The following publication Li, J., Niu, J., Huang, T., & Mak, C. M. (2022). Dynamic effects of frequent step changes in outdoor microclimate environments on thermal sensation and dissatisfaction of pedestrian during summer. Sustainable Cities and Society, 79, 103670 is available at https://doi.org/10.1016/j.scs.2022.103670.

Dynamic effects of frequent step changes in outdoor microclimate environments on thermal sensation and dissatisfaction of pedestrian during summer

Abstract

Humans engaging in outside activities are more likely to be exposed to frequent spatiotemporal step changes in outdoor thermal conditions, as opposed to constant thermal conditions staying indoors. Understanding pedestrians' thermal reactions to such dynamic thermal settings is helpful for enhancing outdoor thermal comfort by providing spatiotemporal variations in thermal conditions. In this study, 48 subjects were tested about their thermal perceptions while being exposed alternately to direct sunlight and shade at different defined frequencies, in a series of 45 minutes experiment period. The experiments were designed to create step changes in microclimate environments. The study was carried out from May to July in a university campus in Hong Kong with subtropical weather conditions. Results show that subjective thermal perceptions varied with alternating exposure to sunlight and shade at different frequencies. *UTCI* was modified to an equivalent *UTCI** for evaluating thermal environments with frequent step changes by taking into account impacts of mixed changes in sun and wind conditions, alternating frequency and expectation on thermal perceptions. With a higher alternating frequency, there was reduced thermal dissatisfaction with hot summer days and a lower comfort requirement for shade, as well as the upper limit of acceptable *UTCI** approaching 43.7°C.

Keywords: Dynamic outdoor thermal conditions; Sunlight and shade; Alternating exposure; Frequency; UTCI; Thermal dissatisfaction

1. Introduction

Most of early studies on the outdoor thermal comfort focused on thermal sensation and thermal comfort of people whose thermal state is assumed to be close to steady in an outdoor place. Thermal comfort models and indices developed in thermally homogenous and stable environments were usually applied to evaluate outdoor thermal sensation (Lai et al., 2020; Li et al., 2020). However, with the depth of studies, researchers found that the complex urban geometries and outdoor settings can produce fast spatiotemporal changes in microclimatic variables, particularly in wind flow and radiation (Ahmed-Ouameur et al., 2007; Chen et al., 2021; Inagaki et al., 2017; Kubaha et al., 2004; Nakayoshi et al., 2015). These changing variables make pedestrian's exposure time in a thermal condition in the range of minutes or even seconds, which are too short for people to reach a steady state (Lai et al., 2020).

Moreover, pedestrians are usually alternately exposed to cool-biased and warm-biased environments during outdoor activities, such as when being exposed to indoor and outdoor places cycles, moving through sunlight area and shade area on the street, and being stimulated by an intermittent breeze and water mist while staying in a relatively hot place. Step changes in microclimate environments occur in above alternate exposures to cool-biased and warm-biased environments, which are characterized with mixed changes mainly in radiation, wind speed and air temperature. Additionally, these step changes always happen at various frequency due to the movement speed, needs of activities and environmental designs. Essentially, people are in a highly dynamic and complex environment when conducting outdoor activities, which is speculated to produce thermal responses different from those in relatively steady environments. This study thus aims to explore a method to evaluate impacts of frequent step changes in microclimate environments which are encountered by pedestrians' activities.

Many previous studies have examined transient physio-psychological thermal responses in one or two temperature step changes. These studies were conducted either in an environment chamber with different temperature settings, for example the studies conducted by Gagge et al. (1967), De Dear et al. (1993), Xiong et al. (2015, 2016) and Ji et al. (2017), or between a building's interior and an outdoor place, for example the studies conducted by Nakano et al. (2006), Yu et al. (2015), Katavoutas et al. (2015) Lai et al. (2017), Chen et al. (2019), and Huang et al. (2020). The transient thermal responses and thermal adaptation after either upward or downward temperature step change were investigated in these studies. Due to the influences of temperature step change magnitude, change direction (upward or downward), exposure time and initial state of people, there would be either overshooting or hysteresis in transient thermal perceptions after a step change.

Following by the transient thermal perceptions, there was a thermal adaptation process. According to Hoppe et al. (2002), he found that for a person coming out of a shaded area of a side walk and entering a 200 m long sunny segment, after 180s his actual skin temperature was approaching to the simulated one by a steady-state thermal comfort model, and his core temperature was relatively lower than the simulated one. He furtherly suggested that around 30 minutes were required for a person to reach steady state after leaving a room in thermal comfort into hot conditions. According to the laboratory step change experiments, the time needed to stabilize the skin temperature varied with different step change directions and magnitudes of temperature step changes (Chen et al., 2011; Du et al., 2014; Liu et al., 2014). In general, 10 minutes were not sufficient for reaching steady states, and the downward step change required more time to reach steady than the upward step change (Huang et al., 2020). Researchers also found that subjective thermal sensations always change faster and tend to stabilize faster than physiological responses after step changes (Nagano et al., 2005; Tsutsumi et al., 2007; Wang, 1992;

Zhang et al., 2014). Due to the transient impacts of step changes in thermal environments and afterwards adaptation process, Yu et al. (Yu et al., 2015) suggested the transient impacts based temperature settings in temporal occupied places for energy saving.

In addition to aforementioned studies on one or two temperature step changes, Shimazaki et al. (2011) investigated the physio-psychological thermal responses under solar radiation step changes and found that there was no significant overshooting of thermal sensation after downward step change. He also indicated that the body thermal load could well predict the change in thermal sensation after the downward step change in solar radiation. Huang et al. (2020) investigated the thermal sensations under an upward step change from a shaded place to a sunlit place and found that a larger difference in thermal conditions between the two places resulted in a faster growth of thermal sensations after the upward step change. Rather than one or two step changes in thermal conditions, Vasilikou et al. (2020) and Lau et al. (2019) have noticed frequent changes in microclimate environments when walking in the urban areas. These frequent changes produced by the complex urban geometry have resulted in a diversity in pedestrians' thermal sensations. Lau et al. (2019) demonstrated that the thermal sensation was found associated with participants' 2-3 minutes thermal experience. In another word, the present thermal sensation was influenced by the previous one.

To simulate the thermal state of a person under a variety of temperature conditions, there are also several thermal comfort models (Katić et al., 2016). Universal Thermal Climate Index (*UTCI*) in temperature and dynamic thermal sensation (*DTS*) in sensation scale are well-known to predict thermal comfort under various steady or unsteady thermal conditions (Fiala et al., 2012; Fiala et al., 2003). They were developed based on predicted dynamic physiological variables by Fiala thermo-regulation model (Fiala, 1998). A non-linear relationship between *DTS* and *UTCI* was proposed by Bröde et al. (2012) based on plenty of simulation works. Because the *UTCI* was considered to be applicable in a wide climate conditions and easy to be calculated with only meteorological parameters, it is then widely used to evaluate outdoor thermal environments (Błażejczyk et al., 2010; Bröde, Krüger, et al., 2012; Shooshtarian et al., 2020; Zhang et al., 2020).

In addition to applying *UTCI*, many studies rose to improve the prediction of dynamic outdoor thermal comfort in other perspectives. Lai et al. (2017) developed a dynamic thermal comfort model using the thermal load and change of the skin temperature in unsteady outdoor environments. Recently, Zhou et al. (2019) updated the Lai's dynamic model by taking into account the change of thermal load induced by rapid shift in sun radiation. Yu et al. (2020) adapted the convective heat transfer coefficients to dynamic outdoor environments application by considering the important impacts of wind turbulence on human body heat transfer process and thermal comfort. Up to now, many efforts have been made to supplement the understanding of dynamic outdoor thermal comfort and improve the evaluation or prediction methods.

Despite the gradually rising studies on dynamic outdoor thermal comfort, there are few studies investigating pedestrians' thermal comfort under frequent step changes in microclimate environments. As aforementioned, the frequent step changes are common in outdoor activities, and are characterized with mixed changes in wind speed, solar radiation and air temperature. However, we have a limited knowledge about their influences on our outdoor thermal comfort. Perkins et al. (2016) found that the visitors in the zoo concentrated in the places with a highly dynamic thermal environments. Yu et al. (2020) indicated that the high wind turbulent intensity can bring cooling perceptions to people. It is speculated that the dynamic thermal environments are welcomed by people, especially on hot days.

Moreover, Höppe et al. (2002) demonstrated that over 180s was required for mean skin temperature to achieve steady after a person entering hot conditions from the shaded area. It is possible that on hot days, a sequential downward step change in microclimate environment appears within the time required to achieve steady state might assist in relieving the heat stress. But it's uncertain whether an upward step change a few moments following a downward one can make us hotter or less hot. Whether the impacts of frequent downward changes interact with those of frequent upward changes is unknown, as well as the psychological effects induced in the frequent step changes. Therefore, the physio-psychological thermal responses induced by frequent step changes are supposed to be different from those in one or two step changes. The frequency of step changes which can be achieved by alternating exposure to cool-biased and warm-biased thermal conditions is important.

Moreover, although the dynamic factors were considered by default in the *UTCI* derivation (Bröde et al, 2012), it is confused that if *UTCI* could accurately characterize the transient and long-term effects of frequent microclimatic changes on thermal responses. According to Bröde, the relationship between *UTCI* and *DTS* was observed by relating the average *DTS* in 2 hours model simulations to *UTCI* values. *UTCI* appears to represent an average dynamic thermal responses, and the actual relationship between dynamic factors and *UTCI* was unclear. Besides, the *UTCI* was derived based on predicted dynamic physiological responses of a person with 2.3 Met in Fiala model.

As the result, it is speculated that current *UTCI* might be insufficient to intuitively evaluate frequent microclimatic changes that influence the thermal comfort of people with relatively low metabolic rate. Furthermore, the mixed changes in wind and sun conditions are the important components in the steps changes in microclimate environments, whereas *UTCI* was found less sensitive to wind and sun conditions than surveyed thermal perceptions (Li et al., 2020).

Accordingly, there is a lack of tools to exam the impacts of frequent step changes characterized with mixed changes in wind speed, solar radiation and air temperature on thermal comfort, leading to limited suggestions on enabling or regulating welcomed dynamic thermal environments by natural or artificial designs.

To address the aforementioned challenges, this study aims to explore how the microclimatic step changes at different frequencies influence thermal comfort on hot summer days and how to predict these influences. On the one hand, the study is expected to update the method of evaluating dynamic thermal comfort by quantifying the dynamic thermal environments as frequent step changes in overall microclimate environments and treating the frequency as the factor. It is intended to serve as a reference for the future study into refining the frequent step changes for evaluating dynamic thermal comfort in terms of the mixed changes in solar radiation, wind speed and air temperature. On the other hand, the study aims to make up the limitations of *UTCI* in estimating impacts of sun and wind conditions, as well as their changes, on thermal comfort and adapt it to evaluate overall thermal comfort influenced by frequent microclimatic step changes.

Furthermore, the study is expected to find the satisfied thermal environments with frequent step changes on summer days. It is to suggest the appropriate distribution of cool spots or artificial cooling instruments to enable the frequent spatiotemporal step changes for cooling on hot summer days. Generally, the study attempts to propose a tool to evaluate and create dynamic microclimate environments in a quantitative and accessible way for outdoor thermal comfort.

2. Methodology

2.1 Experimental conditions

The experiments were conducted in outdoor space contained 4 adjacent places A, B, C and D on campus of a university in May, July and September, 2018 in Hong Kong (Fig. 1). Hong Kong is characterized with a hot-humid subtropical climate (Cwa) according to Köppen-Geiger climate classification. Thermal condition difference between sunlight exposure and shade in months from May to July is supposed to be large. The annual average daily maximum temperature between May and September (1998-2020) is 32.2℃, and the relative humidity is about 70%. The place A is an open area exposed directly to solar radiation during most time of a day, while place B is an area in the shade of a large tree. The place C is an underground beneath a lift-up building (UEB) which is characterized with weak solar radiation and strong wind velocity. Place D is a semi-open area beneath a glass canopy with sunlight pouring down through.

