Energy & Buildings 193 (2019) 92–98

Contents lists available at ScienceDirect

Energy & Buildings

journal homepage: www.elsevier.com/locate/enbuild

Fanning as an alternative to air conditioning – A sustainable solution for reducing indoor occupational heat stress

Ollie Jay[a,b,*], Roman Hoelzl[a,c], Jana Weets[a,c], Nathan Morris[a], Timothy English[a], Lars Nybo[e], Jianlei Niu[f], Richard de Dear[f], Anthony Capon[b,d]

[a] The University of Sydney, Thermal Ergonomics Laboratory, Exercise and Sport Science, Faculty of Health Sciences, NSW 2141, Australia
[b] The University of Sydney, Charles Perkins Centre, NSW 2006, Australia
[c] Technische Universität München, Institute of Ergonomics, Boltzmannstraße 15, 85748 Garching, Germany
[d] The University of Sydney, Sydney School of Public Health, Faculty of Medicine and Health, NSW 2050, Australia
[e] Section for Human Physiology, Faculty of Sciences, University of Copenhagen, Denmark
[f] The University of Sydney, School of Architecture, Design and Planning, NSW 2006, Australia

ARTICLE INFO

Article history:
Received 21 August 2018
Revised 20 March 2019
Accepted 22 March 2019
Available online 23 March 2019

Keywords:
Convection
Climate
Energy conservation
Evaporation
Occupational heat stress

ABSTRACT

We assessed whether increasing airflow with an electric fan is similarly effective as decreasing air temperature with air cooling (AC) in preventing heat-related reductions in productivity, and elevations in body temperatures and discomfort in a warm/humid indoor environment. In 48 experimental trials, we compared the reduction in the human heat stress response of sixteen participants during 135 min of intermittent arm ergometry at a fixed heart rate of 110 beats min^{-1}, from a simulated tropical environment (HOT; 30 °C, 70%RH; wind <0.2 m s^{-1}) to that observed with either a, (i) 7 °C reduction in air temperature (AC; 23 °C, 70%RH, wind <0.2 m s^{-1}); or (ii) facilitated airflow (FAN; 30 °C, 70%RH, wind = 4.2 m s^{-1}). Cumulative work was similarly improved (+11%) by FAN compared to AC. Likewise, reductions in rectal temperature, thermal sensation, and thermal discomfort were similar with the two different cooling strategies. Sweat losses in the FAN trial were higher compared to AC but lower than HOT without fanning. In conclusion, fanning offers an effective method for alleviating thermal stress and preventing productivity losses for workers exposed to environmental heat. Moving air instead of chilling it may require a little more sweating, but it can save electricity and hence lower greenhouse gas emissions compared to AC.

1. Introduction

Progressive increases in global temperatures [12] have already exerted disproportionately negative effects on the health and well-being of people in densely populated low-income countries with tropical climates. These impacts are particularly evident in indoor working environments [22] where goods destined for consumers in high-income countries are often manufactured in factories without air conditioning or any other effective cooling systems in place [5,35].

In hot occupational environments that require elevated physical activity, manual work intensity must be reduced to mitigate rising body temperatures and excessive heat-related elevations in heart rate [18,27] that occur following a cutaneous vasodilation [33], as well as thermal discomfort [10] and dehydration [37]. Indeed, the World Health Organisation (WHO) has recommended that work intensity should be maintained at a level that does not permit heart rate to exceed, on average, 110 beats min^{-1} [38]. However, worker salaries in many developing countries are typically tied to absolute daily productivity [20], so factory employees must work longer hours during the hottest months of the year in order to receive the same income without experiencing excessive heat-related strain/discomfort [17]. Currently, workers in countries such as Bangladesh, Cambodia, India, Pakistan and Viet Nam are estimated to lose ∼1–4% of daylight work hours per year due to extreme heat, with these losses projected to rise to ∼15–20% of daylight working hours over the next 70 years [16,19] if greenhouse gas emission rates continue along the "business as usual" trajectory. It therefore seems inevitable that from legal, ethical and business perspectives better cooling systems must be used on a large scale as global temperatures continue to rise [11].

Cooling air with air conditioning is currently the most effective cooling strategy for mitigating worker heat stress [9] with the indoor temperature set-point in many tropical countries typically

* Corresponding author at: Dr. Ollie Jay, Thermal Ergonomics Laboratory, Faculty of Health Sciences, University of Sydney, 75 East St, Lidcombe, NSW 2141, Australia.
E-mail address: ollie.jay@sydney.edu.au (O. Jay).

https://doi.org/10.1016/j.enbuild.2019.03.037
0378-7788/

~23 °C [21], with air velocity typically < 0.2 m s^{-1} [6]. Yet the immediate and downstream environmental impacts of air conditioner use are enormous in terms of greenhouse gas emissions [5] and the worsening of current [24] and future heat-related weather extremes [26]. The electricity demands required to support such intensive use of air conditioning, even with future advances in energy efficiency, would also likely contribute substantially to emerging energy crises in numerous countries/regions [5].

