Correlational study on thermal comfort and outdoor activities

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Abstract. This research has investigated several correlation patterns between spatial behaviour and outdoor thermal comfort for urban spaces. An eight-hour field work of behavioural snapshots has been carried out at Market square, Cambridge, on a sunny day of May. The universal thermal climatic index (UTCI) was acquired from microclimate simulation in ladybug. The thermal-comfort zones were coupled with four featured behaviours: sitting, standing, strolling and walking. The results have shown a tendency toward occupying shady spaces in general. The canvas awnings have proved the correlation between comfort and behaviour. More interestingly, less comfortable areas appear to be acceptable for more than half of the observed groups with a 4°C increase in UTCI.

1. Introduction
This paper presents a behaviour-oriented approach to integrate thermal comfort in spatially structured datasets (Figure 1), to pinpoint the affordance theory and inform relevant design strategies.

\textbf{Figure 1} A work flow of the correlational study in a 3D rhino-based simulation system. The urban thermal-behavioural database (on the left), and programming for the agent-based modelling (on the right)
The spatial shape of an urban space will affect thermal comfort, and is also closely related to spatial behaviour. One of the fundamental dimensions in the assessment of the quality of urban space is outdoor thermal comfort. Urban spatial characteristics and outdoor thermal comfort largely determine spatial behaviour, and thermal comfort has a huge potential to be optimised via spatial design and planning strategies. Therefore, understanding these triangular and iterative influences is important for the study of urban behaviour science.

Environmental psychologists have been looking for behavioural evidence for the affordance theory (Gibson, 1977), using a variety of behaviour mapping tools. Some theories have implied that there are hidden principles between physical affordance and behaviour motivation (Whyte, 1980). Although human thermal comfort was partially mentioned as an environmental affordance, it has seemed to be overlooked in most of their empirical studies. It remains unknown whether the physical affordance (e.g. enough street furniture) would be able to supplement the inadequacy of environmental affordance (e.g. discomfort caused by the sun or shade). This paper aims to explore their underlying relationships via mixed methods, i.e., numerical modelling, behaviour mapping and spatial statistics.

2. Urban microclimate model

An urban microclimate model is fundamental to the evaluation of outdoor thermal comfort. A test case was chosen at Market Square, which commands a central location in Cambridge. The following microclimate simulation was carried out for contouring the outdoor thermal-comfort zones in the square. There are two modelling tools available for predicting outdoor thermal comfort: Envi-met, and a rhino-based plugin for ladybug. Due to the shortcomings of Envi-met which would produce low-resolution edges when processing nonorthogonal geometries, ladybug was chosen to meet the modelling requirement and keeping the boundary completeness for any nonorthogonal geometries. This would guarantee that the boundary of the microclimate model matches the behaviour model. The basic work flow for building the urban microclimate model is organised by two steps: performing the sun radiation analysis and running the UTCI simulation in ladybug (Mackey, 2017).

2.1. The microclimatic profile of the test case

Ladybug is capable of calculating the total solar irradiance by the given urban contexture. It has been built upon several validated simulation engines such as Radiance and Energy plus, and allows data transfer between its simulation engines. Airport weather data has been approximated to fit the urban context through an urban weather generator. The result demonstrates that the average solar irradiance absorbed by the ground surface is 113.3 KWH/M², with a distinct spatial variation from the lowest 65.1 KWH/M² to the highest 145.6 KWH/M² (Figure 2). The solar irradiance can be further substituted by calculating the mean radiant temperature (MRT). The enormous influence of MRT on outdoor thermal comfort has also been highlighted in other literature (Bröde, 2012). The calculation of MRT has been excluded here, because it is contained within the simulation process to derive the universal thermal climate index (UTCI).

![Figure 2 Annual solar irradiance analysis of Market Square, Cambridge (on the left); spatial variation of absorbed solar radiation on the ground surface in May (on the right)](image-url)
2.2. UTCI and comfort zoning

Universal thermal climate index (UTCI) is a temperature scale index to describe the thermal comfort condition. It includes not only environmental indices such as air temperature, mean radiant temperature, relative humidity and wind velocity, but also human parameters such as metabolic rate and clothing ratio. With a unique thermo-physiological effect, UTCI is a popular benchmark for the incomparable assessments conducted in different climatic conditions (Bröde, 2012). It is claimed to be valid in all climates and seasons, especially for the outdoor thermal environment (Jendritzky, 2002).

