Computational models of human response to urban heat

From physiology to behaviour

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Chapter 7

Summary and conclusions

The urban climate has a direct impact on health and well-being of people living in cities. Understanding the complex process of outdoor thermal comfort (OTC) is necessary in order to improve people's thermal experiences in outdoor environments of current and future cities. This thesis has focused on building the understanding of human response to thermal stimulation through computational modeling of this response on multiple levels: physiological, psychological and behavioural.

Chapter 2 provided the full formulation of a two-node model of human body thermal regulation. We presented the model in terms of a system dynamics stocks-and-flows diagram, which allows for understanding of the complex causal relations between parameters of the physiological system of thermal regulation and the environment. We found that the model, while realistically reproducing steady state conditions, is lacking accuracy when predicting the dynamics of skin temperature – a critical parameter reflecting the thermal state of a body. Using the causal diagram, we identified the core-skin blood flow as the most probable component responsible for observed discrepancies in the model's performance in dynamic scenarios. We optimised the parameters of this component within the ranges found in literature. The new vector of parameters of the skin-blood flow component of the system achieved significantly improved dynamics, comparable to those demonstrated by more complicated and computationally intensive models. We calibrated the model on a wide range of moderate-to-hot environments and validated on data for extremely hot conditions, which are beyond the range the model was calibrated on. The model demonstrated excellent prediction of the dynamics of the skin temperature. Additionally, we found good agreement of predicted evaporative heat loss with that found in literature, which is an indicator of a correct prediction by our model of a sweating rate term – an important parameter of thermal regulation and sensation. Due to the primary focus of this research our model would require additional validation before being applied in cool and cold environments. We demonstrated that our model is comparable, or even outperforms, the more complex multi-node multi-part models in terms of the dynamics of average skin temperature. Our model is limited to the scenarios of assessing the overall thermophysioligical state of a person. More sophisticated models should be used in studies of differential thermal comfort and sensation as well as in the scenarios of non-uniform spatial exposure to thermal stimulation. Overall, the combination of accurate dynamics and low computational cost makes this model an excellent candidate for a model of physiological response to dynamic outdoor thermal environments at an individual level. Moreover, the model can be used in other studies, such as understanding the implications of walking speed on additional heat stress as reported in Chapter 4 and prediction of core temperatures to investigate the effect of thermal environments and physical activity on the performance of the innate immune system response reported in Chapter 6.

Chapter 3 serves as an important connector between the model of physiological response and studies of behavioural response to the thermal environment reported in Chapters 4 and 5. In this chapter, the measures of instantaneous physiological index and accumulated heat stress are proposed as indicators of thermal perception and drivers of thermoregulatory behaviour. As discussed in the introduction of this thesis, thermal perception, a psychological response to the thermal environment, is a complex and under-investigated process. This makes the creation of comprehensive computational models currently not possible. Instead, the research in this thesis relies on the studies of thermal perception of climate performed in particular geographical regions to map values of the physiological index of thermal environment to average perception. The instantaneous value of the physiological index is calculated with the use of our physiological model and can be used along with the localised perception scale to approximate thermal satisfaction and acceptance. This thesis contributes in understanding thermal perception through measuring behaviour. Being a response in-between physiology and behaviour, it can be parameterised based on the observed physiological state and behaviour. Assuming that the magnitude of thermoregulatory behavioural response is governed by the thermal perception, the latter can be inferred through the former. For example, in Chapter 4 we observe no speed adaptation to varying thermal environment, which allows us to conclude, that this environment and associated heat stress (calculated with physiological model) is perceived as satisfactory, i.e. requiring no adaptation, for the observed activity. Alternatively, a pronounced sun avoidance behaviour reported in Chapter 5 suggests that the participants were exposed to stressful thermal environments and that associated heat stress was not thermally acceptable, forcing the participants to employ the behavioural adaptation. These two pedestrian behaviours, speed and path adaptation, are among four hypothesised in Chapter 3 based on the studied literature. Two remaining hypotheses, namely reactive thermal attraction and proactive route planning, could be an interesting subject for future work. Overall, this chapter has an important conceptual and goal-setting role in this thesis and future developments beyond. It formulates a general framework of agent-based modelling of pedestrian movement in physical and dynamic thermal environments, and the remaining chapters of this thesis describe the components of this framework in more detail.

