The effect of urban greening on pedestrian's thermal comfort and walking behaviour

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Abstract. The urban heat island (UHI) phenomenon is becoming increasingly severe due to unprecedented urbanization and global warming paces. The increasing heat stress threatens the environment, the health of residents, and also the city the walkability. However, greenspace can generate a cooling effect to mitigate the UHI. To gain a better understanding of how urban greening contributes to the optimization of outdoor thermal comfort and the improvement of city walkability, this study investigates the relationships between outdoor thermal environment, the thermal comfort of pedestrians, and their traveling behaviours. Thermal environment was simulated using a microclimatic computational fluid dynamic (CFD) model – ENVI-met. Travel behaviour of pedestrians was simulated through agent-based modelling (ABM). A total of 337 pedestrians were monitored and interviewed across several outdoor sites with different urban morphologies in Hong Kong, along with the simultaneous collection of site-specific climatic data. Based on the data, relationships between outdoor thermal conditions, human thermal perceptions, and walking speeds were analysed exploratively and quantitatively. It is found that the walking speed of pedestrians is notably reduced with increased thermal stress levels. The walking speed can be well predicted by a polynomial regression model (R^2=0.719), artificial neural network (ANN) models (R^2=0.907), and a deep neural network (DNN) model (R^2=0.931). Street trees can improve outdoor thermal comfort effectively (a maximum reduction of the mean radiant temperature at 4.23 $°C$ and a maximum reduction of the universal thermal index at 0.88 $°C$). Simulation results of ABM demonstrate that street trees can cause a reduction in perceived travel time (PTT) of up to 3 s per 100 m. The research findings are expected to mitigate urban warming and constitute thermally comfortable and walkable outdoor environments.

1 Introduction

Urban heat island (UHI) effect is a well-known and extensively studied phenomenon. The first evidence about UHI can be traced back to the early 19th century [1]. The higher temperature in urban areas as compared with rural areas may lead to many environmental and health issues [2-4], e.g., environmental pollution, aggravated resource consumption, and a higher risk of heat-related illness. The negative consequences are expected to be worsen with global climate change and associated extreme weather. In particular, UHI adversely affects the walkability of cities in those hot climates since walking is a weather-exposed activity, which is highly influenced by climatic conditions [5]. More walkable urban neighbourhoods have been found to be closely associated with better physical, social, and psychological well-being of their residents [6]. Therefore, UHI mitigation is important for thermal comfort improvement and constructing more active, liveable, and healthier communities.

One major direction is to apply mitigation strategies such as urban greening and high-albedo surface materials to ease such environmental problems. In general, urban greening is believed to be the most effective approach to cooling down the surrounding environment through shading, evaporation, and evapotranspiration [7, 8]. Typical street-level examples and urban parks and street trees [7, 9]. However, due to the limited urban space for adopting ground-level greening, roof-level greening, e.g., green roof and green façade, have been popular [8, 10, 11]. Although UHI mitigation through roof-level strategies has been extensively investigated, their effectiveness on improving the pedestrian-level thermal environment has been questioned [12, 13].

Relationships between urban heat mitigation strategies and UHI have been commonly studied at the mesoscale using numerical models. This may leave out some important micro-scale complexities that influence thermal comfort [14]. Moreover, to evaluate the benefits of heat mitigation strategies on city walkability and to further assist the development of more comfortable walking environments, connections between thermal perception and walking behaviours of pedestrians need to be established [15]. Although previous studies have identified the speed of pedestrians is dependent on the amount of shade, the relationship between outdoor

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thermal conditions and pedestrians' walking behaviours has not been confirmed through field studies [15, 16]. In addition, the complex and ill-defined factors that lead to the variation of pedestrian's movements increase the difficulty of modelling. With recent increases in computational power, artificial neural network (ANN) and deep neural network (DNN) have gained popularity for their capacities to handle non-linear relationships and represent functions with high complexity [17, 18]. The use of agent-based modelling (ABM) to simulate urban crowd activities also provides many possibilities to predict and evaluate human responses to different forms of urban designs [19]. A few studies have used ABM to evaluate human adaptive behaviours in response to thermal comfort [20, 21]. The results demonstrate the potential of using ABM to model adaptive individuals. However, due to complicated urban layouts and volatile outdoor microclimates, it remains a great challenge to use ABM to simulate agents' behaviours in response to the urban thermal environment.

