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RESEARCH ARTICLE

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Wisteria trellises and tents as tools for improved thermal comfort and heat stress mitigation: Meteorological, physiological, and psychological analyses considering the relaxation effect of greenery

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Abstract

In this study, wet-bulb globe temperature (WBGT) was measured under wisteria trellises, under tents, and in direct sunlight. In addition, a subject experiment was conducted to consider the relaxation effect of the greenery. In terms of WBGT, the risk of heatstroke under the wisteria trellis was one level lower than that in direct sunlight. The mitigation effect of the wisteria trellis was greater than that of the tent. The difference in WBGT beneath the wisteria trellis and under the tent was primarily due to varied black-globe temperature (i.e., the difference in radiation environment). The wisteria trellis blocked most of the solar radiation, and its effect on the small aggregation of leaves reduced the increase in the leaf surface temperature and downward longwave radiation. The tent material allowed more solar radiation and increased the temperature of the tent surface. The questionnaire responses revealed that the subjects felt cooler and more comfortable under the wisteria trellis than under the tent, with or without a blindfold.

KEYWORDS

heat stress mitigation, thermal comfort improvement, urban heat island mitigation, urban trees, wet-bulb globe temperature, wisteria trellises

1 | INTRODUCTION

In recent years, Japan has seen a rise in extremely hot days due to global warming and the urban heat island (UHI) effect. Heatstroke is strongly related to air temperature (e.g., Fujibe et al., 2018; Ikeda & Kusaka, 2021). Countermeasures against urban warming are becoming increasingly necessary. Various outdoor UHI and heat stress related countermeasures have been proposed and evaluated. UHI mitigation measures include installing green roofs (e.g., Razzaghmanesh et al., 2016; Smith & Roebber, 2011; Takebayashi & Moriyama, 2007; N. H. Wong et al., 2003), installing cool roofs (e.g., Akbari & Kolokotsa, 2016; Razzaghmanesh et al., 2016; Sharma et al., 2016; Synnefa et al., 2006; Tewari et al., 2019), use of cool pavements (Erell et al., 2014; Qin, 2015; Santamouris et al., 2012; Synnefa et al., 2011), improving the ventilation function of cities (e.g., Tan et al., 2016; M. S. Wong et al., 2010), and urban irrigation (e.g., Broadbent et al., 2018; Wang et al., 2019). Outdoor thermal comfort improvement and heat stress mitigation measures include planting trees along streets (e.g., Armson et al., 2012; Coutts et al., 2016; Manickathan et al., 2018; Rahman et al., 2018), installing artificial shading devices (e.g., Elgheznawy & Eltarabily, 2021; Kántor et al., 2018; Sakai et al., 2012; Vanos et al., 2017), and spraying dry mist (e.g., Huang et al., 2017; Montazeri et al., 2015, 2017; Ulpiani et al., 2019; N. H. Wong & Chong, 2010). Corrective actions against heat stress in outdoor areas have focused on street canyons in urban districts in Japan. However, the importance of parks as a countermeasure and places for people to relax in the Tokyo metropolitan area is increasingly gaining attention.

Planting trees in parks is a heat island countermeasure and an effective method to improve outdoor thermal comfort and mitigate heat stress for people by providing shade. This effect has been confirmed in numerous studies that examined the influence of trees planted along streets. Armson et al. (2012) observed black-globe temperatures in direct sunlight and shade of street trees during summer days and found that trees reduced the black-globe temperature by approximately 10°C compared with that from direct sunlight. Coutts et al. (2016) found that street trees were very effective at reducing the daytime Universal Thermal Climate Index (UTCI) in summer, largely through reduced mean radiant temperature from shade. The thermal stress was lowered from very strong (UTCI >38°C) to strong (UTCI >32°C). Lin et al. (2013) observed that the shade of trees preferred by people on hot days. Artificial shading devices are also reportedly effective in reducing heat stress. Sakai et al. (2012) and Misaka et al. (2017) reported that artificial tree-canopy-like objects employing a fractal structure called Sierpinski gasket ('fractal sunshades') are very successful as heat stress countermeasures. Vanos et al. (2017) described that shade sails reduced solar radiation exposure in children and increased their thermal comfort in a playground.

These collective results indicate that installed trees and artificial shading devices are effective improved thermal comfort measures for people who relax outdoors. However, some issues remain to be addressed. If the park is intended as a place of relaxation, trees have the disadvantage of not being able to provide stable and large shade during lunchtime when users are the most and the temperature is the highest. It is also difficult to set up desks and chairs in the shade of trees. In contrast, artificial shading devices and vine trellises (Figure 1) can shield the top surface from solar radiation, overcome the aforementioned disadvantages, and mitigate the uncomfortable thermal environment and heat stress. However, few studies have examined vine trellises and tents. To the best of our knowledge, no study has directly compared the heat-mitigating effect or the sense of warmth and comfort between vines and tents, and no studies have examined the heat-relieving effect and enhanced sense of coolness and comfort by shade of trees in an experiment that removes the bias of the false sense of comfort and coolness caused by viewing plants (i.e., when vision is blocked).

