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Published in:
E3S Web of Conferences

DOI:
10.1051/e3sconf/202567201037

Published: 01/01/2025

Document Version
Publisher's PDF, also known as Version of record

Can different convective local cooling devices satisfy the demands of elderly people in warm conditions?

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Abstract. Local cooling devices can assist elderly people during heat waves and other hot conditions. However, aging makes elderly people less sensitive to environment change and less tolerance to air velocity and air temperature. It is essential to determine if convective local cooling devices can meet the requirements of elderly people. In this study, three convective local cooling devices were chosen, including normal table fan, evaporative cooling device, and air-cooled jacket. Both thermal manikin and elderly people experiments were conducted in a climate chamber under warm conditions. Three convective local cooling devices were evaluated based on objective physical parameters and subjective psychological parameters gained from these experiments. This study found that all three devices achieved an 80% thermal and airflow acceptance rate at 29 °C. However, at 32 °C, only the evaporative cooling device showed the potential to meet the requirements.

Introduction

Against the backdrop of global warming and an aging population, the issue of thermal comfort for the elderly has received increased attention in recent years [1-3]. Compared to younger adults, older adults experience a decline in physiological functions, making them more vulnerable and susceptible to environmental influences [4,5]. Extreme heat conditions and heatwaves can lead to heat-related casualties among the elderly [6]. To guarantee the health and well-being of the elderly, numerous studies have experimentally determined suitable indoor temperature setpoints for them [7-9]. However, on one hand, many regions (such as the Nordic countries) do not have air conditioning installed in residential buildings. On the other hand, the installation and electricity costs of air conditioning pose a significant financial burden for elderly individuals with reduced income. Therefore, it might be worthwhile to explore other more energy-efficient and cost-effective devices or systems for elderly people.

Personal comfort systems (PCS) refer to devices capable of creating a microenvironment around the human body, often acting on specific body parts [10]. From the perspective of heat transfer method, personal comfort systems can be categorized as conductive, convective, and radiative type [11]. The most commonly used in hot environments are typically convective devices, including various kinds of fans such as table fans, ceiling fans, and garment fans. There are many studies on these convective personal comfort systems [12-15]. However, the participants in these studies are usually young adults and may not represent the conditions experienced by the elderly.

Currently, evaluation metrics for personal comfort systems include corrective power (CP) [16], corrective energy & power (CEP) [17], and equivalent temperature (Teq) [18]. CP is defined as difference between two ambient temperatures at which the same thermal sensation is achieved - one with no PCS (the reference condition), and one with PCS in use. The value of CEP index is the ratio of average heating/cooling power for each person and CP of PCS. Teq is a commonly used metric in manikin testing, defined as the uniform ambient temperature at which the manikin's dry heat loss is equal to that under an actual nonuniform environment. When assessing convective devices, the impact of wind speed should also be considered in the evaluation, especially in the vicinity of the head. This is crucial because the elderly are particularly sensitive to airflow, and high-speed airflow is generally not preferred.

In summary, this study aims to evaluate three convective local cooling devices: table fan, evaporative cooling device, and air-cooled jacket, to determine their effectiveness in meeting the needs of the elderly in different warm environments. Evaluation metrics include equivalent temperature (Teq), airflow velocity near the head (V), and the subjective acceptance level of the elderly. Teq and V are obtained through climate chamber thermal manikin experiments, while the subjective acceptance level of the elderly is assessed through climate chamber participant experiments. Finally, a comprehensive evaluation of the three devices is conducted by combining objective parameters with subjective feedback. This research contributes to providing solutions for ensuring thermal comfort for the elderly in hot environments and serves as a reference for the future design of personalized cooling devices.

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Method
A previous study [19] estimated that in Finland in 2050, rooms without cooling systems will experience more hours above 32 °C, whereas rooms with ventilation systems will experience more hours above 27 °C. A previous study [20] showed that the neutral indoor air temperature for elderly people (when the clothing insulation is 0.5 clo) is 26.5 °C. Thus, a total of three conditions were selected in this study including 26 °C, 29 °C and 33 °C. All experiments were conducted in a climate chamber.