With rising interest in implementing heat mitigation strategies in cities, this study aims to investigate the effect of different kinds of urban greening on pedestrian's thermal comfort and travel behaviour. The study includes three specific objectives: (1) to identify the influences of thermal perception on pedestrian's walking behaviour using field surveys; (2) to model the effect of both pedestrian-level and roof-level greening on thermal comfort using micro-climatic simulation; and (3) to model the effect of different types of greening on city walkability using a variety of predictive models. The research data and results are anticipated to contribute to a better understanding of the impacts of urban thermal environment on pedestrians' thermal perception and walkable mobility. Such information shall be valuable for improving urban thermal comfort and walking environment, especially in the context of global warming and extreme hot weather.

2 Methodology

2.1 Methodology overview

Research data was collected via field studies conducted in Hong Kong. Hong Kong's subtropical climate is characterized by a long, hot, and rainy summer. Coupled with the strong urban heat island effect, there is a high possibility for pedestrians to perceive discomfort in the outdoor environment during the summer seasons [10]. A total of ten field studies were carried out from 14:00 to 17:00 in typical summer conditions in May and June 2021. Each field study comprised three components: (1) meteorological surveys; (2) onsite interviews; and (3) video recordings. For each field study, the three components were simultaneously conducted.

Four commonly used heat mitigation strategies were studied, including three forms of green infrastructure (extensive green roof, intensive green roof, and green façade), and one form of street-level greenspace – street trees. A micro-scale computational fluid dynamics (CFD) model is used to simulate the thermal environments affected by each kind of urban greening, while conventional regression models, neural networks, and ABM are used to evaluate pedestrians' responses to the thermal environments. In ABM, individuals are represented as autonomous "agents" with personal attributes and behavioural possibilities, and rules are created to govern interactions among the agents and between the agents and the surrounding environment [22, 23]. Fig. 1 shows the overall research methodological framework.

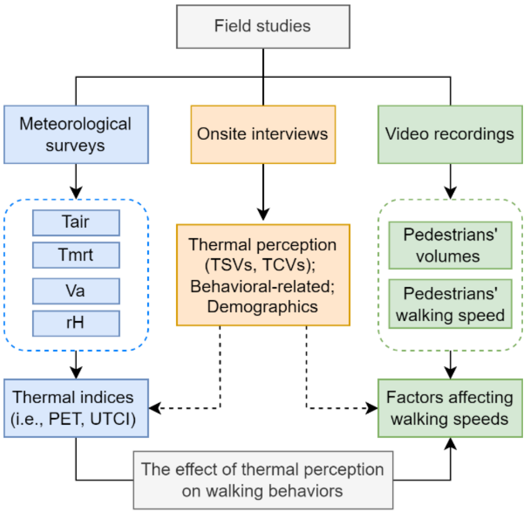

Fig. 1. Research methodology

As indicated in Fig. 1, the meteorological factors collected via onsite surveys were then inputted to calculate universal thermal indices (i.e., PET and UTCI). Information collected during onsite interviews includes the interviewees' thermal sensation votes, thermal comfort votes, behaviour-related or activity-related factors, and demographics. The walking speed of pedestrians was obtained from video recordings.

2.2 Data collection

2.2.1 Collection of climatic parameters

During the entire survey period, onsite climatic data was continuously measured by using a Kestrel 5400 weather station (Nielsen-Kellerman Co. USA). The weather station was set up 1.5 m above the ground level in the middle of the walking path. The data logging interval was set as one second. Four major meteorological factors were collected, including air temperature (T_a), mean radiant temperature (T_{mrt}), wind speed (V_a), and relative humidity (rH). For each interviewed subject, the averages of the recorded climatic data during the subject passing through the walkway were used for quantitative analysis.

2.2.2 Collection of personal information

Onsite interviews were conducted with 337 pedestrians to gain an understanding of their thermal sensation and thermal comfort, along with other factors that may affect their thermal perceptions and movements. Data obtained from each individual matches the meteorological conditions when the subject walked through the survey area. Note that permissions were obtained from the interviewees before using the collected data.