In this study, places B and C were collectively called shades, and places A and D were collectively called sunlight exposures. 48 healthy college students with 20 females and 28 males with even figures were recruited as subjects to participate in the experiments. The female subjects have an average height of 160.6±3.1 cm and an average weight of 49.5±5.3 kg, while the male students have an average height of 175.8±2.6 cm and an average weight of 63.2±3.6 kg. Subjects were asked to expose to sunlight and shade cycles formed by the four places. The procedure was shown in Table 1, and walking from shade to sunlight and from sunlight to shade will be termed as downward and upward step change respectively.

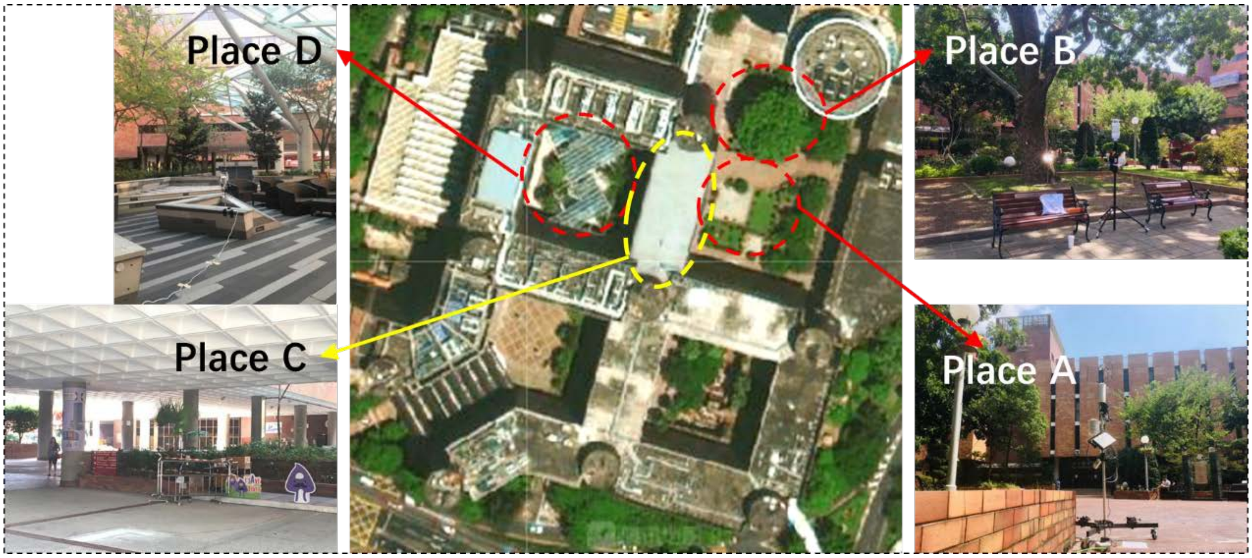

Fig. 1. Locations of selected measurement and survey places. (Place A: Open area; Place B: Tree shade; Place C: UEB; Place D: Semi-open area).

To simulate a person being alternately exposed to cool-biased and warm-biased environments during outdoor activities on hot days, subjects were required to alternate their exposures to sunlight and shade at a designed frequency within 45 minutes. The 45-minutes experiment time period was designed to study outdoor thermal perceptions in a relevant time scale of public space usage and daily outdoor activities of citizens (Cheung et al., 2018). Five frequencies were designed in this study, and it was to quantify and simplify the dynamic thermal environments as frequent step changes in microclimate environments encountered by pedestrians' alternating exposures to shade and sunlight.

The designed frequencies were based on the assumption in the introduction that a sequential downward step change appears within the time required to achieve steady state might assist in relieving the heat stress on hot days. To generate different alternating frequencies, the time exposure in the shade was set to be either longer or shorter than that in sunlight, or to be the same as that in sunlight, which was compatible with the real exposure duration when conducting outdoor activities. Accordingly, the experiment setup was intended to offer quantification and simplification approaches for analyzing dynamic thermal conditions.

Table 1 shows the procedure of subjects' alternating exposures to sunlight and shade during experiments. To form five alternating frequencies, five experiment types characterized with different exposure time in sunlight and shade were designed. In the study, three different combinations of four places were used to create shade and sunshine: combination 1: place D (sunlight) & place C (shade), combination 2: place A (sunlight) & place B (shade), and combination 3: place A (sunlight) & place C (shade). One sequential exposure from sunlight to shade was defined as one sunlight and shade round as shown in Table 1. All experiments started from sunlight exposure and ended at sunlight exposure, and the exposure period in a round was shorter than 10 minutes to achieve steady state.

Table 2 summarized the information of experiments in this study. As shown in Table. 2, for each sunlight and shade combination, five experiment types were carried out on different days. The selected experiment days had similar weather conditions. Each experiment was conducted in the afternoon had no more than 8 rounds and lasted for about 45 minutes. The alternating frequency in Table 2 was defined based on the exposure periods in shade and sunlight in one experiment type, and was calculated by the following equation (1).

$$F_i = \frac{T_{sh\_i}}{T_i} / T_{s\_i} \quad (1)$$

The items in Eq. (1) were explained in the Table 2. The ratio of T_{sh_i} and T_i in Eq. (1) indicates the shade exposure opportunity, and the ratio of $\frac{T_{sh\_i}}{T_i}$ and T_{s_i} indicates the opportunity for shade exposure per time unit of sunlight exposure; in other words, the intensity of shade exposure dependent on sunlight exposure time. As a result of the decreased F_i value, the opportunity or possibility for the next shade exposure was reduced after one minute of sunlight exposure. The proposal of F_i is to distinguish the conditions with the same ratio of sunlight exposure time to shade exposure time, and to investigate the possible impacts of alternating frequency and exposure duration on dynamic thermal responses. As a result, in this study, F_i is applied to describe the frequency of step changes or the intensity of shade exposure in a more reasonable way.

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Table 1 Introduction of alternating exposure experiment

	Sunlight	Shade	Sunlight	Shade	Sunlight	Shade	Sunlight	Shade	Sunlight	Shade	Sunlight	Shade	Sunlight	Shade	Sunlight
Sequence	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Round	1		2		3		4		5		6		7		8
Experiment type1	1min	1min	1min	1min	1min	1min	1min	1min	1min	1min	1min	1min	1min	1min	1min
Experiment type2	3min	6min	3min	6min	3min	6min	3min	6min	3min						
Experiment type3	3min	3min	3min	3min	3min	3min	3min	3min	3min	3min	3min	3min	3min	3min	3min
Experiment type4	6min	3min	6min	3min	6min	3min	6min	3min	6min						
Experiment type5	4min	1min	4min	1min	4min	1min	4min	1min	4min	1min	4min	1min	4min	1min	4min

Table 2 Information of each alternating exposure experiment

Alternating type (i)	Experiment date/Time period	Combination of shade and sunlight	Exposure time in sunlight for each round (T_{s_i})	Exposure time in shade for each round (T_{sh_i})	Exposure time for each round (T_i)	Round	Experiment duration	Alternating frequency (F_i)
1	5/24_14:00-15:00 7/29_12:00-13:00 7/29_13:30-14:30	1 (D&C) 2 (A&B) 3 (A&C)	1 min	1 min	2 min	7	15 min	0.5
2	5/17_14:00-15:00 5/24_11:00-12:00 9/14_14:00-15:00	1 (D&C) 2 (A&B) 3 (A&C)	3 min	6 min	9 min	4	39 min	0.22
3	5/16_14:00-15:00 7/29_14:30-15:30 9/11_14:30-15:30	1 (D&C) 2 (A&B) 3 (A&C)	3 min	3 min	6 min	7	45 min	0.17
4	5/17_13:00-14:00 7/22_12:30-13:30 9/14_14:30-15:30 9/14_13:00-14:00	3 (A&C) 1 (B&C) 2 (A&B) 3 (A&C)	6 min	3 min	9 min	4	42 min	0.06
5	7/28_11:00-12:00 7/28_14:00-15:00 7/29_14:00-14:30	1 (B&C) 2 (A&B) 3 (A&C)	4 min	1 min	5 min	7	39 min	0.05

2.2 Questionnaire survey and microclimate monitoring

Subjects in this study were required to wear short-sleeved T-shirts, short trousers and sports shoes when engaging in experiments. Thus the clothing insulation in this study was controlled at 0.4 clo, the typical summer clothing insulation, to avoid the extra impacts of clothing insulation on thermal perceptions. They were then informed to be seated or take a stroll in the experiment with the metabolic rate ranging from 1.2 to 1.3. Subjects were asked to fill in questionnaire consisted of four questions: ASHRAE 7-point Thermal Sensation Vote (*TSV*), Thermal Comfort Vote (*TCV*), Desire for changing Wind/Solar conditions. The scale of questionnaire is shown in Table. 3

Table 3 The scales of four questions

1. Please describe your current thermal sensation						
-3	-2	-1	0	1	2	3
Cold	Cool	Slightly Cool	Neutral	Slightly warm	Warm	Hot
2. Please describe your current thermal comfort level						
1	2	3	4	5		
Very uncomfortable	Uncomfortable	Temporarily acceptable	Comfortable	Very comfortable		
3. Want to reduce the current solar radiation?						
0 No	1 Yes					
4. Want to amplify the current wind speed?						
0 No	1 Yes					

The meteorological parameters in shade and sunlight during experiments were collected by two sets of mini-weather stations shown in Fig. 2. It should be noted that the weather station and subjects in place B were in a limited space under the large tree shade in which the radiations from six directions were assumed to be uniform and unchanged within the experiment period. Collected meteorological data was averaged into a 10-secondes interval by two mini-weather stations. The specification of measurement instruments and the collected environmental parameters were presented in Table. 4.

To avoid the influences of radiation on the air temperature and humidity measurements, the T_a/RH probe shown in the Fig. 2 was covered by a multi-plate radiation shield to certain the accurate measurements of T_a and RH. The multiple plate design provides a unique profile that blocks direct and reflected solar radiation, yet permits easy passage of air. The plate material is specially formulated for high reflectivity, low thermal conductivity, and maximum weather resistance (Yang et al., 2021). The mean radiant temperature which reflects the radiant heat transfer in a human body is calculated using the method from globe temperature in Eq. (2) (Fanger, 1984). The T_{mrt} calculated from the 75 mm black globe was then adjusted through calibration with three Kipp & Zonen CNR4 net radiometers (Johansson et al., 2014). The radiometers were set to collect radiation flux from six perpendicular directions for more accurate mean radiant temperature calculation (Kántor et al., 2011; Lam et al., 2018; Vanos et al., 2021). (see Appendix)

$$T_{mrt} = \left[(T_g + 273.15)^4 + \frac{1.10\times10^8\times v^{0.6}\times(T_g - T_a)}{\varepsilon D^{0.4}}\right]^{1/4} - 273.15 \qquad (2)$$

where T_g is the globe temperature (°C); T_a is the air temperature (°C); v is the wind speed (m/s); D of 75 mm is the black globe diameter; the emissivity (ε) of the globe was set to 0.95 for a typical black globe sensor.