FIGURE 1 Wisteria trellises. Upper panel indicates the wisteria in spring and lower panel indicates the wisteria in summer. The upper photo was provided by Nishi-ku, Yokohama City. (https://www.city.yokohama.lg.jp/nishi/kurashi/machizukuri_kankyo/jimusho/oshirase/fujinohana0622.html)

In this study, the wet-bulb globe temperature (WBGT) was observed under a wisteria trellis, under a tent, and in direct sunlight. As well, subjects were queried concerning their thermal comfort in the experiment without the relaxation effect provided by the visual perception of greenery. We aimed to clarify the difference in effectiveness of the wisteria trellis and tent as a heat stress mitigation effect in terms of both thermal environment and psychological and physiological effects.

Of the available vines that could be compared with the tent, wisteria was selected because it is a representative plant native to Japan that has been incorporated into dwellings since ancient times. Wisteria also has the advantages of being able to grow anywhere by entangling itself with other trees. In addition, its beauty and fragrant scent are calming (Figure 1). The experimental results obtained in this study are expected to contribute to heat stress mitigation in urban areas and to climate change adaptations.

2 | METHODS

2.1 | Meteorological measurement

To understand the thermal environment under the wisteria trellis, within a tent, and in direct sunlight, we observed air temperature, relative humidity, wind direction and speed, and black-globe temperature 1.5 m above the ground at these three locations using model WS600 and WS601 devices (EKO Instruments). In addition, the four components of radiation were measured under a tent and a wisteria trellis using a model NR01 device (Hukse Flux) and a model MR60 device (EKO Instruments). Downward shortwave radiation was observed in direct sunlight using a model Seiko MS800 device (EKO Instruments), and the corresponding data in direct sunlight were provided by the Centre for Research in Isotopes and Environmental Dynamics at the University of Tsukuba. The surface temperatures of the tent and wisteria trellis were also measured using a model R300SR-S thermal camera (Nippon Avionics). WBGT was calculated using the wet-bulb temperature, dry-bulb temperature, and (black) globe temperature, as shown in Equation (1) (Yaglou & Minard, 1957):

$$\mathrm{WBGT} = 0.1 * T + 0.2 * T_{\mathrm{g}} + 0.7 * T_{\mathrm{w}}, \tag{1}$$

where T, T_{g}, and T_{w} are the dry-bulb, black-globe, and wet-bulb temperatures, respectively. WBGT is a measure of heat stress in the ISO 7243 protocol. The Japan Meteorological Agency, Ministry of Environment, Japanese Society of Biometeorology, and many organizations and researchers have used the WBGT as an index of heatstroke risk in Japan (Table 1).

TABLE 1 Criteria of wet-bulb globe temperature (WBGT) for heatstroke risk level in Japan (Ministry of the Environment, 2021)

Criteria	Heatstroke risk level
WBGT ≥ 31°C	Danger
28°C ≤ WBGT < 31°C	Severe warning
25°C ≤ WBGT < 28°C	Warning
21°C ≤ WBGT < 25°C	Caution
WBGT < 21°C	Almost safe

2.2 | Subjective experiments

2.2.1 | Locations and date

To clarify differences in the effectiveness of the wisteria trellises and tents in heat stress mitigation based on weather and psychological/physiological factors, we conducted a subject experiment where weather observations, physiological measurements, and psychological questionnaires on the sense of warmth and comfort were conducted under the wisteria trellises, tents, and in direct sunlight (Figures 2 and 3). An unblinded and blindfolded eye mask subject experiment was performed to examine the relaxation effect provided by visualizing greenery.

The study was performed at a wisteria trellis located in the University of Tsukuba, Tsukuba City, Ibaraki Prefecture, Japan, which has a humid subtropical climate zone. A tent space was set up located approximately 10 m south of the trellis. Moreover, an area further south of the tents, which were directly exposed to sunlight, was selected. Two tents (300 cm wide × 300 cm deep × 173 cm high) were located side-by-side with no gaps between them. The ground at each site was covered with a weeding sheet 2 m long and 5 m wide to unify the ground surface conditions. A meeting room in the air-conditioned building of the Centre for Computational Science was used as the waiting area for the subjects. The distance between the waiting area and the wisteria trellis was approximately 190 m.

The subject experiments were conducted from 10:10 to 14:10 on August 2–7, 21–25, and September 5, 9, and 10, 2017. In the heatstroke prevention guidelines developed by the Japanese Society of Biometeorology, a condition with a WBGT ≥28°C is defined as a severe warning level with regard to heatstroke risk levels (Table 1), which Japanese Ministry of Environment uses as well. During the observation period, the WBGT always exceeded 28°C on August 6, 7, and 23–25, 2017. Only data from these 5 days were used in subsequent analyses.