The interview consisted of two sections. The first section recorded subjects' thermal experiences (thermal sensation votes or TSVs; thermal comfort votes or TCVs) and behaviour-related information. The TSVs of subjects were described by the ASHRAE 7-point scale (-3 – cold, -2 – cool, -1 – slightly cool, 0 – neutral, 1 – slightly warm, 2 – warm, 3 – hot) [24]. The TCVs were described by a typical 5-point scale from *very uncomfortable* to *very comfortable* [25]. With referring to previous studies [25, 26], the surveyed behaviour-related information included the trip purpose, activity type, whether the subject had been in an air-conditioned space 15 minutes before approaching the survey site, and the length of residence in Hong Kong. The activity information was then converted quantitively to the metabolic rate according to the ASHRAE standard 55 [27] and ISO standard 7730 [28]. The second section recorded demographic information (gender, age, body mass information) and clothing worn at the time of interview and before the trip. The subjects' clothing information was converted to the clothing insulation value (clo) [27, 28]. The questionnaire used for the onsite interview is shown in Fig. 2.

Questionnaire survey (English version)

THE HONG KONG POLYTECHNIC UNIVERSITY 香港理工大學

Thank you very much for your willingness to participate in our survey of how outdoor thermal comfort affects walkability. The results of this study will contribute to the optimization of urban open spaces to better satisfy the needs of citizens.

Research team, CEE department, PolyU

Part 1: Outdoor thermal comfort and walkability

(1) How do you feel the climate at this time in this space?
☐ Neutral ☐ Slightly warm ☐ Warm ☐ Hot
☐ Slightly cool ☐ Cool ☐ Cold

(2) Do you perceive the thermal environment as comfortable or not?
☐ Neutral ☐ Comfortable ☐ Very comfortable
☐ Uncomfortable ☐ Very uncomfortable

(3) What is the main purpose for walking in this space?
☐ Daily commuting (study or work) ☐ Having an appointment
☐ Doing exercise or fitness ☐ Recreational (go for a walk)
☐ Doing daily tasks or housework (e.g., shopping, picking up children, walking the dog) ☐ Others (please specify) __________

(4) Were you in air-conditioned environment for the last 15 minutes?
☐ Yes ☐ No

(5) What is your activity for the past 15 minutes?
☐ Sports (intense) ☐ Sports (medium) ☐ Sports (low)
☐ Sitting ☐ Standing ☐ Walking

(6) How long have you been in Hong Kong?
☐ <1 month ☐ 1-3 months ☐ 3-6 months
☐ 0.5-1 year ☐ 1-3 years ☐ >3 years

(7) Do you think more green spaces (e.g., street trees) will attract you to visit this place or not?
☐ Yes ☐ No

(8) Do you think green spaces (e.g., street trees) will affect your walking speed or not?
☐ Yes, it will increase my speed. ☐ Yes, it will decrease my speed.
☐ No, it will not affect my speed.

Part 2: General information

(1) Sex: ☐ Male ☐ Female

(2) Age group:
☐ <18 ☐ 18-30 ☐ 30-45 ☐ 45-60 ☐ >60

(3) Fitness information / body mass index (*BMI = weight (kg) / [height (m)]^2*)
Please choose the most appropriate classification for your fitness:
☐ Normal (18.5 <BMI < 25 kg/m^2) ☐ Pre-obese (25 <BMI <30 kg/m^2)
☐ Mild thinness (17 <BMI < 18.5 kg/m^2) ☐ Obese (30 kg/m^2<BMI)
☐ Moderate thinness (16 <BMI < 17 kg/m^2) ☐ Have no idea/do not want to answer

(4) Clothing
Please click all clothing you are wearing at this moment (multi-choice):
Head: ☐ Hat
Upper body: ☐ Vest ☐ T-shirt ☐ Shirt ☐ Jacket ☐ Dress (no sleeves) ☐ Dress (with sleeves) ☐ Wind breaker
Lower body: ☐ Short pants ☐ Skirt ☐ Pants (thin) ☐ Pants (thick)
Feet: ☐ Socks ☐ Shoes

Thanks for your participation. Have a nice day!

Fig. 2. Questionnaire survey

For the observation of walking behaviours of pedestrians, a video recorder was placed at a certain distance from the walking path to ensure that video footage covers the entire walking path, which is about 100 m. Time, location, and walking speed of the interviewed subject was recorded before the interview.

