Clothing Strategies on Thermal Adaptation for Outdoor Summer Heat

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ABSTRACT

There are concerns about the health effects of intense summer heat in urban areas because of Urban Heat Islands. Because humans can create their preferred thermal environments quickly and inexpensively by wearing suitable clothing, clothing selection is considered an adaptation measure for Urban Heat Islands. Similar to urban modifications, ventilation and solar reflection techniques were applied in garment design, and their effects were evaluated in the present study. Two types of passive cooling garments, ventilation (loose fitting) and solar shielding (reflective), were investigated by participants in terms of the human thermal load from human energy balance and perceptions. Field measurements during walking were conducted outdoors during summer. The overall human thermal loads during the experimental were 62.5±32.8 W/m^2 for the reflective loose garment, 64.9±26.2 W/m^2 for the reflective tight garment, 85.8±32.0 W/m^2 for the non-reflective loose garment, 114.4±42.7 W/m^2 for non-reflective tight garment, and 147.9±47.3 W/m^2 for undressed conditions of comparison purpose, respectively. The results suggest that outdoor human thermal comfort can be significantly improved by wearing cool garments owing to the reduction in radiation heat gain. However, personal ventilation of clothing had little effect. Our small scheme for heat adaptation in summer garments did not work sufficiently. Therefore, more effective measures are required even under varying climatic conditions.

Keywords: Ventilation, Reflective material, Personal cooling, Individual clothing, Thermal comfort.

Introduction

People, energy, and other factors are concentrated in metropolitan areas, resulting in problems. For instance, cities generate heat released from sources such as air conditioners and vehicles, and artificial surfaces on pavements and closely packed buildings trap and amplify the heat effectively. Thus, major cities experience much warmer temperatures than their nearby rural areas, known as Urban Heat Islands (UHIs), and intense summer heat can lead to uncomfortable conditions or heat-related illnesses for residents and even visitors.

Designers and decision makers worldwide have been trying to deal with this extreme heat problem using technology. Mitigation and adaptation are sought from various perspectives, and human-centered design concepts are becoming popular during this process. To reflect human sensibility in the design of built environments, it is desirable to use human thermal

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comfort or sensation as criteria (Jamei et al. 2016). Thermal comfort is influenced by six major factors: human elements (human activity level and clothing) and climatic elements, such as air temperature, humidity, air flow, and radiation. Based on Fanger's comfort equation (Fanger 1970), the human energy balance, including the above-mentioned influential factors, namely, the heat transfer between humans and the ambient environment, is a good indicator of the human thermal state of comfort.

Urban form modifications and urban material changes to permeability and high albedo are typical countermeasures to UHIs, and reductions in urban temperatures have been reported worldwide (Qin 2015). Regarding human elements, because clothing affects human energy balance, the choice of clothing can be considered an adaptation. Clothing adjustments can reflect personal preferences for thermal comfort; moreover, they can work quickly and inexpensively, depending on the situation. Cooling garments are frequently used in industrial applications (Butts et al. 2017, Chan et al. 2017). Similar to UHI strategies, ventilation and solar shading are promising strategies for outdoor heat. Because the main cooling mechanism in the human energy balance equation outdoors is convective heat loss, there are several ways to enhance airflow, including the selection of fabric, clothing microclimate space, and material thinness. Because the main heat-gain mechanism is irradiation, shielding or reflection from irradiation is an effective way to reduce radiation heat gain.

We observed hot and humid summers at our locations. Considering the importance of spending outdoor space on health and well-being, we attempted to improve the human thermal environment by applying novel functional cool garments to the outdoor stayers.

Material and Methods

An outdoor field experiment was designed to evaluate the differences in the thermal environments of cool garments. Prototype short-sleeve T-shirts were prepared using ventilation and solar shielding. Both the shirts were made of 100% polyester. The same short white trousers were used in each shirt condition.

Participants

Nine healthy male university students aged 22.6±0.9 year voluntarily participated in this study (mean ± S.D.). Their mean height was 169.1±5.4 cm and their mean weight was 64.1±11.3 kg, consequently their Body Mass Index (BMI) was 22.3±3.4 and fit with a Japanese standard body range. The experimental protocol was reviewed and approved by the Ethics Committee of Toyohashi University of Technology.