2.2.2 | Experimental protocol

The experiments in which subjects were not blindfolded were conducted on August 6 and 24. The experiments with blindfolded subjects were conducted on August 7, 23, and 25. The groups without blindfolds comprised 15 healthy students (nine males and six females) approximately 20 years old. The blindfolded group comprised 23 healthy students (14 males and 9 females). The clothing of the subjects at the time of the experiment was as uniform as possible, with a white short-sleeve shirt or top, and short pants or skirt (Figure 3).

FIGURE 2 Scenes of locations (a) under the wisteria trellis, (b) under the tent, and (c) in direct sunlight

FIGURE 3 Scenes of subject experiments with the blindfold (a) under the wisteria trellis, (b) under the tent, and (c) in direct sunlight

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All participants experienced all three locations (in the shade under the wisteria trellis, in the shade under the tent, and in direct sunlight) once. The participants were divided into six groups (A1, B1, C1, A2, B2, and C2). On some days, five groups were used because of the convenience of the participants (Table 2).

On the day of the experiment, each participant was assigned to one of six groups (A1, B1, C1, A2, B2, and C2). After the start of the experiment, led by an experimental supporter, group A1 subjects moved to a location under the wisteria trellis, group B1 to a location under a tent, and group C1 to a location directly in sunlight. At each location, subjects sat on chairs for 20 min, and subsequently, physiological measurements were recorded with a completed questionnaire survey. At that time, the subjects moved to the air-conditioned indoor waiting area and waited for at least 30 min to dissipate the effects of the outdoor stay. After the first three groups (A1, B1, and C1) completed the experiment, the participants of the remaining three groups (A2, B2, and C2) were included in the next experiment, with a similar group assignment to the locations, followed by the measurements and questionnaire. After groups A2, B2, and C2 had completed the experiment, the A1, B1, and C1 groups became the subjects for the third experiment. The subjects were switched around like this, and the experiment was repeated until all subjects experienced all three locations.

2.2.3 | Test and data analyses

The questionnaire survey was completed to elicit subjects' feelings of heat and comfort. The subjects rated their perceptions of heat and coolness on the commonly used seven-point ASHRAE scale as follows: cold = −3, cool = −2, slightly cool = −1, neutral = 0, slightly warm = +1, warm = +2, and hot = +3 (Gagge et al., 1967). They also rated their comfort and discomfort on a four-point scale as follows: uncomfortable = −2, slightly uncomfortable −1, slightly comfortable = +1, and comfortable = +2. Subjects wearing blindfolds were asked questions verbally by the experiment support person, who filled in the responses.

Physiological measurements were also taken at the beginning and end of the stay at each outdoor location. The temperature of the tympanic membrane was measured thrice on the left and right sides using a model MC-510 ear thermometer (Omron Healthcare). The measurement was based on the assumption that the temperature of the tympanic membrane can be regarded as the deep-body temperature. Changes in maximum blood pressure, minimum blood pressure, and pulse rate due to indoor-to-outdoor movement were also measured using a model HEM-6022 device (Omron Healthcare Co., Ltd.).

The experiment was conducted with the permission of the Ethics Committee of the Graduate School of Life and Environmental Sciences, University of Tsukuba.

Meteorological observations were used to calculate 20 min averaged WBGT and to evaluate variations in the WBGT between the locations under the wisteria trellises and those under the tents, and between the locations under the wisteria trellis and those directly in sunlight. Statistical significance was assessed using Welch's *t*-test. To avoid the problem of multiplicity of tests, the *t*-test was followed by multiple comparisons using the Bonferroni method. The sample size of WBGT under the wisteria trellis, under the tents, and in direct sunlight was 27, 30, and 27, respectively. The sample sizes under the wisteria trellis and in direct sunlight were reduced to 27 because, in some cases, some meteorological elements could not be measured.

We also used data from the thermal sensation questionnaire survey and evaluated the differences in thermal

TABLE 2 Subjects of every group

	A1	B1	C1	A2	B2	C2
August 6	Male	Male	Male	Male	Male	–
	Male	Female	Female	–	–	–
August 7	Male	Male	Male	Male	–	Male
	Female	Female	Female	–	–	Female
August 23	Male	Female	Female	Male	Male	Female
	Female	–	–	–	–	–
August 24	Female	Male	Male	Female	Male	Female
	–	Female	–	–	–	–
August 25	Male	Male	Male	Male	Male	Male
	–	Female	–	–	–	–

Note: Experiments in which subjects were not blindfolded were conducted on 6 and 24 August, and those with blindfolded subjects were conducted on 7, 23, and 25 August.

comfort between the three locations. Data obtained from physiological measurements were used to compare the physiological factors between the three locations. The statistical significance of the differences between the three locations was assessed using Friedman's test because the same subjects experienced three different locations. Additionally, a combination of the Wilcoxon signed-rank test and the Bonferroni method was used to evaluate the usefulness of the wisteria trellis.

Finally, the Brunner–Munzel test was used to examine the effect of the presence or absence of blindfold on the psychological and physiological factors of subjects with 23 participants.