An air conditioner cools a person by increasing dry heat loss through lowering air temperature and thus widening the temperature gradient between the skin and the surrounding environment. However one of the two principal dry heat loss components, convection, can also be augmented without lowering air temperature, provided it is lower than skin temperature (~35 °C [13]), by simply increasing the rate at which air flows across the skin surface [8]. Moreover, greater convective flow can also accelerate the rate at which sweat evaporates from the skin surface, thus enhancing latent heat loss [15]. Theoretically therefore, in many situations/conditions blowing air across the skin of a worker with a device such as an electric fan can yield a similar physical, physiological and perceived cooling effect as cooling the air, and likewise moderate heat-related reductions in work performance at a fixed heart rate, but with a much lower electricity requirement/cost and concomitant environmental impact.

The aim of the present study was to assess the efficacy of electric fan use for mitigating heat-related reductions in work output, and elevations in body temperatures and thermal discomfort without exceeding an average heart rate of 110 beats min^{-1} [38] in a hot simulated workplace (30 °C, 70% relative humidity) in comparison to the cooling benefits observed with the reduction in air temperature typically obtained with air conditioner use (i.e. 23 °C). It was hypothesized that given the comparable improvement in dry heat loss between an increase in air velocity from 0.2 to 4.2 m s^{-1} (at 30 °C), and a decrease in air temperature from 30 °C to 23 °C (with 0.2 m s^{-1} air velocity), the cooling benefits with fan use at 30 °C, 70%RH, in terms of a greater work output at a fixed heart rate and a lower thermal strain and discomfort, would be similar to those observed with a reduction in air temperature of 7 °C.

2. Methods

2.1. Participants

Sixteen participants (5 females, 11 males) with a mean ± SD age of 26 ± 5 years and body mass of 73.1 ± 11.5 kg were recruited to participate in the study. Females were tested during their follicular phase (between 2 and 8 days into the menstrual cycle) or were taking oral contraceptive [36]. All participants were healthy and without a history of respiratory, metabolic, cardiovascular disease, or diabetes. Each participant voluntarily provided written informed consent prior to commencing the study. The study received prior approval from the University of Sydney Human Research Ethics Committee conforming to the principles set forth in the Declaration of Helsinki, 2013. All trials were completed in a climate chamber in the Thermal Ergonomics Laboratory at the University of Sydney, New South Wales, Australia. In order to minimise any potential differences in heat acclimatisation status among participants, all data collection took place in the Australian summer months (December 2016 to February 2017 [$n = 12$]; and December 2017 to January 2018 [$n = 4$]). All trials for each participant were conducted within 4 weeks and separated by a minimum of 24 h.

2.2. Fixed heart rate experimental model

A fixed heart rate experimental model (Fig. 1) was used in order to assess the effective cooling attributable to the two different environmental modifications in the present study: an increase in radiative and convective heat loss secondary to a reduction in operative temperature (Air Cooling (AC) trial), and a greater convective and evaporative heat loss due to an increase in air velocity without any change in air temperature (HOT-FAN trial). The increase in skin surface heat loss and parallel reduction in skin temperature serves to diminish the requirement for increases in skin blood flow mediated by a cutaneous vasodilation. The greater volume of oxygenated blood that can be subsequently delivered to the working musculature at a fixed heart rate enables the generation of a higher work output on the arm ergometer. Any differences in work output can thus be directly attributed to differences in skin surface heat loss.

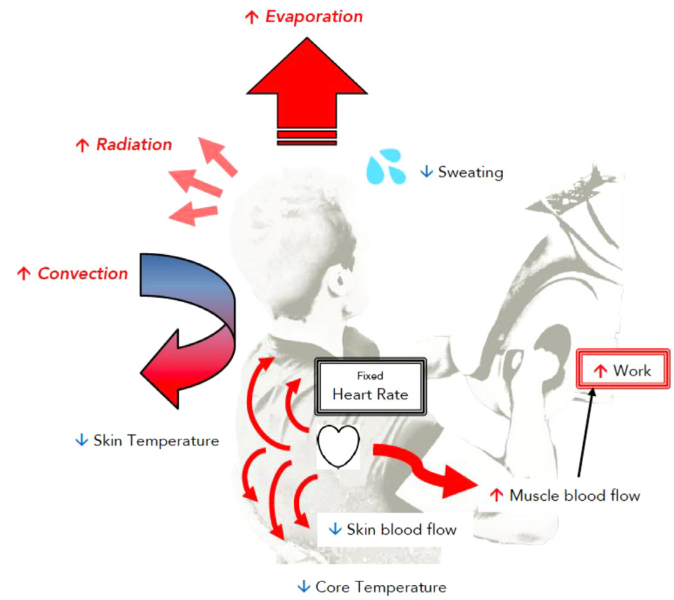

Fig. 1. A description of the link between modifications of skin surface heat loss and measured external work using a fixed heart rate experimental model.