Cool Garments

To induce clothing ventilation, garments with tight and loosely fitted fittings were prepared. For size reference, the area around the chest was 855 mm for the tight fitting, 1060 mm for the loose fitting, and 795 mm for the tight fittings and 1060 mm for the loose fitting. To identify the degree of clothing fit for individuals, a 3D whole-body scanner (VITUS; Vitronic, Wiesbaden, Germany) was utilized for measurement of human shapes. The shapes of both the naked and clothed human bodies were digitalized, and the gap area and volume were calculated for all participants. The scans were conducted vertically for 500 mm every 5 mm, from the neck to the abdomen. The degree of fitting differs among individuals; a preliminary measurement summary of the fitting conditions is presented in Figure 1. The mean gap volume was 1782 cm^3 for the tight fitting and 9173 cm^3 for the loose fitting. Lee et al. (2007) previously reported that the gap volume when wearing shirts was approximately 6000 cm^3, and our measurements showed a similar extent. What if the human body is cylinder shape, the average air gap width is 2.4 cm for loose fit and 0.5 cm for tight fit, respectively.

Reflective and non-reflective garments were prepared to block the solar heat gain. Certain types of ceramics have been blended into reflective clothing. Both materials appear white, and Table 1 presents the characteristics of each garment material based on the measurement method proposed by the authors (Shimazaki et al. 2014). The measured range of wavelengths was 285–3000 nm. Because the white-colored material has a fundamentally higher reflectance, the reflective garment materials in this experiment had a slightly higher solar reflectance than the non-reflective garment material. The garment materials were the same for tight and loosely fitted fittings.

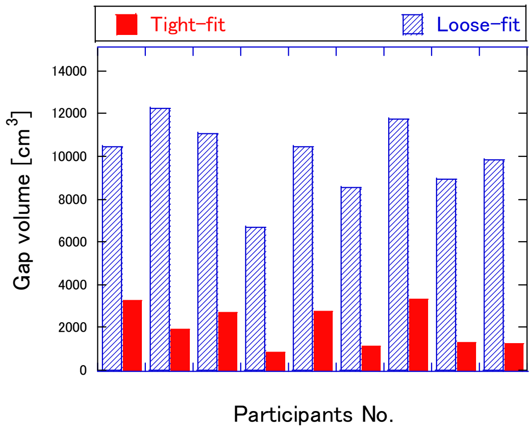

Figure 1. Fitting status for all participants.

Table 1. Properties of garment materials

Item	Reflective	Non-reflective
Reflectance [N.D.]	0.62	0.58
Transmittance [N.D]	0.23	0.33
Absorption [N.D.]	0.15	0.09
Thermal conductivity [W/(m·K)]	0.41	0.41
Permeability [$cm^2/(cm^2 \cdot s)$]	98.7	90.3
Thickness [mm]	0.53	0.53

Human Thermal Environment Assessment

To objectively quantify the outdoor human thermal environment, the human energy balance was evaluated using the human thermal load method (Shimazaki et al. 2011). The human thermal load considers the heat and mass transfer on the human body, and it correlates well with thermal perceptions. The human thermal load Q [W/m^2] is expressed as follows:

$$Q = M - W + R_{net} - E - C \quad (1)$$

where M [W/m^2] is human metabolism, W [W/m^2] is mechanical work, R_{net} [W/m^2] is net radiation, E [W/m^2] is latent heat loss, and C [W/m^2] is convective heat loss. Human metabolism is estimated based on the individual basal metabolism and Metabolic Equivalent of Task value (Mets). To express the ventilation convection with the clothing microclimate, the following relation was used to determine the convective heat transfer coefficient (JSME 2009):

$$Nu = \frac{Ra}{\{24(1+R)\}}\left(1 - exp\left(-2.84(1+R)^{\frac{3}{4}}\right) Ra^{-0.6}\right) \quad (2)$$

where *Nu* [N.D.] is the Nusselt number, *Ra* is the Rayleigh number, and *R* [N.D.] is the ratio of human metabolism to the radiative heat gain on clothing. The convective heat transfer coefficient for the undressed conditions, h [W/(m^{2}K)], is based on the conventional Jürges formula:

$$h = 3.6 + 6.97v^{0.89} \quad (3)$$

where v [m/s] is the wind speed. Detailed calculations for the other factors, such as net radiation, have been reported in the literature (Shimazaki et al. 2021). In this study, the human thermal load was directly calculated based on actual measurements.

A questionnaire survey was conducted to subjectively quantify human perceptions. The air current and sunshine perceptions, typical thermal sensations, and thermal comfort were obtained.

