This is the Accepted Manuscript version of an article published by Elsevier in the journal *Cities* in 2026, which is available at: https://doi.org/10.1016/j.cities.2025.106443
Cite as: Lei B, Liu P, Fujiwara K, Frei M, Miller C, Chua YX, Biljecki F (2026): Multidimensional analysis of human outdoor comfort: Integrating just-in-time adaptive interventions (JITAIs) in urban digital twins. *Cities*, 168: 106443.

Multidimensional analysis of human outdoor comfort: Integrating just-in-time adaptive interventions (JITAIs) in urban digital twins

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Abstract

How can bidirectional information exchange be enhanced in urban digital twins, and support human-centric data and processes? Their key characteristic is the nearly real-time exchange of information, allowing adjustments to physical environments based on simulations and analytics within virtual models. Yet, achieving such interaction remains challenging, particularly regarding device deployment and infrastructure development. Embracing the concept of humans as sensors, this work develops a two-way framework based on the emerging concept of just-in-time adaptive interventions (JITAIs), exploring how urban digital twins can play a role in understanding and enhancing human comfort outdoors. Human comfort outdoors is inherently spatio-temporal and personalised, influenced by multisensory perception. The JITAIs framework involves collecting human comfort data and delivering interventions tailored to contextual and personal conditions. Thus, bidirectional information exchange will be established between humans and urban environments, thereby closing the loop in urban digital twins. A three-week campus experiment with 14 participants demonstrates this framework in two phases: (1) collecting comfort perception data and (2) delivering tailored interventions based on comfort perception and contextual features. End-of-day surveys reveal that 18.4% of responses indicated no behaviour change influenced by JITAIs, while 53.1% acknowledged their role in improving the understanding of outdoor comfort. The JITAIs framework is still nascent, but demonstrates an instance to close information loop in urban digital twins, as well as paves the way for future research. This novel work will facilitate human-centric urban digital twins and their multidisciplinary applications, such as planning comfortable walking routes.

Keywords: Urban technology, Human-environment interaction, Urban sensing, Spatial awareness, Behavioural adaptation

1. Introduction

As an innovative technology, urban digital twins advance complex problem-solving and facilitate decision-making with the integration of numerous data information and techniques, benefiting multiple domains, e.g. transportation, disaster management, and energy simulation (Ferré-Bigorra et al., 2022; Tzachor et al., 2022; Diaz-Sarachaga, 2025). An urban digital twin refers to a virtual representation of built environments that enables information exchange and simulates urban solutions (Batty, 2018; Ketzler et al., 2020; Abdelrahman et al., 2024). As an advanced concept, urban digital twins are intended to achieve a two-way connection between physical and virtual entities with various urban data and semantics, enabling nearly real-time updates to enclose the information loop (Lei et al., 2023a; Luo et al., 2022; Haraguchi et al., 2024). Therefore, urban digital twins can capture the in-situ and dynamic nature of urban contexts and simulate what-if scenarios to provide implications for design and planning, urban strategies, constructions, as well as city management and governance (Figure 1).

Yet, the two-way interaction is not fully developed in the state of the art, hindering the realisation of a 'true' urban digital twin. The gaps rely on three perspectives. First, many urban digital twins primarily focus on one-way representation, such as visualising data collected from the physical environment (e.g. 3D geospatial building information), or monitoring a specific focus (e.g. energy). These digital twins often lack the ability to influence and adapt urban environments based on nearly real-time dynamics and simulations. Second, effectively implementing a bidirectional loop requires timely data input, processing and integration, which is inherently difficult, especially at the city level (Luo et al., 2025).

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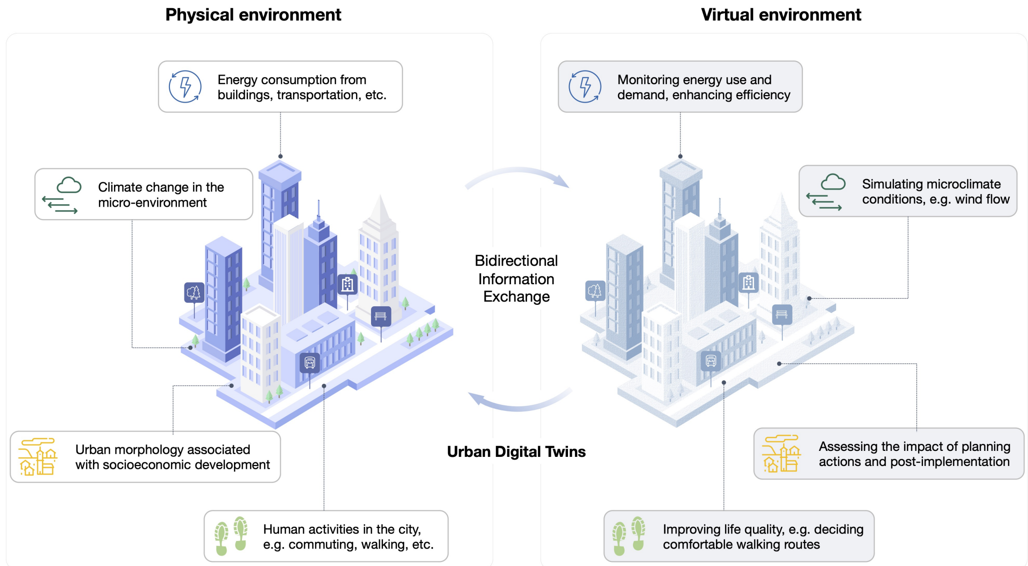

Figure 1: An conceptualisation of urban digital twins, illustrating the bidirectional exchange between the physical environment (e.g. energy use, microclimate, urban form, human activities) and the virtual environment (e.g. monitoring, simulation, what-if planning, and interventions).

Third, existing digital twins primarily model static urban objects (e.g. buildings, road network or infrastructure). However, human behaviour and social interaction are rarely incorporated in urban digital twins, for example, how people adapt to urban changes and how citizen can engage with urban systems (Patel et al., 2024; Ye et al., 2023; Villanueva-Merino et al., 2024). Hence, in this work, our motivation is to develop a bidirectional framework, mirroring the interaction between humans and environments in urban digital twins, enhancing their human-centric perspective. In recent years, there has been a growing interest in using humans as active sources for sensing and understanding cities (Jayathissa et al., 2020; Campbell et al., 2006; Liu et al., 2015; Lei et al., 2023b; Marçal Russo et al., 2025), leading to benefits such as tailoring decisions. Aligning with a socio-technical paradigm in urban digital twins, existing studies have explored their potential in addressing socio-economic problems by including a human lens, such as perception and activities (Nochta et al., 2021; Lei et al., 2023b; Liu et al., 2023). Therefore, we propose an approach that positions humans both as agents of real-world information collection and as active participants whose behaviour will be affected by insights from urban digital twins. Focusing on *human comfort outdoors*, this bidirectional framework will study the interplay between human comfort perception and urban environments in urban digital twins.

Human comfort in built environments has been studied extensively across various domains, including sociology, public health and well-being. Encompassing factors such as thermal comfort (Chen and Ng, 2012; Kawakubo et al., 2023), acoustic comfort (Aletta et al., 2016; Yang and Kang, 2005), smell comfort (Henshaw, 2013), visual comfort and quality (Ito et al., 2024a; Lam et al., 2020), human comfort outdoors is their composite — a collective and holistic perception of urban surroundings at a human scale. Comfort perception, generated by humans in response to their urban surroundings (Lei et al., 2025), is an outcome of both objective experiences and subjective conditions within cities, which is inherently individualised and vary across spatial and temporal scales (Nikolopoulou et al., 2001). For example, while walking, some people will be primarily affected by microclimate conditions (e.g. sun exposure and air temperature), while others may be largely impacted by the streetscape characteristics (e.g. what they see) (Liu et al., 2023; Ignatius et al., 2024). Meanwhile, a variety of urban factors (e.g. microclimate, street design, and noise) influence this perception, contributing to its dynamic and personalised nature. However, outdoor comfort remains underexplored, particularly taking into account multisensory features (e.g. thermal, acoustic, and visual perception).

We adopt the concept of just-in-time adaptive interventions (JITAIs) to better demonstrate the multifaceted characteristics of human comfort outdoors and provide humans with right-here-right-now information (Nahum-Shani et al., 2018; Hardeman et al., 2019; Wang and Miller, 2020). When studying outdoor comfort in urban environments, it is challenging to collect timely perception and, in particular, the corresponding real-time urban dynamics, such as weather conditions. Building on behaviour theories and existing research related to the JITAIs concept, the use of mobile devices and applications (e.g. smartphones and smartwatches) is gaining prevalence in collecting information and sending intervention messages (Nahum-Shani et al., 2018; Miller et al., 2022). Incorporating JITAIs and wearables in our two-way outdoor comfort framework, we attempt to complete the information loop between humans and environments in urban digital twins, thereby providing the right support to humans at the right moment to enhance comfort perception. In detail, our framework consists of two phases — (1) Phase 1: collecting individual perception of outdoor comfort and identifying influencing factors; and (2) Phase 2: sending personalised notifications to inform participants of potential discomfort and provide corresponding behavioural suggestions.

A pioneering research conducted by Miller et al. (2025) demonstrates the implementation of the JITAIs framework in the built environment, validating its usefulness in mitigating the impact of heat and noise on humans. Their work collects participant data and delivers intervention messages tailored to environmental and personal attributes, leveraging Cozie, an iOS smartwatch platform developed by their team (Tartarini et al., 2023). The accomplishments of this approach highlight the viability of two-way information exchange within the JITAIs concept, paving the way for extending the framework into related domains. Building upon this foundation, our study advances the JITAIs framework by introducing a spatially-explicit perspective and expanding its application in the urban living environment. In particular, we focus on the interaction between humans and their urban surroundings in the context of urban digital twins, which inherently rely on geolocation-based and contextualised data. As a complementary extension to Miller et al. (2025), this work advances the state of the art by (1) integrating a representation of human outdoor comfort incorporating multiple dimensions such as thermal, acoustic, and visual comfort; (2) establishing a geospatially-aware intervention strategy, where messages are triggered not only by contextual and personal conditions but also by real-time geolocation information; (3) bridging the gap in urban digital twins with the integration of urban and human information, thereby enabling a true two-way interaction between virtual and physical systems through the JITAIs framework.