2.3. Protocol

Preliminary session: Each participant completed a preliminary trial to become familiar with the experimental protocol and procedures. In order to mitigate any learning effects in the cognitive tasks, each participant completed five alternate repetitions of the d2 test and word recall test separated by 30 s. After, each participant completed 10 min of arm ergometry in order to determine the approximate resistance required to initially elicit the target HR of 110 beats min^{-1}.

Experimental session: Each participant completed three experimental trials presented in a counterbalanced order on separate days. On two occasions environmental conditions were regulated to mimic the mean summer indoor conditions previously measured (personal communication: Prof. Tord Kjellstrom) in a textile factory in Viet Nam (30 °C, 70%RH), with (1) 4.2 m/s of air flow (measured with a hot wire anemometer; (VelociCalc 9535, TSI Inc, Shoreview MN, USA) blowing air from an 18-inch diameter electrical fan (45 cm Moretti High-Speed Fan, Australia) placed a distance of 1 m diagonally behind the participant (HOT-FAN; Fig. 2), or (2) with still air (< 0.2 m/s) on another occasion (HOT-NO FAN). On a third occasion, ambient temperature within the chamber was regulated at 23 °C, 70%RH with still (< 0.2 m/s) air (AC).

Upon arrival, the participant donned a standardized clothing ensemble consisting of a cotton t-shirt, shorts, socks and running shoes, and was instrumented. Following 15 min of baseline rest in

Fig. 2. Photograph of experimental set-up.

a neutral environment, the participant entered the chamber and was weighed. The trial then commenced with thermal sensation and thermal comfort assessed, followed by the cognitive tasks (d2 test and word recall test), which required a total of 10 min, and then 20 min of seated arm ergometry (Angio 917,902, Lode, Netherlands) with the external workload constantly adjusted to maintain a fixed heart rate of 110 beats min^{-1}. This 30-min cycle (10 min cognitive task followed by 20 min of physical work) was repeated a total of 4 times with the last work bout followed by a final 10-min cognitive test and a final body mass measurement, resulting in a total trial length of 130 min.

2.4. Instrumentation

Rectal temperature (T_{re}) was measured using a Mon-a-therm general-purpose thermistor probe 400TM (Covidien, Mansfield, MA, USA) that was self-inserted to 12 cm beyond the anal sphincter. Skin temperature was measured using wireless iButtons (DS1921H, Maxim Integrated Products Inc., San Jose, CA, USA) secured to the chest, shoulder, thigh and calf using hypoallergenic surgical tape [23]. Mean skin temperature (T_{sk}) was estimated using a 4-point weighted mean according to Ramanathan [32]. Heart rate (HR) was monitored using a Polar RS 400 watch with chest strap (Polar Electro Oy, Kempele, Finland). Whole body sweat loss (WBSL) was estimated from pre- and post-trial body mass ($\pm$2 g) measurements [4] using a platform scale (Mettler, Germany).

Participants were asked to rate their thermal sensation (TS) using a bipolar 200 mm scale ranging from “very cold” (0 mm), through “neutral” (100 mm), to “very hot” (200 mm), and thermal discomfort (TD) using the same scale ranking from “not uncomfortable” (0 mm) through “slightly uncomfortable” (40 mm) and “uncomfortable” (80 mm) to “very uncomfortable” (120 mm). Word recall test performance assessing short-term memory was evaluated using the percentage of correctly recalled words from a total of 15 words presented in 2-s intervals on a computer screen. Performance of the “d2 test”, evaluated attention/scanning speed by asking participants to identify on a page any letter “d” with two dots above it or below it, in any order, among surrounding distractors such as a “p” with two dots, or a “d” with one or three marks. Responses were assessed using the percentage of correctly identified and marked “d2s” on a page of a total of 14 rows consisting of 56 d2s each (total = 784 d2s) [2].

2.5. Statistical analysis

Cumulative physical work output for the entire trial and WBSL were assessed using a one-way repeated measures analyses of variance (ANOVA) employing the independent variable of “condition” (3 levels: HOT-FAN, HOT-NO FAN, AC). A two-way repeated measures with the independent variable of condition and “time” (9 levels: baseline (BL), and then at the end of each alternating bout of work [W1, 2, 3 and 4] and then rest [R1, 2, 3 and 4]) was used to assess the dependent variables of HR, T_{re}, T_{sk}, TS, and TD, as well performance in the d2 and word recall tests. All two-way ANOVAs included a Mauchly’s test for sphericity and applied a Greenhouse–Geisser correction factor if required. If a significant main effect or interaction was observed, post-hoc comparisons were conducted using a Holm-Sidak multiple comparisons test. A critical alpha level error of 0.05 was maintained throughout. All statistical analyses were conducted using GraphPad Prism Version 7.0 for Windows (Graphpad Software, La Jolla, CA, USA).

