NOTES AND CORRESPONDENCE
UV Parasol, Dry-Mist Spraying, and Street Trees as Tools for Heat Stress Mitigation

Hiroyuki KUSAKA

Center for Computational Sciences, University of Tsukuba, Tsukuba, Japan

Yusuke NAKAMURA

Center for Research in Isotopes and Environmental Dynamics, University of Tsukuba, Tsukuba, Japan

and

Yuki ASANO

Graduate School of Life and Environmental Sciences, University of Tsukuba, Tsukuba, Japan

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Abstract

Ultraviolet (UV) parasols are a reasonable countermeasure against heat stress as they are portable and inexpensive. This study compared the heat stress mitigation effect of a UV parasol with that of street trees and dry-mist spraying on a hot and humid summer day in Japan. We observed meteorological elements and calculated the universal thermal climate index (UTCI) and wet-bulb globe temperature (WBGT) under UV parasol, street trees, dry-mist spraying, and direct sunlight. The observed UTCI and WBGT under the UV parasol were lower than those in direct sunlight by 4.4°C and 1.3°C, respectively, because of the decrease in black-globe temperature caused by the reduced downward shortwave radiation. This demonstrated that UV parasol reduced heatstroke risk by one level. The effect of the UV parasol was ≥ 75 % of that of the street trees from the perspective of UTCI. The street trees reduced the UTCI and WBGT by 5.9°C and 1.9°C, respectively, compared with those in direct sunlight, resulting in the reduction of heatstroke risk by one level. In contrast, dry-mist spraying did not mitigate heat stress in conditions with moderate winds. Although the results of this study were obtained from observations on a single day, comparison with earlier studies confirms that the values observed in this study are representative results on summer days in Japan.

Keywords UV parasol; dry-mist spraying; heat stress mitigation; wet-bulb globe temperature; universal thermal climate index

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Corresponding author: Hiroyuki Kusaka, Center for Computational Sciences, University of Tsukuba, 1-1-1 Tennoudai, Tsukuba, Ibaraki 305-8577, Japan
E-mail: kusaka@ccs.tsukuba.ac.jp
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1. Introduction

There has been an increase in heatstroke risk in urban areas in Japan due to climate change and the urban heat island effect (e.g., Kusaka et al. 2012; Fujibe 2018). Countermeasures against outdoor heat stress have been proposed and evaluated to reduce the risk of heat stroke. Planting trees along streets is expected to be an effective method for mitigating heat stress for citizens by providing shade (e.g., Coutts et al. 2016; Morakinyo et al. 2017; Rahman et al. 2018). Coutts et al. (2016) found that street trees can reduce the daytime universal thermal climate index (UTCI) from very strong (> 38°C) to strong (> 32°C) during summer days. Installing artificial shading devices and vine trellises can have effects similar to those of street trees (e.g., Sakai et al. 2012; Vanos et al. 2017; Kántor et al. 2018; Kusaka et al. 2022). Spraying dry mist can be an effective mitigation method when the mist reaches pedestrians (e.g., Wong and Cong 2010; Ulpiani et al. 2019). However, its effectiveness may be limited as mist is easily carried away by wind. Further experiments are required to confirm this effect. Installation of these devices in the city to reduce heat stress is positioned as public assistance. How can pedestrians alleviate heat stress on streets without trees or artificial shading devices? In Japan, it is not uncommon to use parasols on hot days. Approximately 26 % of women use ultraviolet (UV) parasols outdoors in summer (Watanabe and Ishii 2016). In Taiwan, 38 % of women walking outdoors use UV parasols in summer (Lin 2009). The term "UV parasol" refers to an umbrella specially designed to block the sun's rays (Fig. 1a). UV parasols are expected to be an effective countermeasure against heat stress as they are easy to carry and use (Watanabe and Ishii 2017; Lee et al. 2018). Watanabe and Ishii (2017) measured the wet-bulb globe temperature (WBGT) under white and black parasols made of a mixture of polyester and cotton and under dark brown parasols made of polyester and found that the latter reduced heat stress the most. However, few studies have been conducted on the heat stress mitigation effects of UV parasols, which are less advanced than the effects of other measures.

