such travel is a viable choice. While the findings may not directly generalize to more heat-stressed or car-dependent environments where outdoor activity might be suppressed, they offer crucial insights into the adaptation patterns that emerge in well-designed urban spaces. Our results are likely most relevant to similar modernizing districts in large cities in China and elsewhere, serving as an important benchmark for future comparative studies.

Our measurement methodology also involves specific trade-offs. Our reliance on visual observation means we could only capture a specific subset of adaptation behaviors. Our methodology cannot account for crucial but less visible strategies such as hydration, strategic route selection to maximize shade, altering travel times to avoid peak heat, or seeking temporary refuge in air-conditioned spaces. This is a key limitation, and it implies that our findings likely underestimate the true, holistic adaptive capacity of the observed individuals. This limitation reflects a methodological trade-off between the scale of observation and the depth of behavioral data. Therefore, our study should be seen as a characterization of visible, in-situ protective measures, rather than a complete account of all adaptation strategies.

Similarly, another limitation concerns the measurement of heat exposure. While we utilized hourly data from the Apple Weather API for the Shijingshan District, this approach does not capture hyperlocal microclimatic variations. Factors such as mean radiant temperature or wind channeling can create a thermal environment that differs significantly from the

reported ambient temperature. However, this methodological choice was aligned with the study's behavioral focus. We aimed to model how individuals react to the publicly reported weather information that guides their daily decision-making. Therefore, while our exposure metric is a limitation for assessing precise physiological heat stress, it is well-suited for investigating the behavioral adaptations driven by the information people actually use. Future research could integrate dynamic, on-site microclimate measurements and estimate more comprehensive thermal indices, such as the Universal Thermal Climate Index or Wet Bulb Globe Temperature, to provide a more physiologically relevant measure of heat stress.

Finally, it is important to clarify the study's focus. The focus on walking, cycling, and e-biking inherently captures behaviors during short-distance trips, many of which may function as first- or last-mile feeders to public transit. The reviewer correctly notes that such trips can be constrained by schedules and specific purposes. We consider this a defining characteristic of the context we are studying, rather than a confounder. The adaptation strategies (or lack thereof) observed are precisely those employed by urban residents during these essential, often hurried, connecting journeys. Our findings should therefore be interpreted as being highly relevant to understanding heat adaptation challenges for multimodal travel.

Looking forward, these limitations highlight clear directions for future research. Studies employing natural experiments or quasi-experimental methods could provide stronger causal identification. Furthermore, integrating individual-level survey data on socioeconomic status, risk perception, and health conditions with behavioral observations would allow for richer models that control for key potential confounders. Despite these limitations, our study makes a significant contribution by applying a sophisticated analytical framework to observational data, providing strong suggestive evidence of the mechanisms behind heat adaptation and identifying vulnerable groups. It lays a critical foundation upon which more definitive causal research can be built.

The primary global significance of our work lies in the methodological template it provides for context-specific inquiry. While the identified adaptation patterns are intrinsically tied to the Beijing context, the underlying behavioral mechanisms explored here may be relevant in other urban settings, warranting further comparative research. The demonstrated methodological advances provide a template for adaptation behavior monitoring that could be replicated in diverse urban settings, contributing to a more nuanced and evidence-based approach to global urban heat adaptation.

Conclusion

Within the specific context of this exploratory study, this research provides strong evidence from a mediation analysis that e-bikes offer a climate-resilient solution for urban mobility, particularly when compared with other modes involving direct and continuous weather exposure, such as traditional cycling and walking. While transport modes like private cars or the metro provide climate-controlled environments, e-bikes demonstrate superior resilience for the significant share of urban trips that remain exposed to the elements, highlighting their critical role in building a heat-adapted active transportation system.

Through our CMA framework combining mobile monitoring with deep learning technology, we reveal that e-bike users maintain remarkably stable mobility patterns during high temperatures. Our analysis demonstrates a non-significant reduction in e-bike ridership (Path A: -0.136) compared to substantial decreases among pedestrians (Path A: -0.387^{**}). Traditional cyclists also showed a significant decrease in their numbers (Path A: -0.511), but those who continued to cycle adopted adaptive behaviors at a very high rate (Path B: 0.710), suggesting a filtering effect. E-bike users also exhibited superior adaptation capabilities, showing a significant positive total adaptation response (Total Effect: 1.320^*) and actively adopting protective measures when traveling (Path B: 0.265^{**}). They were particularly effective in implementing sun protection measures, with strong positive total effects for wearing sunglasses (2.235^*) and wide-brimmed hats (0.757^{**}).