3. Results

3.1. Work output

Cumulative work output (Fig. 3A–D) was altered by condition ($p < 0.001$), with more work completed in the AC (269 ± 92 kJ; $p < 0.001$) and HOT-FAN (261 $\pm$ 92 kJ; $p = 0.001$) trials relative to the HOT-NO FAN trial (236 $\pm$ 84 kJ), but similar work output between AC and HOT-FAN ($p = 0.46$). Notably, 14 of 16 participants performed more work in the HOT-FAN trial relative to the HOT-NO FAN trial (Fig. 3B), and 13 of 16 participants performed more work in the AC trial compared to the HOT-NO FAN trial (Fig. 3C). Yet, only 9 of 16 participants completed more work in the AC trial compared to the HOT-FAN trial (Fig. 3D).

3.2. Heart rate

By design, HR was similar throughout between all trials ($p = 1.00$), with mean HR 109 $\pm$ 2 beats min^{-1} in AC, 109 $\pm$ 2 beats min^{-1} in HOT-FAN, and HR 109 $\pm$ 2 beats min^{-1} in HOT-NO FAN.

3.3. Core and mean skin temperature

While T_{re} increased from baseline once physical work began ($p < 0.001$), the change in T_{re} was influenced by condition ($p = 0.036$) (Fig. 4A) with greater rises in T_{re} observed in the HOT-NO FAN trial during and after the fourth bout of physical work compared to both the HOT-FAN (W4: $p = 0.007$; R4: $p = 0.008$) and AC trials (W4: $p = 0.012$; R4: $p = 0.010$).

Skin temperature was higher ($p < 0.001$) throughout the HOT-NO FAN trial compared to the HOT-FAN and AC trial by ~1.5 °C and ~2.0 °C respectively (Fig. 4B). However, at all but one time point (W2) T_{sk} was ~ 0.5 °C higher in the HOT-FAN trial ($p < 0.028$) compared to AC.

3.4. Whole body sweat loss

Cumulative whole-body sweat losses (Fig. 3C) were altered by condition ($p < 0.001$), with WBSL greater in the HOT-NO FAN trial (724 $\pm$ 283 g) compared to HOT-FAN (645 $\pm$ 259 g; $p = 0.038$) and AC trials (564 $\pm$ 260 g; $p < 0.001$). WBSL was also greater in the HOT-FAN trial compared to the AC trial ($p = 0.038$). Converted into whole-body sweat rates (in g h^{-1}), values were 322 $\pm$ 130,