To date, most studies have investigated the effectiveness of specific heat stress countermeasures. Meanwhile, the relative superiority of each heat stress mitigation method is uncertain. For example, there is a lack of clarity on the effectiveness of a UV parasol as an alternative method when walking in areas that do not have street trees or dry-mist spraying. Therefore, it is necessary to compare and evaluate the heat stress mitigation effects of parasols and other devices in similar conditions. To the best of our knowledge, no study has directly compared the heat stress-mitigating effects of UV parasol, dry-mist spraying, and street trees.

In this study, we conducted field experiments and evaluated the effectiveness of UV parasols, dry-mist spraying, and street trees as heat stress mitigation agents in terms of two thermal indices, WBGT and UTCI. The results obtained in this study are expected to help reduce the number of heatstroke patients and design climate change adaptation strategies.

2. Methods

2.1 Overview

The study was conducted within the campus of the University of Tsukuba, Tsukuba City, Japan, where the climate zone is humid and subtropical. In Japan, WBGT is widely used as a thermal environment index. However, UTCI has been universally standardized as it incorporates the parameters of clothing and wind speed (e.g., Jendritzky et al. 2012; Blazejczyk et al. 2012; Potchter et al. 2018; Iwamoto and Ohashi 2021). Therefore, in this study, we evaluated variations in the WBGT and UTCI between locations for street trees, UV parasols, dry-mist spraying, and direct sunlight. Statistical significance was assessed using Welch's *t*-test. To avoid multiplicity of tests, the *t*-test was followed by multiple comparisons using the Bonferroni method.

2.2 Observations

The meteorological components for estimating WBGT and UTCI were measured under UV parasols, dry-mist spraying, street trees, and direct sunlight (Fig. 1). Each measurement point was approximately 8 m away from the next point, and the meteorological and environmental conditions were measured between these four locations. A standard black-colored UV parasol made of polyester (100 %, + sputtering on the back) and with a rib length of 0.58 m was used. The street tree, a trident maple (*Acer buergerianum*) with a height of 11 m, is the fifth most common street tree species in Japan (Iizuka and Funakubo 2019). The dry mist had the following properties: water volume of 1.3 L min^{-1}, particle size of ~ 20 μm, and area sprayed covered 1.5 m^2. The dry mist was sprayed downward from a height of 2 m above ground level (AGL).

The air temperature and black-globe temperature at 1.5 m AGL were observed using TR-5106 and the relative humidity at 1.5 m AGL was observed using