2.3 Data analysis

2.3.1 Calculation of universal thermal indices

To assess outdoor thermal comfort, several universal thermal indices integrating environmental factors and the energy balance of the human body have been developed [29]. These indices can translate the evaluation of a complex outdoor climatic environment to a single value that can be easily understood and interpreted. Two commonly used universal thermal indices - Physiological Equivalent Temperature (PET) and the Universal Thermal Climate Index (UTCI) were employed in this study to understand pedestrian-level thermal conditions [30, 31]. The micro-climatic modelling software – SOLWEIG [32] was used to calculate PET and UTCI.

To calculate PET and UTCI, mean radiant temperature (T_{mrt}) was determined by the globe thermometer method, as explained in detail by Kuehn et al. [33]. The globe thermometer method was initially developed to measure indoor radiant temperature. For outdoor use, an empirical equation is required to predict T_{mrt} based on additional parameters including wind speed and air temperature (Eq. 1):

$$T_{mrt} = \left[(T_g + 273.15)^4 + \frac{1.1*10^8 {V_a}^{0.6}}{\varepsilon D^{0.4}} * (T_g - T_a)\right]^{0.25} - 273.15 \qquad (1)$$

where T_g and T_a are globe temperature ($°C$) and air temperature ($°C$), respectively, V_a is wind speed (m/s), D is globe diameter (mm), and ε is globe emissivity. In the SOLWEIG simulation, inputs include the major meteorological parameters and the geometry of the modelled areas derived from the high-resolution digital surface model (DSM).

2.3.2 Micro-climatic modelling of thermal comfort

ENVI-met is a CFD-based micro-climate and local air quality model. It has been widely applied to account for the thermal exchange within street canyons [34]. ENVI-met is used here to simulate the outdoor thermal comfort of each location within the modelled environment incorporating different urban greening.

The computational domain is set as X × Y × Z = 250 m × 250 m × 200 m. The grid resolution is 2 m. Key input parameters include weather conditions, initial soil wetness and temperature profiles, structures, the physical properties of urban surfaces, and plants [35]. Simulations in this study are based on a hot summer day. A base scenario without any urban greening is used as a reference. Four optimized simulation scenarios are developed on the base scenario, including (a) extensive green roof; (b) intensive green roof; (c) green façade; and (d) street trees.

2.3.3 Prediction of walking behaviours

The models used for predicting walking behaviours include both conventional regression models and neural network models. The walking speed was used as the dependent variable. Before the conventional regression analysis, relationships between walking speed and a variety of potential influencing factors were exploratively examined. A multivariate polynomial regression analysis was finally conducted.

For neural network models, both ANN and DNN were attempted. The ANN models were further divided into two stages. In stage 1, the neurons in the input layer only consisted of objective data such as behavioural-related and demographic variables. In stage 2, subjective factors reflecting human thermal sensation states were also added in the input layer. In the DNN model, the objective thermal indices and subjective thermal perception were both included as input variables. The number of hidden layers and the neuron numbers within each hidden layer were determined by comparing the coefficient of determination (R^2) and the mean square error (MSE) values of different DNN models. The DNN structure with the best predictive performance was selected. Table 1 summarizes inputs for both the regression model and the neural network models.

Table 1. Model inputs for the predictive models

Models	Input parameters: Personal behaviour and demography	Input parameters: Thermal sensation
Polynomial regression model	Gender; age; purpose of visit; whether in an air-conditioning environment in the past 15 minutes; metabolic rate; body mass index; clothing insulation; length of residence in Hong Kong	TSV
Stage 1 ANN model		/
Stage 2 ANN model		TSV
DNN model		TSV

The data was initially segmented into a training set (70% of the total data points) and a testing set (30%). In the training process, the learning rate was set as 0.001, and the maximum number of epochs was set as 1,000.

2.3.4 Agent-based simulation of walking behaviours

Agent-based simulation of walking behaviours of pedestrians consists of two main modules: a thermal comfort assessment module using ENVI-met and an agent's behaviour simulation module based on ABM. The diurnal profiles of ENVI-met outputs at the walkways of the study area are entered into ABM to examine the interactions between thermal comfort and pedestrians under the thermal environments associated with different kinds of heat mitigation strategies. The pedestrians' perceived travel time (PTT) variations provide an indication of walkability.

ABM is performed by AnyLogic - a JAVA-based programming and simulation tool. In the modelled environment, agents with individual physiological properties such as gender, age, and other behavioural-related attributes move from different origins to a common destination. The walking speed of agents would be continuously affected by thermal comfort. Walkability of the environment incorporating different kinds of urban greening is assessed by PTT calculated based on the cumulative travel time of each location.

