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### Computational models of human response to urban heat

*From physiology to behaviour*

Melnikov, V.

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## Chapter 4

# The impact of pace of life on pedestrian heat stress

In the previous chapter several modes of behavioural adaptation to thermal environments were hypothesised. Adaptation of activity intensity, for example of speed of walking, can serve as an efficient form of thermal regulation through regulation of internal heat production. This chapter first investigates, computationally, the interaction of walking speed and thermal regulation with the use of the thermophysiological model reported in Chapter 2. Based on this investigation, we propose a concept of heat-stress-optimal walking speed. Secondly, we report an empirical study of walking speeds in Singapore, which reveals elevated average walking speed that does not change in response to variation in thermal conditions. This chapter demonstrates that a lack of behavioural adaptation leads to additional heat stress experienced by people in urban environments at a physiological level. This underlines the importance of studying OTC as a multi-level process describing the interaction between people and their thermal environment.

### Abstract

Elevated walking speed is an indicator of increased pace of life in cities, caused by environmental pressures inherent to urban environments, which lead to

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This chapter is based on Melnikov, V. R., Krzhizhanovskaya, V. V., Lees, M. H., & Sloot, P. M. A. (2020). The impact of pace of life on pedestrian heat stress: A computational modelling approach. *Environmental research*, 109397.

short- and long-term consequences for health and well-being. In this chapter we investigate the effect of walking speed on heat stress. We define the heat-stress-optimal walking speed and estimate its values for a wide range of air temperatures with the use of computational modelling of metabolic heat production and thermal regulation. The heat-stress-optimal walking speed shows three distinct phases in relation to air temperature, determined by different modes of interaction between the environment and physiology. Simulation results suggest that different temperature regimes require walking speed adaptation to preserve heat balance. Empirical data collected for Singapore reveals elevated average walking speed, which is not responsive to slight changes in microclimate (4-5 °C). The proposed computational model predicts the amount of additional heat produced by an individual due to the high pace of life. We conclude that there are direct implications of the high pace of life in cities on the immediate heat stress of people, and we show how a lower walking speed significantly reduces self-overheating and improves thermal comfort.

## **4.1 Introduction**

The ongoing process of global urbanisation [145] is the manifestation of cities as a pinnacle of social, economic and political organisation. The complex interaction of millions of people in the city results in economies of scale for more efficient wealth and innovation creation, use of infrastructure and provision of social services such as education and health care [15]. Urbanisation, however, also results in more people being exposed to urban environment stressors such as noise, pollution and crowdedness. As a result, human behaviour, being a function of the environment [146], changes to adapt to the urban pressures and pace of life [147]. The study of Bornstein & Bornstein [14] demonstrated that the logarithm of walking speed is linearly dependent on the logarithm of population size of 15 considered cities. This finding is now commonly considered as one of the urban scaling laws [15]. Later studies of the pace of life by Levine [16] confirmed high variation of average walking speed around the globe. Bornstein & Bornstein suggest that this phenomenon could

be the evidence of avoidance and withdrawal behaviour: “increased walking speeds serve to minimise environmental stimulation”. A recent study [9] has shown that urban noise causes significantly higher walking speeds in the same urban environment. Other personal [148] and environmental [149, 139, 150] parameters were found to also affect the walking speed. In this study we focus on the urban heat – a stressor of a growing concern due to the phenomena of climate change and urban heat island, which pose high risk to human health and well-being [151, 152]. We consider immediate physiological implications of walking speed variation — its effect on metabolic rate and thus internal heat production. In hot urban environments, the increased walking speed would imply that people are producing extra heat amplifying their heat stress. Similar effects have been shown in other research, for example, in the study of the effect of urban pollution on walking speed [153]. In that paper lower-than-usual walking speeds were suggested for walkers to minimise the uptake of pollutants in the body. Previous studies (e.g., [154] in Florida, US) have found a significant difference in walking speeds in between cool air-conditioned and warm outdoor environments, as well as in outdoor environments between cool and hot seasons. Remarkably, the difference in the thermal environment was reflected in the participants’ evaluation of sensation, but did not result in a difference in psychological arousal. The authors suggest that: “pedestrian tempo is ideally suited for identifying conditions under which individuals show little or no awareness of their actions”. They also state that it is still necessary to determine *why* these differences in tempo are observed. In this chapter we study whether thermoregulatory processes of the human body, and behavioural adaptation to the thermal environment [155], can be the determinants of these walking speed variations.

Here we investigate walking speed and climate interaction by means of computational modelling. We combine our model of thermal regulation (see Chapter 2) with the model of energy cost of walking [156] to simulate a wide range of scenarios. We describe the complex interaction of walking speed, internal heat production and its dissipation to the environment. The simulations enable us to approach the phenomenon from two perspectives: to estimate the heat-stress-optimal walking speed for given climatic conditions; and

to evaluate heat stress implications of the pace-of-life in cities. We first demonstrate the dependency of heat-stress-optimal walking speed on thermal conditions and walking distance. We then present the results of our empirical study of walking speeds in Singapore and test them against the model predictions. Using the described models, we calculate the additional heat stress incurred by Singaporeans due to their urban lifestyle. We further discuss the empirical findings such as the effect of usage of smartphone or walking in a group on walking speed. We conclude the discussion with the analysis of simulation of self-overheating due to pace-of-life in 31 cities reported in Levine's study.

The chapter is organised as follows: we describe the models in Section 4.2; we describe and analyse the computational study in Section 4.3; in Section 4.3.2 we describe the procedure and results of the walking speed experiment performed in Singapore. We discuss the results and implications of the computational and empirical studies in Section 4.4 and provide the conclusions in Section 4.5.

## **4.2 Methods**

In this section we describe the models used to perform the simulations and analysis of optimal walking speeds in terms of heat balance: a model of heat production due to walking and a model of thermal regulation of the human body.

### **4.2.1 Model of human body thermal regulation**

Our model of human body thermal regulation is based on the Gagge's two-node model [100], with optimised parameters of core-skin blood flow we performed earlier [157]. This model with modified parameters reproduced accurately the dynamics of skin temperature and sweating in warm and hot microclimates. Figure 4.1 demonstrates how walking speed affects the components of the model.

Below we briefly describe key parameters affected by the phenomenon in the current study: walking in outdoor environments. A complete model can be found in [157].

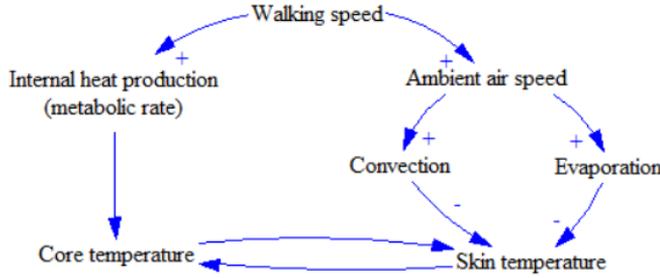


FIGURE 4.1: Causal loop diagram of interaction of walking speed and thermal regulation of human body.