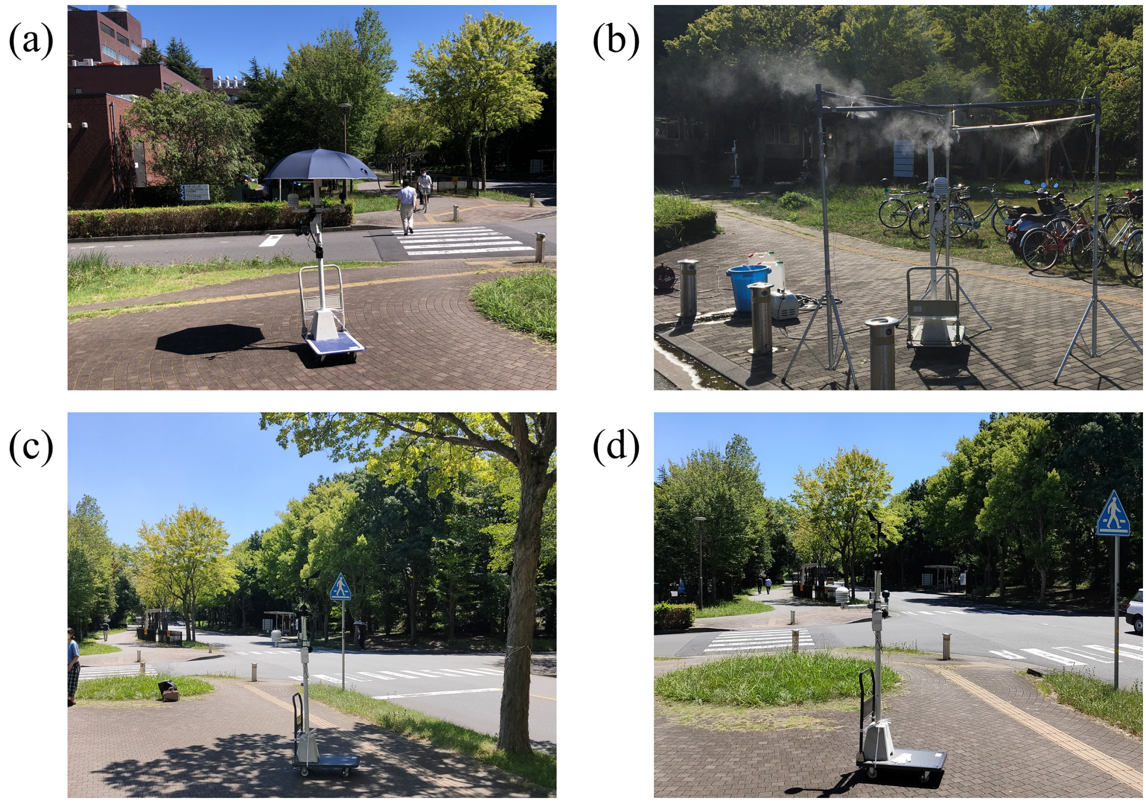

Fig. 1. Scenes of locations (a) under the UV parasol, (b) under the dry-mist spraying, (c) under the street trees, and (d) in direct sunlight.

HHB-3101 (T&D Corporation, Matsumoto, Japan). The wind direction and speed at 2.0 m AGL were observed with a Vantage Pro (Davis Instruments Corporation, Hayward, CA, USA). Surface temperatures were measured using an R300SR-S thermal camera (Nippon Avionics Co., Ltd., Yokohama, Japan). Downward shortwave and longwave radiation data under direct sunlight were provided by the Center for Research in Isotopes and Environmental Dynamics at the University of Tsukuba.

2.3 Calculations of WBGT and UTCI

WBGT was calculated using the wet-bulb temperature (Tw), dry-bulb temperature (T), and black-globe temperature (Tg), as shown in Eq. (1) (Yaglou and Minaed 1957):

$$\mathrm{WBGT} = 0.1T + 0.2Tg + 0.7Tw. \tag{1}$$

Table 1a shows the criteria of WBGT for heatstroke risk level in Japan. The Japanese society of biometeorology (JSB) notes that if WBGT is at the danger level (WBGT ≥ 31), elderlies are at risk of heatstroke even

Table 1. Criteria of (a) WBGT for heatstroke risk level in Japan (Ministry of the Environment 2021) and (b) UTCI for heat and cold stress category (Blazejczyk et al. 2012).

(a)

Criteria [°C]	Heat stroke risk level
WBGT ≥ 31	Danger
28 ≤ WBGT < 31	Severe Warning
25 ≤ WBGT < 28	Warning
21 ≤ WBGT < 25	Caution
WBGT < 21	Almost Safe

(b)

Criteria [°C]	Stress category
UTCI ≥ 46	Extreme heat stress
38 ≤ UTCI < 46	Very strong heat stress
32 ≤ UTCI < 38	Strong heat stress
26 ≤ UTCI < 32	Moderate heat stress
9 ≤ UTCI < 26	No thermal stress