Our demographic and environmental analyses further strengthen these findings about e-bikes' climate resilience. Female users demonstrated particularly strong adaptation responses (Total Effect: 1.685)*, while middle-aged users showed an optimal balance between mobility maintenance and protective behaviors (Total Effect: 0.743). The built environment analysis confirmed the moderating role of urban form, such as the GVI, helping to sustain mobility during heat.

However, we identified critical gaps in adaptation capacity, particularly among elderly populations who showed no significant adaptation patterns, highlighting urgent needs for targeted support. These adaptation patterns were systematically documented through mobile monitoring methodology, achieving 79.3% accuracy in behavior recognition. Our findings demonstrate that e-bikes not only maintain mobility under heat stress but also enable effective adaptation behaviors, offering a promising solution for climate-resilient urban transportation. Future research should examine longitudinal adaptation patterns and socioeconomic factors while expanding the investigation to diverse urban contexts.

Data and methods

Study area

This study selected a typical urban area of 2 × 2 km in Shijingshan District, Beijing, as the research site (Fig. S1). The area is located along Beijing's important Fifth Ring Road, adjacent to the intersection with Fushi Road that connects to Beijing's city center, making it highly accessible. The research area is close to the iconic Shougang Park, a venue for the 2022 Winter Olympics, and contains various functional facilities, including educational, medical, commercial, office, and residential areas, resulting in substantial daily pedestrian flow. Much of this activity is characteristic of short-distance local errands and "first- or last-mile" feeder trips to and from public transit, providing a realistic context for observing adaptation behaviors during necessary and often time-constrained urban travel. Shijingshan District is known for its good green conditions and numerous parks, with the research area having excellent green coverage. This high-quality green environment enables the area to maintain high pedestrian activity even during summer high temperatures, providing an ideal location for observing heat adaptation behaviors. The selection of such a modern, well-planned district was a deliberate choice to study adaptation behaviors in a context where active mobility is actively encouraged and facilitated by the urban form, thus providing a rich environment for observation. This study selected urban roads within the research area as observation objects, with a total observation network length of approximately 50 km, covering various typical urban road environments, including main roads, secondary roads, and branch roads, effectively representing the diversity of the urban built environment.

Beijing was selected as the study area due to several advantageous characteristics for investigating heat adaptation behaviors. As a densely populated megacity experiencing significant urban heat island effects, with summer temperatures frequently exceeding 30 °C, Beijing provides an ideal context for studying heat stress adaptation. The specific Shijingshan District study area represents a typical urban environment with diverse transportation infrastructure, mixed land uses, and varying built environment characteristics. While Beijing's specific urban morphology and cultural context may influence certain adaptation patterns, the physiological mechanisms of heat stress and the physical advantages of different transportation modes likely translate to other urban contexts globally. The methodological framework developed in this study can be readily applied to cities worldwide to verify and expand upon these findings across different climatic, cultural, and infrastructural conditions.

Data collection

This study employed a rotating mobile monitoring method for data collection^{24,25}, following predetermined routes and stopping at intersections to capture maximum pedestrian flow. Mobile data collection methods have proven their effectiveness and broad applicability in various urban environmental studies, including building energy consumption prediction²⁶, urban micro-scale temperature distribution²⁷, and traffic safety risk

assessment²⁸. Compared to traditional fixed-site monitoring, this method provides a more comprehensive capture of spatial heterogeneity in urban environments and the dynamic characteristics of human behavior.

Researchers used electric bicycles as observation tools, with Insta360 panoramic cameras mounted on top and GPS devices (1-s sampling frequency) recording the observation trajectory throughout the collection process (Fig. S2). The advantage of choosing the Insta360 panoramic camera lies in its 360° coverage capability, ensuring simultaneous capture of heat adaptation behaviors of all heat-exposed individuals on the road. Observations were conducted during the midday peak between 11:30–13:30. This specific time window was chosen for two primary reasons: (1) it represents the period of the day with the highest traffic flow and peak solar radiation intensity, making heat adaptation behaviors most necessary and observable, and (2) it allowed us to manage the significant health and safety risks of heat exposure for our field researchers during data collection. During the observation process, researchers stayed at road intersections for 1–3 min to capture maximum pedestrian flow during traffic light changes.

The observation period spanned 10 days from May 26 to August 14, covering two temperature categories: moderate temperature (26–30 °C) and high temperature (31–35 °C), and various weather conditions, including sunny and partly cloudy days, while ensuring coverage of both weekdays and weekends to ensure sample representativeness. The collected video data was later extracted at 1 frame per second and spatiotemporally matched with GPS trajectories to ensure each image had precise geographic location information. To ensure data quality, the research team established strict quality control procedures: first, daily time calibration and maintenance of collection equipment to ensure stable equipment performance; second, equipment function testing and GPS signal strength checking before each observation; third, real-time monitoring of the data collection process to promptly address equipment failures or signal interruptions; finally, completeness checking of the collected raw data, eliminating low-quality data caused by equipment failures or severe obstructions. These measures ensured the reliability and integrity of the research data.