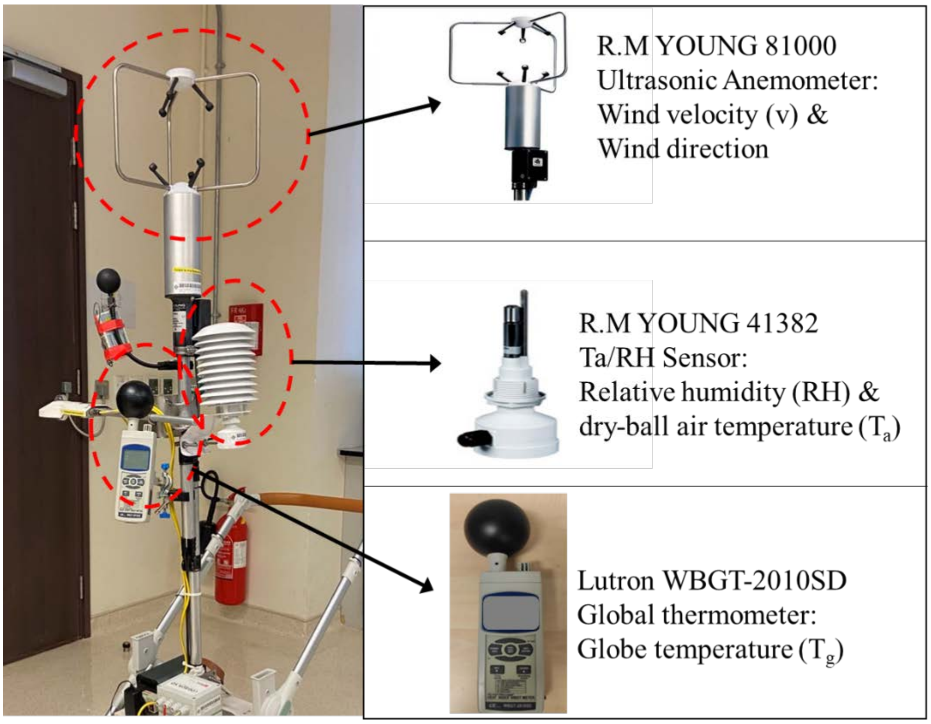


Fig. 2 Mini weather station used in the on-site measurements

Table 4 Specifications of measurement instruments.

Meteorological parameter	Sensor	Measuring range	Accuracy
Air temperature (T_a)	R.M. YOUNG 41382	-50-50 (°C)	±0.3 °C
Relative humidity (*RH*)		0-100 (%)	±1 %
Wind velocity (*v*)	R.M. YOUNG 81000	0-40 (ms^{-1})	±0.05 ms^{-1}
Globe temperature (T_g)	Lutron WBGT-2010SD	-40-60 (°C)	±0.1 °C

There are two phases in one experiment. Taking the condition in which subjects exposed alternately to place A and place B, as an example: 1) the setup phase (10min). Subjects stayed in an indoor lobby of a teaching building with an air temperature of 28°C for 10 min; 2) the phase of frequently alternating exposure to sunlight (place A) and shade (place B) at required frequencies introduced in Table 1 and Table 2. If the exposure time in sunlight or shade was larger than 1 minute, subjects were asked to fill in questionnaires in first minute after entering sunlight or shade and in last minute before leaving the sunlight or shade. Otherwise, they were asked to only fill in one questionnaire. Therefore, 872 valid questionnaires were returned for the analysis.

2.3 Index for assessing dynamic outdoor thermal comfort

2.3.1 Universal Thermal Climate Index and Dynamic Thermal Sensation

Universal Thermal Climate Index (*UTCI*) is defined as the isothermal air temperature of the reference environment that would produce the same dynamic response (strain) of the physiological model (Fiala multi-node model) as that produced under actual environment. The calculation of *UTCI* has been simplified by using only four meteorological parameters including T_a, RH, v at 10 m (v_{10m}), and T_{mrt}, based on the regression analysis (Bröde et al., 2012). The impacts of clothing insulation on thermal responses was determined by the clothing model which was integrated with the Fiala model to define the heat transfer properties between the human skin and the environment (Havenith et al., 2012). The metabolic rate set in the Fiala model was 2.3 Met and the impacts of metabolic rate on thermal comfort evaluated by *UTCI* was constant.

Dynamic Thermal Sensation (*DTS*) was developed with the Fiala model using the seven-point ASHRAE scale running from − 3 for cold to +3 for hot. It can be calculated by skin temperature and hypothalamus temperature, as well as the rate of change in these temperatures (Eqs. 3&4). However, due to the absence of subjects' physiological data in this study, the *DTS* was estimated based on the relationship between *UTCI* and *DTS* averaged over two hours' environmental exposure. The relationship can refer to Fig. 3. As aforementioned, the dynamic factor reflected in Eqs. (3) and (4) was taken into account as a latent variable by *UTCI* after multivariate and regression analyses in the *UTCI* derivation (Bröde et al., 2012).

$$DTS = 3 \times tanh\left[a\Delta T_{sk,m} + g + \frac{0.11\frac{dT_{sk,m}(-)}{dt} + 1.91e^{-0.681t} \times \frac{dT_{sk,m}(+)}{dt}_{max}}{1+g}\right] \quad (3)$$

$$g = 7.94 \times exp\left(\frac{-0.902}{\Delta T_{hy}+0.4} + \frac{7.612}{\Delta T_{sk.m}-4}\right) \quad (4)$$

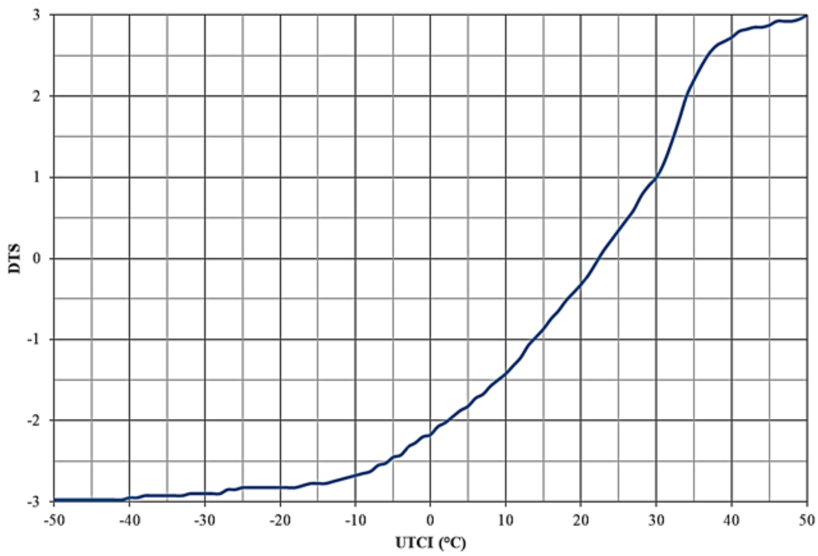


Fig.3 Dynamic thermal sensation (*DTS*) averaged over 2 h exposure time related to *UTCI* (Bröde et al., 2012)

For the comparison, the linear relationship between *UTCI* and the mean surveyed thermal sensation vote obtained for *UTCI* value rounded to 0.1-K-bin in our previous study was shown in Eq. (5) (Huang et al., 2017; Li et al., 2018). The equation was obtained from a series field tests conducted under thermal conditions covering summer, autumn, and winter in Hong Kong. There were 1107 thermal sensation votes collected under assumed steady states which were achieved by subjects' 15 minutes exposure in one place at an average metabolic rate with 1.3 Met. Therefore, the Eq. (5) represents an empirical model to predict outdoor thermal sensations (*PTSV*) with *UTCI* values rounded to 0.1-K-bin from 16.0℃ to 50.0℃ under relatively steady states. It should be noted that the *PTSV* is more applicable to young and middle-aged people wearing typical clothes based on air temperature in hot humid climate conditions. Besides, despite the 2.3 Met metabolic rate defined in the *Fiala-UTCI* model, empirical Eq. (5) has modified *UTCI* to evaluate the impacts of 1.3 Met metabolic rate on thermal sensations when standing or sitting. In view of this, we applied *UTCI*, *PTSV* and *DTS* in this study to evaluate the thermal responses as subjects being exposed to environments with frequent step changes.

$$PTSV = 0.1332UTCI - 3.6039 \qquad (16.0℃ \leq UTCI \leq 50.0℃) \qquad (5)$$

2.3.2 Combined Sun and Wind Conditions Index

In addition to changes in air temperature, changes in solar radiation and wind speed were the major components when subjects alternating their exposures to sunlight and shade. However, according to the findings in our previous study, the cooling effects of wind speed and heating effects of solar radiation evaluated by subjects were found significantly different from those estimated by *UTCI*. *UTCI* underestimated the impacts of sun and wind conditions on thermal responses to some extent (Li, Jianong et al., 2020). Basically, it is speculated that *UTCI* might also perform limitations in evaluating impacts of frequent changes in sun and wind conditions on thermal perceptions.

In view of this, the Combined Sun and Wind Conditions Index (*SWI*) proposed in the previous study (Li et al., 2020) was used in this study to complementally examine the impacts of sun and wind conditions on thermal perceptions. The *SWI* is defined as the difference in the normalized strength between sun and wind condition under a thermal environment, and it can be calculated with Eq. (6). The normalized strengths of sun and wind conditions which reflect the heating effects of radiation and cooling effects of wind, respectively, were yielded by standardizing T_{mrt} and v values using the 0–1 scaling method. Therefore, *SWI* is to directly evaluate the impacts of offsetting the heating effects of T_{mrt} by cooling effects of v on the thermal sensation. The value of *SWI* larger than 0 indicates the dominant heating effects of radiation and that lower than 0 indicates the dominant cooling effects of wind speed. The larger the *SWI* value reflects the stronger heating effects of T_{mrt}.

There is a positive liner relationship between surveyed thermal sensation votes and *SWI* values, as well as a quadratic relationship between percentage of comfortable votes and *SWI* values. *SWI* is thus applicable to predict the outdoor thermal comfort in perspective of the strength difference between sun and wind conditions under a wide air temperature range. The *SWI* range from -0.1 to 0.2 under the air temperature range from 12.0℃ to 36.0℃ can make more than 50% of subjects comfortable. When the air temperature is less than 26.0℃, neutral *SWI* in which thermal sensation vote is equaling to 0 is between 0.1 and 0.2, and when the air temperature is greater than 26.0℃, neutral *SWI* is between -0.2 and -0.1. Accordingly, *SWI* is meant to compensate for *UTCI*'s limitations in predicting the effects of sun and wind conditions on comfort and lead the design of ideal combined sun and wind conditions.

$$SWI = \frac{T_{mrt} - 12.0}{52.0} - \frac{v}{4.0} \quad (6)$$

where T_{mrt} is mean radiant temperature, v is the wind velocity. *SWI* was applied under the range: $12.0 \le T_{mrt} \le 64.0$°C, $0 < v \le 4.0$ m/s and $T_a \ge 26.0$°C.

2.3.3 Thermal dissatisfaction

A conception of thermal dissatisfaction was proposed in this study based on answers of thermal comfort vote (*TCV*) and desire for changing sun and wind conditions. Thermal dissatisfaction was determined with Eq. (7) and classified into 6 levels based on the computing results. It was designed to describe subjects' desire for changing the current thermal environment. As shown in Table 5, level 1 presents a satisfied environment without need to be changed and level 2 presents a less satisfied environment with a welcomed small change. Level 3 and level 4 demonstrate that the environment is not very satisfied but temporarily accepted. Level 5 and Level 6 present unsatisfied environments with a great need to be improved. The higher the dissatisfaction value is, the more unsatisfied thermal environment.

$$Dissatisfaction = TCV * \begin{cases} 0, & no\ need\ to\ change \\ 1, & change\ wind\ or\ solar\ radiation \\ 2, & change\ both\ wind\ and\ solar\ radiation \end{cases} \quad (7)$$

Table 5 Definition of the level scale of thermal dissatisfaction

<table>
<tr><th>Desire / TCV</th><th colspan="2">0</th><th colspan="2">1</th><th colspan="2">2</th></tr>
<tr><td>1</td><td colspan="2" rowspan="3"></td><td>1</td><td rowspan="2">Level 5</td><td>2</td><td rowspan="2">Level 6</td></tr>
<tr><td>2</td><td>2</td><td>4</td></tr>
<tr><td>3</td><td>3</td><td>Level 3</td><td>6</td><td>Level 4</td></tr>
<tr><td>4</td><td>0</td><td rowspan="2">Level 1</td><td>4</td><td rowspan="2">Level 2</td><td colspan="2" rowspan="2"></td></tr>
<tr><td>5</td><td>0</td><td>5</td></tr>
</table>

2.4 Statistical analysis

The data was analyzed using SPSS 24.0. Spearman rank correlation analysis was conducted in this study to examine the relationship between subjective thermal sensation and thermal comfort indices. Such correlation analysis is a non-parametric test that compares a monotonic function to describe statistical dependency between two variables. T-test and one-way/two-way between groups ANOVA analysis were used to examine the differentiation of a dependent variable (e.g., subjective thermal sensation) under the effects of independent variables (e.g., *UTCI* and alternating frequency). The differentiation is verified by statistical significance which is referred to as the P-value, the probability of obtaining a result of a study at least as extreme, given that the null hypothesis was true. For all analysis, P value of lower than 0.05 was considered significant. The effect size is a measurement of how much of the total variance in the dependent variable can be explained by the independent variable (Tabachnick et al., 2007). The effect size of ANOVA was defined by partial eta squared (η_p^2) to indicate the effect size of the main effects. Evaluating partial eta squared (η_p^2) was discussed by Cohen. et al (Cohen, 1988). It is reported that 0.14 of η_p^2 indicates a large effect of independent variable.