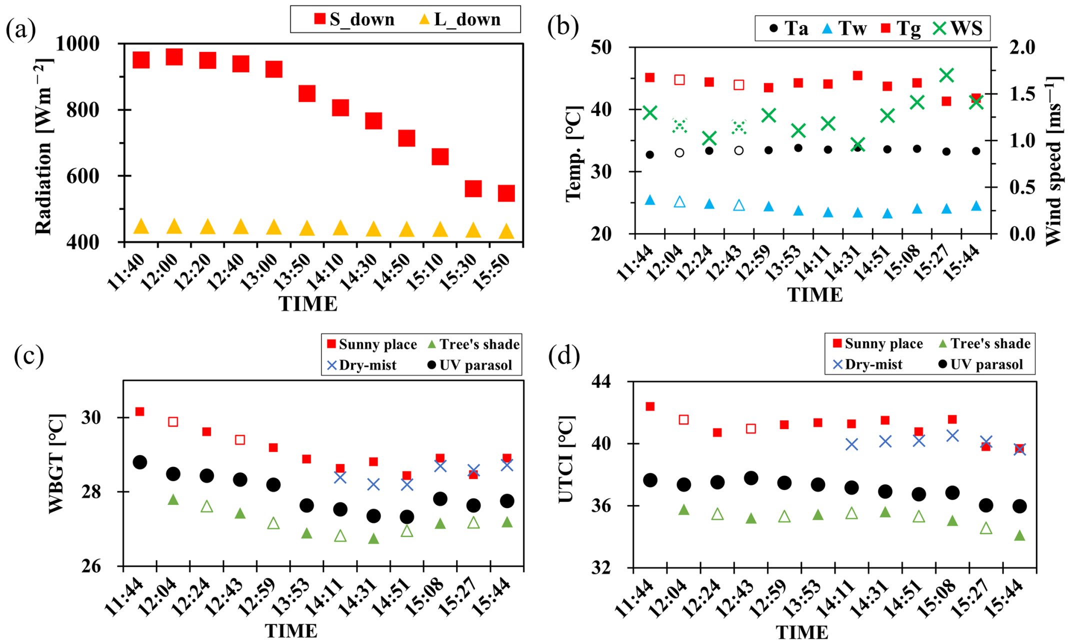

Fig. 2. Time series of observations from 11:40 JST to 15:50 JST on August 5, 2021. The values are averaged for 10 minutes. (a) Short- and long-wave radiations in direct sunlight, and (b) dry-bulb, wet-bulb, and black globe temperatures and wind speed in direct sunlight. Here, S_down, L_down, *Ta*, *Tw*, *Tg*, and WS are downward shortwave radiation, downward longwave radiation, dry-bulb temperature (air temperature), wet-bulb temperature, black-globe temperature, and wind speed, respectively. (c) WBGT and (d) UTCI at the four locations. Here, red square, blue cross, black circle, and green triangle indicate the location in direct sunlight, under the dry-mist spraying, under the UV parasol, and under the street tree, respectively. Closed symbols indicate observations at the official measurement time and the open symbols indicate that the values were interpolated using the observed values at the time before and after the official measurement time.

when they are at rest. Also, they suggest that people should avoid going outside as much as possible and stay in a cool room. The JSB states that people should avoid going outside during hot and sunny days and be aware of the rising room temperature indoors in case of a severe warning level ($28 \leq$ WBGT < 31). JSB also states that adequate rest should be taken regularly, especially during exercising or doing strenuous work, in case of a warning level ($25 \leq$ WBGT < 28).

The calculation of UTCI was based on the Fiala-UTCI multi-node dynamic, a human heat transfer and regulation model, which is much more complex than WBGT. Herein, we will briefly explain UTCI by quoting from the description in Di Napoli et al. (2018). The UTCI is a bioclimate index describing the physiological heat load, called stress, which the human body experiences to maintain thermal equilibrium with the surrounding outdoor environment (Blazejczyk et al. 2012). While simple heat stress indices are based exclusively on meteorological parameters such as air temperature and humidity, the UTCI is computed from an energy balance model called the UTCI-Fiala model (Fiala et al. 2012). For specific calculation methods, please refer to Bröde et al. (2012). Table 1b shows the criteria used for categorizing values of UTCI in terms of thermal stress. The criterion was derived from the UTCI-Fiala model response. Extreme heat stress (UTCI ≥ 46) is a condition in which the average sweat rate is over 650 g h^{-1}. Very strong heat stress ($38 \leq$ UTCI < 46) is a condition in which there is an increase in rectal temperature at every 30 min. Strong heat stress ($32 \leq$ UTCI < 38) is a condition in which instantaneous change in skin temperature is over 0 K min^{-1}.