Chapter 4 presents a study of walking speed as a means of behavioural thermal regulation. We introduce the heat-stress-optimal walking speed V^*_{HS} as the one which minimises the accumulated heat stress over the period of walking. Using the physiological model described in Chapter 2 we have estimated the values of heat-stress-optimal walking speed for a broad range of outdoor environments. We find that this speed is minimal (0.88 m/s) in the most thermally neutral environment of 20°C, and to minimise heat stress in other environments one should increase walking speed. The values of V^*_{HS} result from the complex interaction of metabolic heat production, heat removal through convection and evaporation and time of exposure. We test the theoretically found values against walking speeds observed in the urban environment of Singapore. We find, that the observed walking speeds are systematically higher than those predicted by our model, implying that additional heat stress is incurred by people. We also find that these speeds are not significantly different for three different air temperatures within the range of [27.5, 32.3]°C, suggesting that people do not adapt their activity intensity (walking speed) while walking in microclimates within this range. There are multiple explanations which can be given for this observation, one is that Singapore's pace of life is determined by other social and environmental factors and this overpowers the needs for thermal regulation. Interestingly, we find that the use of smartphones or walking in a group significantly decreases the walking speed, which enhances the thermal experience. Thus, social engagement and interaction might be a factor that compensates for the urban pace of life and environmental over-stimulation resulting in improved thermal comfort. Another reason for no observed walking speed response to change in thermal environment might be due to the relatively low relief promised by such adaptation, which does not justify the change in the walking speed – an inherent parameter of basic human locomotion. Therefore, we might expect to observe this adaptation in conditions in which thermal stimulation has a higher gradient: in different climates or under direct exposure to the sun. Both questions constituting an interesting direction for future work. Overall, the study reported in Chapter 4 provides another, climatic, perspective on the increased pace of life in cities. That is, elevated walking speeds due to pace of life do not only manifest social and environmental pressure, they also result in additional heat gain. Cities that offer environments facilitating relaxed slower walks can reduce the thermal and overall stress of people.

In Chapter 5 we described the results of a behavioural experiment with human participants in a natural outdoor environment in Singapore. The goal of this study was to investigate whether the path planning behaviour is affected by the visually apparent microclimate properties of the space. We found that people are willing to take longer but less sunny path options demonstrating sun avoidance behaviour. We employed video capturing and a 3D model of the experimental area to calculate the position of the sun in order to precisely characterise path options in terms of sun, tree shade and building shade. We proposed a hierarchical model of observed decisions governed by the sun-shade composition and length of the alternatives. With this it was possible to estimate the distance-inflating coefficient of walking under the sun. We have built a perceived tree shade intensity parameter into the model and found an indication that tree shade intensity is perceived by people as less intense (less relieving) than building shade. We found the expected level of this parameter to be 0.5, i.e., path choices observed in our experiment suggest that on average tree shade is considered only half as relieving as building shade under the decision model assumed. The experiment, however, was not designed to infer this parameter and we suggest that dedicated experiments should be designed to properly characterise this parameter. Nevertheless, our findings have direct implications when considering shading potential of green and built infrastructure. The distance-inflating coefficient of sun β_j has an expected value of 1.16 when pooling decisions of all participants. This implies that according to observed path choices, under the assumed model of decisions, participants associate on average 16% more effort when walking under the sun as compared to walking in the shade. The resulting posterior distributions of the distance-inflating coefficient of the sun β_j have significant mass for values less than 1, which corresponds to appreciation of the sun. We argue, that this fact should not be interpreted as evidence of the preference for the sun in some decisions. Rather, other factors which were present in the environment have influenced the observed decisions. If it were possible to perfectly isolate the sun-shade factor in a natural experimental setting, we could expect even higher values of β_j. Nevertheless, decisions of individual participants suggest a personal β_j as high as 1.8. Variation in β_j can be explained not only by differences in individual properties of the participants, but also by the property of the shading available in the environment. This underlines that provision of opportunities for behavioural adaptation results in a higher observed level of adaptation. As behavioural thermal regulation is the only feasible option to maintain thermal comfort in the long run, urban planning and policy for OTC should focus on providing such opportunities in urban environments. The results of our experiment and model of path choices can be directly built into models of pedestrian navigation behaviour in thermal environments. Moreover, the unique combination of microclimate, survey, behaviour, physiological and video-recording data collected in this experiment will serve as a basis for further investigation of all three components of human response to thermal environments covered in this thesis: physiology, perception and behaviour.