3 Results

3.1 The relationship between universal thermal indices and human thermal perception

To more clearly demonstrate the general trends of relationships between the universal thermal indices and thermal perceptions, two parameters are introduced here: mean thermal sensation vote (MTSV) and mean thermal comfort vote (MTCV). They refer to the average TSV or TCV value at a same PET or UTCI level, respectively. The following regression models between universal thermal indices (PET and UTCI) and MTSV/MTCV were developed:

$$MTSV = -5.218 + 0.245 \times PET\ (R^2 = 0.921) \qquad (2)$$

$$MTSV = -7.068 + 0.276 \times UTCI\ (R^2 = 0.860) \qquad (3)$$

$$MTCV = 2.490 - 0.092 \times PET\ (R^2 = 0.790) \qquad (4)$$

$$MTCV = 4.319 - 0.139 \times UTCI\ (R^2 = 0.765) \qquad (5)$$

Thermal perception on walking using different methods. The values of the coefficient of determination (R^2) reveal strong correlations between the universal thermal indices and human thermal perceptions. The regression coefficients of universal thermal indices (UTCI and PET) also indicate that human thermal perception appears to be more sensitive to changes in UTCI than change in PET.

3.2 The relationship between pedestrian's thermal perception and walking behaviour

3.2.1 Prediction using regression analysis

An explorative analysis was firstly conducted to examine relationships between all the potential influencing factors and the walking speed of pedestrians. Based on the findings from the exploative analysis, a multivariate polynomial regression analysis was conducted. The overall model is significant at the 0.05 significance level with R^2 of 0.719, indicating that the majority of variation in walking speed can be captured by the model. The equation for predicting pedestrian's walking speed can be expressed as:

$$y = 1.300 - 0.045TSV - 0.003TSV^3 + 0.023air_{yes} - 0.108gender_{female} + 0.202age - 0.043age^2 - 0.140clo \qquad (6)$$

where whether in an air-conditioned space in the past 15 minutes and gender are categorical variables, and TSV, age, and clo are continuous variables. The regression analysis results indicate that pedestrian's TSV, gender, age, clothing, and whether in an air-conditioned space in the past 15 minutes play significant roles in affecting the walking speed. The impacts of metabolic rate, the length of residence in Hong Kong, the purpose of visit, and BMI are not significant.

3.2.2 Prediction using neural network models

The performance of the three neural network models (namely stage 1 ANN, stage 2 ANN, and DNN models) is shown in Table 2. The model comparison is based on both independent dataset which is the same in different neural network models (101 samples, 30% of the total dataset) and the entire dataset (337 samples). Judged from the independent test dataset, all the models predict walking speed reasonably well, and the DNN model performs the best: 79% of speed variations in the dataset can be captured by the DNN model. According to results of the entire dataset, the R^2 values of three neural network models are all higher than the R^2 of the polynomial regression model. The DNN model yields the best performance among all the models with the R^2 of 0.931 for the entire dataset.

Table 2. Model inputs for the predictive models

Models		The test dataset	The entire dataset
Stage 1 ANN model	Pearson Correlation	.818**	.904**
	R Square	.669	.817
	Std. Error	.102	.074
Stage 2 ANN model	Pearson Correlation	.873**	.953**
	R Square	.762	.907
	Std. Error	.086	.052
DNN model	Pearson Correlation	.889**	.965**
	R Square	.791	.931
	Std. Error	.081	.045

Major findings identified from the predictive results using both regression models and different neural network models are shown below:

- The predictive results using all models show that walking speed of pedestrians is notably reduced with increased thermal stress levels.
- The comparison of the predictive accuracy in stage 1 and stage 2 ANN models indicates the inclusion of thermal sensation can significantly improve the prediction accuracy of walking speed.
- The comparison of the predictive accuracy in ANN and DNN models suggests that the DNN model can provide better fitness with less forecasting errors.
- The regression model can help quantify the impacts of influencing factors on walking speed, although the model performance is slightly worse than the performance of neural network models.

3.3 The effect of greening on thermal comfort

The diurnal profiles of the thermal comfort at the pedestrian level in the reference scenario and four optimized scenarios incorporating urban greening were estimated based on ENVI-met. Due to the higher sensitivity of UTCI to human thermal experience than PET, as shown in Eq. (2-5), UTCI is used to reflect thermal comfort of each scenario. Fig. 3 presents the hourly UTCI variations for all the scenarios. The UTCI shown in the figure is the averaged UTCI values of all locations on the walkways.