Besides technical advances, this work also sheds light on the adoption of urban digital twins in social and political domains and aspires to advance the discussions on involving humans in urban technologies. While urban technologies have been proliferated in making policies and decisions, local governments prioritise a top-down technical model architecture, overlooking an appropriate manner to represent citizens in the process (Seo, 2022). Supporting top-down planning practices, this work advances the role of humans in urban digital systems, encouraging participatory design and co-creation framework in the digital age of planning and design. This research will generate implications to addresses policy concerns, particularly considering the position of individual perception and needs in the policymaking process, such as climate adaptation to mitigate urban heat impacts (Kondo et al., 2021), the equitable distribution of comfortable outdoor spaces (Jian et al., 2021), as well as the integration of real-time human feedback into formal planning frameworks (White et al., 2021). Further, this work will be among the first to extend the JITAIs concept from the realm of health and medicine to urban and geospatial fields. Benefiting from JITAIs, this study brings novelty in understanding how people perceive their urban environments and, conversely, how urban complexity impacts their activities and behaviour combined with spatio-temporal changes. Such a two-way framework can serve as an instrument to improve the outdoor quality of life and foster more comfortable and accessible urban environments. This work provides a combination of human experience (a bottom-up perspective) and planning outcomes (a top-down approach) to explore the relationship between human health and urban development. The implications pave the way for informing policymakers to consider individual needs and adaptive strategies, as well as to foster collaboration between urban planners, public health experts, and citizens in promoting healthy and equitable outdoor urban environments (Niitamo, 2024; Oloonabadi and Baran, 2023; Sevtsuk et al., 2024).

2. Background and literature review

2.1. The concept of just-in-time adaptive interventions

The concept of just-in-time adaptive interventions (JITAIs) introduces an intervention design for delivering precise support at particular times when an individual has needs (Nahum-Shani et al., 2018; Klasnja et al., 2015). Supported by the advancement of emerging technologies and sensing devices, the deployment of JITAIs aims to monitor human outdoor activities and intervene in their behaviours, referring to the capture of dynamic timestamps and locations at an individual level. Benefiting from the two-way dynamics, JITAI has been growingly used to investigate human behaviour in fields such as physical activities (Hardeman et al., 2019), addiction (Perski et al., 2022; Yang et al., 2023), food diet (Goldstein et al., 2017, 2021), and mental health (Balaskas et al., 2021; Coppersmith et al., 2022). The JITAIs underpinning is to capture participants' particular needs and provide the right type of support at the exact time. We reviewed the existing research in the literature and categorised 4 aspects to underline the understanding of JITAIs. Gathering insights from JITAIs in diverse domains, we intend to better position the role of JITAIs in this work, enhancing the scientific motivations in multidisciplinary research.

Timeliness. In JITAIs, *timeliness* is a key characteristic when designing the interventions. Compared to standard adaptive interventions, e.g. sequential multiple assignment randomised trials (SMART), a JITAI is a more granular type of adaptive intervention with an aim to provide precise and rapid support to satisfy individuals' evolving needs timely (Hardeman et al., 2019). Advanced by emerging technologies (e.g. wearable devices), continuous and real-time information can be recorded to document individuals' behaviour, such as movements, activities and emotions (Nahum-Shani et al., 2018; Carpenter et al., 2020). Thus, it enables that interventions can be delivered precisely when needed, facilitating decision-making and increasing their effectiveness. Further, timeliness in JITAIs has the potential to allow real-time adjustments of interventions, and thereby responding to the dynamics and contextual complexity.

Contextual awareness. Emphasising personalisation in JITAIs, *contextual awareness* is an important component for designing interventions, such as locations, individual states, or activities (Xu and Smit, 2023; Ismail and Al Thani, 2022). Individual contexts are also known as tailoring variables in many cases, determining the types of interventions to provide and the conditions under which they are delivered (Nahum-Shani et al., 2018; Goldstein et al., 2017). For example, contextual awareness can be time-based (e.g. in specific time intervals, such as one hour per day), location-based (e.g. within a specific distance to a specific place), as well as condition-based (e.g. when the participants are under stress). Therefore, contextual awareness is a key pillar of decision rules in JITAIs, providing the flexibility needed to deliver individualised interventions in rapidly changing, unexpected and ecological conditions.

Intermittent support. The JITAIs are designed to deliver *intermittent support* in a frequent and actionable manner when triggered by specific variables, conditions or contexts. Thus, JITAIs are able to provide precise and relevant support in a small scale, enabling the individuals to adjust their behaviour in a very short time (e.g. immediately after the interventions). Further, the content of JITAIs is usually brief and straightforward (Nahum-Shani et al., 2018). Relying on contextual awareness, JITAIs are sensitive to the current context of individuals, thereby specifying actions that individuals can easily take. For example, in the studies related to physical activities, researchers design interventions with a message (such as 'please stand up for a while') when the individual has been sitting for more than hours (Müller et al., 2017). Such delivered support is clear and concise, enabling individuals to quickly respond to the interventions in an immediate moment. In this way, the JITAIs can deliver intermittent and precise support to encourage moment-to-moment changes with a capture of individuals' status or events, instead of merely relying on general metrics to make adjustments at pre-set intervals.

Diversity. Intervention options of JITAIs include a *diversity* of support that are tailored for individuals at a given condition, covering support types (e.g. description, recommendations, or feedback), platforms (e.g. smartphones, wearable devices), medium (e.g. phone calls, text messages, and application reminders), the intensity/frequency of support, and the amount of treatments or actions (Nahum-Shani et al., 2015, 2018). In many cases, intervention options are mixed with descriptive information and advice, aiming to deliver timely and feasible messages to individuals to encourage taking actions. For example, when promoting outdoor activities, an intervention option of JITAIs attempt to inform participants about their ecological conditions (e.g. the total time of spending indoors) and recommend taking a outdoor walk with positive reinforcement (Hardeman et al., 2019). Further, technology plays an essential role in JITAIs to accommodate the interventions. To enable the delivery of precise interventions at a right moment, JITAIs requires a large amount of information, data processing and analysis. Considering the dynamic nature of individuals, accurate and real-time data on human behaviour and contexts (e.g. locations, movements, emotions) is a must for designing interventions. With the advancement of emerging technologies, wearable devices and smartphones are widely used for facilitating dynamic information collection and intervention delivery (Nahum-Shani et al., 2018; Hardeman et al., 2019). Other developments, such as machine learning and deep learning, facilitate the design of technical architecture of support delivery, the development of interventions, and the maintenance. In JITAIs, innovative technologies facilitate a more seamless flow between contexts and interventions. This integration ensures that the right support is delivered at the precise time in a quick and responsive manner.

2.2. Human-environment interaction in urban analytics

Urban complexity are inherent to the interplay between humans and their urban surroundings (Moroni et al., 2020; Ortman et al., 2020). Over the years, many theories and models have been developed, seeking to explore how people interact with or adapt to the living environment (Phillips et al., 2010; Kahana, 1982). A well-known conceptualisation, *person-environment fit*, has been applied in various fields, facilitating the understanding of psychological well-being and biosocial behaviour and cognition (Edwards et al., 2006). In general, person-environment fit includes four key features — the person, the physical space of the interacting environment, the behaviour, and the outcomes (Lewin, 1943; Schneider, 1987). The person, or the individual play a role in satisfying their needs and matching the competence with environments. The individuals have different fit strategies to address the discrepancies between personal characteristics and environmental attributes, in order to pursue positive outcomes. Considering the heterogeneity of humans, empirical evidences suggest that personal resources (e.g. personality, health conditions, or socio-economic status) have impacts on maintaining psychological and physiological well-being, therefore entailing a diversity of behaviours in the physical environments (Van Vianen, 2018). Indeed, such behaviours eventually affect outcomes that individuals wish for, such as unmet demands for leisure purposes in open spaces may decrease the human perception of life satisfaction and therefore negatively impact the overall health and well-being (Edwards et al., 1998).

The adoption of person-environment fit can be concluded in two aspect in the landscape — indoors and outdoors. Person-environment fit originates in organisational psychology, referring to the congruence of an individual with their surroundings (Judge et al., 1994). This conceptualisation tends to determine how work environments affect employees, e.g. engagement, productivity, health, and well-being, which therefore help organisations optimise workspace to improve individuals' satisfaction and work effectiveness (Appel-Meulenbroek et al., 2019; Radun and Hongisto, 2023). With an alignment with the origin of person-environment fit, this fit theory is predominantly leveraged to understand indoor environment in the related fields. For example, in architecture, engineering, and construction (AEC) domains, person-environment fit is framed to examine the impact of work environmental supplies (e.g. opportunities), attributes (e.g. culture) and demands (e.g. skills and time) on work stress and satisfaction in a psychological and social level (Xiong et al., 2022). Moreover, in the field of buildings, researchers are looking into how physical settings in the office will have impact on work comfort. For instance, indoor environmental quality has significant impact on worker productivity associated with gender (Appel-Meulenbroek et al., 2019), in terms of thermal satisfaction (Kawakubo et al., 2023; Lei et al., 2024) and noise distraction (Oseland and Hodsman, 2018; Otterbring et al., 2021; Appel-Meulenbroek et al., 2021).

In recent decades, person-environment fit has been broadened to the realm of urban and built environment, comprising only buildings but also dwellings, public transportation, open spaces and neighbourhoods (Zhang et al., 2024; Cvitkovich and Wister, 2001). A number of research studies have found that the quality of physical environments (e.g. type, scale, aesthetics, safety, and accessibility) demonstrates explicit effects on physical health (Oswald et al., 2005), psychological well-being (Hadavi, 2017), perception (Bonaiuto et al., 1999; He et al., 2022), restoration (Ma et al., 2024), social interaction (Gehl, 2011), sense of places (Wang and Vermeulen, 2021; Zabetian and Kheyroddin, 2019), and life satisfaction (Farahani et al., 2022; Park and Lee, 2017). Such impacts typically influence human activities and behaviour outdoors, determining the use of outdoor spaces or leading to unforeseen outcomes in urban design and development, such as exclusive public spaces (Banerjee, 2001) and informal settlements (Li et al., 2021). In this context, when implementing person-environment fit to understand outdoor environments, it is in fact a bidirectional concept. However, the current research is limited to a one-way relationship (i.e. the impact of environmental psychology on individuals), overlooking how reflections from individuals will influence the renewal of outdoor environments.

2.3. The perception of outdoor comfort in urban environments

The studies on human perception have been proliferating over the years, advanced by innovative technologies and diverse data. The perception of outdoor comfort, as generated by how people experience their surroundings, can be categorised into three types in the research landscape.