3. Results

Figure 2a shows the temporal changes in downward shortwave and longwave radiations, and Fig. 2b shows the dry-bulb temperature (air temperature), wet-bulb temperature, black-globe temperature, and wind speed

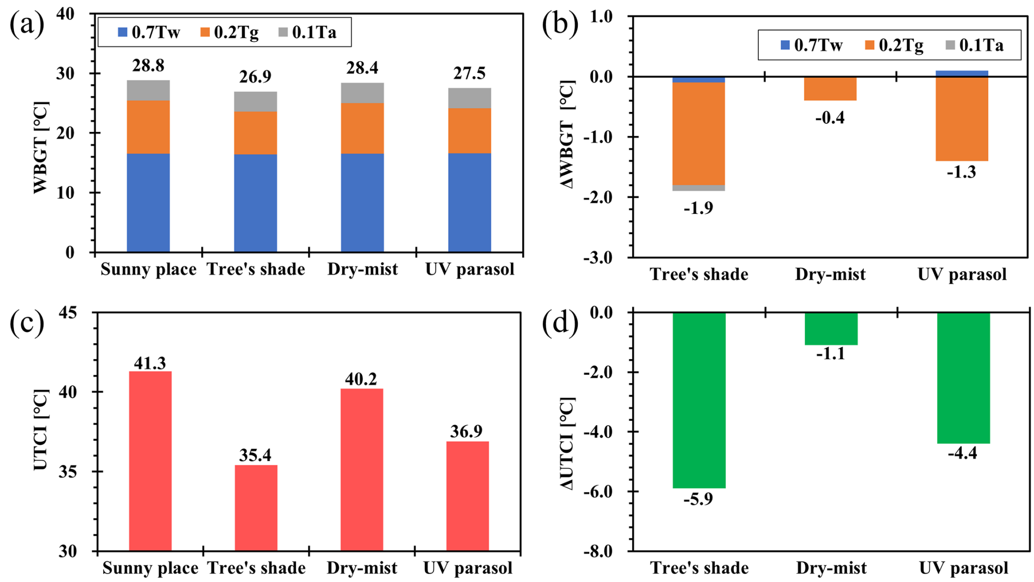

Fig. 3. (a) Mean contribution of dry-bulb (grey), wet-bulb (blue), and black globe-bulb temperatures (orange) to WBGT at the four locations: under the UV parasol, under the dry-mist spraying, under the street tree, and in direct sunlight. These are the average of the data observed from 14:00 JST to 15:00 JST on August 5, 2021. (b) The difference in WBGT under direct sunlight and the other three locations. (c) UTCI at the four locations: under the UV parasol, under the dry-mist spraying, under the street tree, and in direct sunlight. These are the average of the data observed from 14:00 JST to 15:00 JST. (d) The difference in UTCI under direct sunlight and the other three locations.

in direct sunlight from 11:40 Japan Standard Time (JST) to 15:50 JST on August 5, 2021. During the observation period, the study area was covered by the Pacific High and was sunny, with a cloud cover of 0–2. The downward shortwave and downward longwave radiations ranged between 547.5 and 959.6 and 434.3 and 449.7 W m^{-2}, respectively. The time-averaged values of dry-bulb, wet-bulb, and black-bulb temperatures were 33.4, 24.3, and 43.9°C, respectively. The wind speed was generally low, ranging from 1.0 m s^{-1} to 1.7 m s^{-1}. However, there was a slight temporal variation in the winds, with a weakening around 14:00 JST and strengthening around 15:00 JST.

Figure 2c shows the WBGT at the four locations during the observation period. The WBGT in direct sunlight was always > 28°C during the observation period, with a maximum of 30.2°C, indicating that WBGT was at a very high risk level for heatstroke throughout the observation period (Table 1a). The time-averaged value during the observation was 28.8 °C. Herein, we discuss the mitigation effects of street trees, UV parasols, and dry-mist spraying on heat stress. The WBGT under the street trees ranged from 26.8°C to 27.8°C during the observation period. The average value was observed between 14:00 JST and 15:00 JST, when all locations were at 26.9°C, which is 1.9°C lower than that in direct sunlight (Figs. 3a, b). According to the *t*-test and Bonferroni method, the deviations were significant at the 1 % level. The WBGT under UV parasol ranged between 27.3°C and 28.8°C with a mean value of 27.9°C, which was 1.3°C lower than that in direct sunlight. The deviations were significant at the 1 % level. These results suggest that UV parasols can reduce the risk of heatstroke from severe warning to warning level, as per the WBGT rank, and the effect of the UV parasol was approximately 68 % of that of the street trees in terms of WBGT. On the other hand, the difference in the mean WBGT between under the dry-mist spraying and in direct sunlight was small (0.4°C), and there was no statistical significance even at 5 % significance level.