3 | RESULTS

3.1 | Thermal environment in direct sunlight, under the wisteria trellis, and under the tents

Figure 4 shows temporal changes in WBGT, dry-bulb temperature (air temperature), wet-bulb temperature, and black-globe temperature in direct sunlight, under the tents, and under the trellis during the severe heatstroke warning days. The mean value of the WBGT under the wisteria trellis of 28.3°C was 1.1°C lower than the value under the tents and 2.1°C lower than the value in direct sunlight (Figure 5). According to the *t*-test, these deviations were significant at the 1% level. WBGT under the wisteria trellis exceeded 28 and 31°C for 6.3 and 0.0 h, respectively, which corresponded to 90% and 0% of those in direct sunlight, and 63% and 0% of those under the tents. These results indicated that the heat stress under the wisteria trellis was lower than that under the tents and in direct sunlight.

We examined the time-averaged values of black-globe, dry-bulb, and wet-bulb temperatures to understand the lower WBGT under the trellis. The black-globe temperature values under wisteria trellis were significantly lower than those in direct sunlight and under the tent (10.2 and 4.6°C, respectively). The dry-bulb and wet-bulb temperatures under the wisteria shelves did not differ as much between sites as black-globe temperatures. The contribution rate of the reduction in black-globe, dry-bulb, and wet-bulb temperatures to the WBGT reduction effect of the wisteria trellis were 98%, 3%, and −1%, respectively, after considering their respective weight factors of the three terms in Equation (1). Namely, the contribution of black-bulb temperature reduction under the wisteria trellis was 10.2°C times 0.2 (= 2.0°C), accounting for 98% of the total.

3.2 | Differences in radiation environment between locations

The mean values of the downward shortwave radiation in direct sunlight, under the tents, and under the wisteria trellis during the heatstroke severe warning days were 521, 186, and 79 W/m^2, respectively (Figure 6). The respective mean values of downward longwave radiation were 470, 537, and 506 W/m^2. These results indicate that the wisteria trellis blocked approximately 85% of the downward shortwave radiation and approximately −8% of the downward longwave radiation. Compared with the tent, wisteria trellis reduced the shortwave radiation by approximately 58% and the downward longwave radiation by approximately 6% (Figure 6).

Figure 7 shows the breakdown of the net radiation under the tent and under the wisteria trellis at the time of the experiment (10:20–10:40 on August 23, 2017) when the solar radiation was sufficient and the WBGT level was the most dangerous (hazardous level). For both components, the input radiation into the black-globe under the wisteria trellis was lower than that under the tent. The largest difference was observed in the downward shortwave radiation. The visible image in Figure 8 shows that the tents did not completely block the solar radiation and appeared to transmit a considerable portion of the radiation. In contrast, the wisteria trellis only allowed a small amount of sunlight to pass through and did not transmit most of the solar radiation.

Among the four components of radiation, the second largest difference was downward longwave radiation. The difference in downward longwave radiation between the area under the wisteria trellis and the area under the tents was 60 W/m2, which is equivalent to approximately 39% of the difference in downward shortwave radiation. This implies that the wisteria trellis can mitigate heat stress by lowering infrared radiation as well as solar radiation. The difference in the amount of downward longwave radiation under the wisteria trellis and under the tents can be attributed to the difference in surface temperature between the two locations.

3.3 | Results of subjective experiment

The psychological and physiological factors of the subjects were investigated when the WBGT exceeded 28°C. For the blindfolded subjects, the feelings of warmth and comfort differed greatly among the three locations. In response to the question about the sense of warmth and coolness, most subjects answered 'hot (+3)' (57%) and 'warm (+2)' (26%) in direct sunlight, 'hot (+3)' (39%)