Outdoor thermal comfort is one of the most important factors in comfort perception, discussed in various work, referring to a level of human satisfaction obtained from thermal surroundings (Chen and Ng, 2012; Gillerot et al., 2024). A variety of physical features (e.g. urban canyon, sidewalks, and open spaces) and microclimate parameters (e.g. sky view factors, air temperature and sun radiation) have been explored to investigate the thermal adaptation (Liu et al., 2023; Shooshtarian et al., 2020; Lam et al., 2020). Further, considering the various attributes of humans such as personality, background, gender and sensitivity, the current discourse moves a step to take into account personal attributes, seeking to explore the individual comfort of outdoor thermal conditions (Cureau et al., 2022). Outdoor thermal comfort research features two characteristics — scales and methods. Considering the behavioural aspects, outdoor thermal comfort contains assessments for individuals' subjective judgements of their surrounding thermal conditions. Therefore, measurement scales are required to gather appropriate information related to individuals' thermal state and thermal preferences. Self-assessment typically tends to understand outdoor thermal sensation, pleasure, and satisfaction, associated with personal acceptability and tolerance (Dzyuban et al., 2022). A number of thermal indices have been developed to measure outdoor thermal comfort, comprising various parameters, rationale and contexts. The prominent assessment methods include physiological equivalent temperature (PET), universal thermal climate index (UTCI), and standard effective temperature (SET), characterising the impacts of climate conditions on thermal comfort in diverse scenarios (Coccolo et al., 2018). Other than these widely used methods, an innovative tendency is found to include images (e.g. street view imagery and remote sensing imagery) as an additional data source to comprehensively assess environmental conditions and the human outdoor thermal comfort. For example, it is possible to predict environmental parameters from images when weather data is not complete in their study areas (Xue et al., 2021; Fujiwara et al., 2024b,a).

Following the proliferation of images, the evaluation of visual comfort is emerging as a hot spot in recent years, aiming to understand the impact of urban visual quality on human perception. The perceived visual comfort plays a role in assessing the quality of urban physics (e.g. urban streets and open spaces), informing urban planning and design in the future and therefore enhancing urban health and well-being (Kang et al., 2020; Perovic and Folic, 2012; Wang et al., 2019). Visual comfort research primarily focus on physiological well-being, referring to how people feel or perceive the urban environments from a visual aspect, such as whether a street implies a sense of safety or depression (Ulrich et al., 1991; Galea et al., 2005). Given a visual nature in such topics, images and videos are the predominant source that leveraged in the related research. For example, satellite imagery is used for measuring visual quality at a larger spatial resolution such as a neighbourhood (Chen et al., 2020), whereas street view imagery offers a granular perspective to understand individuals' subjective awareness of urban streets (Dubey et al., 2016). Advanced by innovative technologies (e.g. computer vision), urban objects (e.g. buildings and vegetation) can be segmented from images and videos, prepared for exploiting the relationship between specific surrounding objects and human visual comfort, such as understanding how urban greenery impact the visual perception (Ito et al., 2024a; Biljecki et al., 2023b).

While thermal and visual perceptions are critical components, outdoor comfort perceived by humans should be a multifaceted phenomenon including sensory, cognitive and behavioural factors (Li and Liu, 2024; Liu et al., 2023). For example, acoustic comfort involves how people perceive and respond to sounds in the urban environment, becoming a key research area of environmental soundscape (Axelsson et al., 2010; Axelsson, 2015; Pijanowski et al., 2011). In the soundscape research, scholars have found that environmental sounds have impacts on human health and restoration, thereby affecting the action and interaction of environmental and human factors (Aletta et al., 2016; Cain et al., 2013; Zhao et al., 2023). Depending on specific types of urban sounds (e.g. natural sounds and traffic noise), the perceived acoustic comfort varies in different scenarios, such as people may feel more pleasant and less stressful in a quiet park than walking on a sidewalk that close to busy roads (Liu et al., 2014). Moreover, social comfort is another field that reflects public engagement and social interaction in the urban settings (Nandhakumar and Jones, 1997). For example, walking comfort is discussed in the recent literature, revealing that people may demonstrate more walking willingness when pedestrian paths are designed with more accessibility or less crowdedness (Ma et al., 2021; Ovstedal and Ryeng, 2002). Similarly, research on public space utilisation indicates that perceived comfort and attractiveness of spaces influence individuals' preferences to conduct physical activities and get involved in the local community (Duncan et al., 2005; McCormack et al., 2010; Brown et al., 2014).

Reviewing a variety of outdoor comfort perception in the urban environment, it is found that human perception of outdoor comfort can be affected by diverse factors. However, the existing research remains a gap in discussing how these factors comprehensively impact such comfort perception and how individuals respond to their surrounding conditions. Therefore, this work will take into account a variety of urban factors that have been identified with impacts on human comfort perception, and move a further step to understanding human behaviour in different situations. In fact, this work will be among the first to explore the bidirectional interaction between individual comfort perception and their urban surroundings.

3. Methodology

3.1. A JITAIs framework for human comfort outdoors

We design an experimental framework to illustrate how people generate outdoor comfort perception through interacting with their surroundings and change their behaviour to fit the environments (Figure 2). The JITAIs framework includes two main phases — Phase 1 and Phase 2, where urban digital twins play a role in processing and analysing data information. The first aims to collect responses from participants regarding their perception of outdoor comfort and related urban features. Thus, we primarily consider four dimensions to represent urban surroundings: (1) 3D urban morphology, (2) streetscape, (3) urban microclimate, and (4) urban noise. These four dimensions are intended to associate with outdoor comfort perception from diverse aspects to provide a holistic overview of urban environments, e.g. thermal comfort, visual comfort and acoustic comfort. The data collected in Phase 1 serves as input for model training in Phase 2, where it informs interventions tailored to individual comfort perception.

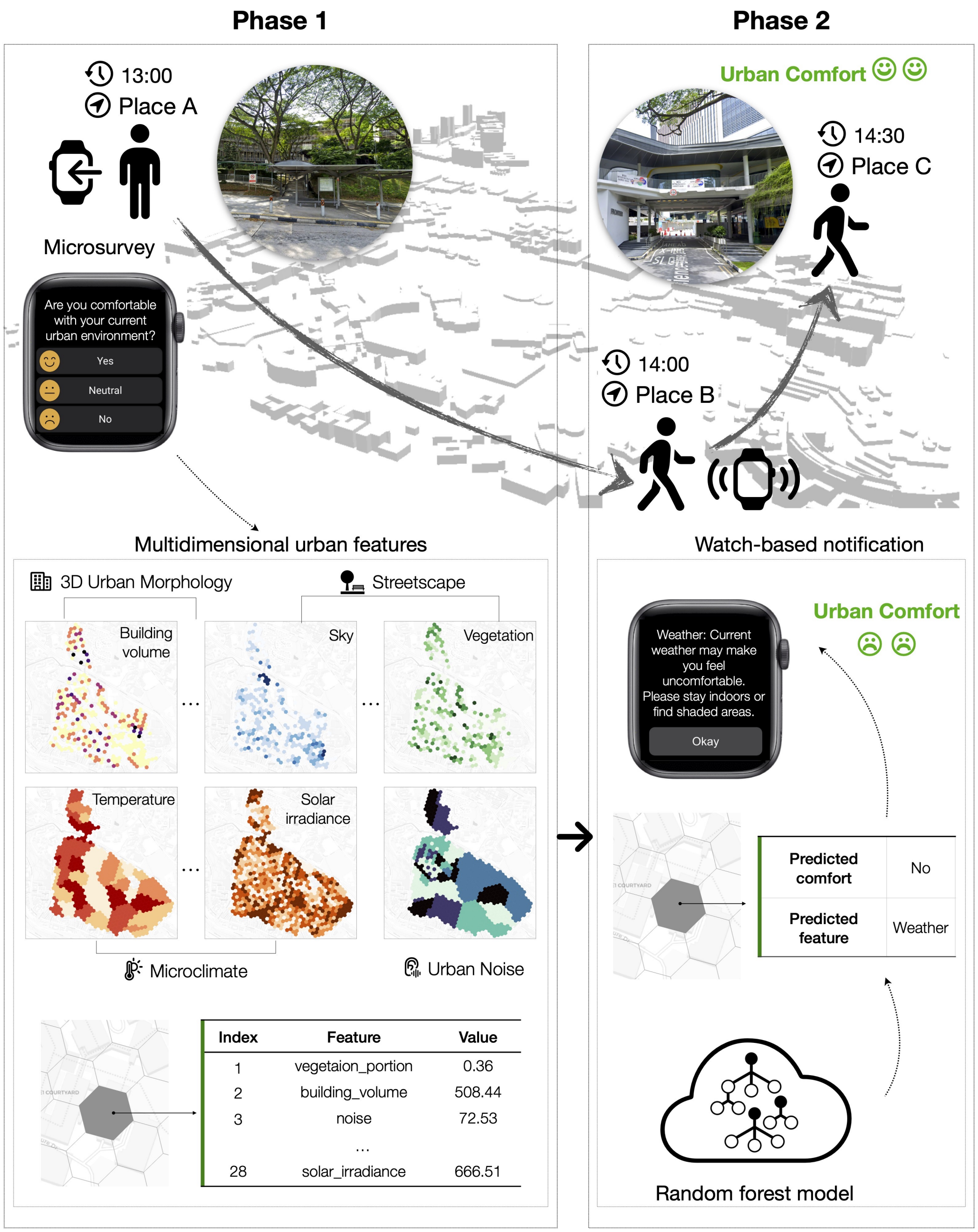

Figure 2: The Just-in-time adaptive interventions (JITAIs) framework for outdoor human comfort, integrating microsurveys, urban features, and predictive modelling to provide personalised and watch-based notifications. The framework illustrates the interplay between humans and urban environments, and contribute towards establishing human-centric and advanced urban digital twins. The illustration depicts the study area of this research — the main campus of the National University of Singapore.