We examined the contribution of black-globe, dry-bulb, and wet-bulb temperatures to understand the causes of the lower WBGT under street trees and UV parasols. The results showed that the contribution of the reduced black-globe temperature values under the street tree (UV parasols) was 1.7°C (1.4°C), whereas changes in dry-bulb and wet-bulb temperatures did not contribute to WBGT reduction as compared with that by black-globe temperature.

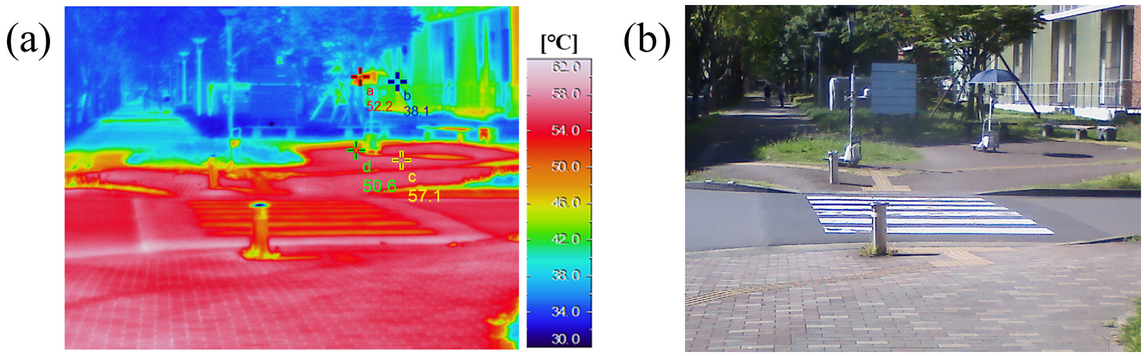

Fig. 4. (a) Infrared and (b) visible images around the observation points. These images were taken at 14:49 JST on August 5, 2021. The colors and the values on the infrared images indicate the surface temperature. Point "a (b)" on the infrared images show the maximum (minimum) surface temperature of the UV parasol [°C]. Point "c" and "d" on the infrared images indicate the maximum (minimum) surface temperature on the sidewalk under the UV parasol.

The results of the analysis of the heat mitigation effect of each device in terms of the UTCI were similar to those in terms of the WBGT. The UTCI under the street trees ranged from 35.1°C to 35.6°C with a mean value of 35.4°C, which is 5.9°C lower than that in direct sunlight, indicating that street trees can reduce the heat stress from a level of Very strong to Strong according to the UTCI rank (Table 1b). The deviations were significant at the 1 % level (Figs. 3c, d). Similarly, the value under UV parasol ranged from 36.7°C to 37.2°C with a mean of 36.9°C, which is 4.4°C lower than that under direct sunlight, suggesting that UV parasols can reduce the heat stress of people from Very strong to Strong according to the UTCI rank. The deviations were significant at the 1 % level. Observed results under street trees and the UV parasol indicate that in weather conditions such as those in the present experiment, the heat stress mitigation effect of UV parasols is approximately 75 % of that of street trees when evaluating UTCI, suggesting that UV parasols are effective alternative devices when walking along streets without street trees. On the other hand, the difference between conditions under the dry-mist spraying and in direct sunlight was negligible (1.1°C), and there was no statistical significance even at the 5 % significance level.

4. Discussion

The results of this experiment showed that on days with a high heatstroke risk level, UV parasols could reduce both WBGT and UTCI by one rank. In the case of the UV parasol used in this experiment, the solar radiation transmittance was 3 % (this was obtained from another experiment). This is equivalent to the fact that solar radiation to the black sphere was blocked by 714 W m^{-2}, averaged from 14:00 JST to 15:00 JST. However, as the UV parasol was heated by solar radiation, the downward longwave radiation reaching the black-globe temperature under the parasol increased by 127 W m^{-2} compared with that under direct sunlight. This value was calculated from the downward longwave radiation amount estimated from the surface temperature of the UV parasol and the observed downward longwave radiation amount under direct sunlight. The estimated black-globe temperatures under the UV parasol were 36.9°C and 37.1°C, obtained using Tonouchi–Murayama's and Okada's empirical formulas, respectively (Tonouchi and Murayama 2008; Okada et al. 2016). These values were similar to the observed value (37.7°C). The reduction in black-globe temperature due to the reduction of the received downward radiation amount (587 W m^{-2}) was estimated to be 12.1°C. This is consistent with the difference in the observed black-globe temperature between under the UV parasol and in direct sunlight in this study, with an error of 2°C. UV parasols are not expected to significantly change the reflection of solar radiation from the ground or the amount of upward longwave radiation. This is because although it depends on the angle of the sun's altitude, a UV parasol, unlike a large tent, does not cast its shadow directly below (Fig. 4).