The ratio of effective radiative area  $\alpha_{rad}$  describes the fraction of body surface directly exposed to the environment and thus exchanging radiative energy with it. This parameter depends on the posture of a person [115], with values varying from 0.61 while sitting to 0.79 while standing with hands up. In our study, the value of  $\alpha_{rad} = 0.72$  for a standing person is used.

Speed of walking directly affects the relative air velocity. In our simulations we assume a zero wind speed  $v_w = 0 \text{ m/s}$ , allowing the relative air velocity  $v_a$  to be equal to walking speed ( $v_a = V$ ). Relative air velocity determines the efficiency of convective and evaporative heat removal from the body. These dependencies are expressed in terms of convection and evaporation coefficients for respective heat flows. From several existing formulations of the convection coefficient [158, 159, 160], we chose the one based on experimental data [159]:

$$h_c = 12.1 \cdot v_a^{0.404} \left[ \frac{W}{m^2 \cdot ^\circ C} \right]. \quad (4.1)$$

The convection coefficient influences evaporation coefficient as follows:

$$h_e = \frac{L \cdot h_c}{1 + 0.92 \cdot I_{cl} \cdot h_c} \left[ \frac{W}{m^2 \cdot mmHg} \right], \quad (4.2)$$

where  $L = 2.2$  is the Lewis relation and  $I_{cl}$  is the level of clothing insulation described below.

Clothing plays an important role in regulation of heat exchange between the body and the environment. In our simulation scenarios we use the level

of clothing  $I_{cl}$  appropriate for the climate, but not lower than 0.3 *clo*, which corresponds to a T-shirt, shorts and sandals [161]. Figure 4.2 demonstrates the appropriate level of clothing as a piecewise linear function of outdoor air temperature, which is adopted from an empirical study of Mediterranean climate in Rome [56].

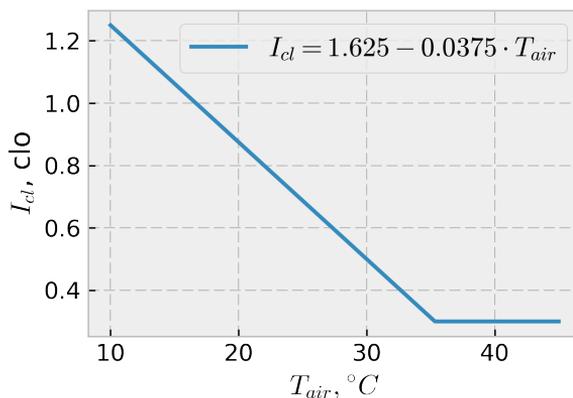


FIGURE 4.2: Linear function of appropriate to climate level of clothing used in simulation scenarios, adopted from [56].

Internal heat production is a vital process of human body. The levels of heat production are often taken from reference tables for different types of activity (e.g. sitting, standing, walking). It is appropriate for approximate evaluation of thermal comfort, but not sufficiently accurate for the purpose of our study. An accurate model of internal heat production is described in the following section.

#### 4.2.2 Model of internal heat production

The thermoregulatory model considers metabolic rate  $M$  being transferred into mechanical work  $W$  and heat, which is stored in the core of the body. For activities like sitting or standing the positive work is considered to be zero. However, a considerable amount of energy is spent on moving limbs and the core of the body while walking. It is important to mention that the ratio of positive work to metabolic rate is not constant for different walking speeds, thus models for both  $M(V)$  and  $W(V)$  are required to infer the amount of energy transferred into heating while walking. We derive the model of metabolic rate

$M(V)$  as polynomial fit of data reported for young adults of average age of 24 years,  $n=6$  [162]. In that study, the metabolic energy production was estimated from oxygen consumption and carbon dioxide production measured with a portable telemetric system. The corresponding data and quadratic fit are shown in Figure 4.3.

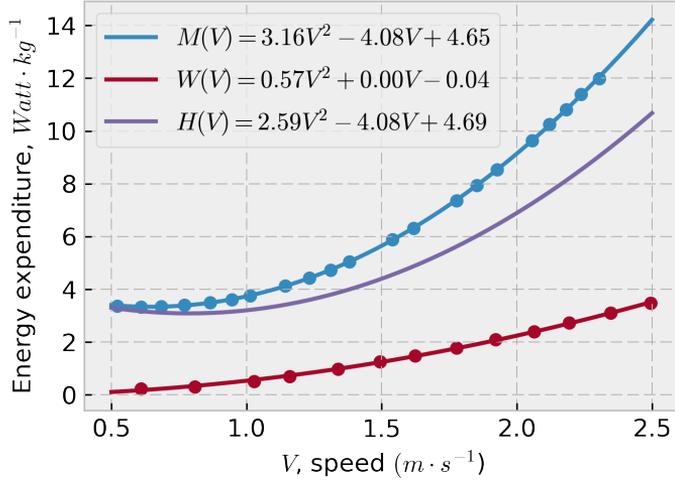


FIGURE 4.3: Dependency of total energy expenditure  $M$ , mechanical work  $W$ , and energy transferred into heat  $H = M - W$  on walking speed  $V$ . Dots represent data points from [163] used to build models (shown by solid lines).

We then define the metabolic rate  $M(V)$  with the following expression:

$$M(V) = 3.16V^2 - 4.08V + 4.65 \quad \left[ \frac{W}{kg} \right] \quad \forall V \in [0.5; 2.5] \text{ m/s} \quad (4.3)$$

We use the data reported in [163] to infer the rate of positive work performed during walking. The calculations were done for young adults ( $n=6$ ) and include positive work of moving the center of body mass and mechanical work of moving limbs relative to the body measured with a force platform and cinematography. The data and resulting fit is shown in Figure 4.3. The model for  $W$  is defined as follows:

$$W(V) = 0.57V^2 + 0.0V - 0.04 \quad \left[ \frac{W}{kg} \right] \quad \forall V \in [0.5; 2.5] \text{ m/s} \quad (4.4)$$

By definition of energy transferred into heat we derive expression for  $H$  as follows:

$$H(V) = M(V) - W(V) = 2.59V^2 - 4.08V + 4.69 \quad \left[ \frac{W}{kg} \right] \quad \forall \quad V \in [0.5; 2.5] m/s \quad (4.5)$$