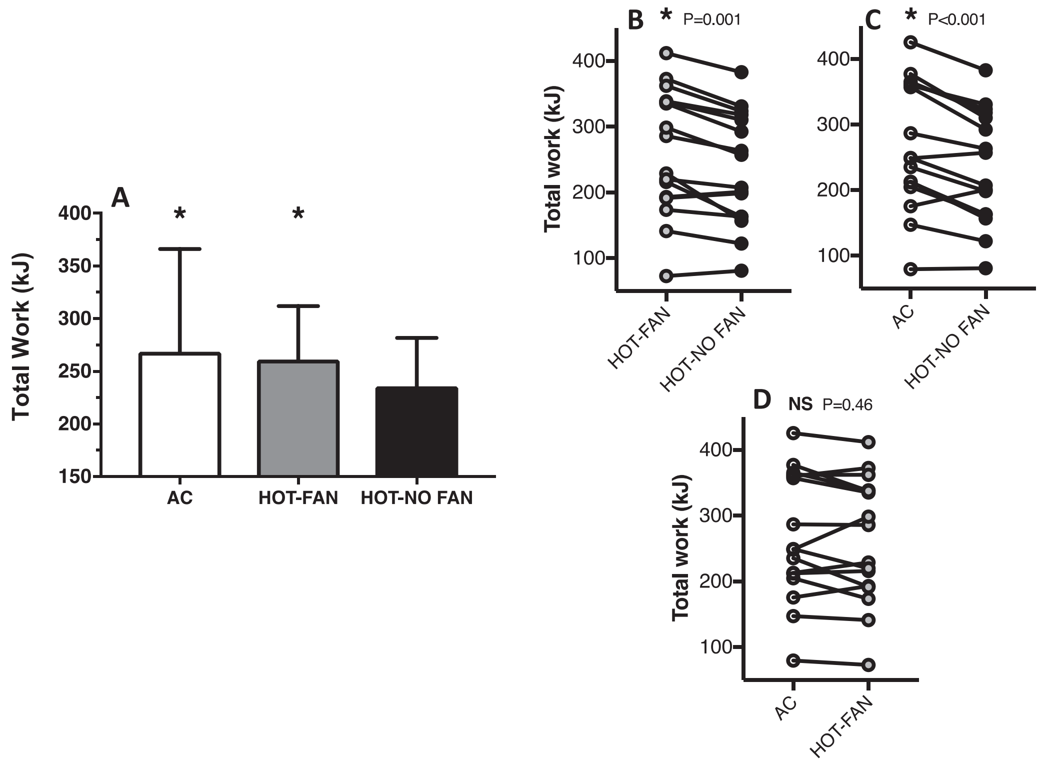

Fig. 3. (**A–D)** Mean total work (A) performed throughout the entire experimental protocol in the hot still air (HOT-NO FAN; black bar), hot with fan use (HOT-FAN; grey bar) and air conditioned (AC; white bar) trials. Error bars are SD. Panels B–D report individual data [$n = 16$] for each condition. Asterisk (*) different to the HOT-NO FAN condition ($p \leq 0.001$).

287 ± 119, and 251 ± 119 g h^{-1} in the HOT-NO FAN, HOT-FAN and AC trials respectively.

3.5. Thermal sensation and discomfort

A greater level of thermal discomfort (Fig. 5A) was reported in the HOT-NO FAN compared to the HOT-FAN and AC trials ($p < 0.001$). Moreover, as trial time progressed a gradual alteration in thermal discomfort was observed ($p = 0.007$) with a greater level of discomfort reported in the AC trial during the third ($p = 0.002$) and fourth ($p = 0.004$) bout of physical work compared to the HOT-FAN trial.

A main effect of condition ($p < 0.001$) was observed for thermal sensation (Fig. 5B), with TS cooler in HOT-FAN and AC trials compared to HOT-NO FAN ($p < 0.001$), but a similar TS observed between HOT-FAN and AC trials throughout ($p = 0.28$).

3.6. Cognitive performance

Performance in the d2 test was not different between conditions ($p = 0.52$) but declined with trial time ($p = 0.035$). The mean number of correct answers was 83 ± 13%, 83 ± 12% and 82 ± 14% in the HOT-NO FAN, HOT-FAN and AC trials respectively. Similarly, word recall test performance was not different between conditions ($p = 0.58$) or altered by trial time ($p = 0.58$), with the mean number of correctly recalled words 9 ± 2, 10 ± 2 and 10 ± 2 in the HOT-NO FAN, HOT-FAN and AC trials respectively.

4. Discussion

An increase in convective flow using a simple electric fan in conditions corresponding to a typical hot occupational environment in South East Asia (30 °C, 70%RH) yielded improvements in cumulative work output, thermal sensation and discomfort at a fixed heart rate of 110 beats min^{-1}, that were all at least equivalent to those resulting from a ~7 °C reduction in air temperature. Despite the greater work output with fan use at 30 °C, 70%RH, skin temperatures were ~1.5 °C lower than without fanning and participants were less dehydrated.

Forcing air across the skin is a much less electricity-intensive cooling strategy than chilling air. In the present study we used an air temperature of 23 °C as a reference condition (air cooling trial) as this is the typical indoor temperature set-point employed in air conditioned places in many SE Asian countries [21], albeit not with the slightly elevated air movement that sometimes accompanies indoor air conditioning. Moreover, it should be noted that 70% RH is very much at the upper humidity limit for thermal comfort at 23 °C [1] and a true air-conditioned environment would likely be at a lower relative humidity. The ambient conditions of 30 °C, 70%RH were chosen to mimic the mean summer indoor conditions in many occupational settings. The electricity requirement of the fan used in the present study was 55 W, which is approximately 30-times lower than the wattage required using central air conditioning to cool a 90 m^3 working space with 6 occupants with a sedentary rate of metabolic heat production with no additional heat from machinery and equipment. Even if each occupant is targeted with an individual fan, this basic and rather conservative estimate suggests that the electricity requirements and associated CO_2 emissions for convectively cooling each individual could still be one-fifth of air conditioning. In view of the projected dramatic rise of potential air conditioner use with global warming in heavily populated countries such as India, China, Indonesia, Viet Nam, Thailand and Bangladesh [5], advocacy of convective cooling as an effective alternative that is cleaner, has lower capital and operating costs, and contributes negligibly to peak demand problems on electricity infrastructure, would seem to be judicious. Indeed,