Phase 2 is designed based on the JITAIs concept, a bidirectional mechanism predicts participants' outdoor comfort perception and nudges their behaviours to change for enhanced personal comfort. In this regard, we leverage random forest algorithm to conduct a prediction model in urban digital twins, considering its wide applicability in various domains and robustness (Wu et al., 2021; Niu et al., 2020; Breiman, 2001; Belgiu and Drăguţ, 2016). The random forest model serves two primary functions: (1) predicting the level of outdoor comfort based on contextual features, and (2) identifying key influencing factors contributing to discomfort. Regarding the model design, we applied random oversampling (ROS) to the training set and used 5-fold cross-validation, with approximately 80% of the resampled data used for training in each fold. Model performance is evaluated using standard classification metrics: accuracy, precision, recall, and F1-score. Rather than designing a complex prediction model (e.g. a graph neural network), our focus is on selecting a widely used algorithm that could provide acceptable accuracy while supporting timely intervention delivery on wearable devices. Meanwhile, the indexing system (H3) provided by Uber Technologies at the scale of resolutions-11 (average cell width of 28.66 metres) is used as spatial units in this work to capture spatial variations in human outdoor comfort (Stough et al., 2020; Woźniak and Szymański, 2021; Conners et al., 1984). Each participant's geolocation is continuously mapped onto hexagonal cells, allowing us to dynamically predict their outdoor comfort based on real-time and historical contextual data.

The triggering mechanism works as follows. When a participant enters a spatial unit predicted to be uncomfortable, a pre-designed intervention will be triggered and sent to their Apple Watch as a behavioural nudge. The prediction model is pre-trained and integrated in urban digital twins, using participant-reported comfort level collected in Phase 1 as the ground truth, incorporating multidimensional urban features as input parameters (i.e. 3D urban morphology, streetscape features, microclimate conditions, and noise level). To adapt to changing environmental conditions, the model is retrained every hour using real-time environmental and contextual data. Avoiding a sense of annoyance, we limit notifications to a maximum of five per day per participant, minimising excessive prompts. Such mechanism is incorporated in our urban digital twin, motivated to achieve our proximal outcome (i.e. enhance human comfort in the outdoor environment) by modelling the two-way information exchange between humans and their surroundings. We clarify that the digital twin in this work serves as a conceptual prototype rather than a fully operational system. Thus, the implementation of the framework aims to demonstrate the feasibility of adopting JITAIs to complete the information loop between humans, environments, and systems. The proof of concept lays the groundwork for functional and operational urban digital twins and the applications in the future. The following subsections will provide more details.

3.2. Watch-based microsurvey and intervention design

We design and deploy our watch surveys supported by Cozie (Tartarini et al., 2023), an open-source iOS application for the Apple Watch. Figure 3 details the flow of the microsurveys. We involve five main questions plus two additional ones, highlighting three contents — right-here-right-now activities, outdoor comfort perception and associated influencing feature. In detail, the answers to the comfort perception question (i.e. 'Are you comfortable with your current urban environments?') use a 3-point scale (i.e. Yes, Neutral and No), where the 'Neutral option' is considered neither comfortable nor uncomfortable. Regarding influencing features, the workflow starts with a question to identify a specific feature that most affect the comfort perception at the present moment. Then, it branches out to 2 parallel questions corresponding to the features 'Weather' and 'Street design'. For example, when the respondent determines that weather condition makes them uncomfortable right now, the next survey question will be asking which specific weather element most affects their outdoor comfort, including options such as air temperature, humidity, sun exposure, rain and none of the above. The Cozie application enables an optional functionality of generating local notifications as microsurvey reminder. Therefore, we activate this feature to remind participants to complete the microsurvey on the smartwatch every hour between 10:00 and 18:00 on weekdays. In order to collect various outdoor information, we customise a function to nudge individuals every one minute when they indicate that they are outdoors. To avoid bothering participants, we limit such reminders to a maximum of 5 notifications per day, and participants can disable the notifications at any time.

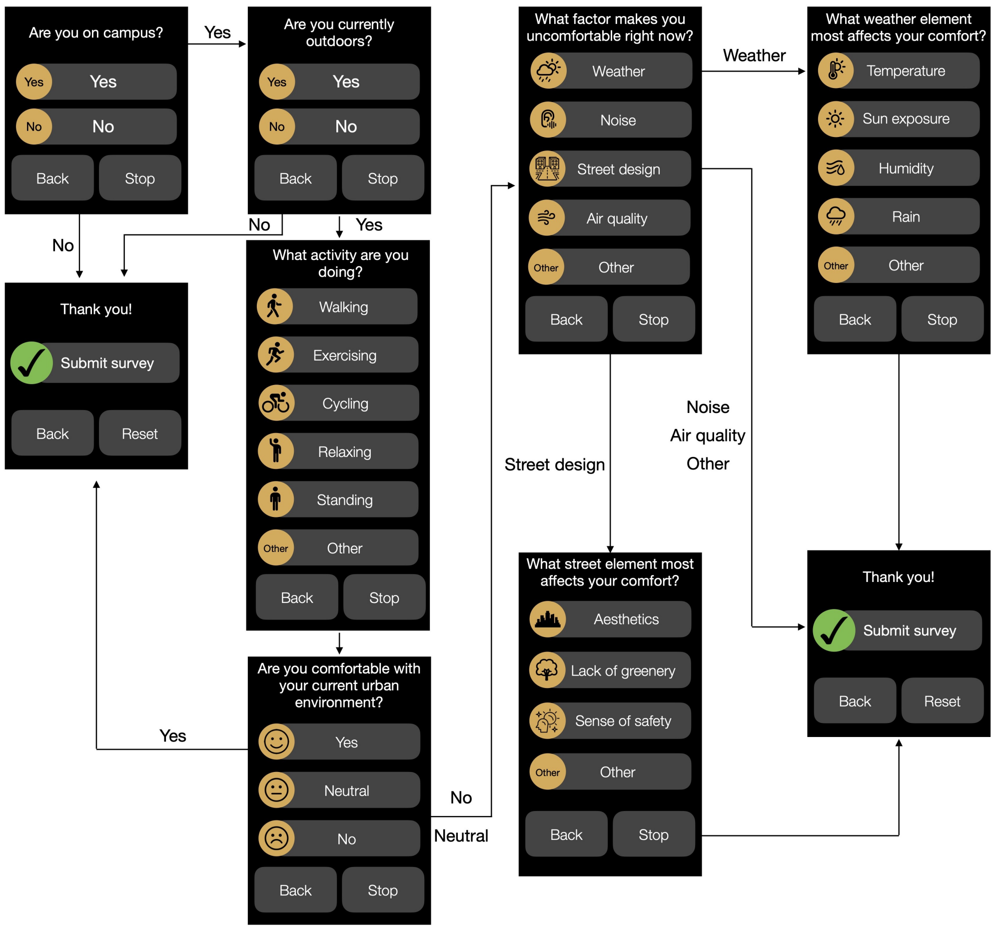

Figure 3: The question flow of microsurvey questions designed to collect participants' comfort responses in urban environments.

Aligning with the JITAIs framework, we develop a corpus of interventions for Phase 2 (see Figure 4), corresponding to identified impact factors in Phase 1. The purpose of our interventions is to notify participants that they are approaching uncomfortable areas because of a specific factor, as well as provide them suggestions for prompting behaviour changes to enhance comfort perception. For example, if an area is predicted with neutral or negative outdoor comfort caused by noise, the intervention related to acoustic comfort (i.e. 'High noise levels ahead. Consider using ear protection or taking a quieter route.') will be pushed to the individual's smartwatch.

Figure 4: Examples of watch-based interventions, grouped into four categories: weather, street design, noise, and air quality.

Further, an end-of-day phone survey is designed to validate the effectiveness of watch-based interventions. The phone survey will be activated in Phase 2 at the end of each weekday and phone survey reminders will be shown at 19:00. Thus, each individual will need to complete a total of 5 phone surveys. The participants are required to evaluate interventions from various aspects — changed behaviour, better understanding their outdoor comfort, effectiveness and annoyance. A summary of this human-centric approach is detailed in Figure 5.

3.3. Experimental deployment

We implement our framework at the Kent Ridge campus of the National University of Singapore (NUS), considering its accommodation for participants' daily activities (e.g. working, studying, dining, and exercising) and over 300 multi-functional buildings (e.g. educational buildings, residential apartment and health-care facilities). Further, the campus enables the feasibility to evaluate our framework in a controlled yet diverse urban microcosm. While it may not capture the full complexity of broader urban systems, we select the campus as a testbed for its

	Phase 1 (2 weeks)	Phase 2 (1 week)
Watch-Based Surveys	• Participants answer watch-based microsurveys • Surveys are delivered every hour between 10:00 and 18:00 on weekdays • Up to 5 additional surveys per day if participants are outdoors.	• Participants answer watch-based microsurveys following the same strategy as in Phase 1 • Participants will receive watch-based notifications informing them of potential discomfort and specific urban features based on their geolocations • Participants are encouraged to adapt interventions and adjust their behaviour to improve outdoor comfort
Phone Surveys	(No phone surveys in Phase 1)	• Participants complete a phone survey at the end of each day, evaluating the effectiveness of that day's interventions

Figure 5: An overview of participant tasks in Phase 1 (microsurveys) and Phase 2 (microsurveys, interventions, and daily phone surveys).

accessibility and environmental variability. As an initial implementation, the success of this proof-of-concept can promise the potential to be scaled to a city level with further customisation. The experiment will last for a period of three weeks, including two phases. Phase 1 aims to collect microsurveys from respondents, and Phase 2 is designed to deliver personalised watch-based interventions and validate the effectiveness of interventions. We recruited 14 individuals from NUS as our human participants to complete the two-phase study. The cohort of participants is composed of both students and staff from various faculties and department, aiming to enhance the overall diversity associated with diverse individual profiles and different regular activity areas. The recruitment primarily took place through social media platforms. The ethical aspects of this project have been approved by the Institutional Review Board of the National University of Singapore.

In the recruitment phase, we conveyed requirements and relevant information to the participants. Considering that we are aiming to collect as much outdoor comfort as possible, we highlighted the expectations for participants to wear smartwatches for three weeks — spending at least four weekdays on campus and spend adequate time outdoors. Regarding wearable devices and compatibility, participants have been recommended to have an Apple Watch and iPhone for downloading and making full use of Cozie application. However, we also provided options for participants to borrow devices from us if they do not have Apple Watch and iPhone, ensuring equity and balanced participation. Further, we designed the onboarding sessions to enrol participants in a thorough manner. The onboarding sessions were structured with two parts: a simple questionnaire and a tutorial. The questionnaire requires participants to fill their personal information (e.g. name, gender and age), as well as individual preference and tolerance for various types of outdoor comfort, such as thermal comfort, visual quality and acoustic impact. Afterwards, we provided a tutorial for each participant, explaining them in detail — how to download and enable Cozie application on their smartwatches, how the experiment will be conducted, how data will be collected and how to prepare themselves for this experiment. In particular, participants were guided to understand specific terms (e.g. outdoor comfort, JITAIs), as well as the workflow of the microsurvey, including each question and its corresponding response options.