### 4.2.3 Optimal walking speed

From the energy and mechanical work expressions (3)-(5), two values for optimal speed can be derived: First, the speed at which total energy expenditure per distance  $M(V)/V$  is minimised [156] and second, the speed maximising efficiency of mechanical work [112]. Figure 4.4 presents the  $M(V)/V$  plot, which takes its minimum at  $V_E^* = 1.21 m/s$ . This fact suggests that people are optimising the amount of energy spent per unit of distance walked, resulting in average speeds that are commonly observed. The efficiency of mechanical work during walking [112] is defined as

$$\eta(V) = \frac{W(V)}{M(V) - M_{stand}} \quad [-] \quad \forall \quad V \in [0.5; 2.5] m/s, \quad (4.6)$$

where  $M_{stand} = 1.94W/kg$  is the metabolic rate while standing. This efficiency  $\eta$  reflects the ratio of positive work to energy expenditure associated with walking activity. The resulting value of optimal walking speed  $V_\eta^* = 1.40 m/s$  is higher than  $V_E^*$ , but is still within the range of reported values [149, 139, 150]. However, the reference energy expenditure  $M_{stand}$ , on which efficiency depends, is chosen arbitrarily, therefore in our future analysis we will use a different value, given by the energy-expenditure-optimal walking speed  $V_E^* = 1.21 m/s$ .

### 4.2.4 Heat-stress-optimal walking speed

We introduce heat storage rate  $S(t)$  as the left-hand side of a heat balance equation (eq. 4.7) which is equal to sum of all the energy fluxes coming to and from the human body: metabolic rate  $M$ , mechanical work  $W$ , shivering  $Sh$ , respiratory heating and humidification of inhaled air  $Re$ , convection  $C$ , evaporation  $E$  and radiation  $R$ . The reader is referred to [157] for a detailed

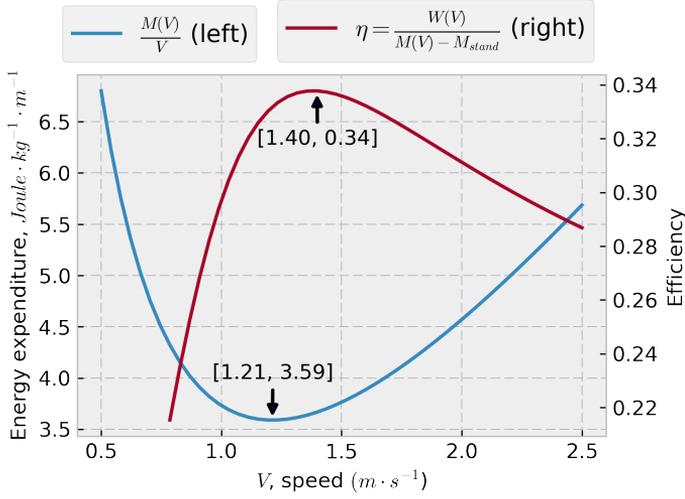


FIGURE 4.4: Optimal speeds defined as minimising the amount of energy spent per 1 meter walked  $\frac{E_{tot}}{V}$  and as maximising the efficiency  $\eta = \frac{W}{M - M_{stand}}$ .

description of these fluxes. At a given point in time the body may experience a particular heat storage rate, which leads to a positive heat gain. Our definition of heat storage (joules) considers the total heat gain over a fixed time period, so the integral of heat storage rate (watts) over some fixed time. The role of thermoregulatory system of the human body is to attain heat balance, i.e. reach the state of  $S = 0$ .

$$S = M + Sh + Re + W + C + E + R \quad [W] \quad (4.7)$$

Here the energy fluxes are not normalised to the body surface area, unlike presented in [157], to avoid confusion with the weight-normalised models of metabolic rate, mechanical work and heat production. Instead we calculate these components for a person with height of 1.8 meters, weight of 75 kilograms, and body surface area of  $1.95 m^2$ .

We adopt the classical definition of stress as proposed by Selye [164]: "Stress is the nonspecific response of the body to any demand". We define heat stress as thermoregulatory response of the human body to a specific stimulus: this happens when the body experiences a non-zero heat storage for some period

of time (a non-zero integral). This definition implies that heat stress is proportional to heat storage, has polarity and magnitude. Thus, our definition differs from the standard definition of heat stress used in occupational health and safety literature, which considers heat stress as amount of heat storage that leads to disorders and disabilities in functioning of human body.

We then define heat-stress-optimal speed  $V_{HS}^*$  as the one at which the absolute value of heat storage  $|S_{d,V}|$  over distance  $d$  is minimised, as this corresponds to the minimal thermal stress of a person. Thus:

$$\begin{aligned} V_{HS}^* &= \arg \min_V |S_{d,V}| \left[ \frac{m}{s} \right], \quad \text{where} \\ S_{d,V} &= \int_0^{t_V} S(t) dt \quad [J] \\ t_V &= \frac{d}{V} \quad [s] \end{aligned} \tag{4.8}$$

Figure 4.5 demonstrates the contributions of different terms into the total heat storage over a stretch of one kilometer in typical conditions of shaded outdoor area of Singapore for two walking speeds. As can be seen, previously found  $V_E^* = 1.21 \text{ m/s}$  promises a higher heat gain than  $V = 1.0 \text{ m/s}$  in this microclimate. In fact we later show that this walking speed corresponds to our definition of heat-stress-optimal walking speed  $V_{HS}^*$  in this microclimate.

## 4.3 Results

### 4.3.1 Simulation results

#### Climate and heat-stress-optimal walking speed

In this subsection we investigate the behaviour of  $V_{HS}^*$  as a function of microclimate.

We start with three scenarios of walking along a stretch of 1 kilometer in cool, neutral and warm thermal environments at  $T_{air} = T_{MRT} = \{15, 22, 30\}^\circ\text{C}$ , where  $T_{MRT}$  is mean radiant temperature. Here arbitrary microclimate conditions  $T_{air} = T_{MRT}$  are used and can be regarded as a clouded or evening-time condition, when the temperature of surrounding surfaces is equal to air