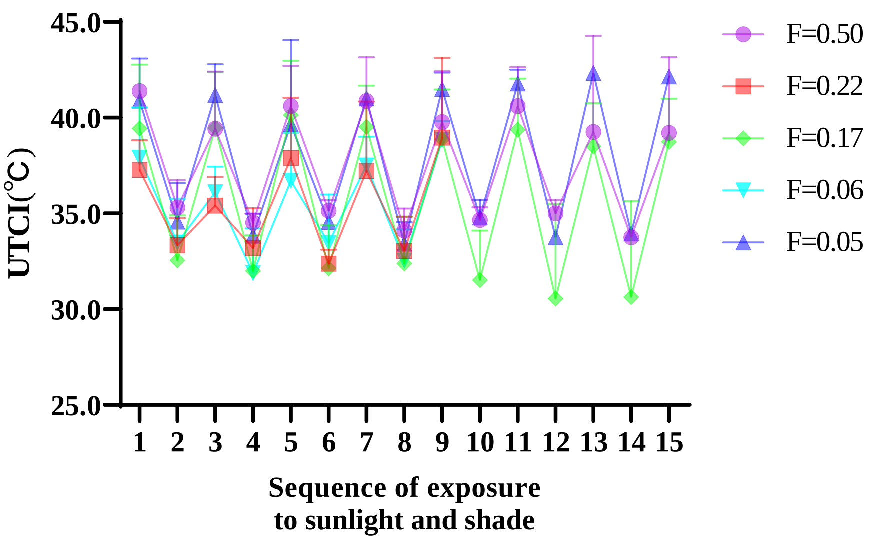
3. Results

3.1 Thermal conditions

In this study, thermal conditions with frequent step changes were resulted from participants being exposed alternately to sunshine and shade. Meteorological conditions during field surveys were summarized in Table. 6. Calculated *UTCI* and *SWI* values were grouped by five alternating frequencies and depicted in Fig. 4. The abscissa of Fig. 4 shows the exposure sequence to sunlight and shade in each experiment. The odd numbers present sunlight exposures and the even numbers present shade exposures. The legends besides the Fig. 4 show the alternating frequency in experiments. According to Fig. 4, *UTCI* and *SWI* values were larger in sunlight exposures than those in shade exposures, and the magnitude of *UTCI* and *SWI* change was not constant.

Table 6 Monitored variables ranges (minimum and maximum values) in experiments categorized by 5 alternating frequency types.

Alternating type (i)	Alternating frequency (F_i)	Experiment date/Time period	T_a (°C)	*RH* (%)	*v* (m/s)	T_{mrt} (°C)
1	0.50	5/24_14:00-15:00	31.0-32.4	61.0-66.3	0.9-2.7	39.6-69.8
		7/29_13:30-14:30	32.7-33.2	52.4-59.0	0.4-1.8	32.8-68.4
		7/29_12:00-13:00	31.9-33.4	59.0-63.0	0.5-1.9	32.6-58.2
2	0.22	5/17_14:00-15:00	30.6-31.8	63.0-70.0	1.0-2.3	34.3-70.0
		5/24_11:00-12:00	30.6-31.6	62.6-68.0	0.5-2.2	32.4-60.7
		9/14_14:00-15:00	30.0-31.9	61.0-69.0	0.6-1.2	31.4-39.8
3	0.17	5/16_14:00-15:00	30.7-31.1	58.7-62.3	0.6-1.9	32.3-53.7
		7/29_14:30-15:30	32.2-33.0	55.5-60.0	1.3-2.8	35.0-72.3
		9/11_14:30-15:30	29.1-33.1	40.0-53.0	0.6-3.1	31.0-63.0
4	0.06	5/17_13:00-14:00	31.0-32.4	51.0-57.0	0.2-0.6	34.4-51.1
		7/22_12:30-13:30	32.6-33.9	49.0-57.0	0.4-2.7	34.6-54.6
		9/14_14:30-15:30	29.0-31.4	64.4-70.0	0.8-2.2	30.6-51.0
		9/14_13:00-14:00	30.3-32.1	59.0-69.1	0.4-2.0	30.6-51.1
5	0.05	7/28_11:00-12:00	30.5-33.3	55.0-67.3	0.3-2.5	31.1-69.2
		7/28_14:00-15:00	31.4-33.1	58.0-67.0	0.6-2.8	34.5-62.3
		7/29_14:00-14:30	32.7-33.6	51.0-55.0	1.5-2.4	34.3-65.7



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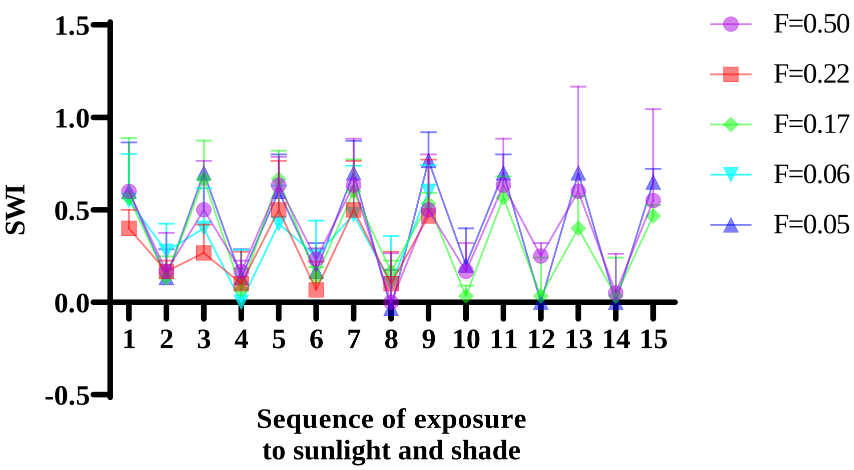


b)

Fig. 4 Thermal conditions of sequential sunlight and shade in experiments classified by five alternating frequency types: a) *UTCI*; b) *SWI*.

3.2 Comparison of surveyed and predicted thermal sensations

The surveyed thermal sensations in each exposure to sunshine and shade were averaged and designated as *MTSV* after a few minutes of exposure to sunlight and shade in a round. Simultaneously, mean *UTCI* value in each sunlight exposure and shade was calculated and matched to *MTSV*. For the comparison, predicted thermal sensations (*PTSV*) were calculated using Eq. (5) and the mean *UTCI* value, as well as the *DTS* based on the *DTS-UTCI* relationship shown as in Fig. 3. Difference between *MTSV* and *PTSV*, as well as *MTSV* and *DTS*, was determined for the same *UTCI* value, namely (*MTSV-PTSV*) and (*MTSV-DTS*), respectively.

3.2.1 Analysis of (MTSV-PTSV)

Fig. 5 displays (*MTSV-PTSV*) values in sunlight and shade exposures under different alternating frequency (Fig. 5a), and variation of (*MTSV-PTSV*) with *UTCI* (Fig. 5b). As shown in Fig. 5a, excluding the alternating frequency of 0.5, mean (*MTSV-PTSV*) values in shade were less than 0. Under the assumption that *PTSV* was accurately predicted, *MTSV-PTSV*<0 in shade reflected that the cooling effects of shade were amplified by subjects as being exposed alternately to sunlight and shade. Additionally, a dropping trend of (*MTSV-PTSV*) with the decreasing of alternating frequency is noted in shade exposures. The finding indicated that the amplified cooling effects of shade could be increased with the reducing of shade exposure opportunity (alternating frequency). On the contrary, mean (*MTSV-PTSV*) values in sunlight were larger than 0, except those under alternating frequency of 0.05. It seems that subjects' thermal sensations in sunlight and shade were strengthened due to their frequently alternating exposure. Two-way ANOVA was conducted for (*MTSV-PTSV*), which revealed significant difference in (*MTSV-PTSV*) based on different alternating frequency ($f(4,217)=13.47$, $p<0.0001$, $\eta_p^2=0.154$), and sunlight and shade exposures ($f(1,217)=37.84$, $P<0.0001$, $\eta_p^2=0.102$).

The (*MTSV-PTSV*) versus *UTCI* in sunlight and shade exposures was discussed under different alternating frequencies in Fig. 5b. The "_s" and "_sh" in the legends stand for sunlight exposure and shade exposure, respectively. Discrete (*MTSV-PTSV*) values were observed within *UTCI* rounded to 1-K-wide bin. We focused on the maximum and minimum (*MTSV-PTSV*) values in sunlight exposure for each *UTCI* bin and made two regression lines line-1 and line-2. The two lines were depicted to limit the possible trends of (*MTSV-PTSV*) with varying of *UTCI* in the sunlight and expressed as Eqs. (8-9).

Line 1: $(MTSV - PTSV)_{\max\_s} = -0.1252 \times UTCI + 6.277 \quad (R^2 = 0.98)$ (8)

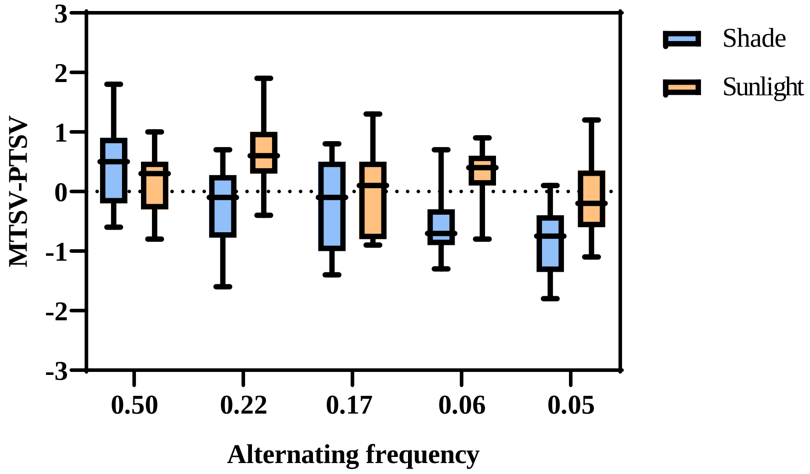
Line 2: $(MTSV - PTSV)_{\min\_s} = -0.1803 \times UTCI + 6.518 \quad (R^2 = 0.98)$ (9)

Regardless of discrete (*MTSV-PTSV*) values between line-1 and line-2, (*MTSV-PTSV*) in sunlight exposure performed a slight dropping trend with the increasing *UTCI*. It is possible that the surveyed *MTSV* was remained largely stable or reduced with rising *UTCI* from 34℃ to 44℃ under the impacts of frequent step changes, based on the growth of *PTSV* under this *UTCI* range in steady status. As for (*MTSV-PTSV*) values in shade, line-3 and line-4 were obtained using the same method for getting line-1 and line-2 and were expressed as the Eqs. (10-11).