Field Experiments

The subject experiments were performed using the above-mentioned garments: tight fitting and reflective, loose fitting and reflective, tight fitting and non-reflective, and loose fitting and non-reflective. For comparison, the undressed naked conditions were also investigated. The experiments were performed on an outdoor paved road around a schoolyard at Toyohashi University of Technology campus during the summer. The climate in Toyohashi is mild and summer (July to September) is hot and humid like other cities in Japan. Each participant participated in only one session per day and their garments were randomly provided. Subjects with different garments were sometimes simultaneously exposed to the outdoor environment for 50 min at the same activity level, including 10 min of rest before and after 30 min of walking at a velocity of 81 m/min (equivalent to 3.3 Mets).

The elements required to calculate the human thermal load were also measured. These factors can be divided into human and environmental. The instruments used in these experiments are listed in Table 2. For human elements, the skin surface temperature (forehead, hand, upper arm, pelvis, thigh, leg, and instep based on the Hardy-DuBois formula (1938)), and rectal temperature were measured at 1 min intervals. Skin surface temperatures were used to calculate the average body temperature. Perspiration was calculated based on the weight change during the experiment. For environmental elements, air temperature and humidity, radiation (solar radiation and infrared) from both downward and upward, and airflow and its direction were measured at 1 min intervals. Clothing conditions were measured for clothing surfaces and clothing microclimates using thermistors at 1 min intervals.

Perceptual questionnaires on thermal sensation (7 point scale from -3: cold to +3: hot), thermal comfort (5 point scale from -2: uncomfortable to +2: comfortable) (ASHRAE 2013), draft sensation (4 point scale from 0: imperceptible to 3: very noticeable) (Lee et al. 2004), and thermal radiation sensation (4 point scale from 0: imperceptible to 3: very noticeable) (McIntyre 1977) were conducted at 5 min interval. All sensations were quantified using linear interpolation. The expressions were translated from their original language into Japanese.

For reference purpose, the experimental situation is presented in Figure 2.

Table 2. Measurement instruments and specifications

Item	Instrument	Accuracy
Air temperature	Thermistor	±0.3 °C
Relative humidity	Capacitance hygrometer	±5%R.H. @25℃, 50 %RH
Wind speed/direction	Ultrasonic anemometer	±1%±0.05 m/s
Solar radiation	Pyranometer	<1.5% @1000W/m^2
Infrared radiation	Pyrgeometer	<25W/m^2 @irradiation 1000W/m^2
Clothing/Skin/rectal temperature	Thermistor	±0.1 °C
Weight change (Sweating)	Electric balance	±1 g

(a)

(b)

Figure 2. Experimental situation. (a) Stationary measurement for climatic variables and (b) subjective evaluation.

Results and discussion

Climatic Conditions

The climatic conditions during the experiments are summarized in Table 3. Values represent mean and standard deviation. The experiments were conducted outdoors, and fluctuations in climatic variables were observed. For example, global solar radiation ranged from 520 to 915 W/m^2 depending on the weather; however, the climatic conditions were typical summer weather in the location.

Table 3. Climatic conditions during the experiments

Item	Value
Air temperature °C	32.4±1.6
Relative humidity %	53.7±6.1
Wind speed m/s	1.2±0.7
Global solar radiation W/m^2	671±121
Sky infrared radiation W/m^2	506±10

Thermal Environment Evaluation with Different Garments

The breakdown of the human thermal loads is shown in Figure 3. The values represent the time averages for all trials. A positive value indicates heat gain and a negative value indicates heat loss. As the participants and their activities were unified, the human metabolism and mechanical work were the same among the conditions. The amount of radiation gain (net radiation) for reflective loose and tight garments was significantly smaller than that for undressed humans based on multiple comparisons. For example, the difference in net radiation between reflective loose and undressed conditions was approximately 100 W/m^2; however, no significant difference was observed between reflective and non-reflective garment wearers. Based on this theory, the Nusselt number, and consequently, the convective heat transfer, increases with increasing air-gap width. Undressed humans can efficiently use the direct wind for heat release. Except for this undressed condition, the values among the dressed conditions were almost the same for the convective heat loss. Totally, the overall human thermal loads during the experimental period of 30 min are 62.5±32.8 W/m^2 for reflective loose garment, 64.9±26.2 W/m^2 for reflective tight garment, 85.8±32.0 W/m^2 for non-reflective loose garment, 114.4±42.7 W/m^2 for non-reflective tight garment, and 147.9±47.3 W/m^2 for undressed conditions, respectively. The overall human thermal load for the undressed condition had the highest value, which was significantly different from the overall human thermal load of reflective loose, reflective tight, and non-reflective loose wearers from multiple comparisons. When we compared the difference between loose and tight fitting garments, we observed a smaller human thermal load when wearing shirts loosely.