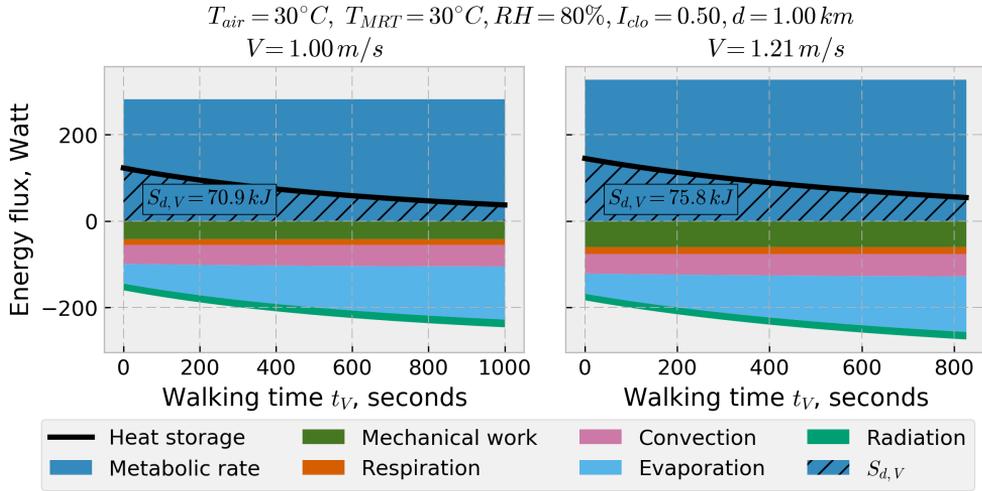


FIGURE 4.5: Simulated energy fluxes from and to human body at two different walking speeds. Heat storage rate  $S(t)$  and total heat storage over the course of walking  $S_{d,V}$  are shown.

temperature. We will investigate the impact of sun radiation and mean radiant temperature  $T_{MRT}$  in the subsequent set of simulations. For each of the three microclimates, an appropriate level of clothing was assigned (see Section 4.2.1). Relative humidity (RH) was assumed 60%. Here and in the following simulations, we assume that people start walking with a thermoregulatory system in a steady state of  $T_{core} = 36.85^\circ C$  and  $T_{skin} = 33.89^\circ C$  achieved in static indoor environment ( $T_{air} = T_{MRT} = 22^\circ C$ , relative humidity 50%, wind speed 0.05 m/s,  $I_{cl} = 1.0 clo$ ,  $M = 80 W/m^2$ ).

The results are shown in Figure 4.6. For the cool environment, heat gain  $S_{d,V}$  decreases with the decrease of walking speed, eventually crossing 0. This means that for walking speeds lower than optimal a loss of heat is expected. Recall that  $V_{HS}^*$  is defined as the speed that produces the minimum absolute heat gain/loss, so in the left most plot of Figure 4.6  $V_{HS}^*$  is set to 1.28 m/s i.e., where  $S_{d,V} = 0$ .

We also observe an intuitive increase in  $V_{HS}^*$  as the environment is changed from neutral to cool, this can be explained by a higher metabolic rate needed to compensate for higher rate of energy dissipation in the cold environment. A similar tendency is observed when switching to a warmer environment

typical for Singapore. Here zero storage rate is not achievable: any walking speed will result in a heat gain. Walking speed minimising this gain is  $V_{HS}^* = 0.98 \text{ m/s}$ , which is higher than the value found for the neutral environment. This value of  $V_{HS}^*$  can be explained by the need to move slightly faster in the warm environment to enhance convection and reduce the time of exposure to heat.

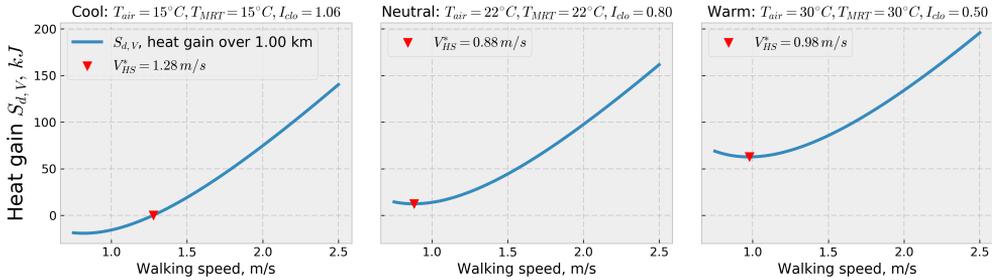


FIGURE 4.6: Dependency of heat gain  $S_{d,V}$  over the distance of 1 km on walking speed  $V$  in cool, neutral and warm thermal environments.  $V_{HS}^*$  is the heat-stress-optimal speed that provides heat balance or minimises heat gain ( $RH = 60\%$ ).

We continue our investigation of thermally comfortable optimal speeds with varying another important parameter of outdoor environments: radiation. This parameter is usually expressed in terms of mean radiant temperature (MRT)  $T_{MRT}$ . Figure 4.7 demonstrates the results for three simulated scenarios corresponding to different levels of radiation: dense clouds (no sun), light clouds, and sunny day. The thermally comfortable walking speed  $V_{HS}^*$  grows with increasing sun radiation  $T_{MRT}$ , reaching the value of  $1.19 \text{ m/s}$  for the scenario of exposure to a direct solar radiation. This is explained by the fact that as  $T_{MRT}$  increases there is an additional source of heating, which is not mitigated, but instead is worsened by lowering the walking speed. This is why the prevailing strategy for minimising the heat stress becomes minimisation of time of exposure by walking faster.

Figure 4.8 demonstrates the results of the computation of values of  $V_{HS}^*$  along a 1 kilometer stretch in a wide range of environmental conditions: from cool to very hot ( $T_{air} = T_{MRT}$ ,  $RH = 60\%$ ). It reveals that the minimum walking speed prescribed by minimal heat gain  $V_{HS}^* = 0.88 \text{ m/s}$  is achieved at  $T_{air} = 20^\circ\text{C}$ , suggesting that these microclimate conditions are the most

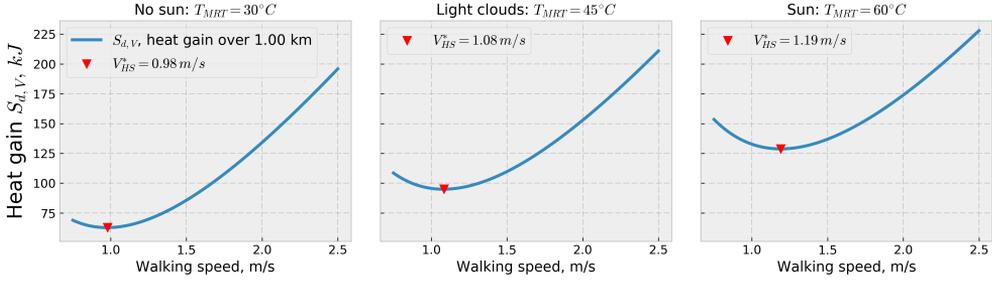


FIGURE 4.7: Dependency of heat gain  $S_{d,V}$  on walking speed  $V$  and thermally comfortable optimal speed  $V_{HS}^*$  in different levels of thermal radiation.  $T_{air} = 30^\circ C$ ,  $RH = 60\%$ ,  $I_{cl} = 0.35 clo$

neutral in terms of human body thermal regulation, requiring no walking speed adaptation. As the environment shifts from  $T_{air} = 20^\circ C$  to the colder or hotter temperatures, the walking speed adaptation is required to preserve the heat balance or minimise heat gain or heat loss. This agrees with the previous observations reported in [154]. There the authors registered the minimum walking speed of 1.24 m/s at  $T_{air} = 23.3^\circ C$  and higher walking speed of 1.52 m/s in cooler season with  $T_{air} = 17.2^\circ C$  and in hotter season with  $T_{air} \approx 29^\circ C$  (no exact value of walking speed is provided). The absolute values of walking speeds predicted by our physiological model and with our formulation of heat-stress-optimal walking speed, are however systematically lower. Energy-expenditure-optimal walking speed shown in Section 4.2.3  $V_E^* = 1.21 m/s$  corresponds to  $V_{HS}^*$  for conditions of  $T_{air} = 16^\circ C$ .