1.1 Climate chamber and local cooling devices

The climate chamber, situated in a laboratory hall, measured 5.5 meters in length, 3.8 meters in width, and 3.2 meters in height. It was equipped with a diffuse-ceiling ventilation system, heated simulation windows, and humidifiers. Ventilation air was introduced through 14-mm diameter nozzles strategically drilled along the ceiling panels, spanning the entire ceiling. The chamber's walls incorporated seven heated windows, each measuring 0.6 meters × 1.79 meters. The temperature of these windows was regulated using a water system.

By adjusting the systems and facilities of the climate chamber, the air temperature was maintained at target values of 26 °C, 29 °C, and 33 °C, with relative humidity set between 40% and 50%. Throughout the experiment, air temperature (T_a) and relative humidity (RH) in the climate chamber were continuously measured by six TinyTag 2 plus data loggers (T_a accuracy: ± 0.5 °C, RH accuracy: ± 3%). Additionally, the operative temperature (T_o) and air velocity (v) were measured by ComfortSense probes (T_o accuracy: ± 0.2 °C, v accuracy: ± 0.02 m/s). The air velocity is maintained below 0.05 m/s. The measured environmental parameters in the climate chamber are presented in **Table 1**.

Table 1. Test conditions and actual measured parameters.

Test condition (T_o)		Measured parameters (mean ± SD)	
		T_o	RH
Neutral	26 °C	25.7 ± 0.2 °C	42 ± 2%
Warm	29 °C	29.0 ± 0.2 °C	42 ± 3%
Hot	33 °C	32.6 ± 0.2 °C	38 ± 2%

This study selected three convective local cooling devices that are available on the market and have similar electrical power: the table fan (**Fig. 1(a)**), evaporative cooling device (**Fig. 1(b)**), and air-cooled jacket (**Fig. 1(c)**). The table fan was 230 mm in diameter with an electric power range of 0–25 W (it has two speeds, represented by 50% and 100% power in this study). The evaporative cooling device was 180 mm × 180 mm × 182 mm. It had a medium that was humidified via capillary action using water from a small side tank (1000 mL) and a small fan with an electric power range of 0–10 W (it has ten speeds, represented by 10%, 20%,..., and 100% power in this study). The air-cooled jacket, designed to be worn over clothing, consisted of a spacer vest liner with an impermeable outer layer, two 97-mm wide fans placed symmetrically on the lower back, an internal pocket for a rechargeable battery, and weighed 0.7 kg. The total electric power range is 0–20 W(it has four speeds, represented by 25%, 50%, 75%, and 100% power in this study).

Fig. 1. Local cooling devices: (a) table fan, (b) evaporative cooling device, and (c) air-cooled jacket.

The table fan and air-cooled jacket drew room air, and the evaporative cooling device produced cooler (approximately 2 °C) but more humid air. The table fan and evaporative cooling device were affixed to the table, positioned 1 meter away from the subject. The angle of the device was adjusted to direct airflow towards the torso, mitigating potential adverse effects such as dry eyes and headaches. The size of the jacket (small, medium, or large) was chosen according to the participant's body size.

1.2 Thermal manikin test

To obtain the equivalent temperature (Teq), experiments were conducted using a thermal manikin. We used a thermal manikin from PT TEKNIK, comprising 27 segments. The surface temperature of the manikin's segments was regulated to match a person's skin temperature in a state of thermal neutrality. The experiment was conducted under three conditions: neutral (26 °C), warm (29 °C), and hot (32 °C). As the manikin lacks a sweating module, relative humidity (RH) does not affect it. The thermal manikin simulated a participant seated in a chair, attired in a short-sleeved T-shirt, trousers, socks, and shoes (totalling 0.5 clo) (**Fig. 2**). Across the three conditions, utilizing different devices with varying power levels, the surface temperature and electricity consumption of the 27 segments were recorded every 10 seconds by the accompanying software until all parameters achieved a steady state.

Fig. 2. Thermal manikin test with (a) table fan and (b) air-cooled jacket. (Experiments with the evaporative cooling device fixed in the same position as the table fan were performed as well.).