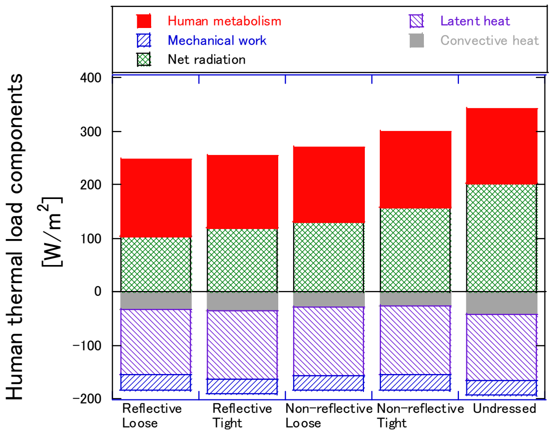

Figure 3. Human thermal load components for each garment condition.

The draft and thermal radiation sensations are shown in Figure 4. Wearers with loose fitting garments tended to feel more drafts for both reflective and non-reflective garments. Based on multiple comparisons among the conditions, no significant differences were observed. Under all conditions, humans still received a certain level of radiation, and no significant difference was observed in thermal radiation sensation. No significant differences were observed in the other sensation values. The relationship between thermal sensation and thermal comfort is shown in Figure 5. Because humans feel discomfort due to both cold and hot, and feel comfortable when the source of discomfort, namely any thermal loads from the neutral, is absent, the plots become mountain-like. Our results are consistent with these findings. The plots were widely distributed in terms of thermal sensation from 0 to +3, suggesting that the environmental conditions varied depending on the trial. Climatic conditions, particularly solar radiation, may exhibit variations in real environments, which may affect experimental uniformity.

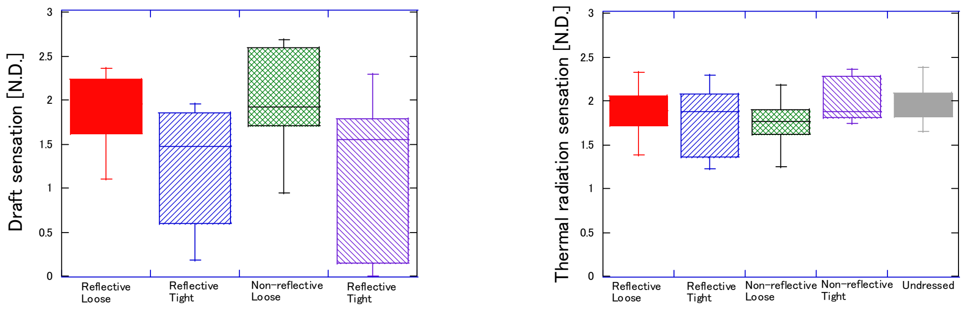

Figure 4. Box-and-whisker plot for human perceptions. (a) Draft sensation and (b) thermal radiation sensation.

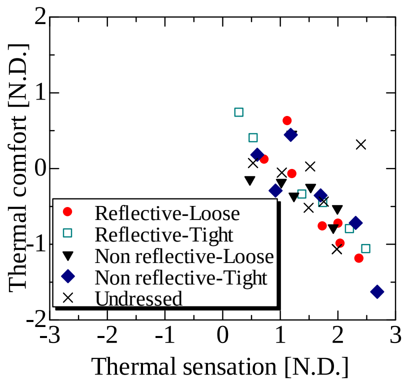

Figure 5. Relationship between thermal sensation and thermal comfort.

Although undressed humans can achieve convective heat loss owing to the direct wind without garments, they receive more direct solar heat. Fundamentally, the amount of convective heat is limited compared to the amount of outdoor radiative heat, and it is important to consider the optical properties of materials in the microclimate. Thus, radiation shielding is effective; in particular, reflective garments exhibit smaller radiation gains. Moreover, the formation of clothing ventilation in a real environment is a complex mechanism, and a detailed understanding of the formation and application of airflow under garments is required in future studies.