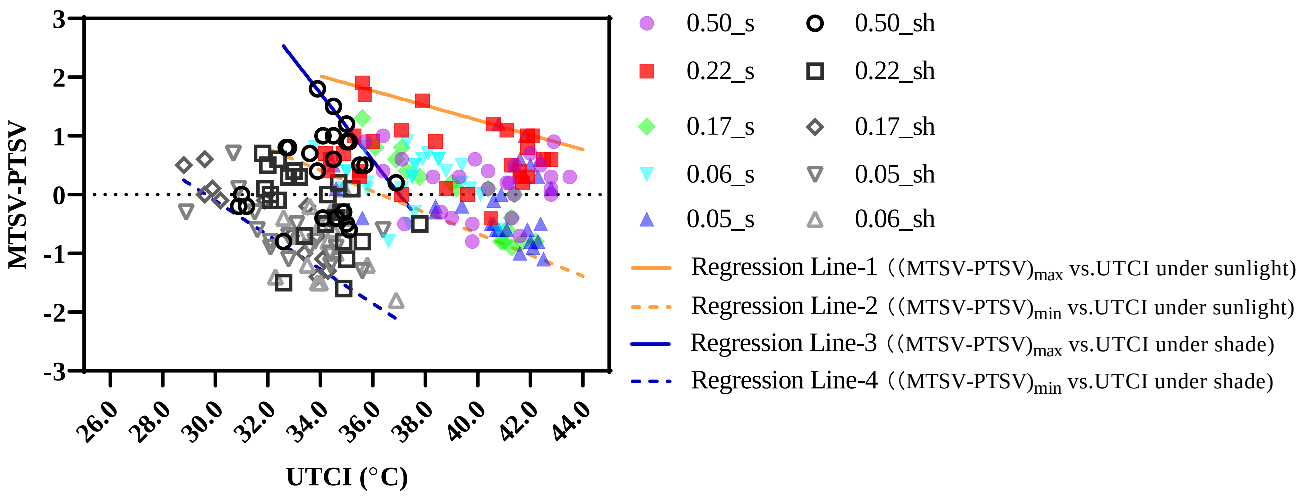
Line 3: $(MTSV - PTSV)_{\max\_sh} = -0.5722 \times UTCI + 21.19 \quad (R^2 = 0.99)$ (10)

Line 4: $(MTSV - PTSV)_{\min\_sh} = -0.2913 \times UTCI + 8.639 \quad (R^2 = 0.90)$ (11)

Similarly, a dropping trend of (*MTSV-PTSV*) values with the increasing *UTCI* from 29℃ to 37℃ was observed in shade, demonstrating a relatively unchanged or decreased surveyed thermal sensations within the rising *UTCI*. Worth noted is that within the *UTCI* range from 34℃ to 37℃, (*MTSV-PTSV*) values varied between -2 to 2. As shown in Fig. 5, measured thermal sensations in environments with step changes differed considerably from *PTSV* obtained near stable states for the same *UTCI* bin. Moreover, under the impacts of frequent step changes, measured thermal sensations perform less sensitivity to the magnitude of *UTCI* and even decrease as *UTCI* rises. People appear to be able to discriminate between hot and not hot rather than the intensity of hot feelings under unstable and dynamic settings.



a)



b)

Fig. 5 Distribution of (*MTSV-PTSV*) in sunlight and shade classified by a) alternating frequency and variation of (*MTSV-PTSV*) against b) *UTCI*.

It should be noted that despite the frequently reported thermal responses, "anchoring bias" which was proposed by Raccuglia et al (2018) and thought to increase thermal sensations did not play a role in influencing the thermal sensations in frequent step changes. There was no significant spearman rank correlation between sequence of questionnaire survey and surveyed thermal sensations (Coefficient=0.194, p=0.068). Besides, subjects were not reminded by previous votes during the experiments.

3.2.2 Analysis of (*MTSV-DTS*)

Fig. 6 exhibits the (*MTSV-DTS*) values in sunlight and shade under different alternating frequencies (Fig. 6a) and variation of (*MTSV-DTS*) with *UTCI* (Fig. 6b). Illustrated from Fig. 6a, mean (*MTSV-DTS*) values in both sunlight and shade were smaller than 0 and reduced when compared with the (*MTSV-PTSV*) values shown in Fig. 5a. The amplified cooling effects of shade were also exhibited by smaller mean (*MTSV-DTS*) values in shade than those in sunlight. The average *DTS* determined by *UTCI* might overestimated thermal sensations of subjects alternately exposing to sunlight and shade. The result should be attributed to the larger *DTS* simulated by Fiala-UTCI model, in which the metabolic rate was set as 2.3 Met larger than 1.3 Met in this study. Besides, the results were also possibly caused by cooling effects of frequent step changes on thermal sensations.

Two-way ANOVA analysis revealed significant difference in (*MTSV-DTS*) based on different alternating frequency ($f(4,217)=12.07$, $p<0.0001$, $\eta_p^2=0.121$), and sunlight and shade exposure ($f(1,217)=28.37$, $P<0.0001$, $\eta_p^2=0.085$). The difference of mean (*MTSV-PTSV*) corresponding to each alternating frequency was respectively determined in sunlight and shade for the comparison.

Similar analysis was conducted for (*MTSV-DTS*), and the results were shown in Table

7. The significant difference in statistical analysis ($p<0.05$) was marked in red. In shade exposures, (*MTSV-PTSV*) and (*MTSV-DTS*) at alternating frequency of 0.5 and frequency of 0.05 were significantly different with others. While in sunlight exposures, (*MTSV-PTSV*) and (*MTSV-DTS*) at alternating frequency of 0.22 were significantly larger than others. It is expected that a law governs the influences of frequent step changes on thermal reactions.

Table. 7 Difference of mean (*MTSV-PTSV*) and difference of (*MTSV-DTS*) under different alternating frequency

	Difference of mean (*MTSV-PTSV*)				Difference of mean (*MTSV-DTS*)			
Shade	*F*=0.22	*F*=0.17	*F*=0.06	*F*=0.05	*F*=0.22	*F*=0.17	*F*=0.06	*F*=0.05
F=0.50	0.6935	0.7035	1.0120	1.2810	0.6197	0.4739	0.8634	1.3050
F=0.22		0.0100	0.3184	0.5875		-0.1458	0.2436	0.6854
F=0.17			0.3084	0.5775			0.3895	0.8313
F=0.06				0.2691				0.4418
Sunlight	*F*=0.22	*F*=0.17	*F*=0.06	*F*=0.05	*F*=0.22	*F*=0.17	*F*=0.06	*F*=0.05
F=0.50	-0.5121	0.2035	-0.1037	0.2974	-0.4512	0.2721	0.0925	0.2707
F=0.22		0.7156	0.4084	0.8095		0.7233	0.5438	0.7220
F=0.17			-0.3072	0.0939			-0.1795	-0.001
F=0.06				0.4011				0.1781

In Fig. 6b, by regressing the maximum and minimum *MTSV* values to *UTCI* bins under shade and sunlight, line-1' to line-4' were obtained to investigate the possible variation of (*MTSV-DTS*) with *UTCI*. The line-1' to line-4' were presented as Eqs. (12-15).

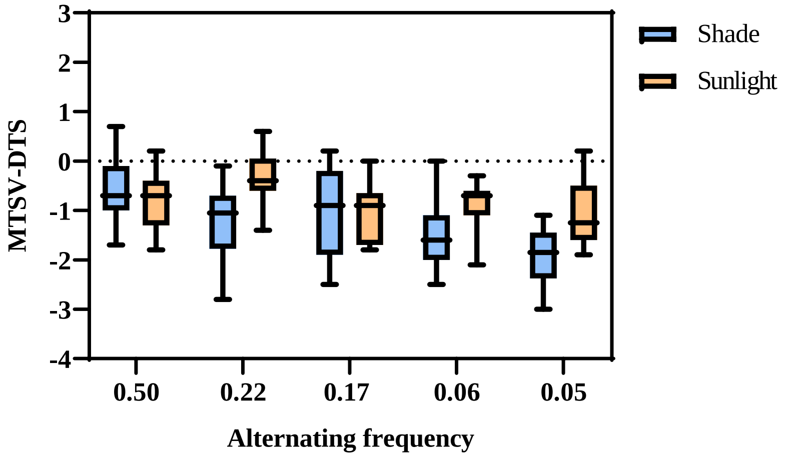
Line-1': $(MTSV - DTS)_{\max\_s} = -0.0541 \times UTCI + 2.376 \quad (R^2 = 0.53)$ (12)

Line-2': $(MTSV - DTS)_{\min\_s} = -0.1681 \times UTCI + 4.847 \quad (R^2 = 0.64)$ (13)

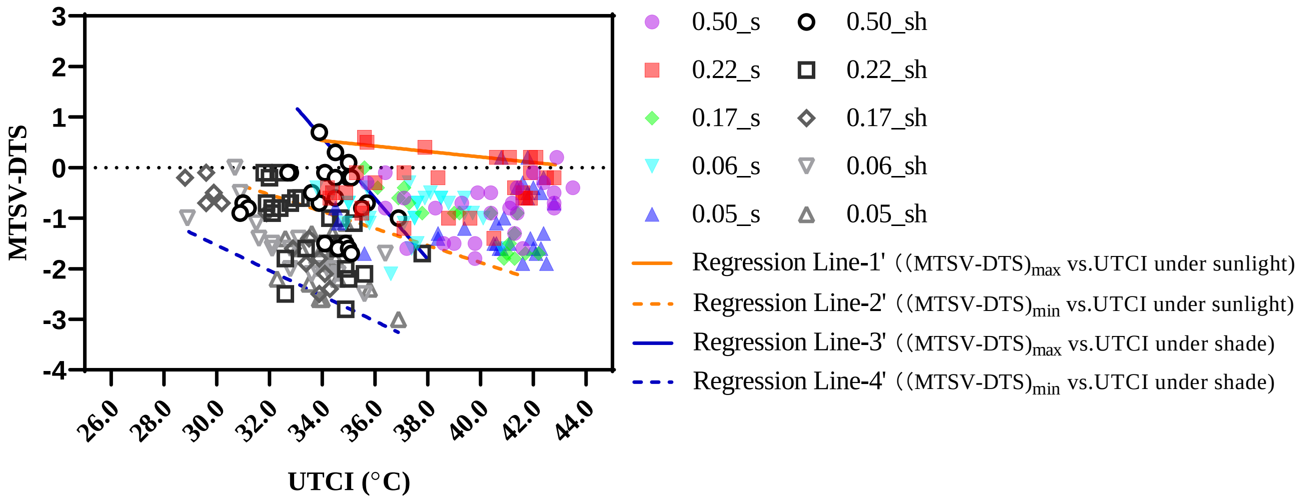
Line-3': $(MTSV - DTS)_{\max\_sh} = -0.6016 \times UTCI + 21.05 \quad (R^2 = 0.98)$ (14)

Line-4': $(MTSV - DTS)_{\min\_sh} = -0.2502 \times UTCI + 5.973 \quad (R^2 = 0.90)$ (15)

Despite the significant non-zero of the slope for line-1’ and line-2’, (*MTSV-DTS*) slowly declined with changing *UTCI* in sunlight and their values were almost below zero, whereas an obvious dropping (*MTSV-DTS*) with the increasing *UTCI* in shade was observed. The (*MTSV-DTS*) varied from -3 to 1 under the *UTCI* ranging from 34℃ to 37℃. Illustrated from Fig. 5 and Fig. 6, the relationships between *UTCI* and *PTSV*, as well as *UTCI* and *DTS*, were ineffective in predicting thermal sensations in environments with frequent step changes. Therefore, it is essential to explore an approach to evaluate impacts of unsteady environments with frequent step changes on thermal responses.



a)



b)

Fig. 6 Distribution of (*MTSV-DTS*) in sunlight and shade classified by a) alternating frequency and variation of (*MTSV-DTS*) against b) *UTCI*.

3.3 Exploring an approach to evaluate frequent step changes effectiveness

3.3.1 Spearman rank correlation analysis

According to our previous study, v and T_{mrt} had significant influences on thermal sensations of subjects in Hong Kong at the T_a ranging from 12.0°C to 36.0°C and *RH* ranging from 50% to 76%. Moreover, the changes in solar radiation and wind speed are dominant in environments with frequent step changes. However, it is reported that *UTCI* underestimated impacts of v and T_{mrt} on surveyed thermal sensations at higher temperature. Considering the applicability of *SWI* for assessing outdoor thermal sensations in the perspective of the combined sun and wind conditions (Section 2.3.2), this section attempted to integrate *SWI* and *UTCI* to evaluate thermal comfort in environments with frequent step changes. We first analyzed Spearman rank correlations among surveyed thermal sensations, *UTCI*, *SWI* and other meteorological parameters under each alternating frequency, and the results were shown in Table. 8.