To obtain the air velocity near the head (V), we placed a SensoAnemo 5100SF sensor (accuracy: ± 0.02 m/s) in front of the manikin's face. The sensor recorded the air velocity at different power levels for each device. It is worth noting that for the table fan and evaporative cooling device, the airflow was frontal, whereas for the air-cooled jacket, the airflow exited from the collar. Therefore, when measuring the air-cooled jacket, the sensor was positioned near the chin, as depicted in **Fig. 3**.

Fig. 3. Location of air velocity measurement near the head when using the air-cooled jacket.

1.3 Elderly people test

The Aalto University Research Ethics Committee authorized and supported this study (D/793/03.04/2021, approved on September 23, 2021). Participants included 26 healthy Finnish elderly people, 7 males and 19 females. Because not every participant was able to participate each time, the number of test participants (N) in each condition varied. The experiment was conducted under three conditions: neutral (26 °C, N = 26), warm (29 °C, N = 24), and hot (33 °C, N = 23). The experimental process is shown in **Table 2**.

Table 2. Schedule of the experiment.

Step	Phase	Time	Participant activities	Data collection
1	Preparation	25 min	Change clothe and prepare	–
2	Rest	35 min	Remain sedentary (unable to use device)	Fill questionnaire at the 35th minute
3	Local cooling	35 min	Free use of local cooling device for 35 minutes	Fill questionnaire at the 15th minute

Each test involved three participants. In step 1, participants entered the climate chamber 25 min earlier for pre-test preparations, such as clothing changes (clothing insulation was 0.5 clo in all tests). In step 2, during the rest phase, the participants were instructed to remain sedentary to adapt to the test environment. During this period, participants were permitted to use computers or read. During the subsequent local cooling phase (step 3), the participants were permitted to rotate the knobs to modify the speed mode of the given local cooling device based on their individual needs; however, they were not permitted to alter the position or angle of the table fan or the evaporative cooling device. Each adjustment to the devices must be documented, including the time and the power level of the device at that moment. After step 3, participants exchanged positions to switch to different local cooling devices. Subsequently, Steps 2 and 3 were repeated until each participant had used all three local cooling devices. At the end of each phase, participants were instructed to complete a questionnaire. The questionnaire including thermal acceptability vote (-3 to +3: clearly unacceptable to clearly acceptable) and airflow acceptability vote (-3 to +3: clearly unacceptable to clearly acceptable).

1.4 Data analysis

In the thermal manikin test, despite the manikin having 27 segments, each of which can yield local equivalent temperatures, this study primarily focused on overall changes. Therefore, only the overall equivalent temperature (Teq) was utilized. The calculation formula is as follows:

$$T_{eq} = T_{sk} - Q/h_{cal} \quad (1)$$

where T_{eq} is the overall equivalent temperature, T_{sk} is the surface temperature of thermal manikin, Q is the electrical power of the thermal manikin, and h_{cal} is the calibration coefficient.

As participants have the flexibility to change the power of local cooling devices based on personal requirements, they may not consistently use the same power level throughout the entire local cooling phase. Therefore, this study employs the average power during the entire local cooling phase to describe the participants' usage of different devices under three conditions. In the thermal manikin test, we only measured the equivalent temperature (Teq) for each power level of the devices independently, without accounting for variations in power. Hence, if the average power for a participant is not an integer, Teq is calculated using interpolation. Unlike Teq, this study opted for the air velocity at the stable state at the end of the local cooling phase as the indicator. Additionally, the air velocity (V) measurement is specifically focused on the area around the head.

The assessment of participants' acceptability in this study refers to the guidelines provided by ASHRAE [21]: "The environment was generally considered to be satisfactory when approximately 80% or more of the occupants accept the environment."

Result

Section 3.1 reports the overall equivalent temperature (Teq) and the air velocity around the head (V) corresponding to different powers of three local cooling devices under three conditions. Section 3.2 illustrates participants' thermal acceptance and airflow acceptance during the rest phase when local cooling devices are not in use. Section 3.3 separately presents the thermal acceptance and airflow acceptance under different Teq and V when using local cooling devices.