Although downward radiation is undoubtedly an influential factor, solar reflection affects human heat gains in some cases, such as in light-colored pavements. In the experiment, subjects walked on an asphalt-paved road next to a wide open area. Normal asphalt pavements has an albedo of approximately 0.1 (Li et al. 2013). Reflective garments are more effective at improving thermal comfort under reflective urban conditions. Therefore, understanding the relative importance of urban albedo and clothing reflectivity is beneficial for adapting to the summer heat.

Conclusion

Because clothing affects the human energy balance, and thus human thermal comfort, the choice of clothing can be considered an adaptation. We experimentally examined outdoor thermal environmental improvements using novel ventilation and solar-shielding garments. The quantitative human thermal load and subjective perception evaluations were conducted. Wearing clothing fundamentally acts as a buffer against outer environments; thus, any garment condition experiences a reduction in both radiative heat gain and convective heat loss, suggesting comfort. Our small scheme for heat adaptation in summer garments seems conceptually correct; however, it does not work sufficiently. Therefore, more effective measures are required even under varying climatic conditions.

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References

Jamei,E., Rajagopalan, P, Seyedmahmoudian, M., Jamei, Y. 2016. Review on the impact of urban geometry and pedestrian level greening on outdoor thermal comfort. *Renewable and Sustainable Energy Reviews* 54, 1002-1017. https://doi.org/10.1016/j.rser.2015.10.104.

Fanger P.O. (1970). *Thermal comfort*. Danish Technical Press. Copenhagen (Denmark).

Qin, Y. 2015. A review on the development of cool pavements to mitigate urban heat island effect. *Renewable and Sustainable Energy Reviews* 52, 445-459. https://doi.org/10.1016/j.rser.2015.07.177.

Butts, C.L., Smith, C.R., Ganio, M.S., McDermott, B.P. 2017. Physiological and perceptual effects of a cooling garment during simulated industrial work in the heat. *Applied Ergonomics* 59, 442-448. https://doi.org/10.1016/j.apergo.2016.10.001

Chan, A.P.C., Zhang, Y., Wang, F., Wong, F.F.K., Chan, D.W.M. 2017. A field study of the effectiveness and practicality of a novel hybrid personal cooling vest worn during rest in Hong Kong construction industry. *Journal of Thermal Biology* 70, 21-27. https://doi.org/10.1016/j.jtherbio.2017.07.012.

Lee, Y., Hong, K., Hong, S.A. 2007. 3D quantification of microclimate volume in layered clothing for the prediction of clothing insulation. *Applied Ergonomics* 38, 349-355. https://doi.org/10.1016/j.apergo.2006.04.017.

Shimazaki, Y., Aoki, M., Nitta, J., Okajima, H., Yoshida, A. 2021. Experimental determination of pedestrian thermal comfort on water-retaining pavement for UHI adaptation strategy. *Atmosphere* 12 (2), 127. https://doi.org/10.3390/atmos12020127.

Shimazaki, Y., Yoshida, A., Satsumoto, Y., Taketani, S. 2014. Effect of properties of sports surface and clothing materials on human thermal load under hot environment. *Procedia Engineering* 72, 502-507. https://doi.org/10.1016/j.proeng.2014.06.087.

Shimazaki, Y., Yoshida, A., Suzuki, R., Kawabata, T., Imai, D., Kinoshita, S. 2011. Application of human thermal load into unsteady condition for improvement of outdoor thermal comfort. *Building and Environment* 46, 1716-1724. https://doi.org/10.1016/j.buildenv.2011.02.013.

JSME. (2009). *JSME data book: heat transfer*. JSME. Tokyo (Japan).

Hardy, J.D., DuBois E.F., Soderstrom, G.F. 1938. The technic of measuring radiation and convection. *The Journal of Nutrition* 15 (5), 461-475.

ASHRAE. (2013). *ASHRAE Handbook—Fundamentals*. ASHRAE. Atlanta (U.S.).

Lee, .S.J., Tanabe, S., Nobe, T. 2004. Thermal comfort of task air conditioning with isothermal air flow unit. Journal of Environmental Engineering (Transactions of AIJ) 69 (575), 75-82. https://doi.org/10.3130/aije.69.75_1.

McIntyre, D.A. 1977. Sensitivity and discomfort associated with overhead thermal radiation. *Ergonomics* 20 (3), 287-296. https://doi.org/10.1080/00140137708931628

Li, H., Harvey, J.T., Holland, T.J., Kayhanian M. 2013. The use of reflective and permeable pavements as a potential practice for heat island mitigation and stormwater management.

*Environmental Research Letter*s 8, 015023. https://doi.org/10.1088/1748-9326/8/1/015023.