Table.8 Spearman rank correlation among *SWI*, *UTCI*, meteorological parameters and *TSV* under different alternating frequencies

	TSV at *F*=0.50	*TSV* at *F*=0.22	*TSV* at *F*=0.17	*TSV* at *F*=0.06	*TSV* at *F*=0.05
SWI	0.425**	0.651**	0.714**	0.647**	0.816**
UTCI	0.396**	0.677**	0.577**	0.715**	0.721**
T_{mrt}	0.375**	0.642**	0.578**	0.595**	0.687**
v	-0.309*	0.202	-0.307*	-0.302*	-0.291*
T_a	0.295*	0.194	0.149	0.031	0.18
RH	0.041	0.296*	0.087	0.137	0.088

** Correlation significant at the 0.01 level (two-tailed).

* Correlation significant at the 0.05 level (one-tailed).

As seen in Table. 8, there was a strong positive correlation between SWI and surveyed thermal sensations, indicating a strong dependence of thermal sensation on the changes in sun and wind conditions. The spearman rank correlation coefficients of *SWI* with surveyed thermal sensations were even larger than those of *UTCI* with surveyed thermal sensations. As introduced in section 2.3.2, *SWI* is to evaluate the impacts of the offsetting heating effects of T_{mrt} by cooling effects of v on the thermal comfort. Therefore, in environments with frequent step changes mainly characterized with changes in sun and wind conditions, *SWI* can be used as an additional element to compensate for the *UTCI* when evaluating thermal comfort.

3.3.2 Definition of the equivalent *UTCI**

To intergrade the *UTCI* and *SWI*, the relationship between *UTCI* and *SWI* was first investigated in Fig. 7. It is noted that a given *UTCI* value rounded to 0.1-K-bin corresponded to dispersed *SWI* values, or a variety of combined sun and wind conditions. To explore the relationship between *UTCI* and *SWI*, we focused on the maximum and minimum values of *SWI* within *UTCI* rounded to 1-K-wide bin. Regression line-a and regression line-b in Fig. 7 were produced by regressing the maximum and minimum values of *SWI* to *UTCI* bins, respectively, which were expressed as Eqs. (16-17). Based on the two regression lines, the range of *SWI* with a given *UTCI* value could be predicted.

Line-a: $SWI_{max} = 0.06447 \times UTCI - 1.723 \quad R^2 = 0.99$ (16)

Line-b: $SWI_{min} = 0.09603 \times UTCI - 3.433 \quad R^2 = 0.99$ (17)

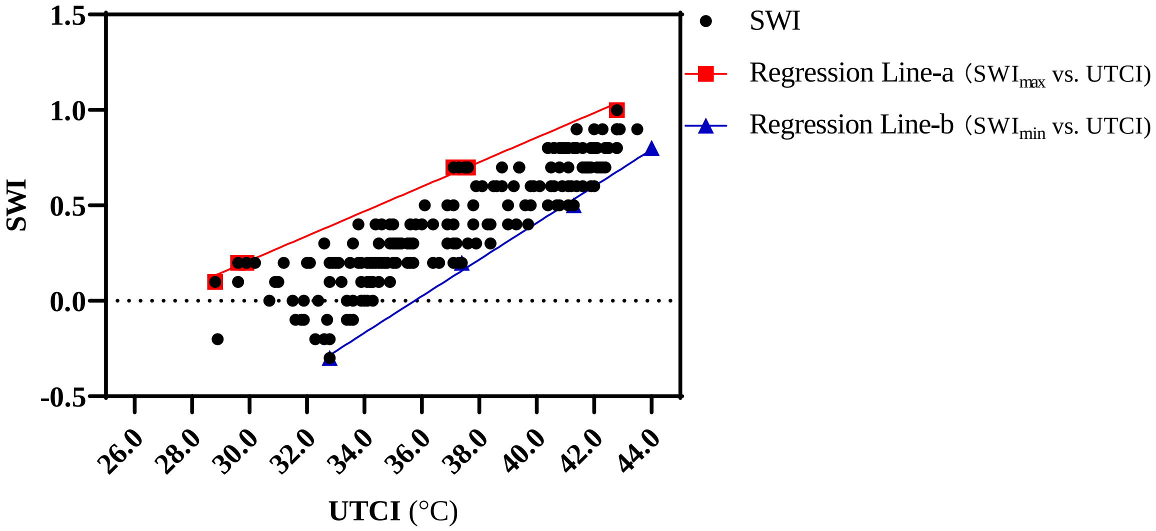


Fig. 7 The relationship between *UTCI* and *SWI*

Fig. 7 might be the reason that actual thermal sensation and *UTCI* had different sensitivities to sun and wind conditions. Moreover, the difference between *PTSV* obtained near steady state and *MTSV* obtained in conditions with frequent step changes might be related to the relationship between *SWI* and *UTCI*. In view of this, we made a following hypothesis to explore approach to evaluate environments with frequent step changes.

First, the relationships between *MTSV* and *UTCI* and between *PTSV* and *UTCI* were assumed to be identical. The calculated *UTCI* with *MTSV* using Eq. (5) was thus treated as the equivalent *UTCI** (Eq. 18), which was defined as the *UTCI* in the steady state that would produce the same thermal sensations as that produced in environments with frequent step changes. Then the hypothesis is that the difference between actual *UTCI* and *UTCI** was caused by the underestimation of *SWI* impacts in frequent step changes on thermal perceptions, as well as the impacts of different alternating frequencies. Therefore, the difference between *UTCI* and *UTCI** was assumed to be the function of *SWI* and frequent step changes effectiveness, which was expressed as the Eq. (19).

$$UTCI* = \frac{MTSV+3.6039}{0.1332} \tag{18}$$

$$\frac{SWI-SWI_{min}}{SWI_{max}-SWI_{min}} = \frac{UTCI*-UTCI}{\alpha UTCI} \tag{19}$$

$\alpha UTCI$ in Eq. (19) was the possible range of equivalent *UTCI** determined by *SWI* range at a given *UTCI* value, for example $UTCI_0$. The inherent effects of sun and wind condition (heating effects of T_{mrt} and cooling effects of v) evaluated by $UTCI_0$ was assumed to be presented by SWI_{min} value regarding to $UTCI_0$. With T_{mrt} and v that calculated $UTCI_0$, SWI_0 was determined. Therefore, the influence of SWI_0 on equivalent UTCI* was presented by the relative position of SWI_0 in the *SWI* range regarding to

$UTCI_0$. It is based on the assumption that equivalent *UTCI** was totally resulted from SWI_0 and *UTCI** was positively correlated with SWI_0. Therefore, with the known of *UTCI, SWI* and *UTCI**, the α in Eq. (19) was calculated to examine our hypothesis and explore the influences of different alternating frequencies.

If α was larger than 0, *UTCI* underestimated the impacts of sun and wind on thermal perceptions in environments with frequent step changes. If α was smaller than 0, *UTCI** was smaller than *UTCI*, which was considered to be caused by amplified cooling effects due to frequent step changes. If α was a null value, the left part of Eq. (19) could be 0. The error between *UTCI** and *UTCI* can be also explained by the uncertain impacts of frequent step changes.

3.3.3 Derivation of the equivalent *UTCI**

The information of calculated α in different alternating frequency was shown in Fig. 8. A one-way ANOVA was conducted to decide the significant difference in α based on different alternating frequency (f=5.372, p=0.005, η_p^2=0.173). It seems that mean value of "$\alpha > 0$" and the percentage of "$\alpha > 0$" both dropped with the decreasing alternating frequency. The higher the alternating frequency was, the more possibilities that the difference between *UTCI* and *UTCI** was caused by underestimating impacts of sun and wind conditions by *UTCI*. However, the percentage of "$\alpha \leq 0$" or "α=null" grew as the alternating frequency decreased, demonstrating that the frequent step change effectiveness was dominating as the alternating frequency decreased. Based on the percentage of α, our hypothesis that the difference between actual *UTCI* and *UTCI** was determined by *SWI* and effects of frequent step changes, was accepted.

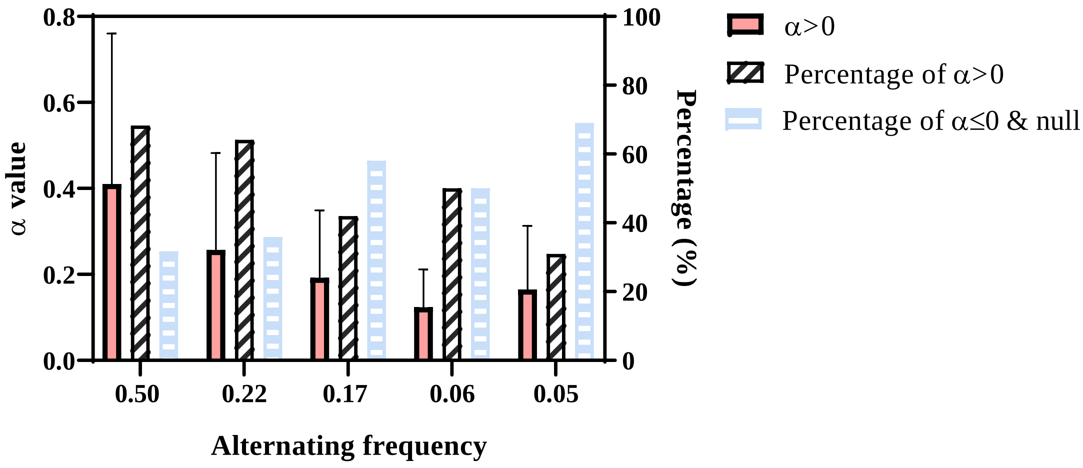


Fig. 8 α value and the percentage of α value under different alternating frequency class

Fig. 9 depicts the difference between *UTCI** and *UTCI* (*UTCI*-UTCI*) corresponding to "$\alpha \leq 0$" and "α=null" under each alternating frequency. Worth noted is that the mean difference was around -5 under all alternating frequencies. The result was attributed to the cooling effects of frequent step changes on subjective responses. A one-way ANOVA was conducted to examine the significant difference in (*UTCI*-UTCI*) based on different alternating frequency (f=5.372, p=0.005, η_p^2=0.173). It is found that the magnitude of (*UTCI*-UTCI*) under higher alternating frequency was slightly smaller than that under lower alternating frequency.

Basically, alternating exposures to sunlight and shade at a higher frequency produced less cooling effects instead. On the one hand, it may be owing to small heat accumulation in the body as result of frequent step changes, making the thermal perceptions less sensitive to cooling effects of shade and the heating effects of sunlight. On the other hand, as the intensity to shade exposure increased on hot days, a high expectation to cooler conditions than shade might be induced, making subjects feel hotter in both shade and sunlight from a psychological standpoint. Based on Fig. 8 and Fig. 9, equivalent *UTCI** was thus derived by compensated effects of sun and wind conditions reflected by *SWI* and cooling effects of frequent step changes. With method of weighted average, equivalent *UTCI** can be calculated by Eq. (20).

$$UTCI^{*} = \left[UTCI \times \left(1 + \alpha_i \frac{SWI - SWI_{min}}{SWI_{max} - SWI_{min}}\right)\right] \times P_{(\alpha>0)i} + (UTCI - Error_i) \times P_{(\alpha\leq 0\&null)i} \quad (20)$$

where, i=0.5, 0.22, 0.17, 0.06, 0.05; α refers to the mean value of α>0 corresponding to each alternating frequency; $P_{(\alpha>0)}$ is the percentage of "α>0" and $P_{(\alpha\leq 0\&null)}$ is the percentage of "$\alpha\leq 0$" & "α=null" for each alternating frequency; $Error$ refers to the mean (*UTCI*-UTCI*) value produced by cooling effects of frequent step changes as $\alpha\leq 0$ and α was null.

