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Impact of wind turbulence on thermal perception in the urban microclimate

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ABSTRACT

Ongoing urbanization has led to complexities in the urban terrain, increasing roughness length within the atmospheric surface layer, and introduced highly turbulent wind flow at pedestrian height. This research aims to explicitly examine the effect of wind flow turbulence on thermal perception under outdoor conditions. A wind tunnel with passive grid was used to introduce turbulence into simulated wind conditions. Thermal physiological (skin temperature) and perceptual (questionnaire) responses were collected from 20 college-age subjects during the exposures to various simulated urban wind conditions. Results confirm that increased turbulence intensity enhances perceived coolness by reducing the skin temperature. Findings contribute to the broader goal of a thermal comfort model for application to urban microclimate.

1. Introduction

A sedentary lifestyle negatively impacts health, increasing the risk of cardiovascular diseases, diabetes, and obesity (Godbey, 2009). To compensate for diminished activity, communities are encouraged to spend more time engaged in outdoor activities. However, in warm-to-hot climate zones where the rate of urbanisation is greatest, the urban heat island effect not only suppresses outdoor activities, but also deters citizens from walking to everyday destinations – shops, public transport hubs, and schools (Asimakopoulus & Santamouris, 2012). City designers, landscape architects, and engineers efforts to manage urban warming are focusing on performance testing various cooling strategies including artificial and natural shading (Lin et al., 2013) and enhancing air movement between buildings (Xie et al., 2018).
Compared with retrofitting environmental remediation based on user feedback, it would be more efficient to design urban cooling strategies in the planning phase. Predictive thermal comfort models represent a useful tool in this endeavour. Such models link urban microclimatic characteristics (air temperature, mean radiant temperature, relative humidity, wind velocity) to pedestrians' thermal perceptions, usually expressed on a 7-point thermal sensation scale (-3=cold, -2=cool, -1=slightly cool, 0=neutral, 1=slightly warm, 2=warm, 3=hot) (ASHRAE, 2017). Thermal environmental parameters, taken together with expected clothing insulation and activity intensity are the main inputs to a thermophysiological model that mathematically describes the heat exchanges at the body's surface, inside the body (passive system), and the thermal regulation process (active system) that those effects

in the passive system would induce. Based on the calculated physiological parameters, thermal sensation model can then predict people's thermal perception.

Substantive improvements have been made since the simple two-node thermoregulatory model was first developed half a century ago model (Gagge, 1971; Givoni & Goldman, 1972). Despite refinements in the active system the heat exchanges between the passive system and its thermal environment remain oversimplified, ignoring the highly turbulent condition of the atmospheric boundary layer. Wind is represented by mean velocity only, with its fluctuating characteristics being filtered out. This unrealistic characterisation of air flowing over the surface of contemporary thermoregulation models may be one of the explanations of a persistent discrepancy between comfort model predictions and field observations (Xie et al., 2018).

A recent study in which a thermal manikin was exposed to an outdoor air velocity range (0.7 to 6.9 m/s) confirmed that ignoring turbulence intensity of 30% resulted in convective heat transfer at the manikin's skin surface being underestimated by as much as 50% (Yu et al., 2020). Discrepancies of this magnitude emphasise that the effects of turbulence intensity cannot be dismissed as negligible, and therefore should be incorporated into contemporary thermal regulation models and their associated comfort predictions.

This study aims to first examine the impact of turbulence intensity on thermal sensation, and then to correlate instantaneous and steady-state thermal sensation vote of human subjects with skin temperature observations across diverse combinations of metabolic rate, wind speed, and wind direction.

2. Materials and methods

The experiments were conducted in the Boundary Layer Wind Tunnel (BLWT) in the School of Civil Engineering at The University of Sydney (Figure 1a). The tunnel is 20 m long, 2.5 m wide and 2 m high. The incoming air velocity was controlled through the rotational speed of the wind tunnel fan, and a coarse grid at the inlet was used to simulate outdoor urban wind environments with realistic turbulence intensity ranges (Zou et al., 2021). The wind speed at the test section reached stable within 5 s after the wind tunnel fan being turned on. Vertically averaged turbulence intensity across the occupied zone (0.1-1.7 m) was approximately 35% for the high turbulence intensity measurements (TI-high), with the participant stood at 2.5m downwind of the grid system; and 17% for the low turbulence intensity measurements (TI-low) (Figure 1c), with the distance increased to 5 m.