3.4. Multi-source data acquisition

The collected data can be grouped into four dimensions.

First, 3D geoinformation is used to represent the intricate nature of urban morphology. Using OpenStreetMap (a globally crowdsourced dataset with rich data on buildings (Biljecki et al., 2023a)), we construct an urban digital twin model on campus and incorporate building semantics such as functions and the number of storeys. Such a model not only provides a 3D representation of urban contexts, but can also serve as a platform to accommodate multidimensional data (e.g. microsurvey responses and weather conditions).

Second, we leverage street-level panoramic imagery captured by the university, reflecting urban environments on the ground. The Mask2Former model (Cheng et al., 2022), which is pre-trained on the CityScapes dataset (Cordts et al., 2016), is used for semantic segmentation of panorama images, representing urban surroundings, such as the portion of buildings at the street level.

Third, we collect real-time weather data, thanks to the installed 41 weather stations at ground and roof levels across the campus (Han et al., 2024; Lim et al., 2024). The stations are spread out to collect microclimate data (i.e. temperature, humidity, global solar radiation, and wind) at locations that represent various urban settings. Further, we include solar irradiance as an additional environmental factor, which is a metric for investigating the shading effect of trees and buildings. Adopting an open-source method (Fujiwara et al., 2024a), we estimate the value of street-level solar irradiance using panoramic imagery and solar irradiance data from rooftop weather stations. Hence, we are intended to cover a dynamic and holistic overview of microclimate on campus, associated with the outdoor comfort perception.

Fourth, we utilise the Cozie application to gather physiological and psychological data from participants. In particular, physiological information primarily includes heart rate measurements when participants are conducting outdoor activities. Surrounding noise is another feature to indicate their acoustic environments. The psychological information comes from microsurvey responses regarding individuals' subjective awareness of their comfort perception.

4. Results

4.1. Phase 1: Human comfort outdoors varies from individuals and environmental features

We visualise the mechanism of Phase 1 in Figure 6, detailing the spatial relationship between outdoor comfort perception and the surrounding environments. At this stage, urban digital twins serve as a platform to locate the geolocations of perceived comfort and visualise the relationship between outdoor comfort and urban surroundings. Taking one of the participants as an example (Participant No. 6, a 40-49-year-old female), it is evident that their comfort perception varies in diverse geolocations and dynamic conditions. For instance, this participant obtained a number of positive perceptions of comfort on campus, particularly when they were located around buildings that were commonly constructed with shelters or semi-open spaces. Further, the participant tends to perceive neutral and negative comfort when they are close to the roads and are affected by different features depending on the right-here-right-now conditions (e.g. rain or noise).

Filtering out invalid responses from the participants, we collected 1,003 responses regarding their outdoor comfort. It finds that 61.6% of responses to comfort perception are positive, suggesting that participants enjoy their urban surroundings when conducting outdoor activities. However, a portion of 38.2% responses indicates neutral (25.1%) and negative (13.3%) perception of urban environments. In this regard, we dive into non-positive comfort perception, aiming to figure out the associated influencing features accordingly. Grouping into neutral and negative comfort perception, we demonstrate the distribution of influencing features in Figure 7. Weather conditions emerge as the most significant factor influencing participants' outdoor comfort, with urban noise exerting a notable impact as well. In detail, 79.2% of negative outdoor comfort perception is attributed to weather conditions, such as sun exposure and rain. Regarding neutral outdoor comfort perception, the impact of weather accounts for 51.5%, while noise (34.7%) is another feature that cannot be ignored. Such findings imply that weather is a critical determinant in shaping outdoor comfort perception, while

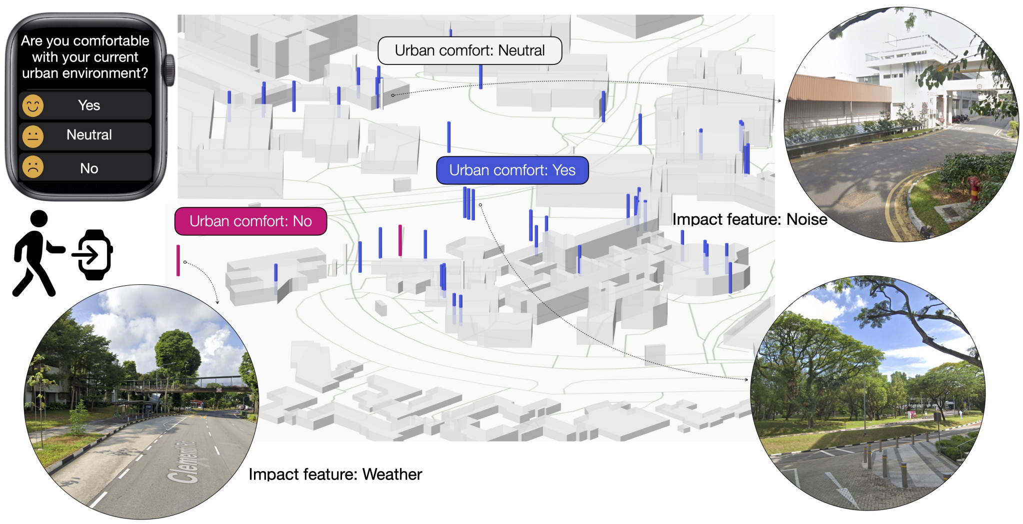

Figure 6: A 3D visualisation of perceived outdoor comfort and urban environments, taking one of the participants and their movement and input as an example. Sources: Google Street View.

urban noise plays a significant role in influencing the degree of perceived discomfort.

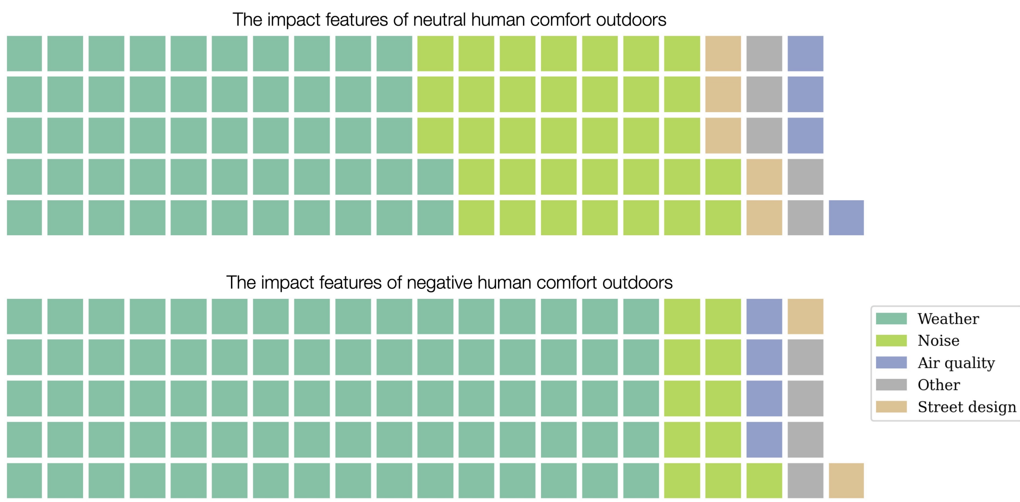

Figure 7: Influencing features contributing to neutral and negative human comfort outdoors, categorised by weather, noise, air quality, street design, and other factors. Each square represents a percentage of the total contributing features, illustrating the relative impact of different urban features on comfort perception.

Further, we analyse participants' responses regarding the subdivided elements of weather and street design that affect outdoor comfort. Figure 8 illustrates the distribution of these features across two categories of non-comfortable perceptions. For weather-related discomfort, we examine the relationship between outdoor comfort and specific weather factors. The results indicate that air temperature is the most significant contributor to participants' non-positive comfort, while sun exposure has a comparatively less noticeable impact overall. However, among participants who report negative comfort due to weather conditions, air temperature and sun exposure contribute relatively equally to their uncomfortable perception. From the perspective of street design which is considered as the visual quality, both the sense of safety and street aesthetics have rather even contributions to participants' discomfort. Notably, responses indicating negative comfort perception highlight a concern about urban greenery, which plays a critical role in enhancing human health (e.g. promoting psychological restoration) and addressing climate change (e.g. mitigating carbon emissions).

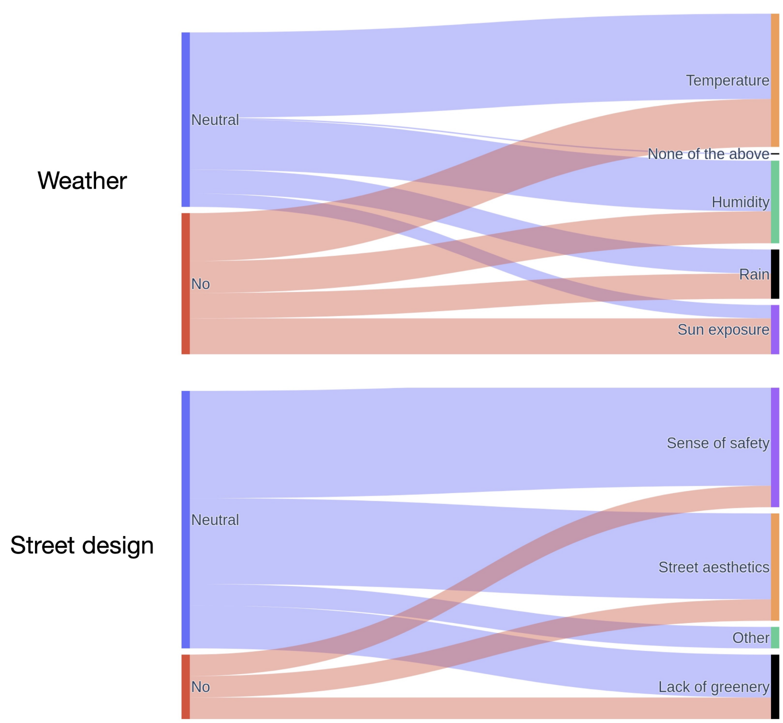

Figure 8: The impact of weather- and streetscape-related features on neutral and negative outdoor comfort perception.