Three segments of the curve can be distinguished in Figure 4.8a, each explained by a different regime of heat gain/loss regulation:

- $T_{air} < 20^\circ C$ , where the  $V_{HS}^*$  increases fast for colder air temperatures. This increase in walking speed is dictated by the need to produce additional energy to compensate for the heat loss in the environments cooler than  $20^\circ C$ . The form of this segment can be explained by the form of heat production curve  $H(V)$  shown in Figure 4.3: it is a quadratic function of walking speed. This implies that at higher walking speeds a smaller increase of walking speed is required to attain heat gain, which

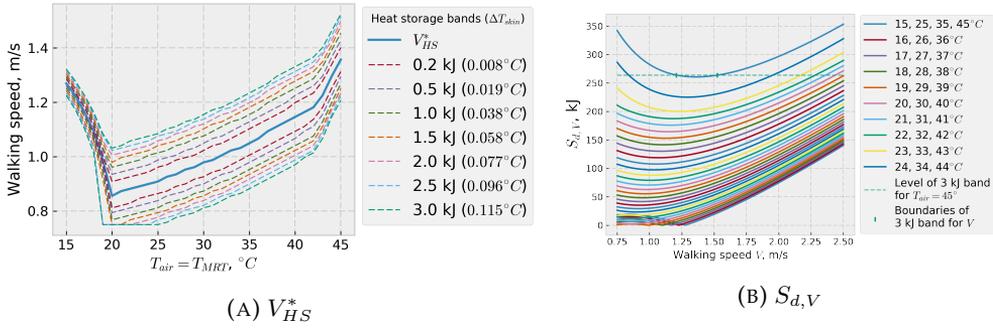


FIGURE 4.8: (a) The dependency of heat-stress-optimal walking speed on the microclimate. (b) The heat gain curves for considered microclimates. Here the minimums of the curves correspond to the value of heat-stress-optimal walking speed in a given microclimate.

results in a higher growth rate of walking speed close to the transition point of  $20^{\circ}C$ .

- $T_{air} \in [20, 42]^{\circ}C$ , where  $V_{HS}^*$  increases almost linearly at the rate of  $\approx 0.015 \frac{m \cdot s^{-1}}{K}$ . In this range of microclimates the thermoregulatory system has the means to counterbalance the heat gain (primarily through sweating and evaporation of sweat), so the increase of walking speed (to enhance convection and evaporation and minimise time of exposure) is relatively slow.
- $T_{air} > 42^{\circ}C$ , where the growth rate of  $V_{HS}^*$  becomes nearly 4 times faster ( $\approx 0.06 \frac{m \cdot s^{-1}}{K}$ ). At  $T_{air} = 42^{\circ}C$ , the value of skin wettedness reaches 1, so there is no more capacity for the thermoregulatory system to compensate for overheating through evaporation of sweat, therefore minimisation of time of exposure becomes the only way to reduce overheating.

The dashed lines in Figure 4.8a represent the levels of walking speed  $V$  that would result in a certain amount of heat gain (lines above  $V_{HS}^*$ ) or heat loss (lines below  $V_{HS}^*$ ). We define several heat gain/loss bands in terms of kilojoules. For interpretability purposes, we also provide a rough estimate of skin temperature change  $\Delta T_{skin}$  caused by this heat gain/loss, assuming that all the heat is gained/lost through the skin. Humans are very sensitive to skin temperature stimulation, and can feel the slightest change in skin temperature

of as low as  $0.005^\circ C$  [165]. The bands shown in in Figure 4.8a correspond to those from almost undetectable to significant changes in  $T_{skin}$ .

Figure 4.8b demonstrates the curves of  $S_{d,V}$  for the considered values of air temperature. It also shows how the bands are defined and corresponding range of  $V$  is determined. In Figure 4.8a, we can see that the bands result in wider ranges of  $V$  in the middle segment of the considered climate ( $T_{air} \in [20, 42]^\circ C$ ). This is due to the fact that the left and right segments correspond to more thermally stressful conditions and thus less deviation of  $V$  is needed for the considered heat gain/loss compared to the central segment. This implies that one should expect greater variation in walking speeds in more moderate climatic conditions (i.e.  $T_{air} \in [20, 42]^\circ C$ ).

### Distance and heat-stress-optimal walking speed

In this section we analyse whether the difference in walking distance in the same thermal environment suggests a different level of heat-stress-optimal walking speed. In all our scenarios a one kilometer walking distance is used, however, most of the walks performed in urban environments are significantly shorter. For example, the average walking distance in Singapore is 259 meters [166]. This, however, depends on the purpose of walking, and much longer walks are also possible. This is why we simulated the thermally comfortable walking speed for distances from 100 to 3000 meters for thermal environments ranging from cool ( $15^\circ C$ ) to severely hot ( $45^\circ C$ ), assuming  $T_{MRT} = T_{air}$  for a clear comparison. The level of clothing appropriate to each thermal environment was used.

The results are shown in Figure 4.9. Figure 4.9a shows that the lowest walking speed of  $V_{HS}^*$  is observed at temperature  $T_{air} = 20^\circ C$ , which is in agreement with Figure 4.4. As the environment diverges from neutral on both the cooler and hotter side, the level of thermally comfortable walking speed increases. As the walking distance increases, the optimal walking speed level tends to decrease. The optimal speed for 1 km distance in  $T_{air} = 30^\circ C$  (found in Section 4.3.1) is 11% lower than the walking speed for a distance of 0.25 km (0.96 versus 1.08 m/s).