1.1 Teq and v of local cooling devices

The overall equivalent temperature (Teq) and air velocity around the head (V) for different powers of three local cooling devices under different conditions are presented in **Table 3**.

Table 3. The overall equivalent temperature (Teq) and the air velocity around the head (V).

Device	Power	Teq under three conditions (°C			V (m/s
		26 °C	29 °C	32 °C	
Table fan	50%	24.8	28.3	31.9	0.16
	100%	24.7	28.1	31.7	0.16
Evaporative cooling device	10%	25.4	28.8	31.4	0.08
	20%	25.3	28.6	31.3	0.09
	30%	25.3	28.5	31.2	0.10
	40%	25.2	28.3	31.1	0.10
	50%	25.1	28.1	31.0	0.11
	60%	24.9	27.8	30.8	0.12
	70%	24.9	27.7	30.8	0.13
	80%	24.8	27.5	30.7	0.13
	90%	24.7	27.3	30.6	0.14
	100%	24.7	27.2	30.5	0.15
Air-cooled jacket	0%	27.0	29.8	32.4	0.03
	25%	24.9	28.4	31.6	1.19
	50%	24.2	27.8	31.2	1.76
	75%	23.9	27.7	31.3	2.04
	100%	23.5	27.4	31.3	2.33

Although the three selected devices in this study have similar electrical power, **Table 3** indicates that their objective effects are dissimilar. The table fan provides the narrowest Teq range (28.1~28.3 °C in warm condition and 31.7~31.9 °C in hot condition), followed by the air-cooled jacket (27.4~28.4 °C in warm condition and 31.3~31.6 °C in hot condition), while the Evaporative Cooling Device offers the widest Teq range (27.2~28.8 °C in warm condition and 30.5~31.4 °C in hot condition). It can be observed that under the 28 °C condition, the air-cooled jacket and the evaporative cooling device can provide a lower Teq. It can also be observed that the greater the number of power levels available for a device, the wider the range of Teq it can provide.

Using the table fan, the V=0.16 m/s; using the evaporative cooling device, the V is smaller than that when using the table fan, ranging from 0.08 m/s to 0.15 m/s; using the air-cooled jacket, the V=1.2~2.3 m/s. The results consist with the cooling principles of these devices: for the evaporative cooling device, the air velocity is lower than the table fan when reaching the same Teq due to its lower outlet air temperature; for the air-cooled jacket, as it relies on high-speed airflow between inner clothing and jacket for cooling, its air velocity is significantly higher than the table fan while maintaining a lower Teq.

Table 3 also presents another information: when wearing the air-cooled jacket without using, Teq is 29.8 °C in 29 °C condition and 32.4 °C in 32 °C condition, reflecting the clothing insulation of the air-cooled jacket itself.

1.2 Thermal and airflow acceptance before using local cooling devices

In the different test condition without using local cooling devices, the thermal acceptance and airflow acceptance of elderly individuals are depicted in **Fig. 4**. The x-axis represents the operating temperature, while the y-axis represents the proportion of thermal acceptability vote (TAV) and airflow acceptability vote (AAV) greater than 0, which means accepting the current condition.

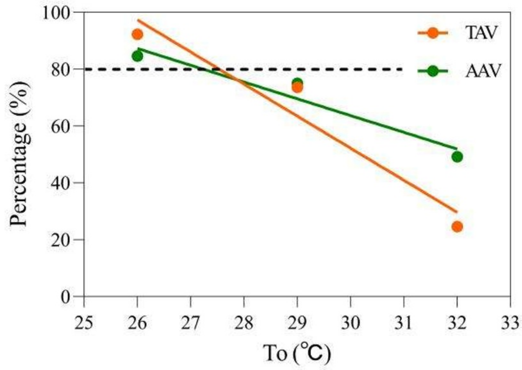

Fig. 4. Thermal acceptance and airflow acceptance before using the devices. (TAV: thermal acceptability vote; AAV: airflow acceptability vote)

Both thermal acceptance and airflow acceptance decreased as the indoor operating temperature increased, with thermal acceptance decreasing faster than airflow acceptance. According to **Table 3**, when not using local cooling devices, the air velocity around the participants is approximately 0.03 m/s. Therefore, to maintain thermal acceptance and airflow acceptance at 80% or above, the indoor temperature should be kept below 27 °C.