4.2. Phase 2: JITAIs help understand human comfort outdoors but fail to nudge behaviour changes

In Phase 2, we leverage the triggering mechanism and information loop in urban digital twins to tailor intervention messages. A number of watch-based notifications were sent to inform participants regarding their right-time-right-here (i.e. real-time and location-specific) outdoor comfort perception and the associated features, along with our recommendations. At the end of each day, during Phase 2, participants were required to complete a phone survey encompassing 5 questions, validating the effectiveness of the interventions. We apply a 5-point scale to measure the agreeableness of each question. Figure 9 summarises the results and clarifies the distribution of the degree of agreeableness.

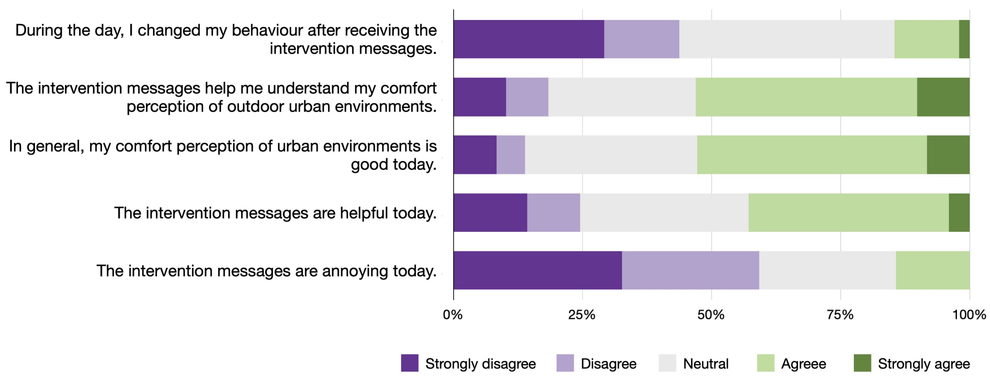

Figure 9: Participants' responses to JITAIs, presenting how intervention messages influenced behaviour change, comfort perception, and understanding of outdoor environments, as well as their perceived helpfulness and tolerance toward the messages.

While human comfort outdoors as a novel concept in this work representing diverse types of comfort as a whole, the designed interventions significantly help participants to better understand their urban surroundings and the impact of perceived outdoor comfort. For example, a portion of 53.1% positive responses evidence the value of JITAIs in understanding outdoor urban environments. A total of 59.2% responses highlight participants' good tolerance of interventions during the days, implying an appropriate number of interventions was considered in the methodology design. Meanwhile, as suggested by surveys, participants perceive overall positive comfort (52.7%) when they are outdoors.

However, JITAIs fall short when it comes to influencing behaviour in our experiment. For behaviour changes, 43.8% of responses indicate that they did not change their behaviour after receiving interventions. Only a percentage of 14.5% responses suggest that they took actions to adjust their outdoor activities after being nudged by the notifications. A detailed look at the responses reveals that participants who were less likely to change their behaviour belonged to the 18–24 age group (71.4%) and all reported enjoying being outdoors. However, this cohort was also more often to feel overwhelmed by urban surroundings. In contrast, participants who were more likely to follow the interventions demonstrated a higher tolerance for urban environments and were predominantly female across different age groups.

4.3. Individual attributes and the interventions

Further, we investigate the relationship between participants' profiles and their responses to evaluate interventions and understand their determinants (Figure 10). The individual profiles are collected from onboarding sessions before the experiments. In this regard, we tend to understand the personal attributes of each participant, such as willingness to be outdoors, and sensitiveness to weather, smells, visual quality and urban noise. Processing responses from onboarding questionaries and end-of-day surveys, we analyse the correlation across personal attributes and the attitudes towards JITAIs.

- Helpful message and improved understanding of human comfort outdoors (correlation coefficient: 0.72). Such a strong positive correlation suggests that the helpfulness of JITAIs significantly enhances participants' understanding of outdoor comfort. The better they understand the comprehensive outdoor comfort generated from the environments, the more they will find the notifications help promote their comfort perception.

- Helpful message and changed behaviour (correlation coefficient: 0.31). Likewise, when participants acknowledge the effectiveness of interventions, they are more willing to adjust their behaviour. Further, the implications indicate that how helpful the interventions are plays a role in nudging behaviour changes.

- Enjoy outdoors and sensitive to urban noise (correlation coefficient: -0.49). It is noted that participants who are less sensitive to urban noise tend to enjoy outdoor environments more. In this context, acoustic comfort impacts participants' enjoyment of urban environments, therefore significantly contributing to the overall perception of outdoor comfort.

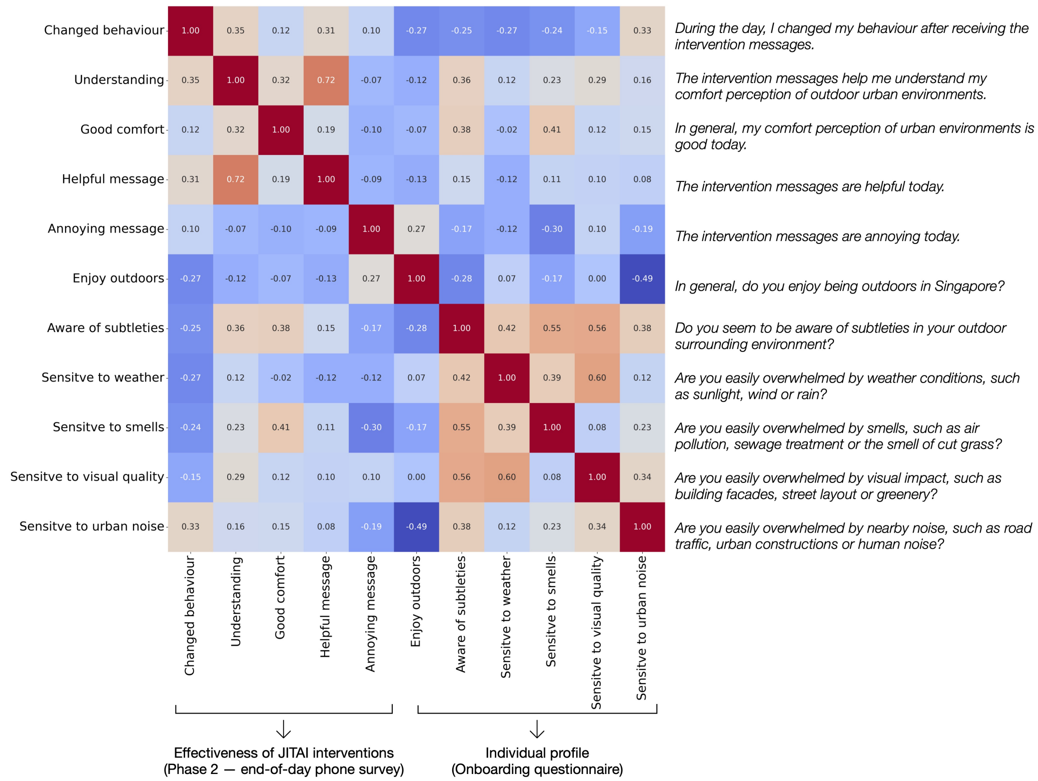

Figure 10: Correlation analysis between personal attributes and the effectiveness of JITAIs.

- Changed behaviour and sensitivity to urban noise (correlation coefficient: 0.33). The correlation implies that participants who are more sensitive to urban noise are somewhat more likely to change their behaviour after being notified of the JITAIs. Further, the result suggests that sensitivity to noise may motivate people to take actions outdoors, tending to reduce exposure to noise or mitigate the impact on their perceived comfort.

4.4. Feature impact on human comfort outdoors

Taking into account the heterogeneity of participants, a key innovation in this work is the development of personalised models for each participant. Our approach ensures that individuals receive tailored interventions based on their unique comfort perceptions, associated urban features, and spatial locations. The results highlight the variability in outdoor comfort perception among participants, as well as the differing determinants of their comfort. Therefore, the performance of each model varies depending on the quantity and quality of the collected responses.

We summarise the evaluation metrics for each model in Figure 11, and provide detailed analyses of feature importance using two randomly selected participants as examples. The accuracy of outdoor comfort prediction ranges from 46.3% to 91.1%, with an average accuracy of 73.4%. For Participant 06, the model achieves an accuracy of 83.2%, along with other common evaluation metrics (e.g. precision, recall and F1-score). Investigating the importance of features, streetscape (0.44), which influences visual comfort, contributes most to this participant's outdoor comfort among the four defined dimensions. Such results imply that Participant 06 may be more sensitive to visual quality compared to other aspects of comfort. In contrast, Participant 13's outdoor comfort is predominantly influenced by weather conditions (0.52) and noise (0.30), while visual quality is not identified as a key factor affecting their comfort perception. Such findings underscore the personalised nature of outdoor comfort determinants and the importance of tailored models to account for individual differences.

Participant	Accuracy	Precision	Recall	F1-score
1	0.91	0.92	0.91	0.91
2	0.88	0.90	0.88	0.87
3	0.59	0.59	0.59	0.59
4	0.46	0.46	0.46	0.46
5	0.87	0.90	0.87	0.86
6	0.83	0.84	0.83	0.83
7	0.57	0.57	0.57	0.56
8	0.78	0.78	0.78	0.78
9	0.89	0.89	0.89	0.89
10	0.56	0.57	0.56	0.55
11	0.81	0.84	0.81	0.81
12	0.60	0.60	0.60	0.59
13	0.85	0.87	0.85	0.85
14	0.68	0.68	0.68	0.68

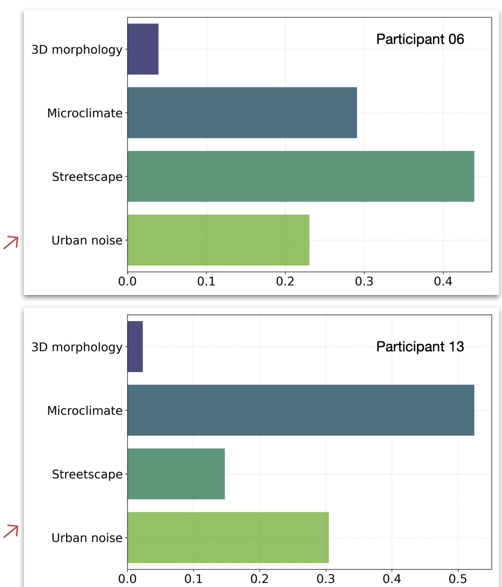

Figure 11: A summary of performance metrics for individual models, with detailed breakdowns of feature impact for Participants 06 and 13.