There is a difference in the shape between the curves for the  $T_{air} = 40^\circ C$  and  $T_{air} = 45^\circ C$ , which requires further investigation. We provide simulation results performed for the range  $T_{air} \in [40, 45]^\circ C$  with a step of one degree Celsius. The results shown in Figure 4.9b shows the relationship between heat-stress-optimal walking speed and distance. For all air temperatures two regimes can be observed, for short distances the optimal speed decreases rapidly (e.g., for  $T_{air} = 45^\circ C$  going from 1.65 m/s to 1.4 m/s between 100 meters and 500 meters) then at some distance the speed decrease begins to happens more slowly (e.g., for  $T_{air} = 45^\circ C$  at 500 meters the optimal speed is 1.4 m/s and 1.25 m/s at 3000 meters). Interestingly, the distance at which this changes occurs varies for different air temperatures, for  $T_{air} = 45^\circ C$  this happens at 500 meters whereas for  $T_{air} = 42^\circ C$  this happens at 1500 meters. Interpreting this observation: walking speed reduction (i.e. reduction of internal heat production) is more efficient for shorter walking distances and more moderate thermal conditions as compared to longer distances and hotter environments.

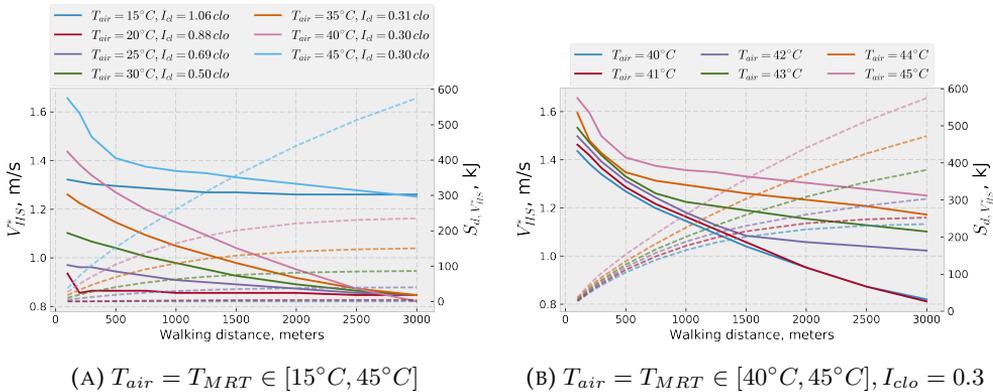


FIGURE 4.9: The dependency of heat-stress-optimal walking speed on walking distance in different thermal environments. The dashed lines of corresponding colour demonstrate the value of heat gain  $S_{d, V_{HS}^*}$  (minimal for considered climate-distance scenario) achieved at  $V_{HS}^*$ .

### 4.3.2 Empirical results

We have performed an empirical study of walking speeds in Singapore, a city-state with hot and humid tropical climate and population exceeding 5

millions. Singapore's climate is characterised by low variation of air temperature with an annual mean of  $27.5^{\circ}\text{C}$ , and high relative humidity with annual mean of 83.5%. Previous studies of walking speed in this city performed in 1984 estimated average walking speed to be 1.23 m/s [167]. This result is in agreement with the 1999 Levine's study of pace-of-life [16], which reported a value of 1.24 m/s.

Unlike in the previous studies, we have not studied a downtown area of the city, where other urban factors could impact thermal stimulation and could not be singled out. Instead, we chose a walk path leading to Lakeside MRT (subway) station situated in mostly residential area of the city. It is characterised by a straight clearly observable walking path of 30 meters long and 2 meters wide, so we consider movement is happening in 1 dimension along the pathway. The pedestrians were recorded on a video camera from a distance, so that their entrance and exit from the measurement region could be clearly identified (see Figure 4.10).

All the recordings were taken for a duration of 30-40 minutes and started at around 17:00, so that the effect of diurnal variation of properties of pedestrian flows can be ruled out. Collecting data in the evening ensures that the samples representative of population are less affected by the time constraints people typically have in the morning. We took videos on three days characterised by different air temperatures, spanning a good range of temperatures typical for Singapore (see Table 4.1). Microclimate parameters were measured by a portable weather station Kestrel 5400 mounted on a tripod near the point of camera installation.

The entrance and exit events were later labeled manually by two researchers to derive the traversing time. The event of entrance and exit were defined as walker crossing the mark on the screen. The entrance time and exit time (in precision of second) of each participant were recorded, their difference was considered the traversing time. Walking speed was calculated by dividing the distance of 30 meters by the traversal time. All the pedestrians were labeled with the following attributes: direction (to or from the station), gender, age group by appearance (younger than 12, 12 to 18, 18 to 45, older than 45), level of clothing (short top and bottom, either of top or bottom is long, both top and



FIGURE 4.10: A frame from the video recording of experimental area. Red cross-sections indicate the boundaries of the measured walking path. The distance between the two entrances is 30 meters.

bottom are long), usage of smartphone (binary), carrying excessive load (binary) and walking in a group (number of co-walkers, only one characteristic person from a group was considered). All the recorded walkers were considered, i.e. no subjective inclusion criteria were applied. Exclusion criteria were: people appearing performing activity other than walking (e.g. standing and looking around), people entering the area not from the defined ends of a stretch, people walking in a group (of which only one representative walker was recorded).

In our primary analysis we have included only those walkers appearing 12 to 45 years old, not carrying excessive load, not using smartphones, and not walking in a group. The results reported in Table 4.1 reveal that there is no significant difference in average walking speed between the days (here and hereafter we assume the statistical significance level of 0.05). Thus, we could not find a reactivity of the average walking speed to the change in microclimate conditions typical for Singapore's climate in the range of  $T_{air} \in [27.5, 32.2]$  °C, i.e. the change of up to  $\Delta T_{air} = 4.7$  °C).

A detailed analysis of experimental data is summarised in Table 4.2. Here we evaluate the influence of other factors on the variation of walking speed. We found no significant difference in walking speeds of people walking in two opposite directions, which suggests that people were experiencing comparable time pressure while going to and from the station. Walking speeds of walkers of different genders were significantly different considering all three

TABLE 4.1: The results of measurement of average walking speeds on three days with different air temperatures. The results of pair-wise Welch’s t-test of samples demonstrate no significant difference in average walking speed on three considered dates.

Date	$\overline{T}_{air}, ^\circ C$	$\overline{V}, m/s$	N	Welch’s t-test, p-value		
				22 Oct 2019	23 Oct 2019	7 Nov 2019
22 Oct 2019	27.5	1.37	69	1	0.178	0.132
23 Oct 2019	29.8	1.32	60		1	0.974
7 Nov 2019	32.3	1.32	63			1

days combined, but not each day individually. This observation agrees with the commonly observed higher walking speeds of males compared to females [167, 150, 139]. The use of smartphones and walking in groups significantly decreased the walking speed.

In the next section we discuss these empirical results in relation to the computational study reported earlier in this chapter.

TABLE 4.2: Results of statistical testing of several control parameters. Significantly lower average walking speeds are observed for pedestrians using smartphone or walking in groups, as well as for females compared to males.