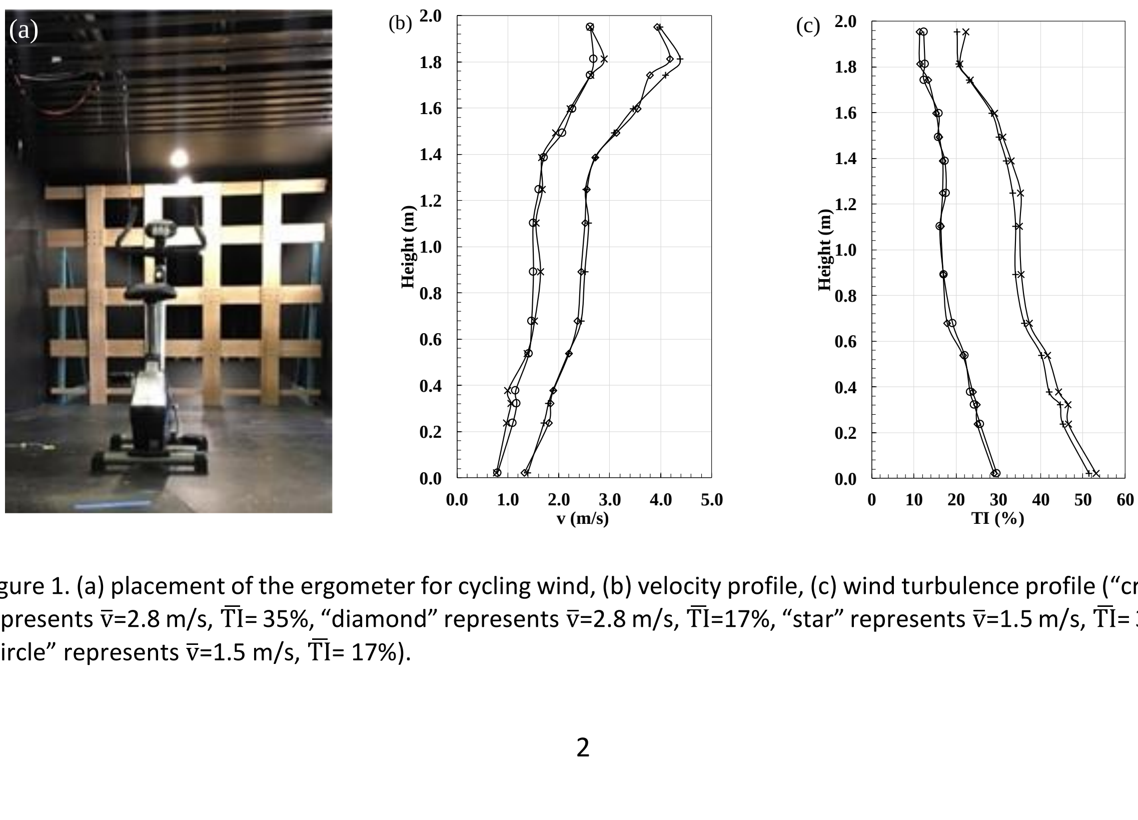


Figure 1. (a) placement of the ergometer for cycling wind, (b) velocity profile, (c) wind turbulence profile ("cross" represents $\overline{v}$=2.8 m/s, $\overline{TI}$= 35%, "diamond" represents $\overline{v}$=2.8 m/s, $\overline{TI}$=17%, "star" represents $\overline{v}$=1.5 m/s, $\overline{TI}$= 35%, "circle" represents $\overline{v}$=1.5 m/s, $\overline{TI}$= 17%).