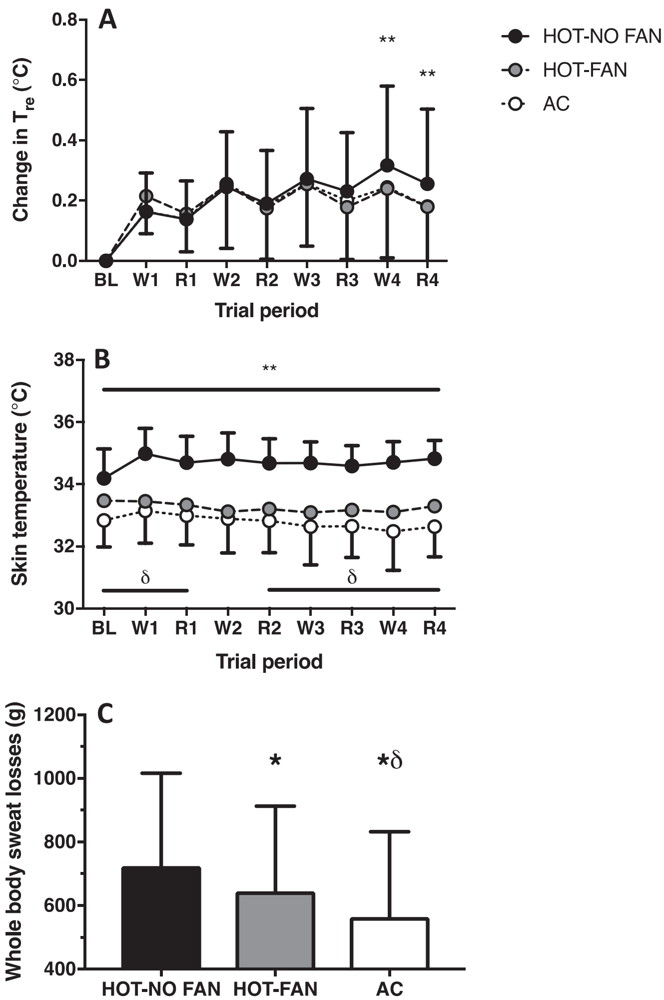

Fig. 4. **(A–C)** Mean change in rectal temperature (A), and mean skin temperature (B) during baseline (BL), four work (W1-4) and four rest (R1-4) periods; and whole body sweat loss (C) throughout the entire trial in the HOT-NO FAN (black), HOT-FAN (grey) and AC (white) trials. Error bars are 95% CIs. Asterisk (*) different to HOT-NO FAN. Double asterisk (**) both AC and HOT-FAN different to HOT-NO FAN. Delta (δ) different to HOT-FAN.

moving rather than chilling air may be cleaner still if the energy demands required to generate convective flow are met using renewable means (e.g. solar power). It is unclear whether other low-energy cooling strategies, such as cooling vests, may elicit a similar effect on work output in the same setting. However, it is usually necessary to regularly replace the cooling stimulus (e.g. ice/cold packs) to prevent a diminished efficacy of conductive skin contact cooling, and relatively large-scale refrigeration/freezing is still required to individually equip a workforce with such cooling garments.

A greater amount of work at a fixed heart rate was possible in the HOT-FAN and AC trials compared to the HOT-NO FAN condition, presumably due to a lower physiological requirement to deliver blood to the skin surface and therefore a greater availability of blood to deliver oxygen to working muscles. While skin blood flow was not measured, the blunted rise in skin temperature in the HOT-FAN and AC trials likely led to a lower locally mediated cutaneous vasodilation [25]. In both cases elevations in skin temperature were mitigated by a greater dry heat loss, augmented by a greater convective heat transfer coefficient in the HOT-FAN trial, and a greater temperature gradient between skin and air enhancing heat loss by both convection and radiation in the AC trial. In the case of the HOT-FAN trial, skin temperature rises would have been further blunted by enhanced sweat evaporation secondary to a higher evaporative heat transfer coefficient. Despite the greater metabolic rate associated with higher work rates in the HOT-FAN trial and AC trials, the rate of dehydration, indicated by whole-body sweat losses, was lower in both trials compared to the HOT-NO FAN trial. In both trials higher rates of internal heat production would have been offset by greater non-evaporative heat loss (i.e. convection and/or radiation) requiring less evaporation, and therefore sweating to attain heat balance. Moreover, the greater convective flow across the skin with fan use would have also increased evaporative efficiency resulting in the evaporation of a greater proportion of secreted sweat compared to a relatively still environment [3].

The rise in rectal temperature was slightly blunted (~0.1 °C) by either fan use or air cooling towards the end of the 135-min trial, despite a greater internal heat production associated with a higher work output. Moreover, the environment was perceived to be cooler and less uncomfortable in both the HOT-FAN and AC trials compared to the HOT-NO FAN trial. Notably, these subjective sensations were at least as cool and comfortable with fan use at 30 °C than without fan use at 23 °C. The slightly greater level of discomfort reported in the AC trial relative to the HOT-FAN trial may be attributable to a greater wettedness since a more complete evaporation of secreted sweat on the skin surfaces exposed to greater air flow would be expected with fan use and therefore a lower local skin wettedness despite a higher whole-body sweat rate [7]. Again, it should be noted that in a truly air-conditioned environment air velocity may be elevated in some areas, and relative humidity would likely be lower, relative to the present AC trial such that these differences may not be observed in a real-world setting. No differences in cognitive performance were observed between trials using the tasks selected to assess short-term memory (word recall) and attention/scanning speed (d2 test). Recent evidence suggests that while minimal to no influence of the heat