5. Discussion

5.1. JITAIs framework and human-environment interaction

Our work demonstrates for the first time how just-in-time adaptive interventions can be applied to capture the interactions between humans and urban environments in the larger urban context, in particular focusing on human comfort outdoors. Addressing various aspects of outdoor comfort, such as thermal, visual and acoustic dimensions, we introduce a comprehensive concept of human comfort outdoors to encapsulate diverse comfort perception generated from the urban surroundings.

In general, participants reported positive levels of comfort perception outdoors; however, their discomfort determinants varied depending on urban features influenced by spatial and temporal dynamics. In this regard, our work highlights the importance of individualisation in considering such variability, accounting for participants' diversity when delivering watch-based JITAIs. The end-of-day phone surveys provide further insights into participants' attitudes toward watch-based interventions. The results suggest that nearly half of the interventions are considered useful in maintaining positive comfort during outdoor activities. Further, participants demonstrate a relatively high level of tolerance for JITAI notifications, suggesting a balance between promoting behaviour changes and minimising annoyance (Hulme et al., 2018). However, we recognise that intervention fatigue remains a potential risk, particularly in long-term or large-scale applications. Future work will explore adaptive strategies that consider both the timing and frequency of interventions. Participant responsiveness, preferences, and contextual factors will be more explored and integrated into the model training to deliver more accurate and meaningful messages. Further, we will consider personalisation algorithms in the future work, such as reinforcement learning or relevance tuning, improving the model performance to capture and exploit the human-environment complexity over time and space.

However, we notice that participants are less likely to change their behaviour after receiving notifications, even when they acknowledge the effectiveness of the interventions. Compared to the deployment of JITAIs in other domains (e.g. medicine), our findings highlight challenges unique to urban-scale applications (Perski et al., 2022), which need to incorporate strategies for broader implementations. In particular, individuals present a higher degree of autonomy when moving in the outdoor urban environments leading to the situational variability, which impacts the adherence to the intervention messages. For example, when we send a notification addressing outdoor discomfort that may be caused by sun exposure and recommend seeking shaded areas, participants' responses may depend on various factors, including the purpose of their ongoing outdoor activities (e.g. leisure walking or rushing to a destination), the opportunity and access to respite places (e.g. the proximity of shaded areas), as well as their willingness to act on the advice. Further, while humans have the capability to adapt their environments, our JITAIs serve as suggestible and context-aware messages to support their decision-making. In this proof-of-concept, the portion of changing behaviour is rather smaller than acknowledging the helpfulness of JITAIs. However, such results imply that our interventions help participants be more aware of their subjective experience and understand how the urban characteristic may impact their outdoor comfort. This innovation highlights the feasibility of urban JITAIs at this stage, as well as the potential to achieve behaviour changes and maintain urban health in the long term when integrating tailored strategies (e.g. taking into account the purpose of outdoor activities).

Therefore, successful behaviour changes in response to JITAIs require both favourable objective conditions at the urban scale and personal willingness to comply. Further exploration of adaptive strategies and detailed recommendations can be considered in future research.

5.2. Planning and policy implications

In the context of JITAIs, the proximal outcome in this work is defined as the improvement of human comfort outdoors, as reflected in participants' self-evaluation of JITAIs performance. Further, distal outcomes extend to diverse aspects such as mental well-being, restorative health, and increased opportunities to engage in outdoor activities. Such long-term outcomes rely on the success of urban design and planning, such as mitigating the impacts of urban heat or reactivating urban streets to be more inclusive and vibrant. Therefore, strategic interventions in urban planning plays a role in enhancing outdoor health and promoting public well-being.

Our findings resonate with international initiatives that focus on the quality of local life and promote healthy and sustainable living, such as the 15-minute city concept popularised in global cities (e.g. Paris and Barcelona) to prioritise the needs of urbanites (e.g. their access to public facilities and friendly walking streets) (Caprotti et al., 2024; Guzman et al., 2024). Meanwhile, our work aligns with global healthy city initiatives, underscoring the importance of integrating urban technology, context-aware interventions, and individual perception into urban planning to enhance public health and well-being (Kocak and Sancaktutan, 2025). Drawing inspiration from the international precedents, our study provides insights into feasible planning interventions to sustain comfortable outdoor activities, such as the creation of green corridors for shaded pathways, implementation of zoning regulations to reduce noise pollution, or the development of accessible pocket parks. Such strategic scenarios can be further evaluated in urban digital twins to assess their feasibility and anticipated impacts. Therefore, we position our study within the broader discourse of planning and policy making, highlighting new insights and the alignment with worldwide initiatives. For example, the challenges and successes identified in our framework echo planning practices in balancing individual differences and urban development to improve the living environment and overall liveability. Indeed, trade-offs should be considered to make inclusive and sustainable decisions (e.g. equity in access, respite facilities, and behavioural governance), which can be informed and evaluated from the implementation of our JITAIs framework. Further, this work has the potential to contribute directly to the policy dialogue on creating inclusive urban environments through responsible and human-centric technologies.

This study provides novel insights into the human-environment interplay, demonstrating how watch-based interventions can improve individual comfort in a timely manner while also informing long-term urban planning strategies. Adopting a human-environment perspective, our work offers a pathway to guide future urban development and design practices toward fostering more comfortable and inclusive urban spaces. In detail, this study provides actionable recommendations for researcher and practitioners of interest in adopting human-centric urban digital twins with JITAIs, enhancing urban health and well-being across diverse urban contexts:

- Integrating multisensory information into urban planning and design to understand urban discomfort and provide robust analytical evidence for decision-making.

- Incorporating individual experiences and perception into planning and design to prioritise spatial equity and individual adaptation.

- Fostering inclusive and participatory planning processes to engage local communities actively in revitalising urban areas and enhancing outdoor comfort.

- Encouraging interdisciplinary partnerships among urban planners, public health experts, and the general public to co-create integrative solutions that comprehensively address outdoor comfort, health, and well-being.

5.3. Implications for urban digital twins

Aligning with the concept of human-centric urban digital twins (Lei et al., 2023b; Liu et al., 2023; Nochta and Oti-Sarpong, 2024), this work provides a use case that addresses the two-way information exchange in urban digital twins, advanced through the JITAIs framework. In particular, we develop a JITAIs framework to understand human perception of outdoor comfort and conversely intervene in human behaviour to enhance comfort perception. While the current operation of urban digital twins is hindered by various challenges (Lei et al., 2023a), the integration of the JITAIs framework completes the information loop between humans, urban environments, and virtual models. Gathering human responses to urban surroundings, we implement the JITAIs framework to trigger personalised interventions considering their spatio-temporal dynamics and provide right-here-right-now support. This bidirectional communication substantiates a key characteristic of urban digital twins — the nearly real-time information exchange between physical and virtual entities, thereby advancing the realisation of urban digital twins. Notably, our work contributes to the social and human-oriented dimensions of urban digital twins, showcasing their potential for diverse applications across multiple domains, including public health, human behaviour analysis, urban sustainability, and liveability. Such contributions tend to pave the way for future research and innovation, giving prominence to the integration of human-centric approaches in the development of urban digital twin technologies.

5.3.1. Scalability and challenges

While the JITAIs framework is implemented on a university campus, it presents the potential to generalise to more complex and larger-scale environments. We design the framework to be an applicable and transferable means, which can be further tailored to adapt various urban contexts. In the related work, the deployment of frameworks at a relatively small scale is a common approach to evaluating their feasibility (i.e. a proof-of-concept study), which can be easily controlled and remain practical value (Fernandez-Anez et al., 2018; Van Winden and Van den Buuse, 2017). In particular, such approach is widely recognised in digital twin implementation and smart city practices, offering a pathway from conceptual validation to broader application.

Understanding the scalability of our JITAIs framework in urban digital twins, we discuss challenges that may be encountered when adopted at large scale, as well as suggest practical solutions to achieve the scalable implementation, such as spatial coverage, data availability (e.g. data infrastructure and real-time prediction), as well as computational demands (e.g. time for personalised predictions) (Mazzetto, 2024; Xu et al., 2024).

Scaling the JITAIs framework in a larger level needs to incorporate a more comprehensive representation of local urban settings. While the campus area has the potential to represent a microcosm of a city (e.g. incorporating a variety of physical buildings and social activities), the whole city is large, growing and changing constantly. Cities are composed of diverse districts with varying urban morphology, functions, and regulations, entailing challenges scaling the JITAIs framework spatially. For example, the spatial distribution of land use types, such as public space, industrial zones or residential areas, not only determines contextual conditions but also impact patterns of human activities and their perceived comfort. Therefore, establishing a one-size-fits-all digital twin becomes increasingly challenging when spatial boundaries extend. Our framework incorporates four dimensions to represent the campus area (e.g. forms and streetscape), however, it is highly customised, enabling more dimensions to appropriately reflect the spatial context. For example, when adopting this framework in a city-level urban digital twin, additional information should be taken into account to mirror the specific and localised urban environment, associated with outdoor comfort, e.g. land use, traffic flow, air quality, or the accessibility to public services and recreational facilities. Meanwhile, considering the spatial heterogeneity, a context-aware design approach can be considered when developing the interventions. Thus, the intervention logic and communication strategies may be updated to accommodate diverse physical, societal and cultural characteristics of specific districts, thereby effectively understanding and improving human comfort outdoors.

Further, the future deployment at a city level may encounter the challenge of data availability which are inherent to the heterogeneity of urban data input (Sanchez-Sepulveda et al., 2024). In contrast to the information available in the campus case, many parts of a city may lack sufficient infrastructure to acquire data (e.g. uneven weather station distribution, network latency, and information integration and interoperability), leading to data sparsity at the city level. The data challenge may compromise the efficiency of two-way interaction modelling in a city-level digital twin and, in turn, impact the quality of adaptive interventions. Taking into account the potential obstacles, future implementations can incorporate hybrid strategies to make the multi-scale adoption available. For example, while scalability is a widely recognised challenge in urban digital twins, several solutions have been discussed that contribute to the body of knowledge. For example, spatial interpolation techniques (e.g. kriging) are adopted for missing data prediction (e.g. weather data and noise data), where artificial intelligence has advanced the algorithm and accuracy thoroughly (Wei et al., 2025; Han et al., 2024). Further, the use of synthetic data becomes a trend to solve the scalability problem, combining with real-time data to learn more generalisable information (Almirall et al., 2022).