Air temperature and relative humidity were measured using 'iButton' sensors (Onsolution, Thermochron, TCS) positioned throughout the occupied zone of the wind tunnel's working section. During the three-week experimental campaign air temperature and relative humidity inside the wind tunnel ranged from 25.9-28.7 °C, and 49-62% respectively, they were relatively stable throughout each sequential pair of experiment (two different turbulence intensity levels).
Twenty university students (All human subjects in this project were recruited in compliance with The University of Sydney Human Research Ethics Committee protocol number 2018/090) participated in the experiment (demographic anthropometric information shown in Table 1). They were required to wear typical summer clothing (short sleeve t-shirts, sports shorts, socks, and sneakers); and as such the clothing insulation was estimated at around 0.35 clo (1 clo = 0.155 m2 °C/W) (ASHRAE, 2017).

Table 1. Demographic and anthropometric details of experimental subjects.

Gender	n	Age (years)	Height (cm)	Weight (kg)	BMI (kg/m^2)
Male	10	23.4 ± 2.8	176.0 ± 6.2	72.6 ± 7.9	23.4 ± 2.4
Female	10	24.6 ± 4.9	163.2 ± 6.4	$58.4. \pm 6.7$	22.0 ± 3.4
All	20	23.9 ± 3.9	169.0 ± 9.0	$64.7. \pm 10.2$	22.6 ± 2.9

Each participant came to the wind tunnel twice, and each visit included one standing test condition (A or D in Table 2) and one cycling test condition (B or C in Table 2). Each test condition was repeated at low and high turbulence intensity (randomly chosen from the sequence I or II) for 10-minute and was followed by a 15-minute break interval (Figure 2). Only one subject took part in the experiment at each time.

Table 2. Four test conditions of the research design.

Condition	Wind velocity (m/s)	Wind direction	Activity
A	1.5	facing	standing
B	1.5	side on	cycling
C	2.8	facing	cycling
D	2.8	side on	standing

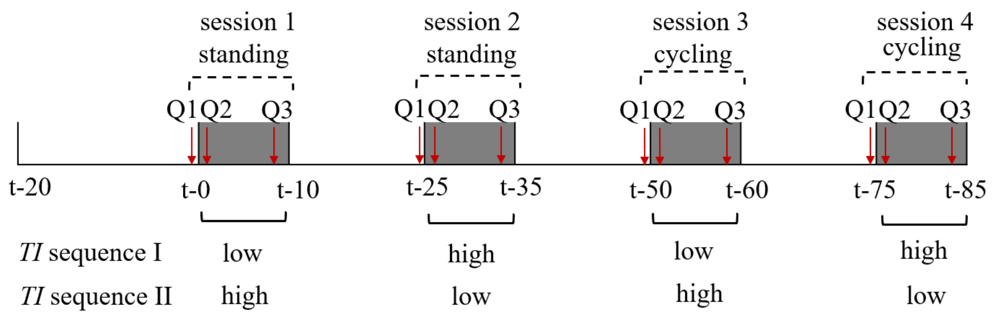


Figure 2. Timeline of the research protocol

After arriving, participants first acclimatized themselves in a 23 °C air-conditioned chamber for 20 minutes, during which their resting heart rate (HR_{rest}) was measured through the Wahoo TICKR X H10 rate monitor – a soft textile strap fitted across the chest (Crouter et al., 2004). Their real-time heart rate was shown on the ergometer screen when cycling, with the cadence on the ergometer set to 60 rpm they were instructed to adjust the resistance to maintain the real-time heart rate around the target value (HR), at which their metabolic rate would be the same (Yokota et al., 2008).

In each test condition, the first questionnaire (Q1) ensured that subjects started with a neutral thermal sensation (i.e. zero on the ASHRAE 7-point scale). If that was not the case the subject was instructed to rest in the adjacent air-conditioned anteroom until neutrality was attained. After the wind tunnel fan was turned on, participants were requested to cast a thermal sensation vote the instant they felt the wind (Q2, t ~ 0.3 min). Thermal sensation votes were cast again in a stable condition at the end of each session (Q3, t = 8 min).

Skin temperatures at 14 body sites were continuously sampled at 1 Hz by thermocouples (±0.5 ℃ accuracy, 0.1 s time constant; Omega T-TT-36). The measurement points included left-face, forehead, neck, chest, back, abdomen, upper arms (covered by clothing), forearms, hands, left-front-thigh (not covered by clothing), and shin. The mean skin temperature was calculated as an eight-point weighted average (Gagge & Nishi, 1977), with around half of the body area, including chest, back, upper arm, forearm, and hand, on the leeward side, when the wind blows from the left in condition B and D. The absolute value of mean skin temperature might vary depending on different measurement points.