Date	Welch’s t-test, p-values					
	$\overline{V}_A (N_A)$	$\overline{V}_B (N_B)$	p-value	$\overline{V}_A (N_A)$	$\overline{V}_B (N_B)$	p-value
	Direction (A – to, B – from the station)			Using smartphone (A – yes, B – no)		
22 Oct 2019	1.45 (17)	1.35 (52)	0.061	1.25 (34)	1.37 (69)	<b>0.006</b>
23 Oct 2019	1.34 (22)	1.31 (38)	0.585	1.22 (20)	1.32 (60)	<b>0.021</b>
7 Nov 2019	1.37 (15)	1.31 (48)	0.222	1.18 (34)	1.32 (63)	<b>0.000</b>
All	1.38 (54)	1.33 (138)	0.054	1.21 (88)	1.34 (192)	<b>0.000</b>
	In a group (A – yes, B – no)			Gender (A – male, B – female)		
22 Oct 2019	1.05 (22)	1.37 (69)	<b>0.000</b>	1.42 (51)	1.25 (18)	<b>0.004</b>
23 Oct 2019	0.88 (11)	1.32 (60)	<b>0.047</b>	1.35 (37)	1.29 (23)	0.217
7 Nov 2019	1.17 (11)	1.32 (63)	<b>0.049</b>	1.33 (32)	1.32 (31)	0.738
All	1.04 (44)	1.34 (192)	<b>0.000</b>	1.37 (120)	1.29 (72)	<b>0.004</b>

## 4.4 Discussion

The computational study reported in Section 4.3 has the following implications:

1. Energy-expenditure-optimal walking speed is estimated to be  $V_E^* = 1.21 \text{ m/s}$  and is essentially independent of the environmental conditions.
2. Heat-stress-optimal walking speed is predicted to be dependent on climate and walking distance.

### 4.4.1 Heat stress implications of observed walking speeds

The results of our empirical studies demonstrated that in the range of air temperatures between 27.5 and 32.2 °C average walking speeds do not differ significantly, averaging to 1.34 m/s, with a 95% confidence interval of [1.315, 1.368] m/s. This observation contradicts the expectation that walking speed is determined by process of optimisation for certain parameters:

1. The observed walking speed is considerably (10%) higher than the one found to be energy-expenditure-optimal. This finding can serve as a proof of increased pace-of-life in Singapore: the urban environment dictates parameters, other than internal energy expenditure, for people to optimise for. Thus the Singaporeans pay some energy costs in order to maintain the city's pace of life. Remarkably, the value of average walking speed in our experimental study in a mostly residential area of Singapore are considerably higher (by nearly 10%) than those obtained in a busy downtown area in studies dating 1986 and 1999 [167, 16]. Thus, we can see an increase in the pace of life in Singapore in the 21st century.
2. It is unlikely that the microclimate parameter of the urban environment is the one optimised for by Singaporeans. Not only are the observed values much higher than the ones predicted by heat-stress-optimal walking speed, but they also do not demonstrate the responsiveness to variation in microclimate, contrary to the prediction of our computational models.

The latter implies that there is a considerable amount of additional heat stress taken by each person individually. The computational models described earlier in this chapter can quantitatively estimate the amount of this additional heat stress for the observed environmental parameters. The results are provided in Table 4.3. We see that indeed the observed average walking speeds are higher than the heat-stress-optimal walking speeds, but for the hottest conditions (on 7 November 2019)  $V_{HS}^* = 1.23 \text{ m/s}$ :

- is much higher than for the other two days;
- is closer to our observed experimental value of  $\bar{V} = 1.34 \text{ m/s}$ ;
- is close to values found for average walking speeds of Singapore reported in 1986 and 1999;
- is very close to energy-expenditure-optimal walking speed ( $V_E^* = 1.21 \text{ m/s}$ ).

The consequences of these elevated average walking speeds in terms of additional increase of skin temperature  $\Delta T_{skin}$  are also provided in Table 4.3: we see that on the hottest day they were the lowest and relatively neglectable, whereas on two cooler days they can be considered as significant overheating. Another, seemingly counter-intuitive, observation is that hotter weather leads to less heat gained additionally due to the high walking speed. This is due to the fact that at the higher temperatures higher walking speeds are prescribed as heat-stress-optimal, so while absolute heat gains rise with the temperature, they become more influenced by exposure to the environment, rather than overheating due to selected walking speed. In other words, the hotter the environment is, the smaller is the contribution of the pace of life to the heat stress.

#### 4.4.2 Walking speed variation and factors affecting it

The fact that we did not observe the sensitivity of walking speed to the changes in air temperatures can be explained by the very tight range of considered temperatures. We can suggest that the behavioural adaptation of walking speed does not have a linear response curve (as follows from simulation of our *physiological* model), but rather has a step or sigmoidal form found in other

TABLE 4.3: Comparison of experimentally observed average walking speeds  $\bar{V}$  and heat-stress-optimal  $V_{HS}^*$ . The computationally estimated quantities (5 right-most columns) assume walking distance  $d = 500$  meters (approximate distance between subway station and surrounding residential buildings) and outer body compartment (skin) mass of 7.5 kg.

Units	Microclimate			Thermophysiological quantities					
	$^{\circ}C$		%	m/s		kJ			$^{\circ}C$
Date	$T_{air}$	$T_{MRT}$	RH	$\bar{V}$	$V_{HS}^*$	$S_{d,\bar{V}}$	$S_{d,V_{HS}^*}$	$\Delta S_{d,V}$	$\Delta T_{skin}$
22 Oct 2019	27.5	35.7	81.6	1.37	1.07	48.52	43.55	4.98	0.191
23 Oct 2019	29.8	34.7	74.3	1.32	1.08	52.39	49.27	3.12	0.120
7 Nov 2019	32.3	49.0	62.3	1.32	1.23	76.97	76.54	0.43	0.017

studies [168, 169]. This implies that should a certain threshold be reached, a critical transition may happen, leading to the behavioural adaptation by means of changing the walking speed. We hypothesise that in Singapore the difference could be observed when comparing sun and shade conditions. We plan to test this hypothesis in the upcoming experimental study.

In this chapter, we observed the adaptation of walking speed to rather discrete conditions: usage of a smartphone and walking in a group (see Table 4.2). Average walking speed of those using smartphone was found to be  $\bar{V}_{SP} = 1.21 \text{ m/s}$  – strikingly equal to the energy-expenditure-optimal walking speed  $V_E^* = 1.21 \text{ m/s}$ . We can hypothesise that the extra cognitive load of being engaged in interaction with smartphone leads to a cutoff of the environmental stimulation and, as a consequence, to the physiologically optimal walking speed unaffected by the pace of life. Analogously, interaction with others while walking in a group brings average walking speed even lower to the level of  $\bar{V}_G = 1.04 \text{ m/s}$ . As our physiological simulations predict heat-stress-optimal walking speed to be in general lower than usually observed for normal walkers (see Figure 4.8b), we can speculate that, for a wide range of warm microclimates, external cognitive load, such as phone usage or walking in a group, may compensate for the pace-of-life pressures and result in an improved thermophysiological experience.