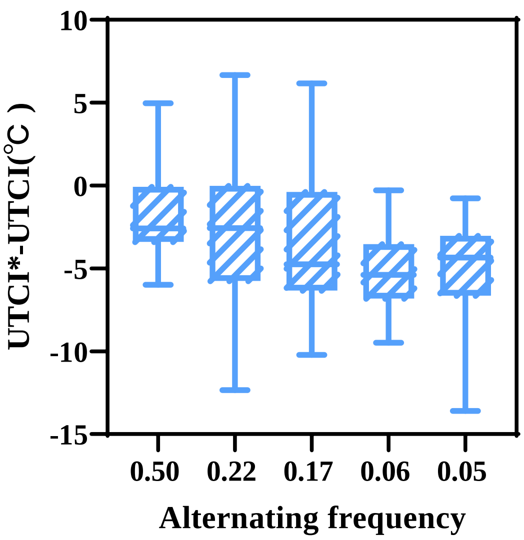


Fig. 9 Distribution of (*UTCI*-UTCI*) corresponding to $\alpha\leq 0$ and null values under different alternating frequencies

It should be noted that the *UTCI** derived in this study focused on evaluating the overall environmental changes on thermal perceptions when subjects alternating their exposures to sunlight and shade. The average change in v, T_{mrt} and T_a in few minutes were considered based on the objective in this study. The applicability of *UTCI** on evaluating environment with faster changes in meteorological parameters will be validated and improved in the future study by extending the alternating frequencies. Furthermore, as the result of exploiting the relationship between *UTCI* and *PTSV* expressed as Eq. (5) in the Eq. (20), the *UTCI** has been adjusted to evaluate the thermal responses at low metabolic rates of about 1.3 Met in this study.

3.3.4 Validation of the derived *UTCI**

To validate the application of derived *UTCI**, the mean values of derived *UTCI**, original *UTCI*, and *SWI* were first determined under *TSV'* values rounded to 0.1-sclae-bin. *TSV'* was the mean value of surveyed thermal sensations collected in each questionnaire survey during experiments to avoid the individual errors. The linear regression analysis was then conducted for mean values of *UTCI**, original *UTCI*, *SWI* and *MTSV* bins, which were expressed in detail in Table 9. As shown in Table 9, the linear relationship between *UTCI** and *TSV'* bins, indicated by R^2 of 0.83 of the fitted line, is better than the relationship between *UTCI* and *TSV'* bins, indicated by R^2 of 0.63 of the fitted line, and the relationship between *SWI* and *TSV'* bins, indicated by R^2 of 0.72 of the fitted line. The result demonstrated that effects of frequently alternating thermal conditions on subjects most likely to lead to the relationship between *UTCI** and *TSV'*.

Table 9 Linear relationship between *UTCI** and *TSV’* bins, as well as between original *UTCI* and *TSV’* bins and *SWI* and *TSV’* bins

		*UTCI** vs. *TSV'*	*UTCI* vs. *TSV'*	*SWI* vs. *TSV'*
Linear equation		$UTCI^* = 3.484 \cdot TSV' + 32.64$ (Eq. 21)	$UTCI = 2.033 \cdot TSV' + 33.94$ (Eq. 22)	$SWI = 3.719 \cdot TSV' - 0.1135$ (Eq. 23)
Goodness of Fit	R^2	0.8259	0.6301	0.7295
Significant none-zero of the slope	*P* value	<0.0001	<0.0001	<0.0001
	f	147.1	56.21	94.41

The spearman rank correlation between surveyed thermal sensations and *UTCI** was examined for each alternating frequency and compared with correlations among surveyed thermal sensations, original *UTCI* and *SWI*. The results were shown in Table 10. It can be observed that the spearman correlation between *UTCI** and surveyed thermal sensations were significantly improved and stronger than that between original *UTCI* and surveyed thermal sensations. However, the relationship between *UTCI** and surveyed thermal sensations under alternating frequency of 0.5 was still relatively low, which requires further investigations. Generally, illustrated from Table 9 and Table 10, the derived *UTCI** is able to assess impacts of thermal settings with frequent step changes on thermal perceptions by complementing the influences of sun and wind conditions reflected by *SWI* and the impacts of frequent step changes. Although the application of *UTCI** needs further validations and further improvement, we proposed a new angle to evaluate the effects of dynamic thermal conditions in a quantitative method.

Table 10 Spearman rank correlation among *SWI*, *UTCI*, derived *UTCI** and surveyed thermal sensations under different alternating frequencies

	TSV at *F*=0.5	*TSV* at *F*=0.22	*TSV* at *F*=0.17	*TSV* at *F*=0.06	*TSV* at *F*=0.05
*UTCI**	0.438**	0.739**	0.630**	0.727**	0.820**
UTCI	0.396**	0.677**	0.577**	0.715**	0.721**
SWI	0.425**	0.651**	0.714**	0.647**	0.816**

3.4 Thermal dissatisfaction in thermal environments with frequent step changes

3.4.1 Surveyed thermal sensation and thermal dissatisfaction

In addition to thermal sensation, thermal dissatisfaction is another important index to evaluate thermal environments with frequent step changes. Fig. 10 displays the percentage of thermal dissatisfaction under combinations of different alternating frequency (opportunity to shade exposure) and *TSV* rounded to 1-scale-wide bin. The percentage of thermal dissatisfaction were reflected by cells' color. Fig. 10 is to investigate the impacts of both thermal sensation and alternating frequency on the thermal dissatisfaction. It can be seen that even subjects had the similar *TSV* values, their thermal dissatisfaction could be influenced by different alternating frequency they were experiencing. Despite that subjects felt cooler than natural ($TSV \leqslant 0$) at a moment, the percentage of "$Disstisfaction \leqslant 2$"; in another word the percentage of satisfaction, dropped if their alternating frequency or the opportunity of shade exposures reduced.

When subjects felt hotter than neutral ($TSV \geqslant 1$) at a moment, more than 30% of them voting for "$Dissatisfaction \leqslant 4$"; in another word the acceptable thermal environments, when they were frequently shifting between sunlight and shade. The findings demonstrated that, in addition to thermal sensations, environments with frequent step changes might have major impact on thermal satisfaction. As shown in Fig. 10, it is effective to boost thermal satisfaction on even hot summer days by allowing frequent microclimatic step changes or increasing possibilities to cool or shade areas by expanding spatiotemporal distributions of cool or shade sites.

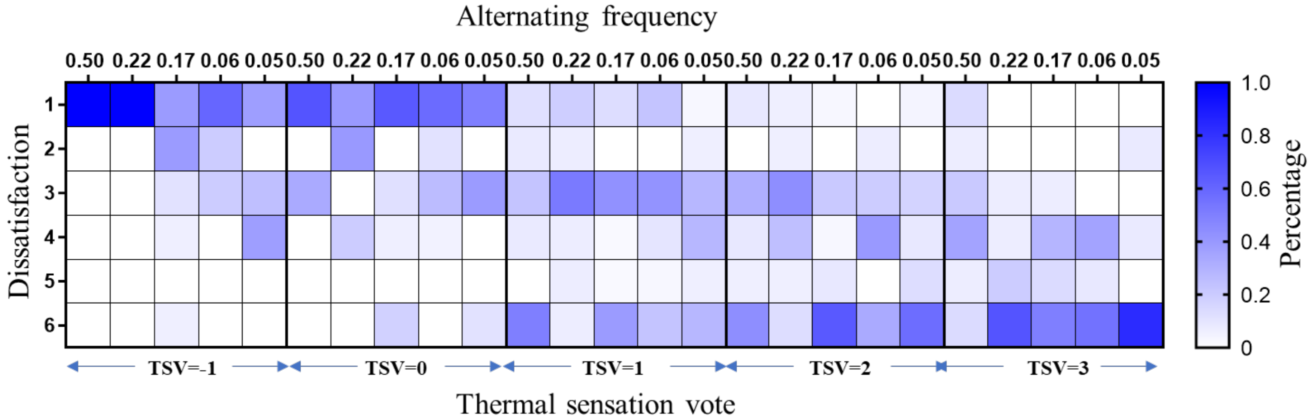


Fig. 10 Percentage of thermal dissatisfaction influenced by thermal sensation rounded to 1-scale-wide bin and alternating frequency

3.4.2 Thermal dissatisfaction and *UTCI**

Mean *UTCI** in every sunlight exposure and shade under each alternating frequency were determined. Fig. 11 shows the averaged dissatisfaction which was reflected by cells ‘color for each combination of alternating frequency and *UTCI** bin value. If a *UTCI** value in the range of 34℃ to 38℃ was achieved under higher alternating frequency of larger than 0.17, the dissatisfaction level in this *UTCI** would be less than 3. However, if this *UTCI** was obtained under lower alternating frequency, the corresponding dissatisfaction level would be larger than 3. Furthermore, even the *UTCI** obtained under higher alternating frequencies of 0.22 and 0.50 is greater than 38℃, the corresponding dissatisfaction level is comparable to that when the *UTCI** is between 32℃ and 37℃ at low alternating frequencies. Illustrated from Fig. 10, people may show more tolerance to thermal environments on hot days if the alternating frequency is reasonably high. Besides, there is no need to make the step change magnitude large for cooling benefits on hot days.

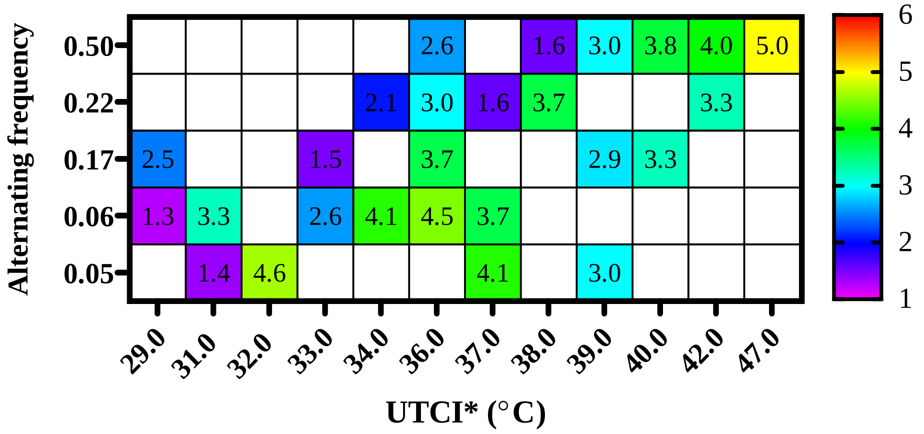


Fig. 11 The averaged dissatisfaction in sunlight and shade under different alternating frequency

3.4.3 Upper limit of acceptable *UTCI**

Dissatisfaction value of 4 was treated as the threshold of intolerance to thermal condition in this study. Linear regression analysis was conducted for the percentage of "*Dissatisfaction*≤4" and *UTCI** bin with 1-K width under different alternating frequency to explore the upper limit of acceptable *UTCI**. Two regression lines Line-a' and Line-b' were obtained, which were shown in Fig. 12. Line-a' suggests the relationship between percentage of "*Dissatisfaction*≤4" and *UTCI** at high alternating frequency (F=0.50, F =0.22), and the Line-b' suggests the relationship at medium and low alternating frequency (F= 0.17, F=0.06, and F=0.05). Line-a' and Line-b' are expressed as the Eqs. (24-25).

Line-a': $P_{Dissatisfaction\leq4} = -4.289 \times UTCI^{*} + 237.3 \;\; R^2 = 0.57$ (24)

Line-b': $P_{Dissatisfaction\leq4} = -7.289 \times UTCI^{*} + 315.8 \;\; R^2 = 0.79$ (25)

where, $P_{Dissatisfaction\leq4}$ presents the percentage of "*Dissatisfaction*≤4"

R^2 values of Line-a' and Line-b' demonstrated acceptable fitness of two regression lines. We made an assumption that thermal environments with more than 50% of "*Dissatisfaction*≤4" were thought acceptable. According to Fig. 12, the intersections of 50% line and Line-a' and Line-b' can reveal the upper limits of acceptable *UTCI**. The intersection of 50% line with Line-b' was 36.5°C and that of the 50% line with Line-a' was 43.7°C. The alternating exposure in a relatively high frequency can enlarge the range of acceptable *UTCI**. It is anticipated that thermal satisfaction could be notably increased by increasing the frequency of alternate sunlight and shade exposures even though the *UTCI** is relatively high.