A paired t-test was applied to the within-subject difference between thermal sensation votes and skin temperatures recorded at two turbulence levels. The statistical analysis was performed with SPSS, and the significance level was set to 0.05 ($p < 0.05$).

3. Results and discussion

The participants were required to report their thermal sensation vote by filling in a questionnaire on their mobile device as soon as they felt the wind. This process took up to an average of 25 s over all the participants. Previous studies have suggested that the subjective sensation under a dynamic thermal stimulation is directly proportional to the impulse accumulated by the thermoreceptors within the first 20 s (de Dear et al., 1993). Therefore, we here adopted the skin temperature change within the first 20 s to correspond to the instantaneous thermal sensation vote (Q2). To compare the turbulence-induced psychological and physiological differences, we standardised the instantaneous and stable-state skin temperature and thermal sensation vote (TSV) by calculating the difference from its nearest resting-state value as in Equations (4)-(7).

$$TSV_{\text{instant}} = TSV_{\text{Q2}} - TSV_{\text{Q1}} \quad (1)$$

$$\text{T}_{\text{skin\_instant}} = \text{T\_skin}_{\text{t=0.3min}} - \text{T\_skin}_{\text{t=0}} \quad (2)$$

$$TSV_{\text{stable}} = TSV_{\text{Q3}} - TSV_{\text{Q1}} \quad (3)$$

$$\text{T}_{\text{skin\_stable}} = \text{T\_skin}_{\text{t=8 min}} - \text{T\_skin}_{\text{t=0}} \quad (4)$$

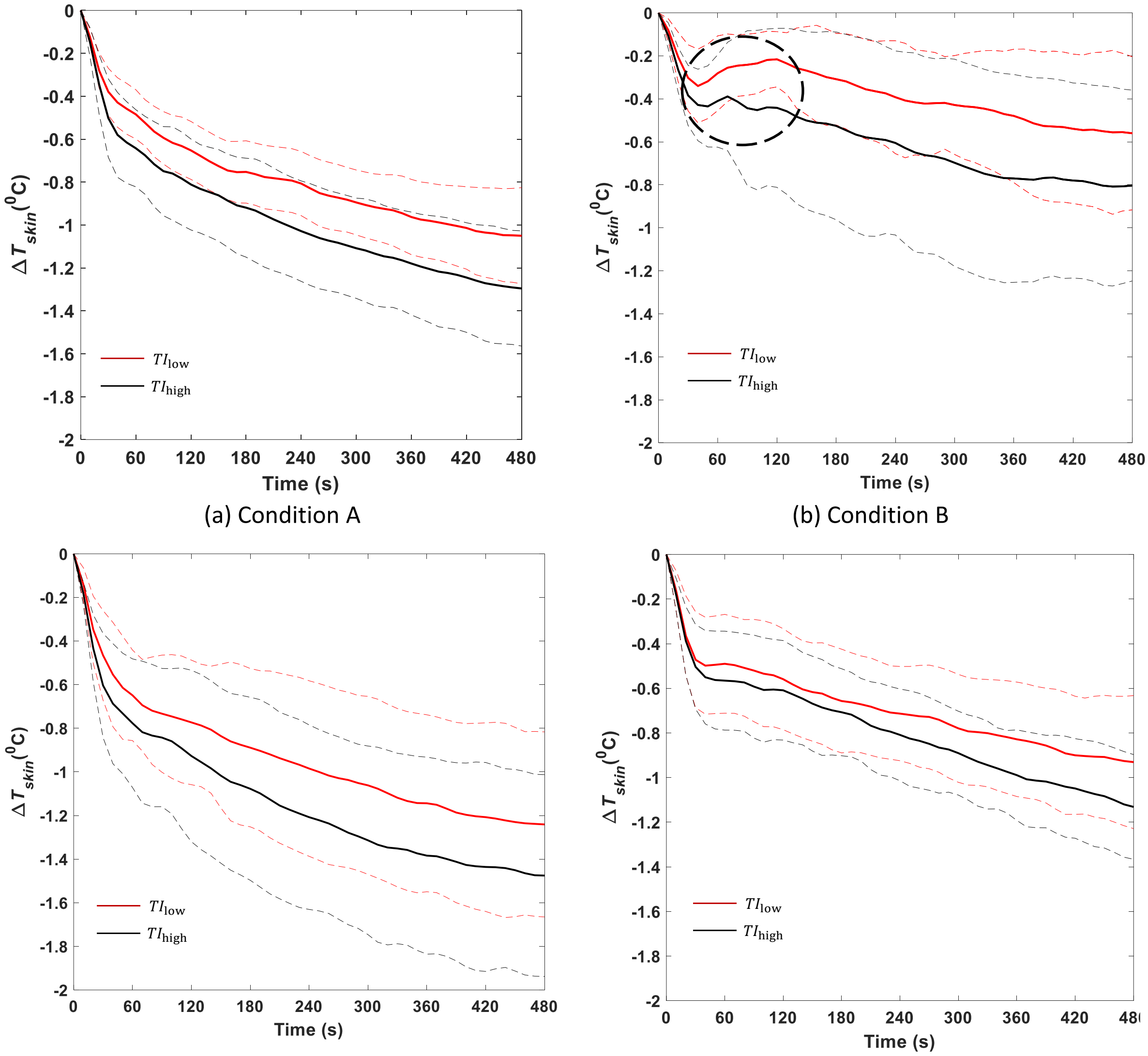
The increase of turbulence intensity could be reflected in a perceivable instantaneous thermal sensation difference for two facing conditions (A and C) (Table 3). While after 8-min exposure, the impact of different turbulence intensity on whole-body thermal sensation was more pronounced for two cycling conditions (B and C). When subjects were standing, the cold sensation gradually increased within the 8-min exposure. For cycling, the heat generated by the muscles compensated the heat convected by the wind from the skin surfaces, leading to a thermal sensation near neutral at the end of the test; and the thermal sensation difference between two TI levels enlarged over time.