As shown below (Figure 3), the diurnal variation of UTCI is huge, and is much lower during the early morning and the late afternoon: 7°C and 0.5°C lower than the actual air temperature at 9:30 am and 12:30 pm, respectively. This may result from the changing positions of the sun and shade, not to mention the indefinite wind speed. Spatially, there is also a wide comfort gap between the central and boundary areas. It is clearly observed from the contour lines (Figure 3, middle), extracted from the gradient map (Figure 3, right). According to the documentation of the UTCI comfort category, the comfort zone has been defined ranging from 9°C to 26°C. So, areas which share close comfort values have been marked with the same legend.

![Figure 3 UTCI, Market Square, Cambridge (on the left), Comfort zoning (middle), UTCI gradient map (on the right)](image)

3. Urban behaviour model

Two methods were used and separately established for the urban behaviour model. First, an agent-based approach was employed for matching the comfort zones, which was derived from the previous studies. Considering its limitation to involve any environmental factors, manual behaviour mapping was necessary in the second half to calibrate the spatial-behaviour modelling.

3.1. Agent-based modelling

The agent-based model was scripted in a grasshopper component called PedSIM. It was designed as a microscopic simulation system for the crowd mobility. Each agent represents a pedestrian with a personal template. An event log is required to be programmed into an agent’s template for targeting their day-long activities. Agent will interact with each other and walk at various speeds towards the preset attractions in the virtual space before the modelling begins. For this paper, all of the market stalls have been positioned as the attractions, which may lead to different levels of detour. The building boundaries, stall structures, and other agents will be identified as obstacles in the algorithm. The gates, namely the flux input and output, represent the eight exits in the square, including an inconspicuous supermarket entrance to a backyard and Regent Street (Figure 1, right).

Since the modelling process is real-time and could be never-ending, the ‘visit ratio’ for each unit is calculated by dividing the number of the passers-by by the maximum visiting number, which is globally counted. This accumulative operation was tested for 24 hours. In the first two hours, the local visiting incidence changed drastically, and this situation did not stabilize until a diurnal simulation, so finally at the 24th hour, the flux distribution was extracted for overlaying (Figure 4, left).

However, the current agent-based model cannot integrate any environmental information into its virtual system, such as acoustics, light, and heat. This is a technological gap for the software developers to fill in. Future scripting work may demand solid evidence from empirical studies to support optimizing the agent-base model and predicting a variety of behaviours.
3.2. Behaviour snapshot

In comparison with agent-based modelling, an on-site behaviour snapshot would reflect the thermal-comfort impact, albeit with a much smaller sample size. The hourly snapshots were carried out in the square from 9:00 to 17:00, on May 21st, 2019. Most outdoor activities are likely to occur in the transitional seasons such as May and June throughout the year. Four behaviours were classified by time estimation: Sitting, standing, strolling and walking. The sitting behaviour includes dining at outdoor sets (more than 20 mins), listening to the music (5–15 mins), sunbathing (5–15 mins), waiting (5–15 mins), chatting with friends (5–15 mins), etc. The standing behaviour includes having snacks (5–15 mins), queuing (2–10 mins), waiting orders (2–10 mins), chatting or flirting (2–5 mins), window shopping (2–5 mins), listening to the guides (2–5 mins), etc. The strolling behaviour includes lingering back and forth, window shopping, comparing shops and items, following the guides, etc. Walking behaviour was recorded if someone passed straight and fast.

In total 2171 samples were collected and marked with behaviour category, location, whether staying in the sun or shade, and time record. Strolling took the largest proportion with 697 records, compared to standing (572) and sitting (218). Specifically, the diurnal variation of sitting behaviour has shown a general downward trend, exactly contrary to the ascending UTCI. The hourly percentage of the sitting numbers in the sun dropped from 10:30 (50%) to 13:30 (30%), and so did standing and strolling (10%). This is primarily caused by the radical surge of UTCI (5.4°C), due to the growth of the sunny area where long-time sitting could be less comfortable. On the contrary, the proportion of walking changed with UTCI on almost the same rhythm (Figure 5).