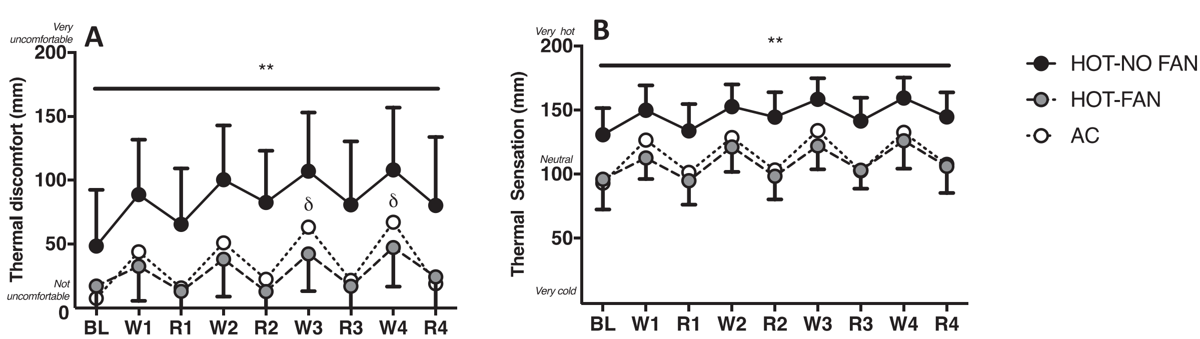

Fig. 5. **(A,B)** Mean thermal discomfort (A) and thermal sensation (B) scores at baseline (BL) and during the four work (W1-4) and four rest (R1-4) periods in the HOT-NO FAN (black), HOT-FAN (grey) and AC (white) trials. Error bars are 95% CIs. Asterisk (*) different to HOT-NO FAN. Double asterisk (**) both AC and HOT-FAN different to HOT-NO FAN. Delta (δ) AC different to HOT-FAN.

is observed on simple cognitive tasks, the performance of combined cognitive and complex motor tasks may be impaired [31]. Whether heat-related decrements in these more complex tasks are improved by convective flow, if indeed they are ecologically relevant to a particular occupational setting, is yet to be determined.

The fixed heart rate experimental model employed in the present study was chosen above other fixed physiological parameters for several reasons; indeed, if sweat rate was the fixed variable then work output may have declined with fan use. A fixed heart rate seems to be most consistent with how exercise (and thus work) output is self-regulated with an increasing heat load. Rather than simply accepting ever increasing body temperatures, work output tends to be selected to maintain a stable cardiovascular load [14,29,30]. Variables such as sweat rate only indirectly determine self-selected work output secondarily throughout alterations in cardiovascular load, and only after reaching a critical level of dehydration [34]. Practically speaking, heart rate is also easily measured with good accuracy. The average heart rate limit of 110 beats min^{-1} employed in the present study was based on a recommendation from a WHO scientific report for working conditions of heat stress [38] for workers conducting physical activity for a complete work day, and not 130 min. As the authors of the report suggest, several factors including worker age and physical condition must also be considered when choosing an appropriate target heart rate. Future studies employing activities that engage larger muscles groups (e.g. treadmill walking) and different clothing properties for similarly shorter durations might require a higher target heart rate limit as the combined heat stress might elicit average heart rates exceeding 110 beats min^{-1} with little or even no work performed. For future studies using the arm ergometry model employed in the present study, within-subject comparisons might be better performed using a fixed change in heart rate from thermoneutral rest, as participants with low resting heart rates require quite a high work output to achieve 110 beats min^{-1} which can prove quite difficult due to local muscular fatigue.