Table 3. Instantaneous and stable whole-body thermal sensation change (as defined in Equation 1 and 3) at the two turbulence intensity levels (mean ± standard deviation)

		Condition A		Condition B		Condition C		Condition D
TSV_{instant}	TI-low	(-1.3 ± 0.4)	*	-1.3 ± 1.2		(-1.6 ± 1.3)	*	-1.4 ± 0.9
	TI-high	(-1.8 ± 0.8)		-1.5 ± 1.3		(-2.0 ± 1.2)		-1.6 ± 0.9
TSV_{stable}	TI-low	-1.6 ± 0.6		(0.4 ± 1.6)	*	(0.2 ± 1.7)	*	-2.0 ± 0.9
	TI-high	-1.9 ± 1.0		(0.0 ± 1.1)		(-0.4 ± 0.8)		-2.1 ± 0.6

*significant difference according to t-test ($p < 0.05$) between two turbulence intensity levels

The body mean skin temperature decreased linearly within the first 20 s, and the decreasing trend flattened at the end of the test (Figure 3). The most substantial decrement in skin temperature appeared in condition C - a combined outcome of higher wind speed and larger windward area. The turbulence-induced skin temperature difference is readily discernible from the space between two solid lines in Figure 3. The stable state mean skin temperature ($\overline{T_{skin\_stable}}$) was at least 20% larger when the subject experienced a higher TI compared with a lower one for all four test conditions (Table 4).



(a) Condition A (b) Condition B (c) Condition C (d) Condition D

Figure3. (a)-(d) Time series data of mean skin temperature for different test conditions, where the solid lines represent the mean value, and the dashed lines represent one standard deviation.