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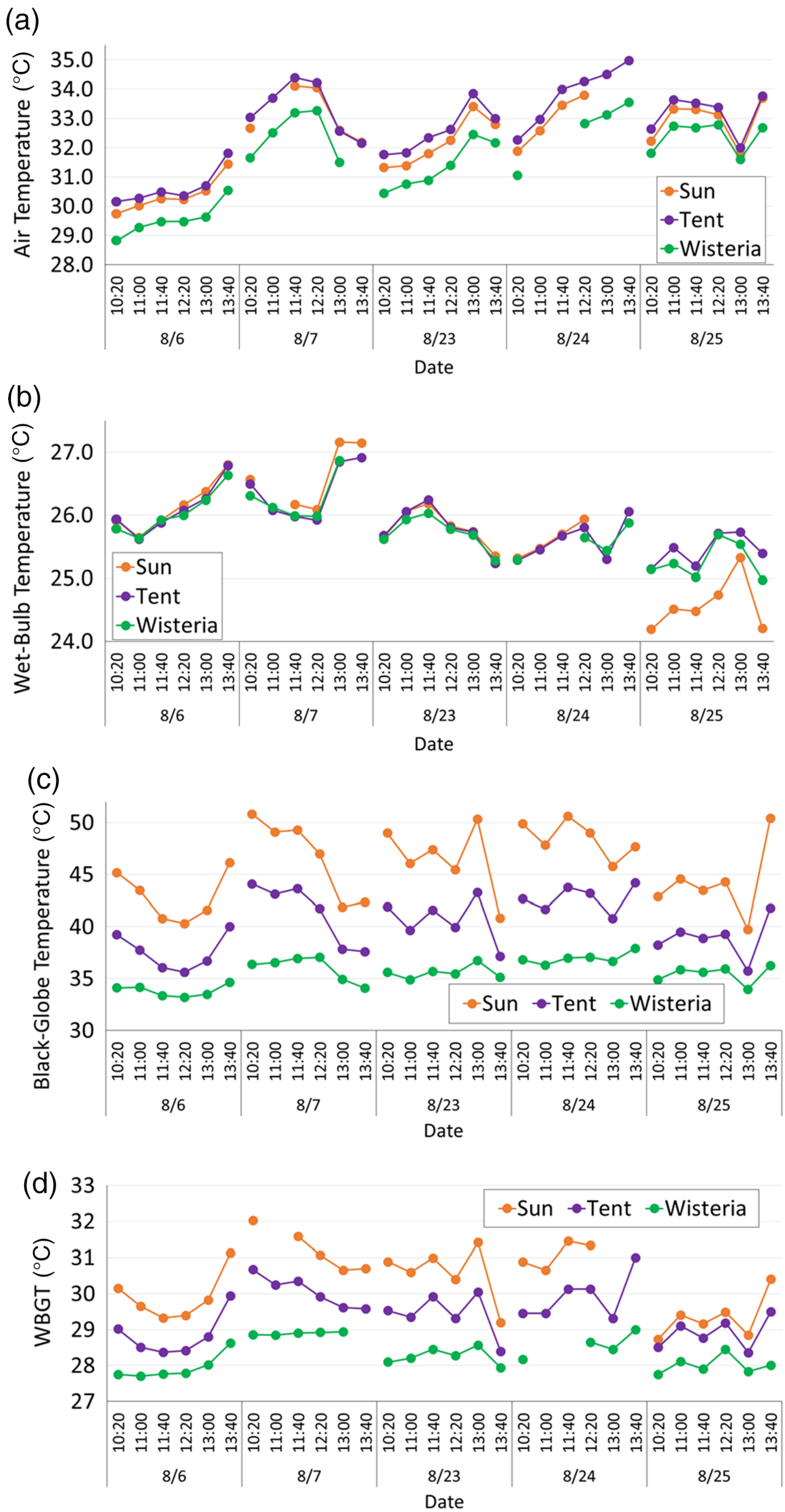

FIGURE 4 Mean (a) air temperature, (b) wet-bulb temperature, (c) black-globe temperature, and (d) WBGT during 20-min outdoor sitting on experiment days when WBGT in direct sunlight exceeded 28°C. Colours indicate the environment of measurements

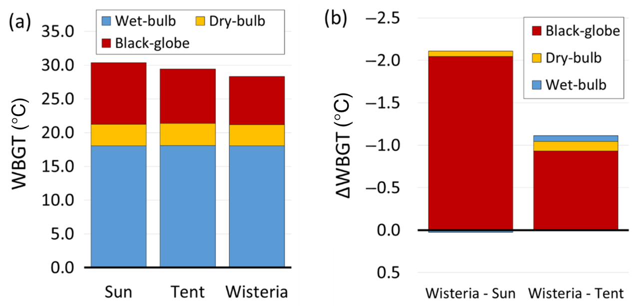

FIGURE 5 (a) Mean contribution of black-globe temperature (red), dry-bulb temperature (yellow), and wet-bulb temperature (blue) to wet-bulb globe temperature (WBGT) during the time when WBGT exceeded 28°C. These are the average of the data observed at 10:20–10:40, 11:00–11:20, 11:40–12:00, 12:20–12:40, 13:00–13:20 and 13:40–14:00 JST on August 6, 7, 23, 24 and 25, 2017. Each value was calculated from Equation (1).
(b) Differences in the mean contribution of black-globe temperature (red), dry-bulb temperature (yellow), and wet-bulb temperature (blue) to WBGT between under the wisteria trellis and in direct sunlight, and between under the wisteria trellis and tent

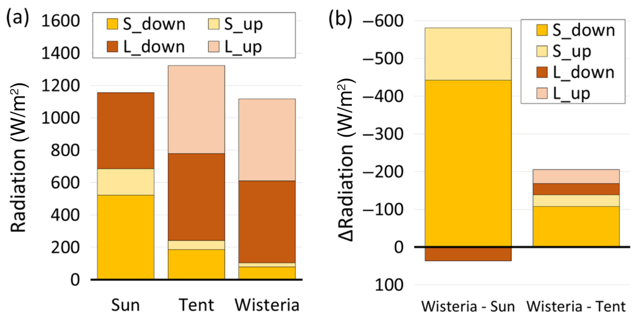

FIGURE 6 Mean (a) downward shortwave (yellow), upward shortwave (light yellow), downward longwave (brown), and upward longwave (light brown) radiation during the time when wet-bulb globe temperature exceeded 28°C. These are the average of the data observed at 10:20–10:40, 11:00–11:20, 11:40–12:00, 12:20–12:40, 13:00–13:20, and 13:40–14:00 JST on 6, 7, 23, 24, and 25 August 2017. The mean upward shortwave radiation in direct sunlight was calculated from the mean downward shortwave radiation and the albedo there. The albedo was the mean value of the albedo under the wisteria trellis and the tent. The upward longwave radiation was not measured in direct sunlight.
(b) Differences in the mean radiations between under the wisteria trellis and in direct sunlight, and between under the wisteria trellis and tent