4. Correlation model

One of the objectives of the correlation model is to establish new understanding of creative methods and their application in practice-as-research, extending knowledge bases in the fields of biometeorology and
urban design. This model was built upon the comfort-behaviour database. This paper presents the correlative patterns of four behaviours and a further pilot analysis of their spatial coupling in 3D Rhino.

4.1. Measuring the distribution of four behaviours in various comfort zones

A statistical approach was employed to evaluate the preferred UTCI range by ranking the incidences of four behaviours along the UTCI axis. Each dataset was split into two segments at the turning point at the lowest behaviour record. The segmentation eliminated non-monotonic trend and replot each dataset with one or two-tail distribution. The turning point of UTCI for the sitting record was 11.8 °C, for standing was 10.4°C, for strolling was 10.5°C, and for walking was only 9.6 °C (Figure 6).

Above the turning point (the orange charts), sitting and walking shared a similar right-skewed distribution, both peaking at around 13.5°C with 33 and 70 records respectively. Standing and strolling showed no such distinct bias, but slightly swung up at 12.8°C. This could be partially explained by the affordance theory, i.e., a type of behaviour could afford how much freedom of choice is available (Steemers, 2004). Since plenty of benches have been placed in the middle of the square without any shade, someone has to accept the sun, if they insist on being seated. Likewise, more than three quarters of the fast-passing sidewalks are either exposed under the sun, or along the south-facing facades.

Below the turning point (the grey charts), a range from 7°C to 7.3°C peaked with the highest frequency among all behaviours. This exponential increase indicates users’ demands for the shade.

4.2. Results from spatial coupling

The following remarks are concluded from the spatial coupling results between thermal comfort zones and the recorded behaviours. Although the preliminary findings of spatial coupling are qualitative at this stage, the behavioural evidence emerged by examining the environmental affordance. A further quantitative approach will be necessary in response to the previous statistical findings (Figure 7).
5. Conclusions
As has been shown, the data are consistent across the three separate test models. The urban microclimate model suggests that the boundary area possesses the most comfort zones; the behaviour model reveals that the flux tends to stick to the peripheral area, with the exception of some lingering behaviour in the centre. The final point to the correlation model has recapitulated the research findings – generally, there is a tendency toward occupying shady spaces, for this case at Cambridge during the transitional seasons in May and June. The shading devices such as canvas awnings and parasols are effective to ameliorate outdoor thermal comfort up to 4°C. The north-south layout of the stall’s corridor has contributed to extending the shaded area, which synergistically promotes the coupling degree of the spatial behaviour.

6. Further steps
The temporal and spatial correlative patterns between outdoor environment and behaviours reveal the essence of adaptation and affordance theory. The longer one stays, the less adaptive one becomes to staying-beyond-comfort zones. It draws more attention to the uncoupled areas, where long-time activities usually occur. This paper has demonstrated the evidence of comfort-motivated behaviours, for raising scholars’ awareness of the value in conducting interdisciplinary research of biometeorology. However, the negative correlation between thermal comfort and spatial behaviour is not carefully discussed in this paper. Some observed persons would prefer being ‘charged up’ in the sun, whereas others prefer the shade. This is partially due to the disparity of individual thermal experiences, which requires further exploration in the field of physiology and psychophysics.

Practitioners desire solid evidence for their designs to be convinced. To bring this paper to end, some suggestions are made to inform decision making for the environmental planning process. From a behavioural perspective, the thermal comfort study would be valuable for improving the overall quality of a design. Moreover, the numerical modelling method would enable designers to predict and compare the environmental performance between virtual scenarios. This paper recommends the rhino-based simulation tools such as grasshopper, ladybug and PedSIM for scenario tests, especially at the early stage of design when the building geometries are still not complicated. Bigdata technology will be suggested for enlarging the sample size and reducing imprecision in subsequent steps.

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