The computational demands in relation to computing resources and processing time need to be managed when implementing the framework in a city-scale urban digital twin. While our current approach employs individualised models for personalised interventions, scaling the strategy to amount of participants scattered in the city, will raise feasibility concerns regarding model training and prediction, on-time behaviour interventions, and data management. Therefore, future work can explore modular and hierarchical modelling approaches (e.g. federated learning, meta-learning), maintaining personalisation while optimising resource use. Meanwhile, data facilities, such as distributed systems or cloud-edge hybrid infrastructure can be included to manage personalised models in parallel at the same time, managing computational demands at larger scales. Further, our work acknowledges the importance of developing individualised models. However, the further adoption of the JITAIs framework in a city can be modified to satisfy specific research objectives. For example, if the personalisation is not the main focus, the implementation can consider hierarchical or multi-level modelling for prediction and interventions, such as deploying hierarchical graph neural networks to model the spatial heterogeneity and aggregate local behaviour to city-wide patterns efficiently.

5.3.2. Data privacy and ethics

Considering the notion of JITAIs, which are closely tied to human behaviour, further operations must also consider privacy concerns and ethical challenges (e.g. information sensitivity) when integrating human-centric perspectives in urban digital twins. In this work, we involved 14 participants who completed both Phase 1 and Phase 2 experiments. Each participant contributed between 33 and 255 usable responses, depending on their level of engagement. While some participants provided a limited number of responses, the analytical results are sufficient for a proof-of-concept study, given the accumulation of microsurvey responses and the campus-scale study area. While the response volume varies among participants, our aim is not to generalise findings to a wider population, but rather to validate the feasibility of a two-way JITAIs framework and demonstrate its integration in urban digital twins.

However, when scaling the JITAIs framework in a city-scale urban digital twin, a larger number of participants will be included, introducing uncertain impediments to operation (Dembski et al., 2020). For example, sensitivity related to personal information is an inevitable challenge in this case. A key novelty of this two-way framework lies in the spatial triggers, which enable interventions based on participants' geolocations. However, it will raise concerns regarding the potential leakage of personal information, particularly accommodating a broad range of participant demographics (e.g. gender, age, and cultural background) in a larger and more diverse urban environment. Therefore, challenges related to ethical information and data security should be considered when developing a human-centric urban digital twin, especially when leveraging humans as agents to formalise two-way interaction. Future work should incorporate established standards and protocols for the ethical use, sharing, and protection of human data, e.g. federated learning, data anonymisation and information consent (Liu et al., 2024; Cui et al., 2018). Meanwhile, integrating features that enable participatory feedback will be essential for fostering public trust and adaptability (Nochta and Oti-Sarpong, 2024; Lei et al., 2023a). Developing tailored strategies that prioritise transparency and responsiveness, human-centric urban digital twins can better address privacy concerns and enhance societal acceptance in large-scale deployments (Sharma et al., 2022).

5.4. Limitations and future work

This study represents an experimental proof of concept and the first attempt to investigate the spatio-temporal dynamics of bidirectional interaction between humans and urban environments through the lens of just-in-time adaptive interventions (JITAIs). However, several limitations are identified, providing opportunities for improvement in future research.

The first limitation lies in the bias inherent in urban data collection. In this study, we deploy street view imagery collected by cars to represent visual quality. However, such images are only available on roadways, which cannot fully cover pedestrian-only paths. Therefore, when participants are in car-restricted areas, there may be incomplete representations of participants' surroundings (Ito et al., 2024b). In this regard, future research can consider a 'humans as sensors' approach (Lei et al., 2023b), encouraging participants to actively collect data, such as using wearable devices (e.g. GoPro cameras) to capture on-site SVI. Hence, it will enhance the spatial coverage and completeness of urban data, providing a comprehensive representation of urban contexts.

Second, the concept of human comfort outdoors introduced in this study encapsulates a variety of comfort perception in a sensible and changing manner. However, due to data availability, the current JITAIs are limited to notification types related to thermal, acoustic, and visual perception. In future work, we tend to incorporate more dimensions that contribute to outdoor comfort perception, such as overcrowdedness, emotional stress, walkability, accessibility, and social inclusion. An expansion of outdoor comfort aspects will provide a more holistic understanding of how people experience the urban environments and enable more comprehensive interventions.

Third, while the campus area satisfies our research aims at this stage of such developments in this novel research line, we are aware of potential limitations when generalising broader applications. For example, the demographic distribution in our study is uneven, with 78.6% female and 21.4% male participants spanning diverse age groups. Further, the campus itself represents a well-constructed environment, ensuring a good-quality layout and aesthetics. However, it may limit the generalisability of findings, as the influence of visual quality on outdoor comfort may be less tangible on campus compared to other urban areas. Moreover, daily campus life tends to involve more regular routines centred around work and study. Despite our efforts to include a diverse range of participants (e.g. both students and staff from various demographic groups), such patterns may not fully capture the variability of behaviour and comfort perception observed in city-scale environments. When extending the study to larger and more heterogeneous urban areas, we will take into account diverse demographics and complex urban contexts to ensure the robustness and generalisability of the results.

Finally, our study is focused on Singapore, a highly-urbanised tropical city-state, thus, the results may not be fully transferable elsewhere, especially other climates and urban morphologies.

6. Conclusion

Urban digital twins have emerged as an innovative technology, demonstrating the potential to facilitate planning and enhance decision-making. We advance urban digital twins, enabling a two-way information exchange between humans and virtual models, a rarity. The two-way interaction between virtual and physical systems is a key characteristic to deliver the promise of a ‘true’ urban digital twin. However, it is not fully addressed in research and practice. Complementing the mainstream discussion on one-way urban digital twins (e.g. monitoring and visualisation), this work is the first endeavour of proposing a bidirectional framework to model the two-way interaction between humans and urban digital twins, leveraging humans as sensors. In particular, we adapt the concept of just-in-time adaptive interventions (JITAIs), integrating human perception of outdoor comfort to realise this bidirectional information loop in urban digital twins, which is still rare (Haraguchi et al., 2024).

While JITAIs have been widely used in health-related domains, our study is among the first to apply this concept within the context of urban digital twins to complete the information loop between humans and urban environments. Here, humans serve as 'sensors' who contribute subjective comfort data (e.g. thermal, visual, and acoustic) back to the urban digital twin. Meanwhile, our urban digital twin processes human responses alongside physical urban information (e.g. streetscapes, microclimate conditions) in near real-time, thereby creating a two-way information flow. Aligning with person-environment fit theory and JITAIs, we thus design a two-phase human outdoor comfort JITAIs framework for the information loop in urban digital twins. This framework not only quantifies how urban surroundings affect human comfort perception but also enables actionable interventions to improve comfort perception, leveraging urban digital twins. In the implementation of our JITAIs framework, we take a university campus as the study area and involve 14 participants in the experiments who were required to wear Apple Watches and answer microsurveys (supported by the Cozie application, adapted by the team) while conducting outdoor activities. Their responses feed directly into the urban digital twin, making it possible to generate comfort predictions and tailor interventions over time.

In Phase 1, we collected participants' responses regarding measuring their comfort perception and associated urban features — such data are incorporated into our digital twin to calibrate models of geolocation-based comfort levels. Phase 2 is advanced by JITAIs and urban digital twins to deliver watch-based notifications. The predictive models identify when and where discomfort is likely to occur, and the system then sends participants personalised messages that offer context-specific strategies to mitigate discomfort. For example, if the urban digital twin forecasts unpleasant sound environment in an upcoming location, participants receive interventions from a pre-developed corpus of noise-related notifications. This represents a true bidirectional interaction in urban digital twins — comfort perception continually update the digital twin models, and the system, in turn, sends targeted prompts back to humans to improve their comfort just-in-time. We also design end-of-day phone surveys in Phase 2, evaluating and validating the effectiveness of our interventions, thereby closing the loop in urban digital twins.

We collected more than 1,000 responses from Phase 1, merging with contextual urban data (e.g. streetscape and weather data) and integrating these combined datasets into our digital twin to develop prediction models advanced by the random forest algorithm. We build separate models for each participant within the urban digital twin, enabling personalised interventions to be sent to participants in Phase 2, addressing spatio-temporal dynamics. Analysing participants' evaluation of JITAIs, the results indicate that most notifications help them better understand the perception of outdoor comfort (e.g. how their comfort is affected by urban environments). Yet, JITAIs largely fail to induce behaviour change — only 14.5% of responses indicate adherence to the interventions. We also find that compliance with interventions is related to individual heterogeneity, for example, preference for being outdoors, or varying sensitivity to urban subtleties (e.g. visual changes). In turn, the impact of urban features on comfort perception differs among participants, illustrating how the digital twin can account for both common and individualised factors. Through this bidirectional interplay — where human-generated information updates urban digital twins, and the twin provides tailored interventions, this framework has enhanced real-time outdoor comfort (i.e. proximal outcome) and continuously inform urban design and planning to promote public health and well-being in the long term (i.e. distal outcome). In summary, JITAIs are useful in understanding comfort perception but fall short in confidently influencing behaviour of people. However, despite the latter, this research delivers novel results that will help drive future work in this novel research line.

The JITAIs framework substantiates the potential to be integrated into urban digital twins, facilitating a two-way exchange of information between physical and virtual entities through a lens of humans. This work enriches the capacity of urban digital twins to represent and respond to spatio-temporal dynamics, bridging the gap between individual behaviour, urban environments, and innovative technology. Further, this study paves the way for multidisciplinary applications of urban digital twins across domains, opening the door for multidisciplinary applications. Such a human-centric approach underscores the potential of urban digital twins in fostering liveable and inclusive cities.

Acknowledgements

We gratefully acknowledge the participants of the survey and the input data. We thank the members of the NUS Urban Analytics Lab for the discussions, especially Xiucheng Liang for helpful suggestions. The Institutional Review Board of the National University of Singapore has reviewed and approved the ethical aspects of this research (Reference Code: NUS-IRB-2024-104). This research is part of the projects: (1) Multi-scale Digital Twins for the Urban Environment: From Heartbeats to Cities, which is supported by the Singapore Ministry of Education Academic Research Fund Tier 1; (2) Large-scale 3D Geospatial Data for

Urban Analytics, which is supported by the National University of Singapore under the Start Up Grant R-295-000-171-133; (3) From Models to Pavements: Advancing Urban Digital Twins with a Multi-Dimensional Human-Centric Approach for a Smart Walkability Analysis, which is supported by the Humanities Social Sciences Seed Fund at the National University of Singapore (A-8001957-00-00). This research has been supported by Takenaka Corporation. This research was secondarily supported by the National Research Foundation, Prime Minister's Office, Singapore, under its Campus for Research Excellence and Technological Enterprise (CREATE) programme.

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