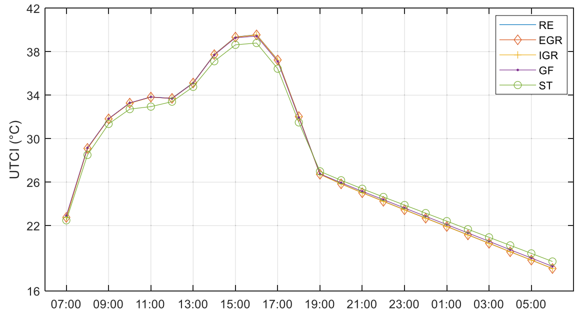

Fig. 3. Diurnal profiles of UTCI for all the scenarios
Note: RE = reference, EGR = extensive green roof, IGR = intensive green roof, GF = green façade, ST = street tree.

The UTCI values of different scenarios demonstrate similar diurnal patterns with the maximum occurring at around 16:00 and the minimum at around 06:00. In the daytime, UTCI is relatively high compared to the value at night. The value of UTCI reduces dramatically during the sunset period. Among all scenarios, street trees result in the lowest UTCI values in the daytime, with a maximum UTCI reduction of 0.88°C occurring at 11:00. The UTCI values of all other kinds of greening are only slightly lower than those of the reference. The results demonstrate that adding street trees is significantly effective in improving the thermal comfort of pedestrian-level, while the effect of roof-level greening on thermal comfort improvement is relatively weak.

3.4 The effect of greening on walking behaviour

3.4.1 Agent-based model development

The variations of walking behaviours of pedestrians in outdoor environments with different thermal comforts can be predicted based on the findings identified from field surveys, namely the relationship between universal thermal indices and human thermal perception (see section 3.1, Eq. (2-5)); and the relationship between thermal perception and walking behaviours (see section 3.2). Then, an agent-based model (ABM) was constructed to simulate how pedestrians move in the modelled environment in response to outdoor thermal comfort affected by different kinds of urban greening.

There are three main entities in the ABM: (1) Agents. The agents are dynamic entities with different physiological properties in the modelled environment. A total number of 50,000 agents enter the environment with an arrival rate of one second per person starting from different gates. Once the agents entered the environment, the traveling time was tracked. During the movement of agents, their walking speeds are affected by the thermal comfort of each pixel and change constantly. (2) Environment. The environment is the static physical environment within which the agents act. ABM modelled environment is as same as the environment used in the ENVI-met model. (3) Controller. The controller is a top-level module that regulates the agent population and model scheduling processes. The controller used here is the effect of outdoor thermal comfort on walking behaviours of pedestrians.

The model interface is shown in Fig. 4. There are a total of 16 paths from different origins to the destination. The street canyon has a total length of 2270 m and a width of 5 m. The thermal comfort at each location of the walkways in the study area, which was predicted by ENVI-met, is translated into perceived travel time (PTT). The data labels on the left of the ABM interface display in real-time the number of agents passing a particular path as well as the mean PTT of the agents. The histogram at the top displays the distribution of real-time PTTs of all passed agents.

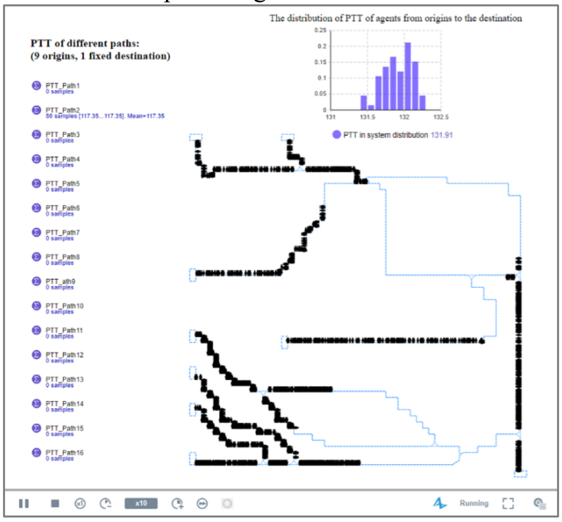

Fig. 4. ABM interface

In an ideal situation where no thermal stress is experienced by the pedestrian, pedestrian's movement behaviour will not be affected, while either cold or hot stress may cause an additional increase in their traveling time on paths. How speed varies with standard stress or comfort ranges of the universal thermal indices is shown in Fig. 5. Due to the higher regression coefficients of UTCI in Eq. (3) and (5) than the coefficients of PET in Eq. (2) and (4), UTCI was adopted to represent the universal thermal conditions. In addition, UTCI standard classes were adjusted based on such local relationships to better describe local human responses to outdoor thermal conditions.