Table 4. Instantaneous and stable whole-body mean skin temperature change (as defined in Equation 2 and 4) at two turbulence intensity levels (mean ± standard deviation)

		Condition A		Condition B		Condition C		Condition D	
$\overline{T_{skin\_instant}}$(°C)	*TI*-low	(-0.38 ± 0.11)	*	-0.30 ± 0.15		(-0.47 ± 0.20)	*	-0.47 ± 0.22	
	TI-high	(-0.50 ± 0.18)		-0.35 ± 0.14		(-0.60 ± 0.24)		-0.48 ± 0.18	
$\overline{T_{skin\_stable}}$(°C)	*TI*-low	(-1.05 ± 0.22)	*	(-0.56 ± 0.36)	*	(-1.24 ± 0.42)	*	(-0.95 ± 0.25)	*
	TI-high	(-1.30 ± 0.27)		(-0.80 ± 0.44)		(-1.48 ± 0.46)		(-1.16 ± 0.21)	

4. Conclusions

This study confirms the impact of turbulence-induced cooling on both physiological and perceptual responses of human subjects to wind. The thermophysiological model needs to update its convective heat transfer coefficient to reflect more accurately the effects of turbulence intensity on skin temperature. When directly facing the wind, the subjects could almost instantly feel the difference between two levels of turbulence intensity (35% and 17%), which was reflected by the proportional change of skin temperature. The mean skin temperature difference between two turbulence levels continues to increase, and reached statistically significant after 10-min under all test conditions, while the difference in sensation was only perceptible under the cycling conditions. During cycling, the higher turbulence intensity amplified the evaporation of sweat, causing cooler sensation in these active parts of the body.

In this study, all the participants wore typical summer clothing and started each test with a neutral thermal sensation. Thus we are not able to conclude the cross-impact between air temperature, humidity, and turbulence intensity on the thermal perception. Future studies require a broader test range so as to cover typical outdoor environmental conditions, and to investigate the cross-impact of air temperature, humidity, and turbulence intensity on the thermal perception. Besides, it is also important to validate these experimental findings in real outdoor scenarios, paying particular attention to the relative motion when the pedestrians are moving.

References

Godbey, G. (2009). Outdoor Recreation, Health, and Wellness: Understanding and Enhancing the Relationship. SSRN Electronic Journal, RFF Discussion Paper No. 09-21.

Asimakopoulus, D., & Santamouris, M. (2012). Energy and climate in the urban built environment: Routledge.

Lin, T.P., Tsai, K.T., Liao, C.C., & Huang, Y.C. (2013). Effects of thermal comfort and adaptation on park attendance regarding different shading levels and activity types. Building and Environment, 59, 599-611.

Xie, Y., Huang, T., Li, J., Liu, J., Niu, J., Mak, C. M., & Lin, Z. (2018). Evaluation of a multi-nodal thermal regulation model for assessment of outdoor thermal comfort: Sensitivity to wind speed and solar radiation. Building and Environment, 132, 45-56.

Yu, Y., Liu, J., Chauhan, K., de Dear, R., & Niu, J. (2020). Experimental study on convective heat transfer coefficients for the human body exposed to turbulent wind conditions. Building and Environment, 169, 106533.

Zou, J., Yu, Y., Liu, J., Niu, J., Chauhan, K., & Lei, C. (2021). Field measurement of the urban pedestrian level wind turbulence. Building and Environment, 194, 107713.

ASHRAE. (2017). ASHRAE handbook: Fundamentals. American Society of Heating, Refrigerating and Air-Conditioning Engineers.

Gagge, A. P., Stolwijk, J., & Nishi, Y. (1971). An effective temperature scale based on a simple model of human physiological regulatory response. ASHRAE Trans., 77, 247-262.

Givoni, B., & Goldman, R. F. (1972). Predicting rectal temperature response to work, environment, and clothing. Journal of Applied Physiology, 32(6), 812-822.

Crouter, S. E., Albright, C., & Bassett, D. R. (2004). Accuracy of polar S410 heart rate monitor to estimate energy cost of exercise. Medicine and Science in Sports and Exercise, 36, 1433-1439.

Yokota, M., Berglund, L., Cheuvront, S., Santee, W., Latzka, W., Montain, S., . . . Moran, D. (2008). Thermoregulatory model to predict physiological status from ambient environment and heart rate. Computers in Biology and Medicine, 38(11-12), 1187.

Gagge, A. P., & Nishi, Y. (1977). Heat exchange between human skin surface and thermal environment. InComprehensive Physiology, S26 Handbook of physiology, reactions to environmental agents (pp. 69-92).

de Dear, R., Ring, J. W., & Fanger, P. O. (1993). Thermal Sensations Resulting From Sudden Ambient Temperature Changes. Indoor Air, 3(3), 181-192.