Chapter 6 covered an important and under-investigated question of the effect of heat stress on the functioning of the human innate immune system (HIIS). We used a computational model of HIIS to estimate ranges of body core temperatures, which are beneficial and detrimental to performance of HIIS. We found that core temperatures beyond 38°C have detrimental effects on the performance of HIIS response. Using the physiological model of thermal regulation formulated in Chapter 2 we identified the regimes of exposure to the thermal environment and levels of physical activity, which result in body core temperature crossing a threshold value of 38°C. In tropical climate conditions of Singapore the core temperature would cross the threshold after 6.35 minutes or only 1.5 km (3.6%) into the run. These results suggest that behavioural adaptation (i.e. regulation of activity intensity and duration of exposure) is critical to not only maintain the thermal comfort, but to preserve proper functioning of the HIIS. Overall, gaining a comprehensive understanding of heat stress effect on human short- and long-term health is an important challenge for future research.

The work in this thesis has identified a number of research gaps and directions for future work.

While our physiological model reported in Chapter 2 provides means for personalised prediction of thermal state, through parameters of clothing, activity level (metabolic heat production), height and weight, additional parameters such as gender, age, fitness and acclimatisation and their effects on the system could be integrated in the future. Making the model of thermal regulation more individualised is crucial to not only make it more precise, but also to account for the variation in the physiological response among individuals, which is driving the observed differences in thermal perception and behaviour of people.

The perception of the thermal environment depends on physiological state as well as psychological condition of individual and properties of the environment. This complex and highly personal process still requires a major interdisciplinary research effort. Advancing the understanding about the thermal perception of people will require extensive controlled experimentation and development of means of quantitative measurement of human psychological response to thermal stimulation, using the tools of such disciplines as neuroscience and behavioural science. In our studies we demonstrated the application of the latter for objective measurement of individual perception of the thermal environment, as opposed to subjective measures, to which previous research resorts almost exclusively.

In our human behaviour studies we took the reductionist approach to isolate thermal parameter of environment. This allowed us to measure the effect of heat on human behavioural response with utmost certainty. Natural human environments, however, vary in multitude of other stimuli and integrating the thermal response into an overall model of human-environment interaction constitutes a challenge for future work. In Chapter 3 we propose an agent-based framework for modelling this phenomenon, but implementation of the complete model would require gaining understanding of human response to other individual stimuli and integration of these responses into an overall response to the environment. This thesis proposed the comprehensive approach of multi-level modelling of human response to environmental stimuli. Its application in studying thermal environments suggests further adoption for investigation of other environmental factors such as noise, lighting and social interactions. The latter is especially important at the time of writing of this thesis as the ongoing Covid-19 pandemic emphasises the need to control the spread of the virus while minimising the impact on social life and economic activity.

Understanding the long- and short-term consequences of heat stress for health is crucial for an informed response on individual and population levels. Accurate computational models are invaluable to gain this understanding, and empirical data is critical to inform, calibrate and validate these models. In our study of the interaction of heat stress and the human innate immune system (HIIS), the qualitative dynamics of HIIS parameters in response to heat from the existing literature was used to inform the model. The next step would require dedicated experiments to obtain quantitative information on the dynamics of selected parameters to validate and improve the accuracy of the model.

For the prevention of heat stress and related illness, methods of objective, continuous, non-invasive monitoring and detection of heat stress should be developed. In our experiments with human participants we used biofeedback wristbands to collect several physiological signals of participants while simultaneously recording their exposure through video-cameras and weather stations. This dataset can be used to develop statistical methods of monitoring, prediction and prevention of heat stress.

This thesis provides a comprehensive understanding of the complex response of people to dynamic thermal environments. For each level of response – physiological, perceptional and behavioural – computational models are proposed. The models can be readily built into existing platforms of agent-based simulation of pedestrian flows to assess, predict and enhance outdoor thermal comfort of people in current and future cities. Individual models can be used in studies of the interaction of the thermoregulatory response with other systems and processes. Approaches taken in our study of human response to heat can be adopted to investigate the human response to other stimuli paving the way towards complete understanding of overall process of human-environment interaction.