User identification and demographic recognition

This study developed an automatic human and demographic feature recognition system based on deep learning. First, a YOLOv8 detection model was used for person detection (accuracy 95.3%), then a YOLOv8 classification model was applied to classify the detected persons, including transportation mode classification (pedestrians, cyclists, e-bike users, accuracy 92.1%), gender classification (male, female, accuracy 88.7%), and age group identification (children, youth, middle-aged, elderly, accuracy 85.4%). The model training and validation followed a rigorous process: first, 1000 images containing different scenes and lighting conditions were randomly selected from the total sample, with 80% used as the training set and 20% as the validation set, ensuring that both datasets had similar class distributions. During the training process, a five-fold cross-validation method was used to evaluate model performance, and model performance was optimized by adjusting hyperparameters such as learning rate and batchsize. The parameters for the transportation mode, gender, and age classification models were: `learning_rate = 1`, `batchsize = 1000`, `imgsize = 640`.

Heat adaptation behavior recognition

This study identified 11 main personal heat adaptation behaviors (see Table 2). These behaviors help individuals cope with heat stress through different mechanisms: sun umbrellas and sun hats mainly reduce human radiation heat gain by blocking direct solar radiation; UV-protective clothing and cooling sleeves enhance evaporative cooling efficiency through special materials; seeking shade as an active avoidance behavior can significantly reduce the perceived temperature.

For identifying heat adaptation behavior, we employed a two-phase approach: (1) manual expert annotation for the primary analysis dataset, and (2) development of an automated recognition model as a methodological contribution for future large-scale studies. The manual annotation

Table 2 | Heat adaptation behaviors and their adaptation mechanisms

Adaptation behavior	Adaptation mechanism	Model accuracy (%)
Using a Sun Umbrella ²²	Blocks direct solar radiation, reduces radiative heat gain	72.8
Wearing a Wide-Brimmed Hat Usage ¹⁸	Blocks direct solar radiation to the head, reduces heat load	78.3
Wearing UV-Protective Clothing ¹⁷	Special materials reflect UV radiation while promoting evaporative cooling	83.7
Wearing a UV-Blocking Face Mask ³⁰	Protects facial skin from direct solar radiation	76.9
Wearing Sunglasses ³¹	Reduces eye exposure to UV radiation, lowers thermal discomfort	72.4
Cooling Sleeves ¹⁸	Special materials protect limbs while enhancing evaporative cooling	83.8
Wearing Sunshade for E-Bikes ³²	Provides mobile shade for riders, reduces direct sun exposure	94.1
Seeking Shade ³³	Reduces radiative heat gain by avoiding direct sunlight	80.5
Wearing Cooling Sun-Protection Gloves ¹⁷	Reduces hand sun exposure while maintaining dexterity	58.4
Using Portable Fan ³⁴	Accelerates body heat dissipation through forced convection	-
Carrying Water ²¹	Maintains water balance, supports the sweating mechanism for heat dissipation	-

process involved two researchers independently coding all observations using the LabelMe tool. When annotation results differed, a third researcher reviewed and confirmed the final classification. This manual annotation achieved a high inter-annotator agreement coefficient (Cohen's Kappa = 0.86), indicating excellent reliability of the primary dataset used for all main analyses presented in this study.

In parallel, we developed an automated recognition model using the YOLOv8 classification framework (learning_rate = 1, batchsize = 1000, imgsize = 640). This automated approach achieved an overall accuracy of 79.3% across the 9 identified adaptation behaviors, demonstrating the feasibility of using deep learning technology for large-scale behavioral monitoring in natural urban settings. While this accuracy is sufficient for preliminary automated screening, our primary analyses relied on the more precise manually annotated dataset to ensure maximum reliability of findings.

Environmental variable measurement

Environmental variable measurements included the following aspects: (1) Meteorological data: hourly temperature, humidity, UV index, and other data were obtained through the Apple Weather API; (2) GVI and SVF: based on the collected panoramic images, an improved DeepLab v3+ semantic segmentation model was used for automatic extraction, with model accuracies on the validation set of 91.2 and 89.8%, respectively; (3) Road width: measured on the QGIS platform based on Google satellite imagery.