### 4.4.3 Heat stress due to the high pace of life

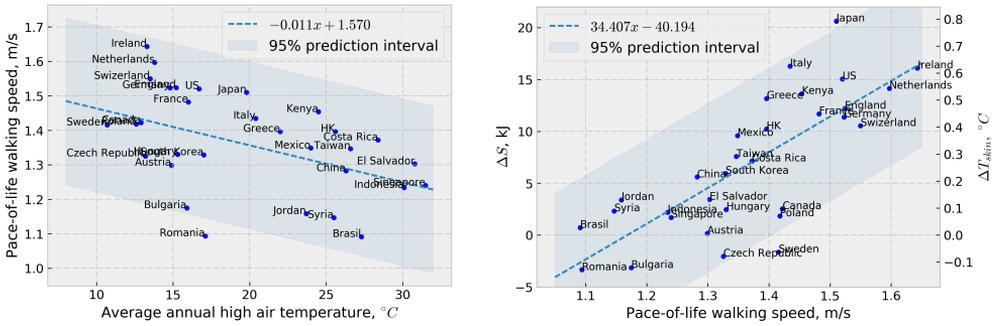
We have performed the simulation of heat gain during walking for the 31 countries reported in the pace-of-life study of Levine [16]. We considered the typical walking distance for all the countries to be 500 meters. We assigned air temperature of a city equal to the annual average high temperature reported on the Wikipedia pages of the cities. We assumed  $T_{MRT} = T_{air}$ , relative humidity of 60%, and clothing level appropriate to the air temperature. The data of temperature and walking speed is presented in Figure 4.11a.

For each of the city we calculated the heat-stress-optimal walking speed  $V_{HS}^*$  and corresponding heat gain  $S_{d,V_{HS}^*}$ . Additionally we calculated the pace-of-life heat gain  $S_{d,V_{PoL}}$  resulting from walking with a speed observed by Levine for a given city. The difference  $\Delta S = S_{d,V_{PoL}} - S_{d,V_{HS}^*}$  can then be considered a heat stress of citizens of a particular city attributable to the pace of life in this city. The results are presented in Figure 4.11b. It follows from simulation that Austria's and Brazil's pace of life has no effect on heat stress; countries like Romania or Bulgaria have relatively low walking speeds, resulting in a cold stress; whereas the pace of life in Japan has the most pronounced effect on additional heat stress resulting in almost  $0.8^\circ C$  of additional increase in skin temperature.

The computational model used in our study has been shown to accurately reproduce the dynamics of skin temperature and evaporation of sweat in a wide range of air temperatures of  $[20, 48]^\circ C$ . Exact values of quantities reported in this study are bound to a model-specific assumptions and simplifications (such as average person assumption). This implies that while comparative analysis of scenarios using the model is a valid approach, the estimated absolute quantities can have a discrepancy with the real-life measurements of individual people or scenarios.

## 4.5 Conclusions

Increased pace of life is an intrinsic characteristic of big cities. It contributes to the city efficiency in economic and social development. On the other hand, it causes a constant stress in our experience of urban environments. One of



(A) Average walking speeds related to average annual high air temperature based on data available on Wikipedia pages of cities.

(B) Simulated heat stress attributable to the pace of life for walking 500 meters.

FIGURE 4.11: Results of simulation of 31 country of pace-of-life study [16].

the main evidences of increased pace of life is the increased average walking speed in cities, which was shown to scale with the city size.

In this work we studied the heat stress implications of increased walking speeds – a critical issue in conditions of global urbanisation and climate change. We described the computational model of complex interaction between the thermal environment, human physiology and walking speed. We defined the heat-stress-optimal walking speed  $V_{HS}^*$  as the one minimising heat gain or loss in a given thermal environment on a given distance. Simulating walking scenarios for a wide range of air temperatures, we found that one should employ behavioural adaptation of walking speed if optimising for thermal comfort (see Figure 4.8a). Heat-stress-optimal walking speed takes its minimum of 0.88 m/s in most thermally neutral environment of air temperature around  $20^\circ C$ . It rises rapidly as the environment becomes colder, because the increased internal heat production due to faster walking is the only mechanism of compensation for the heat loss. Heat-stress-optimal walking speed increases more moderately in warmer environments, as there are thermoregulatory mechanisms to cope with heat load that make minimisation of time of exposure due to faster walking a secondary heat mitigation mechanism. Minimisation of time of exposure becomes the primary means of the heat gain minimisation, and  $V_{HS}^*$  grows fast in air temperatures above  $42^\circ C$ , because the thermoregulatory mechanisms (evaporation of sweat) reach their capacity

at this point.

We then applied the developed models to investigate the implications of Singaporean pace of life for the thermal experience of its citizens. The results of empirical measurements showed stable average walking speed of 1.34 m/s, which is not responsive to the change of air temperature in a range typical for Singapore [27.5; 32.2] °C. This observation brings us to the conclusion that:

1. Citizens of Singapore do not employ walking speed adaptation as the means of behavioural response to slight change in thermal environment.
2. Singapore has an increased pace of life in terms of walking speed, which grew by approximately 10% since the studies reported in 1986 and 1999.

Modelling results for heat gain in measured conditions of Singapore show that the increased walking speed results in a significant additional heat load in relatively cooler conditions (27.5 and 29.8 °C). As environment becomes hotter, less and less heat stress can be attributed to the increased pace of life, since heat-stress-optimal speed for hotter environment is higher and closer to the empirically observed values of walking speed in Singapore.

For the example of Singapore, we have shown with the computational model, that the urban pace of life has an important implication for people's well-being in hot climates: extra heat stress. Our study suggests that people should slow down to improve thermal comfort in warm and hot climates – a suggestion seemingly contradicting the ever growing pace of life. We have observed, however, that the use of smartphones or walking in a group slows down the walking speed to a level close to the thermally optimal – a remarkable example of how the overstimulating urban environment can be compensated for by social interaction.

In this chapter we find that behavioural adaptation of walking speed can help to reduce heat stress. Singapore citizens, however, do not exhibit this behaviour in response to air temperatures changing in the narrow range of Singapore's climate and incur additional heat stress. In Chapter 5 we demonstrate how presence of another thermal parameter, sun exposure, induces a pronounced sun-avoidance behaviour through path choice.