1.3 Thermal and airflow acceptance after using local cooling devices

1.3.1 Thermal acceptance and Teq

After using different local cooling devices, the thermal acceptance of participants is illustrated in **Fig. 5**. The red dots in the graph represent the proportion of participants using that Teq, while the green bars represent the proportion of TAV>0 at that Teq, indicating the percentage of individuals accepting the current thermal condition.

Under 29 °C condition, for the table fan, the maximum usage proportion is 46% at Teq=28.3 °C; for the evaporative cooling device, the maximum usage proportion is 42% at Teq=28.4 °C; for the air-cooled jacket, the usage proportion is relatively equal for each

Teq. It can be observed that as long as a device was used, the thermal acceptance rate would be above 80%.

maximum usage proportion is 96% at V=0.16 m/s; for the evaporative cooling device, the maximum usage

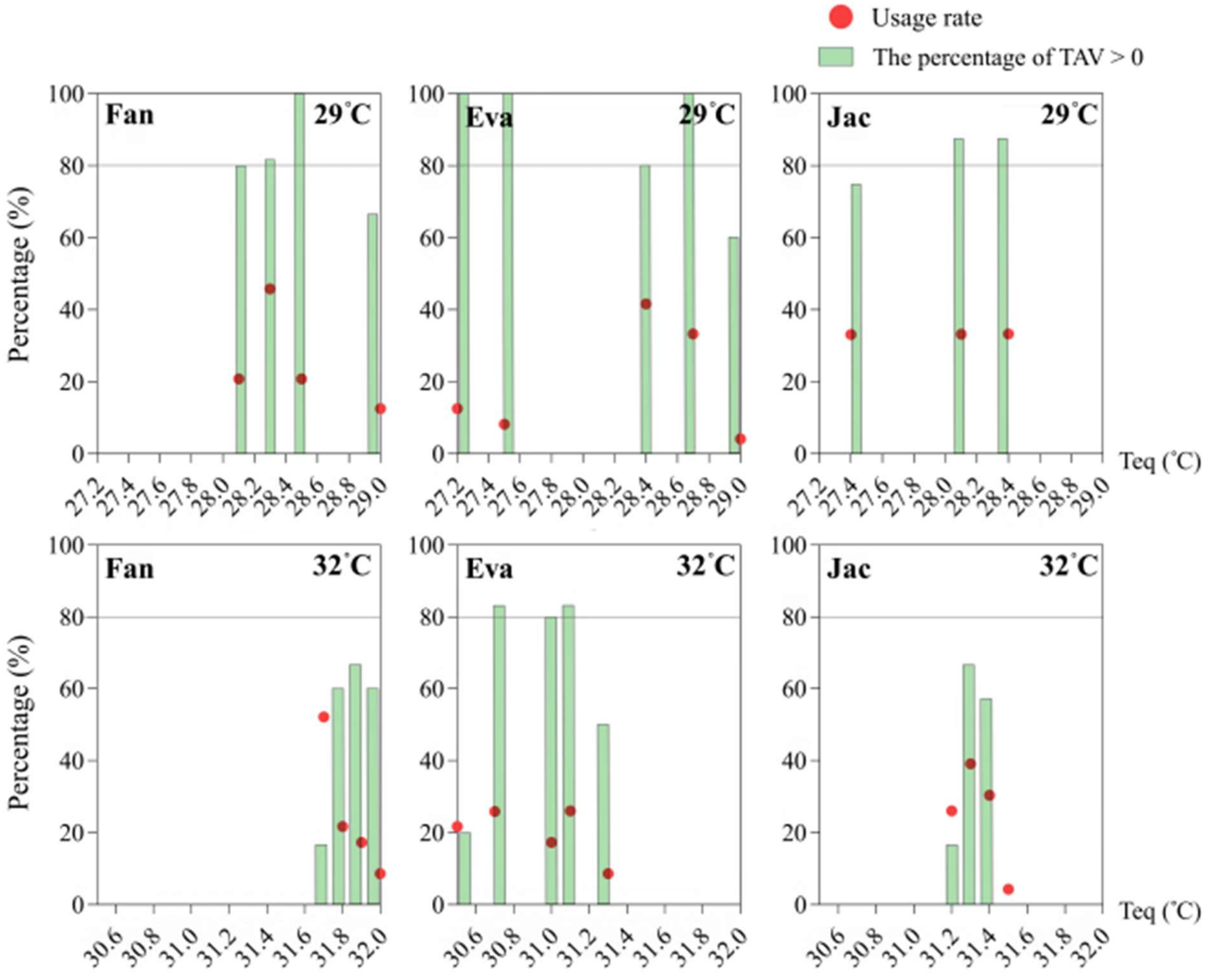

Fig. 5. Thermal acceptance at different Teq values for three local cooling devices under different conditions. (Fan: table fan; Eva: evaporative cooling device; Jac: air-cooled jacket)

Under 32 °C condition, for the table fan, the maximum usage proportion is 52% at Teq=31.7 °C; for the evaporative cooling device, the maximum usage proportion is 26% at Teq=30.7 °C; for the air-cooled jacket, the maximum usage proportion is 39% at Teq=31.3 °C. However, thermal acceptance rate demonstrated a trend above 80% only when Teq was below 31 °C. Therefore, table fan and air-cooled jacket that cannot provide Teq below 31 °C fail to meet the 80% standard.

1.3.2 Airflow acceptance and V