and ‘slightly warm (+1)’ (26%) under the tent, and ‘warm (+2)’ (26%), ‘slightly warm (+1)’ (22%) and ‘slightly cool (−1)’ (22%) under the wisteria trellis (Figure 9). In addition, 96% of the subjects in direct sunlight and 83% of the subjects under the tent answered on

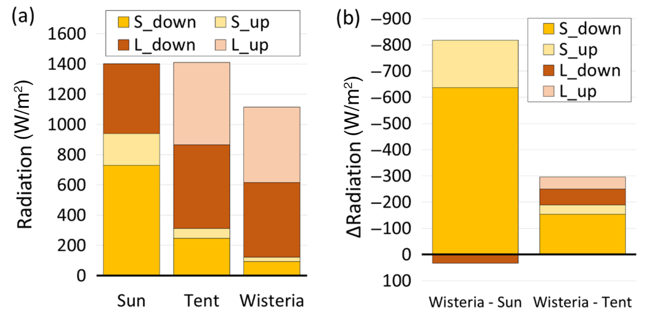

FIGURE 7 As same as Figure 6 but for the average of the data observed at 10:20–10:40 JST on 23 August 2017. The upward longwave radiation was not measured in direct sunlight

the warm side. In contrast, only 52% of the subjects located under the trellis perceived the environment as warm.

Regarding the question about the sense of comfort, more subjects felt that the wisteria trellis provided comfortable environment compared with the other two sites (Figure 10). Only 4% of the respondents located in direct sunlight were comfortable or slightly comfortable. Only 31% of the respondents under the tents were comfortable or slightly comfortable. In marked contrast, 83% of subjects under the trellis felt comfortable. The difference between the locations under the wisteria trellis and under the tents was significant at a significance level of 1% for both warmth and comfort, and was significant at a significance level of 1% between under the wisteria trellis and in direct sunlight.

The pulse rate change between under the wisteria trellis and direct sunlight were significantly differed at a significance level of 5% (Figure 11). Specifically, the median values of pulse changes in direct sunlight, under the tents, and under the wisteria trellis were +1.0, −1.0, and −6.0, respectively. There is a natural variation in pulse rate, whose values generally range from 2 to 4 beats per minute (e.g., Kobayashi et al., 2009). Deep-body temperature and blood pressure did not significantly vary between the locations.

The results of the subject experiment without the blindfold were fundamentally the same as those of the subject experiment with a blindfold. There was no statistically significant difference between the two experiments ($p > 0.1$). For instance, the mean value of the difference in the results of the comfort sensation survey was <1.0 between the two experiments with and without blindfolds for all three locations. The same results were obtained for heat and cold sensations as comfort sensations. There was also no statistically significant difference between the results of the physiological measurements for subjects with and without blindfolds.