The dry-mist spray was ineffective as the mist was swept away by strong winds, resulting in reduced evaporation around the black globe. Figures 5a and 5b show that under dry-mist spraying, the stronger the wind, the larger the WBGT and UTCI. In contrast, such a relationship was not observed under direct sun-

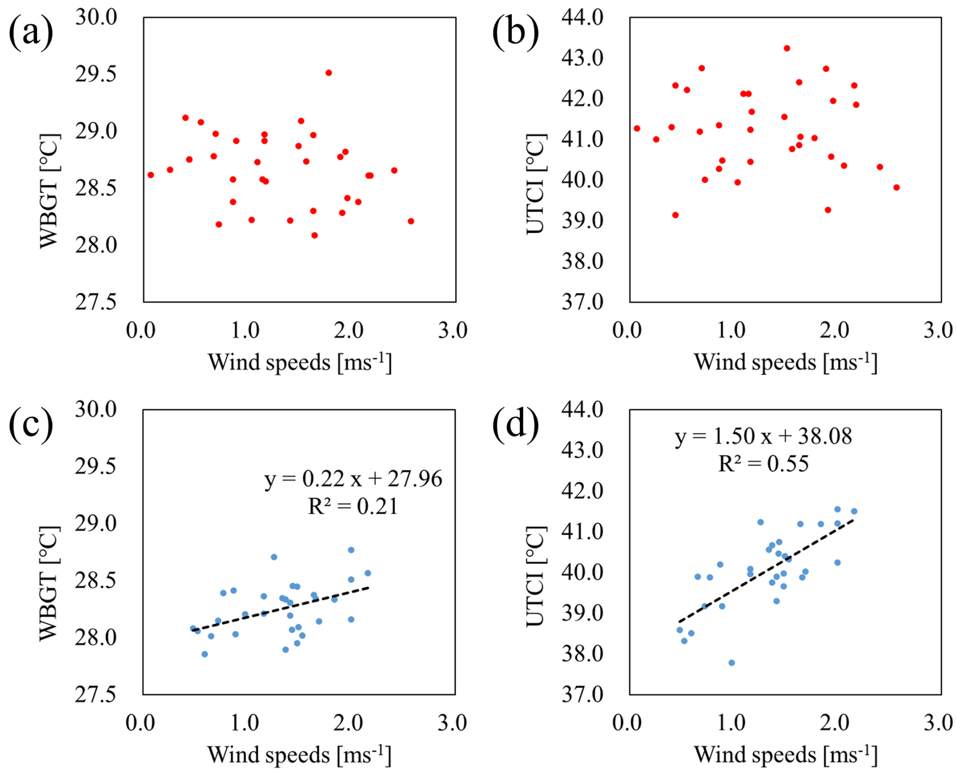

Fig. 5. Scatter diagram of (a) WBGT vs wind speed in direct sunlight, (b) UTCI vs wind speed in direct sunlight, (c) WBGT vs wind speed under the dry-mist spraying, and (d) UTCI vs wind speed under the dry-mist spraying from 14:00 JST to 15:00 JST.

light (Figs. 5c, d). This weakness of dry-mist spraying under strong winds is also supported by the comparison between Figs. 3 and 6. To use dry-mist spraying as an effective heat stress mitigation measure, some kind of device is needed, such as spraying the mist from the side, so that the mist can reach the vicinity of the pedestrians.