Data processing and analysis

This study adopted a 30-m equidistant sampling strategy to set observation points along the mobile routes. This spacing design was based on pre-experimental results, both maximizing the avoidance of repeat counting of the same individual while ensuring complete coverage of the research area. For each sampling point, the following indicators were calculated: (1) Overall heat adaptation behavior rate: number of people adopting any heat adaptation behavior/total number of people at that point; (2) Behavior type-specific adaptation rate: number of people adopting a specific type of heat adaptation behavior/total number of people at that point; (3) Group-specific adaptation rate: number of people in a specific group (e.g., gender, age, transportation mode) adopting heat adaptation behaviors/total number of people in that group at that point.

The research protocol for this study was reviewed and approved by the Institutional Review Board (IRB) of the University of Science and Technology Beijing (Approval No: 2024-3-109). All data collection was conducted in public spaces where individuals do not have a reasonable expectation of privacy. The panoramic images were used solely for the purpose of identifying transportation modes and recognizing anonymized demographic characteristics and adaptation behaviors. To protect privacy,

no personally identifiable information was collected, and the visual data was stored on a secure, encrypted server accessible only to the research team. As the observations were of people in public thoroughfares and involved no interaction with the subjects, the review board waived the requirement for individual informed consent.

Environment-behavior causal analysis

To rigorously estimate the causal pathways through which temperature influences heat adaptation behaviors, we adopted a modern causal mediation analysis framework based on the counterfactual (potential outcomes) model. This approach allows for the decomposition of the total effect of a treatment variable (Temperature, X) on an outcome variable (Adaptation Behavior Count, Y) into two distinct components: the Average Causal Mediation Effect (ACME) and the Average Direct Effect (ADE). The ACME represents the indirect pathway, quantifying how much of the temperature's effect is transmitted through the mediating variable (Pedestrian Flow, M). The ADE represents the direct pathway, capturing the temperature's effect on adaptation behaviors that do not operate through changes in pedestrian flow. The total effect is the sum of these two components (Total Effect = ACME + ADE).

We use regression models to estimate potential outcomes²⁹. We fit two ordinary least squares models: Mediator Model, which regresses the mediator (Pedestrian Flow) on the treatment (Temperature) and a set of control variables, and Outcome Model, which regresses the outcome (Adaptation Behavior Count) on the treatment, the mediator, and the same set of control variables.

To derive robust, non-parametric estimates and valid confidence intervals for the ACME and ADE, we employed a bootstrapping procedure with 1000 iterations. For each iteration, we resampled the dataset with replacement, re-fit both models, and calculated the resulting ACME and ADE. The final point estimates are the means of these bootstrapped distributions, and the 95% confidence intervals and p -values are derived directly from these empirical distributions. This method avoids the often implausible assumptions required by traditional methods like the Baron-Kenny procedure and provides more reliable causal inference.

To investigate the moderating roles of demographic and transportation-related factors, we conducted stratified analyses. The full causal mediation model was run independently for each subgroup defined by gender (male, female), age group (youth, middle-aged, old), and transportation mode (pedestrian, cyclist, e-bike user), as well as for combinations of these factors. This allows for a formal comparison of the causal effects across different populations. In all models, we controlled for potential confounders, including environmental factors (GVI, SVF, Road Width) and temporal factors (weekend/weekday, and weather conditions). All continuous variables were standardized using a z -score transformation prior to analysis to ensure comparability of coefficients.

Data availability

The processed data generated and analyzed during the current study are available in the Mendelely Data repository with the accession code [<https://doi.org/10.17632/frkng6st9s.1>]. These publicly available data include the effect analysis results and thermal adaptation result tables necessary to reproduce the figures and findings. The raw video data collected via mobile monitoring are not publicly available due to privacy restrictions and ethical requirements mandated by the IRB of the University of Science and Technology Beijing to protect the anonymity of observed individuals. The data provided in the repository constitute the minimal dataset necessary to interpret, replicate, and build upon the findings reported in this article.

Code availability

The custom code and scripts used for the Climate-Mobility-Adaptation (CMA) mediation analysis and data processing are available in the Mendelely Data repository with DOI [<https://doi.org/10.17632/frkng6st9s.1>]. The repository includes the version-controlled scripts and a README file specifying the software environment and parameters required to reproduce the analysis.

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Author contributions

Y.Z. and Y.L. contributed to the idea of the project; Y.Z., P.D., and Y.L. jointly designed the project; Y.Z., P.D., and W.M. performed the research and data

collection; Q.L. and M.S. analyzed the data; Y.Z. wrote the initial draft of the paper; Y.L., M.S., and Q.L. reviewed and edited the manuscript. All authors contributed to the discussion, interpretation of the results, and revising the manuscript.

Competing interests

The authors declare no competing interests.

Additional information

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