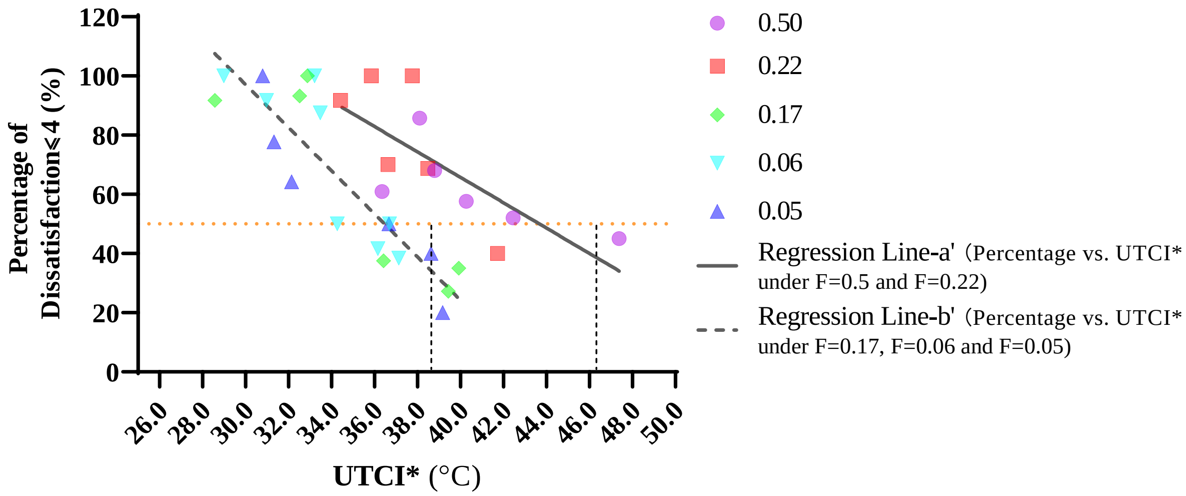


Fig. 12 Percentage of "*Dissatisfaction*≤4" against *UTCI** classified by different alternating frequency.

4. Discussion

This study focuses mainly on the effects of frequent step changes on the respective of the subjective thermal responses. Due to the absence of subjects' physiological data and some uncertainties and uncontrollable factors in the experiment, some mechanism of thermal responses during frequently exposure to sunlight and shade might not be explained very clearly.

4.1 Assumptions for deriving equivalent *UTCI**

One assumption in the derivation process of *UTCI** in section 3.3.2 was that the impacts of sun and wind conditions evaluated by the given *UTCI* were presented by the value of SWI_{min} at the given *UTCI* value. Based on the Eq. (20), *UTCI** was assumed to be positively related to actual *SWI* and always larger than *UTCI*. If *UTCI** was smaller than *UTCI*, it was considered to be caused by cooling effects of frequently alternating exposure. This assumption might overlook the effects of actual sun and wind conditions evaluated by given *UTCI*. In addition to cooling effects, *UTCI** smaller than *UTCI* might be caused by *UTCI* overestimating effects of sun and wind conditions on subjective responses. However, *UTCI** lower or larger than *UTCI* was both examined in this study regardless of the exact reasons. The above assumption did not significantly affect the derivation of *UTCI**.

4.2 Potential psychological effects

When subjects alternating exposures to sunlight and shade at different frequencies, psychological factors induced in the process may play a significant role making thermal perceptions varied with alternating frequencies. One of the psychological factors might be the thermal expectation. According to the study conducted by Luo et al. (2016), people living in the excellently conditioned indoor thermal settings have greater thermal expectations and may complain about the thermal conditions more frequently. As shown in Fig. 8 and Fig. 9, the cooling impacts of frequent step changes were relatively small at higher alternating frequencies (Fig. 8 and Fig. 9). The results might be partly attributed to the subjects' higher expectation of cooler thermal conditions than shade when the opportunity to shade was plentiful, thus hindered the cooling effects of alternating exposures and made their hot-biased thermal sensations unintentionally. The weight of such expectation impact could be reflected by percentage of α values and (*UTCI*-UTCI*) values against different alternating frequencies in Section 3.3.3 to some extent.

Another psychological factor might be the lower thermal expectation or alliesthesia proposed by De Dear et al. (2011), which was reflected by the amplified cooling effects of alternating exposure at a relatively low frequency (Fig. 8 and Fig. 9). The alliesthesia is the condition whereby the degree of relative changes in subjective thermal responses exceeds that of physical or physiological responses due to a rise or reduction in the departure of certain controlled variables from their set point. Accordingly, when the opportunity to shade was suitably restricted and the exposure time in sunlight was suitably prolonged, the cooling benefits of shade might instead be amplified owing to alliesthesia effects. The weight of such alliesthesia effect could be also reflected by α value in Section 3.3.3 to some extent. Despite these amplified cooling effects, thermal dissatisfaction level which is shown in Fig. 11 and Fig. 12 is higher at low alternating frequencies. The results might be attributed to the subjects' unwillingness to return to sunlight following the alliesthesia effects. Generally, psychological factors might be particularly significant in influencing thermal perceptions in dynamic thermal environments, which necessitates additional research based on more data.

4.3 Validation and application

This work offers a method for evaluating dynamic thermal comfort by simplifying dynamic thermal environments as frequent microclimatic step changes and analyzing the effects of the change frequency on overall thermal comfort. However, it should be cautioned that effects of frequent step changes were observed and discussed within 45 minutes, the effects in prolonged exposure time outdoors and adaptation effects were not clear, which necessities future studies. Effects of typical alternating frequencies with short exposure time (lower than or equal to 6 minutes) in both sunlight and shade were discussed, and the range of *UTCI* in this study was from 29℃ to 43℃. The study mainly focused on environments with frequent step changes during hot summer days in which air temperature was less than 35℃. Therefore, the impacts of different clothing behavior on thermal perceptions were not discussed in this study. Besides, the *UTCI** is more applicable to evaluate dynamic thermal comfort of people with relatively low metabolic rate. Although *UTCI** could describe effects of outdoor environments with frequent step changes in this study, it should be furtherly validated and improved based on more collected data in different climate regions and different group of people.

The proposed *UTCI** updates the calculated *UTCI* considering impacts of the frequency of microclimatic step changes within a periods on overall thermal sensations. It overcame the limitation of *UTCI* in evaluating impacts of sun and wind conditions, especially the impacts of fast changes in them on perceived heat stress and treated the dynamic factor, the frequency of microclimatic step changes, as the evident variable to evaluate dynamic thermal comfort. Moreover, the *UTCI** counted for the cooling effects of frequent step changes in microclimate conditions on hot summer days in the psychological perspective. The adaptation of *UTCI* to *UTCI** expend the *UTCI* application in a more complex outdoor thermal environments considering both physiological and psychological factors.

It is expected that in the future study, the dynamic thermal environments will be characterized with frequency of microclimatic changes, and their impacts on overall heat stress can be evaluated by *UTCI** directly using Eq. (20). A higher *UTCI** value suggests an increased heat stress perceived by people under dynamic thermal settings, demonstrating the ineffective frequency of microclimatic step changes. Therefore, such ineffective or unwelcomed frequency can be intuitively adjusted through Eq. (20). Accordingly, *UTCI** could be used at the design stage for guiding the spatiotemporal distribution of cool spots or instruments to enable or regulate frequent spatiotemporal microclimatic step changes that are welcomed by people on hot summer days in artificial, natural or even automatic ways.

5. Conclusion

A study to evaluate influences of frequently alternating exposure to sunlight and shade at different frequencies on pedestrians' thermal perceptions was conducted. Main conclusions were obtained as follows.

1) Assessment of dynamic thermal comfort can be achieved by simplifying dynamic thermal environments as frequent microclimatic step changes and analyzing their effects on thermal sensation.

2) Thermal sensations under alternating exposures to sunlight and shade differ significantly from *PTSV* produced in steady states and *DTS*. They tend to be less sensitive to variations in *UTCI*, even decreasing as *UTCI* rises.

3) The frequency of microclimatic step changes is an essential element to predict dynamic thermal sensations, which was overlooked by the evaluation with *UTCI*.

4) *UTCI** derived from *SWI* and frequency of microclimatic step changes improves the accuracy of measuring the thermal comfort under complex thermal environments.

5) *UTCI** improves the prediction of the mixed effects of sun and wind conditions on thermal comfort on hot days, and accounts for the cooling effects of frequent microclimatic step changes in the psychological respective.

6) Thermal dissatisfaction on hot summer days is determined by thermal sensation and frequency of microclimatic step changes. It can be reduced by enabling a more frequent microclimatic step changes.

7) The range of acceptable *UTCI** is from 36.5℃ to 43.7℃ under different change

frequencies. The needs for much cooler shade for comfort on hot days can be reduced under higher frequency of 0.22 and 0.50.

Acknowledgements

The work described in this paper was fully supported by a grant from the Research Grants Council of the Hong Kong Special Administrative Region, China (Project No. C5002-14G). The authors would like to express their appreciation to Mr. Hung Kit Kenny in preparing instruments, and to Miss Lo Tan Fung for her assistance in conducting on-site measurements.

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Appendix

Three Kipp & Zonen CNR4 net radiometers and black globe thermometers were set simultaneously to evaluate T_{mrt} (Fig. A1). T_{mrt} calculated from the black globe thermometer was calibrated with the T_{mrt} calculated through 6-direction short-wave and long-wave radiation measured by net radiometers (Lam et al., 2020). Eq. (A1) was applied for calculating T_{mrt} through 6-direction radiation. A linear regression was conducted to correct the T_{mrt} values calculated by the black globe method after measurements (Fig. A2).

Fig. A1 Simultaneous evaluation of 15 min T_{mrt} with black globe thermometer method and 6-direction radiation measurement method.

$$T_{mrt} = \left(\frac{\sum F_i \times (\alpha_s Q_s + \alpha_l Q_l}{\alpha_s \sigma}\right)^{1/4} - 273.5 \qquad \text{(A1)}$$

In Eq. (A1) σ is Stefan-Boltzmann constant and equals to 5.67 ·10-8(W/M2K4). α_s and α_l which can be respectively assumed as 0.7 and 0.97 represent the absorption coefficients of human for short-wave and long-wave radiation in normal dressing. F_i presents the angular factor between human and the ambient environment. For a normal standing person, F_i = 0.06 for upper and lower vertical directions, and F_i=0.22 for the four horizontal directions.

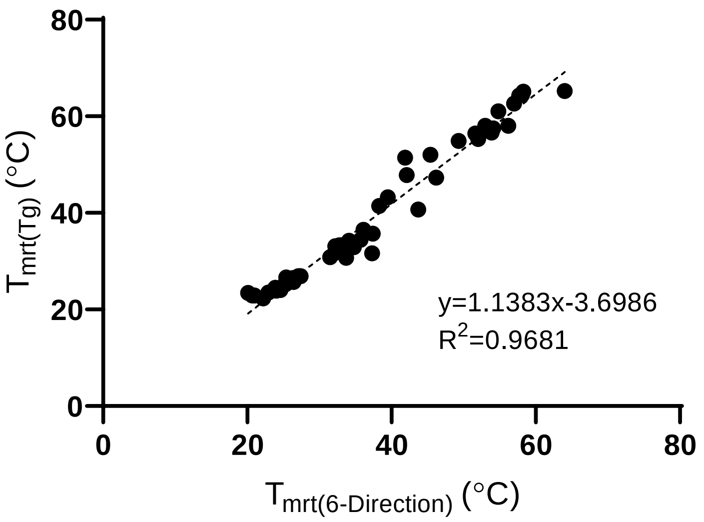

Fig. A2 Relationship between $T_{mrt(Tg)}$ and $T_{mrt(6\text{-}direction)}$. The $T_{mrt(Tg)}$ was calculated by the black globe thermometer method, whereas $T_{mrt(6\text{-}direction)}$ was calculated by the 6-direction radiation measurement methods.

T_{mrt} calculated from the black globe thermometers was thus calculated using Eq. (A2). This equation obtained from linear regression analysis between the two measurement methods (black globe thermometers and 6-direction radiation measurements).

$$T_{mrt(Tg)} = 1.1383 \times T_{mrt(6-Direction)} - 3.6986 \quad \text{(A2)}$$