This study quantitatively evaluated and compared the heat stress mitigation effects of street trees, dry-mist spraying, and a UV parasol, based on the observation on a single day. Here, we discuss the results shown in the present study from the perspective of universality. We compare our results of mitigation effects with the previous studies in each countermeasure. The mitigation effects of UV parasols and dry-mist spraying found in the present study were comparable to those of the earlier studies. For example, Watanabe and Ishii (2017, 2020) reported that the use of UV parasols can reduce WBGT by 0.9–1.8°C and UTCI by 1.8–3.7°C on sunny summery days, depending on the material and color of the UV parasol. The dry-mist spraying can reduce WBGT by 0.4°C (Kodama et al. 2004) and UTCI by 2.2°C (Oh et al. 2020). On the other hand, Nonomura and Masuda (2009) and Watanabe and Sugiyama (2020) reported that the street trees can reduce WBGT by 2.7°C and UTCI by 7.9°C on sunny summery days. Although the trees mitigated slightly less heat stress in the present study than earlier studies due to smaller trees, there was no essential difference between the two. Therefore, we conclude that the respective heat mitigation effects obtained in this study were representative of those observed on the hot summer days in Japan. Further studies are necessary to compare and evaluate heat stress mitigation effects in the same thermal conditions to make the present conclusions more robust.

5. Conclusions

We evaluated the heat stress mitigation effect of a UV parasol by comparing it with that of street trees and dry-mist spraying. We observed UTCI and WBGT under a UV parasol, street trees, dry-mist spraying, and direct sunlight on a hot and humid summer day in Japan.

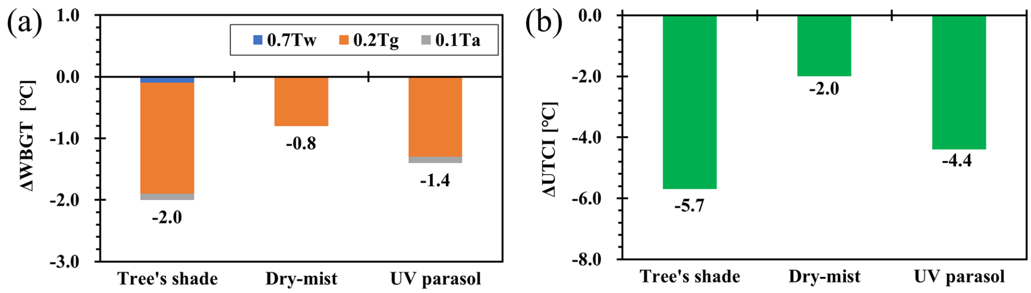

Fig. 6. Impacts of the three countermeasures on heat stress. (a) Same as Fig. 3b, but for using the observations when the wind speed is less than 1 m s^{-1}. (b) Same as Fig. 3d, but for using the observations when the wind speed is less than 1 m s^{-1}.

Street trees were the best of all the countermeasures conducted in the present experiment and decreased the UTCI and WBGT by 5.9°C and 1.9°C, respectively, as compared with that in direct sunlight. This decrease resulted in a reduction in the heatstroke risk by one level.

UV parasol also decreased heatstroke risk by one level. The thermal mitigation effect of the UV parasol was equivalent to 75 % of that of street trees from the perspective of UTCI. The UV parasol was able to decrease the UTCI by 4.4°C and WBGT by 1.3°C, which was due to the reduction in the black-globe temperature. Under the UV parasol, the reduction in downward shortwave radiation was much higher than the increase in downward longwave radiation due to the increase in surface temperature of the UV parasol. When choosing a parasol, it is necessary to focus not only on the transmission rate but also on resistance to warming.

On the other hand, the thermal mitigation effect of dry-mist spraying was smaller than that of the UV parasol. Dry-mist spraying barely mitigated heat stress in a condition with moderate wind ($\geq$ 2 m s^{-1}), whereas it reduced the UTCI and WBGT by 2.0°C and 0.8°C, respectively, with weak winds (< 1 m s^{-1}). This was because stronger winds blew the dry mist, causing less cooling around the meteorological measurement equipment.

There is a need to conduct experiments accompanied by researchers from different fields, including meteorology, physiology, and building engineering to gain a deeper understanding of heat stress countermeasures and the robustness of the results of the present study. Such a project would enable us to conduct experiments to simultaneously assess the effects of many countermeasures under the same weather conditions.

Data Availability Statement

A part of the analyzed datasets is available in J-STAGE Data. https://doi.org/10.34474/data.jmsj.19556413. The other part of the datasets is available at http://doi.org/10.24575/0001.198108.

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