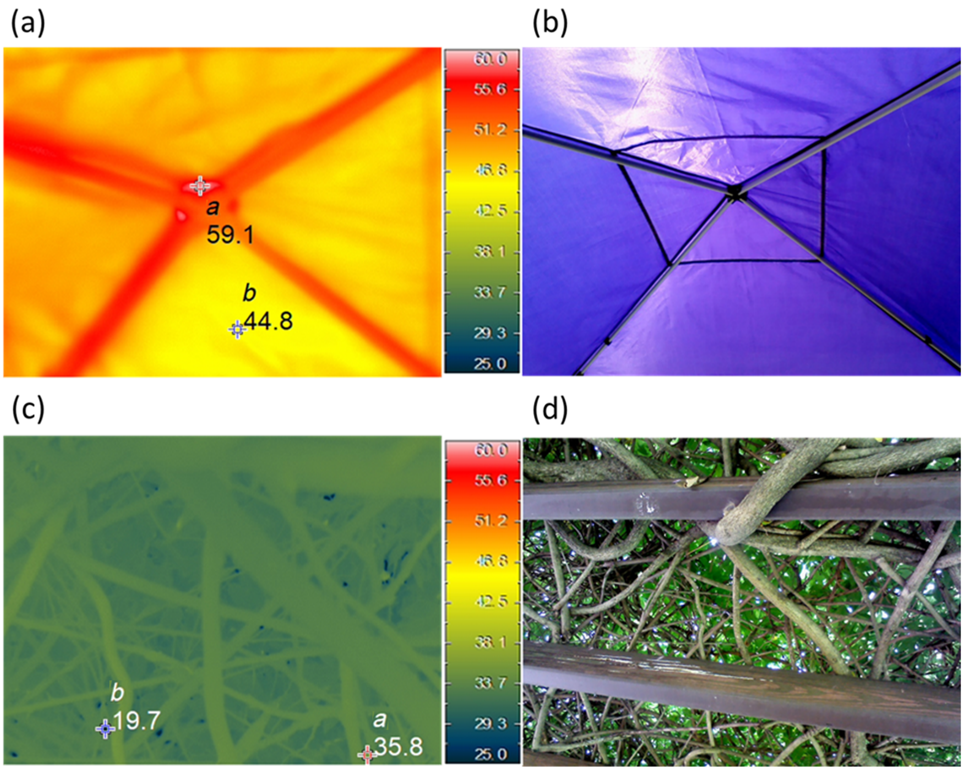

FIGURE 8 Infrared (left) and visible (right) images of the underside of the tent (upper) and wisteria trellis (lower). These images were taken at 10:20 on August 23, 2017. The colours and the values on the infrared images indicate the surface temperature. Point '*a* (*b*)' on the infrared images show the maximum (minimum) surface temperature (°C)

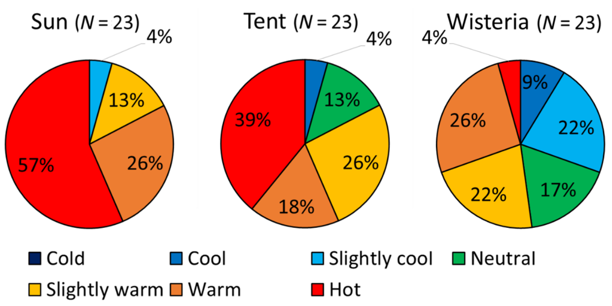

FIGURE 9 Pie charts of questionnaire surveys with the blindfold on warmth when wet-bulb globe temperature exceeded 28°C. Colour indicates subjects' feelings of heat. *N* is the number of subjects

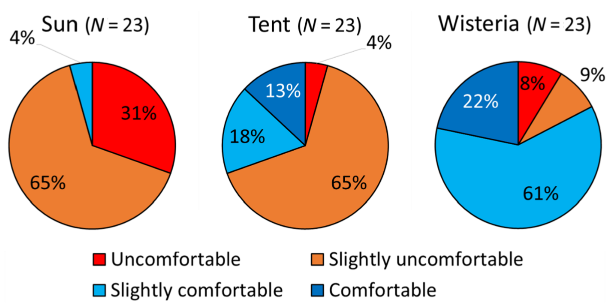

FIGURE 10 Pie charts of questionnaire surveys with the blindfold on comfort when wet-bulb globe temperature exceeded 28°C. Colour indicates subjects' feelings of comfort. *N* is the number of subjects

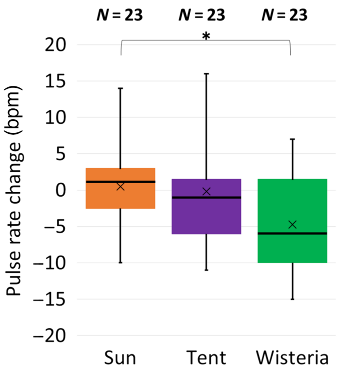

FIGURE 11 Box plots of pulse rate change after 20-min sitting in direct sunlight (orange), under the tent (purple), or under the wisteria trellis (green) when the wet-bulb globe temperature exceeded 28°C. These changes were measured with the blindfolded subjects. The upper (lower) edge of the whiskers, the upper (lower) edge of the boxes, the horizontal line, and the x-mark on the boxes indicate the maximum (minimum), third (first) quartile, the median, and the mean, respectively. * represents that the significance level of Wilcoxon signed-rank test in combination with Bonferroni method is less than 5%. *N* is the number of subjects

4 | DISCUSSION

On days of high heatstroke risk level, the WBGT under the wisteria trellis was on average approximately 1.1°C lower than that under the tents. The dominant factor in this was the difference in shortwave radiation transmission between the wisteria trellis and tent, followed by the difference in downward longwave radiation. Although the transmission into the tent depends on the tent's material, the solar radiation transmission rate may be higher than expected. In contrast, the leaf area index (LAI) of a wisteria trellis is well above 1, so its solar radiation transmission rate may be lower than that generally thought. The wisteria trellis is a thin vine comprised of small leaves, creating a tent-like roof. As pointed out by Sakai et al. (2012), small objects are difficult to warm up because of their short fetch. Therefore, the surface of the wisteria shelf was not as warm as that under the tent, and the amount of downward longwave radiation was not as large as that under the tent. The humidity under the wisteria trellis was 62%, which was 3% higher than that under the tent. However, as mentioned earlier, the WBGT under the wisteria was actually lower than that under the tent, indicating that the improved radiant environment had a much greater impact than this negative effect. Wisteria flowers are in full bloom during the spring. Leaves grow from spring to summer and are shed during winter. Therefore, unlike artificial shading devices, wisteria trellises are only effective in improving thermal comfort from spring to autumn. As the risk of heatstroke in Japan increases only in summer, the wisteria trellis will be an effective source of comfort.