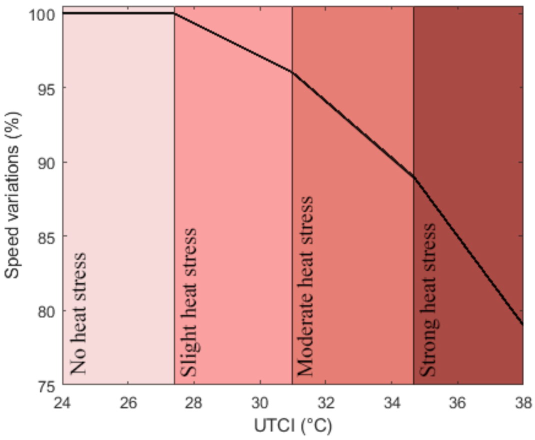

Fig. 5. Speed reduction for each reclassified UTCI class

Obviously, the average walking speed is reduced with increased UTCI heat stress levels. Under strong heat stress, a reduction in walking speed over at least 10 percent from the baseline condition is expected.

3.4.2 Agent-based model results

The ABM results for all scenarios are summarized and shown in Table 3. The results indicate that both roof-level and pedestrian-level urban greening can cause some reductions in PTT. For the most part, there are only small differences in PTT between the scenarios, the exception being the street trees (ST) scenario. The mean PTT reduction for agents walking within the modelled environment is 5.42 seconds under the ST scenario compared to the mean PTT in the reference scenario. For some paths, the PPT reduction can be up to 3 seconds per 100 m. However, for the other scenarios, the averaged PTT reductions are less than 0.5 seconds.

Table 3. The mean PTT of all paths within modelled environment for all scenarios

Mean PTT (s)	RE	EGR	IGR	ST	GF
1	142.04	142.03	142.02	141.02	142.04
2	74.45	74.45	74.44	73.99	74.45
3	161.72	161.65	161.62	159.02	161.72
4	298.03	297.94	297.85	294.97	298.03
5	271.70	271.67	271.65	265.55	271.70
6	263.32	263.28	263.23	258.45	263.32
7	531.42	531.18	531.05	522.43	531.42
8	523.04	522.79	522.63	515.33	523.04
9	534.19	533.95	533.78	524.10	534.19
10	525.81	525.56	525.36	517.00	525.81
11	505.92	505.73	505.55	498.72	505.92
12	497.54	497.34	497.13	491.62	497.54
13	510.81	510.65	510.48	503.48	510.81
14	502.43	502.26	502.06	496.38	502.43
15	481.66	481.55	481.39	473.90	481.66
16	473.28	473.16	472.92	466.80	473.28

4 Conclusion

Relationships between outdoor thermal conditions, human thermal perceptions, and walking speeds were analysed exploratively and quantitatively based on onsite field surveys and a wide range of models. A total of 337 pedestrians were interviewed during typical summer days of Hong Kong. Microclimatic CFD model – ENVI-met is used to simulate the thermal environment incorporating different kinds of greening. Conventional regression and neural network models are used to model the relationship between human thermal perception and walking behaviours, while the agent-based simulation is performed to model travel behaviours of pedestrians with individual attributes.

The findings indicate that thermal environment influences pedestrians' thermal perceptions, and further affects their walking behaviours. The walking speed of pedestrians is notably reduced with increased thermal stress levels. Urban greening is effective to improve outdoor thermal comfort and encourage pedestrians' walking behaviours. Especially, pedestrian-level greening, e.g., street trees, improves outdoor thermal comfort and saves PTT significantly, while green infrastructure beyond the ground level can still be an alternative choice for cooling the pedestrian-level environment. The findings are helpful to enhance the performance of urban greening in UHI mitigation and provide insights in urban planning and design for optimizing both thermal environment and walkability. The predictive models (i.e., the DNN model) developed in this study present very good fitness in predicting the walking behaviours of pedestrians. Such methodologies may also be extended to other regions.

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