After using different local cooling devices, the airflow acceptance of participants is illustrated in **Fig. 6**. The red dots in the graph represent the proportion of participants using that V, while the blue bars represent the proportion of AAV>0 at that V, indicating the percentage of individuals accepting the current airflow condition.

Under 29 °C condition, for the table fan, the maximum usage proportion is 71% at V=0.16 m/s; for the evaporative cooling device, the maximum usage proportion is 58% at V=0.12 m/s; for the air-cooled jacket, the maximum usage proportion is 38% at V=1.9 m/s. Under 32 °C condition, for the table fan, the proportion is 52% at V=0.1 m/s; for the air-cooled jacket, the maximum usage proportion is 57% at V=2.3 m/s.

Whether under the 29 °C or 32 °C condition, for both the table fan and the evaporative cooling device, when V > 0.12 m/s, the airflow acceptance rate dropped below 80%. This may represent an upper limit of airflow acceptance for the elderly. However, the airflow acceptance rate for the air-cooled jacket, which has much higher velocity than the table fan and the evaporative cooling device, is not as low as expected. This might be due to the fact that the airflow escaped from the collar. Compared to the direct impact on the sensitive face by the table fan and the evaporative cooling device, the elderly individuals may be less affected by the airflow when it acts on the chin.

Conclusion

Through climate chamber manikin experiments and experiments involving elderly individuals, we assessed the effects of three convective local cooling devices in warm environments and reached the following conclusions:

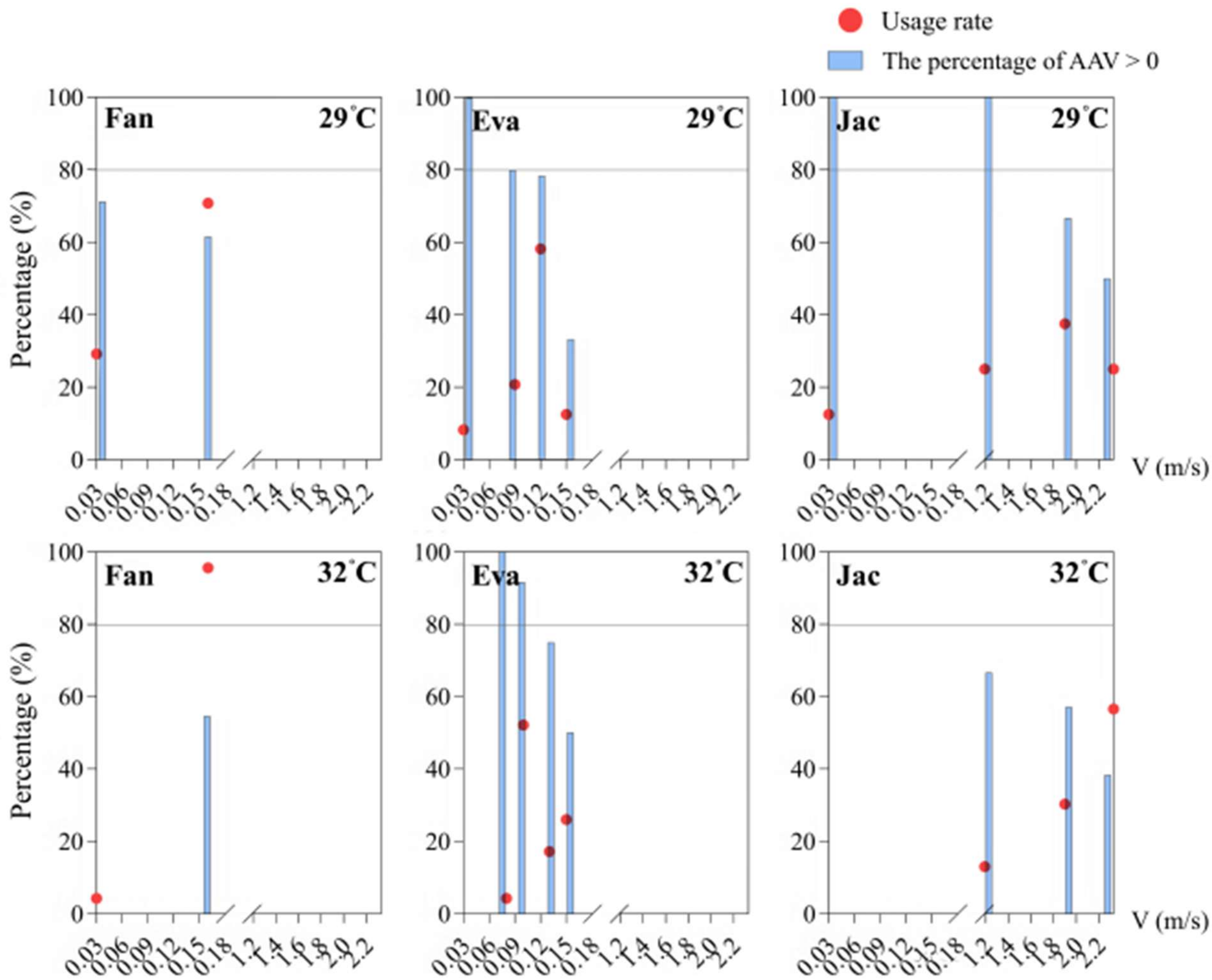

Fig. 6. Airflow acceptance at different V values for three local cooling devices under different conditions. (Fan: table fan; Eva: evaporative cooling device; Jac: air-cooled jacket)

The minimum Teq provided by the table fan is up to 0.2 °C lower than room temperature, while the minimum Teq provided by the evaporative cooling device is around 1.6 °C lower than room temperature under both 29 °C and 32 °C conditions. The air-cooled jacket can provide a minimum Teq that 1.6 °C lower than room temperature under 29 °C, and a minimum Teq that 0.7 °C lower than room temperature under 32 °C.

Without using local cooling devices (v=0.03 m/s), the thermal acceptance rate and airflow acceptance rate are unable to meet 80% when the operating temperature exceeds 27.5 °C.

Under the 29 °C condition, as long as localized cooling devices are used, 80% thermal acceptance rate can be achieved. However, under the 32 °C condition, Teq must be below 31 °C to achieve an 80% thermal acceptance rate.

For airflow directly impacting the face, the air velocity reaching the face needs to be below 0.12 m/s to meet an 80% airflow acceptance rate under both 29 °C and 32 °C conditions.

Among the three selected devices, only the evaporative cooling device has the potential to achieve an 80% acceptance rate under all conditions.

Acknowledgments
This study is part of the following projects: HEATCLIM (Heat and health in the changing climate, Grant Numbers. 329306, 329307) funded by the Academy of Finland within the CLIHE (Climate change and health) program

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