The thermal environment under the tents was worse than that under the wisteria trellis but better than that in direct sunlight. The WBGT on heatstroke severe warning days was approximately 1°C lower under the tent than in direct sunlight, which was consistent with the findings of the Ministry of the Environment (2018).

The questionnaire survey revealed the benefit of the wisteria trellis in terms of coolness and increased comfort. The results did not depend on whether subjects were blindfolded or not. It was possible that the two visual effects were not detected in the experiments because the difference in thermal sensation depending on the location was much larger than the relaxation effect of being able to visualize greenery or the increased sensitivity to warmth and coolness due to the obstructed view. It is also possible that the two conflicting visual effects (relaxation effect and the increased sensitivity to warmth) cancelled each other out. According to Anai (2003), people with sensory difficulties, such as touch and hearing, are generally more sensitive to sensory organs other than sight. Further experiments are needed to determine visual effects in humans. With regard to the physiological factors, a significant difference in pulse data was observed between the wisteria trellis and the other two locations during the blindfold experiment. However, no significant difference was observed for the other factors at all locations, regardless of whether the subjects were blindfolded or not. This is thought to be because the subjects did not stay outdoors long enough to change the physiological factors in the subject experiment.

In Japan, various countermeasures against heat stress have been implemented, including the installation of trees, dry mist spraying, and the use of parasols. All previous studies and the present study compared the effects of two or three of the many heat stress countermeasures. If we can conduct experiments to evaluate the effects of many countermeasures at the same time under the same weather conditions, we can expect to gain deeper knowledge about heat stress countermeasures and strengthen the results of our research. To do so, it will be necessary to set up a large project where several teams from different fields such as meteorology, physiology, and building engineering can conduct experiments together.

5 | CONCLUSIONS

In this study, the WBGT was measured under a wisteria trellis, under tents, and in direct sunlight. Concurrently, examination of subjects accounted for the relaxation effect produced by viewing greenery. The experimental results clarified the difference in effectiveness between the wisteria trellis and the tents in heat stress mitigation for both weather conditions and psychological and physiological effects. The wisteria trellis mitigated the heat stress more effectively than the tents. Specifically, the WBGT under the wisteria trellis on a heat stroke severe warning day was 2.1°C lower than in direct sunlight (i.e., a one level reduction of WBGT) and 1.1°C lower than under the tents. These differences were significant at a significance level of 1%. The findings highlight that the efficacy of the wisteria trellis and the tents as heat stress mitigation measures was more different than commonly thought.

Variations in WBGT between under the wisteria trellis and under the tents, and between under the wisteria and in direct sunlight were primarily caused by the difference in black-globe temperature (i.e., the difference in radiation environment). The downward shortwave radiation under the wisteria trellis was 442 W/m^2 lower than that in direct sunlight (15% of that in direct sunlight) and 107 W/m^2 lower than that under the tent (42% of that under the tent). Downward longwave radiation under the wisteria trellis was 36 W/m^2 larger than that in direct sunlight (108% of that in direct sunlight) and 31 W/m^2 lower than that under the tent (94% of that under the tent). The wisteria trellis blocked most of the solar radiation and also reduced the downward longwave radiation due to the plants' own resistance to a temperature increase. In contrast, the tents blocked only part of the solar radiation and increased the temperature of the tent surface.

The results of the questionnaire survey indicated that wisteria trellis was cooler and more comfortable than the tent, regardless of whether the research participants were blindfolded or not. Only in the blindfolded experiment was there a significant difference in the pulse rate change between under the wisteria trellis and in direct sunlight. However, this value was comparable to the natural variation in the pulse. There were no significant differences in the blood pressure or deep-body temperature. This was probably due to the short duration of the experiment (20 min).

The experimental results indicate that wisteria trellises are more effective than tents in heat stress mitigation. Additionally, wisteria trellises are expected to contribute to adaptive measures to climate change. In Japanese schools, tents are often used to provide shade during sporting events. Wisteria trellis can provide a better thermal environment than a tent, has a nice view, is popular with children, and can be used for science learning. Because it has a multifaceted effect, it can be used in schools, parks, and other places.

AUTHOR CONTRIBUTIONS

Hiroyuki Kusaka: Conceptualization (equal); formal analysis (supporting); funding acquisition (lead); investigation (supporting); methodology (supporting); project administration (lead); resources (lead); supervision (lead); visualization (supporting); writing – original draft (lead); writing – review and editing (lead). **Yuki Asano:** Data curation (equal); formal analysis (lead); investigation (equal); methodology (supporting); validation (lead); visualization (equal); writing – original draft (supporting); writing – review and editing (supporting). **Ryuhei Kimura:** Conceptualization (equal); data curation (equal); formal analysis (supporting); investigation (equal); methodology (equal); validation (supporting); visualization (equal); writing – original draft (supporting).

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