A major limitation for using the horizontal movement of air mass to induce convective flow across the skin in some occupational environments is the potentially hazardous disturbance of particulate matter or gases causing ocular and/or respiratory distress. However for jobs that require the worker to be seated, the recent development of personal comfort systems composed of a user-controlled chair with built-in low-energy fans individually targeting the back of the torso and upper legs [28] may provide a safe alternative to the use of pedestal and floor fans or inducing high levels of environmental mass flow. The efficacy of these devices for cooling seated but physically active workers in hot occupational environments would require experimental verification. Other future research directions include the assessment of the impact of clothing, which may vary considerably between different countries and cultures, upon the cooling effect of moving air instead of chilling it. Moreover, while the upper ambient temperature tested in the present study was based on in-situ environmental measurements, the potentially diminishing benefit of convective cooling at higher air temperatures, particularly those over 35 °C when increases in dry heat loss with greater air flow become dry heat gain, need to be determined with different humidity levels. Even at the same ambient temperature as the present study, greater level of humidity would also limit the observed benefit of fanning. Collectively, while the present study demonstrates proof-of-concept for fan use as an alternative cooling strategy to air cooling, applications will ultimately be limited depending on the environment, as well as clothing of the individual. While the fixed heart rate method is based on the notion that workers will naturally self-regulate work output to attain a stable cardiovascular load [14], it is possible that if self-pacing was permitted in the present study the differences in work output would have been eliminated; however this would have presumably occurred at the expense of a greater physiological and perceptual strain. Finally, fanning within spaces that are still air-conditioned also has the potential to drastically reduce net HVAC energy demands. The greater convective and evaporative heat loss for a given air temperature ($<$35 °C) with more air movement means that the same net cooling effect can be achieved with less air cooling. The high air speeds used in the present study would likely induce thermal discomfort at lower air temperatures but augmented air movement up to ~1 m s^{-1} [1] should still elevate the upper air temperature at which thermal discomfort for a particular workload occurs.

In conclusion, compared to no fan use in conditions representative of a typical hot occupational environment in South East Asia (30 °C, 70%RH), the use of a simple electric fan yielded equivalent improvements in work output (~11%) at a fixed average heart rate (of 110 beats min^{-1}) to a ~7 °C reduction in air temperature. In parallel, reductions in skin temperature, thermal sensation, and the rate of dehydration, as well as improvements in thermal comfort with fan use compared to no fan use at 30 °C, 70%RH were all similar to a 23 °C, 70%RH environment. Cognitive performance of tasks selected to assess short-term memory and attention/scanning speed were similar in all conditions.

Funding

This study was funded by a University of Sydney Bridging Grant.

Declaration of interests

None.

References

[1] ANSI/ASHARE, Standard 55: 2017, Thermal Environmental Conditions for Human Occupancy, ASHRAE, Atlanta, 2017.
[2] M.E. Bates, E.P. Lemay Jr., The d2 test of attention: construct validity and extensions in scoring techniques, J. Int. Neuropsychol. Soc. 10 (2004) 392–400.
[3] V. Candas, J.P. Libert, J.J. Vogt, Influence of air velocity and heat acclimation on human skin wettedness and sweating efficiency, J. Appl. Physiol. 47 (1979) 1194–1200.
[4] S.N. Cheuvront, R.W. Kenefick, CORP: improving the status quo for measuring whole body sweat losses, J. Appl. Physiol. 123 (2017) 632–636.
[5] L.W. Davis, P.J. Gertler, Contribution of air conditioning adoption to future energy use under global warming, P. Natl. Acad. Sci. USA 112 (2015) 5962–5967.
[6] R.J. DeDear, G. Brager, Developing an adaptive model of thermal comfort and preference, ASHRAE Trans. 104 (1998) 145–167.
[7] T. Fukazawa, G. Havenith, Differences in comfort perception in relation to local and whole body skin wettedness, Eur. J. Appl. Physiol. 106 (2009) 15–24.
[8] A.P. Gagge, Y. Nishi, Heat exchange between human skin surface and thermal environment, sect. 9, in: Handbook of Physiology, American Physiological Society, Bethesda, MD, 1977, pp. 69–92.
[9] F. Golbabaei, A. Mazloumi, S.M. Khani, Z. Kazemi, M. Hosseini, M. Abbasinia, S.F. Dehghan, The effects of heat stress on selective attention and reaction time among workers of a hot industry: application of computerized version of Stroop test, J. Health Saf. Work 5 (2015) 240–246.
[10] R.T. Gun, G.M. Budd, Effects of thermal, personal and behavioural factors on the physiological strain, thermal comfort and productivity of Australian shearers in hot weather, Ergonomics 38 (1995) 1368–1384.
[11] S. Hallegatte, Strategies to adapt to an uncertain climate change, Global Environ. Change 19 (2009) 240–247.
[12] J. Hansen, M. Sato, R. Ruedy, K. Lo, D.W. Lea, M. Medina-Elizade, Global temperature change, Proc. Natl. Acad. Sci. USA 103 (2006) 14288–14293.
[13] J.D. Hardy, E.F. Dubois, The technique of measuring radiation and convection, J. Nutr. 15 (1938) 461–475.
[14] N. Junge, R. Jørgenson, A.D. Flouris, L. Nybo, Prolonged self-paced exercise in the heat–environmental factors affecting performance, Temperature 3 (2016) 539–548.
[15] G.P. Kenny, O. Jay, Thermometry, calorimetry, and mean body temperature during heat stress, Compr. Physiol. 3 (2013) 1689–1719.
[16] T. Kjellstrom, Impact of climate conditions on occupational health and related economic losses: a new feature of global and urban health in the context of climate change, Asia Pac. J. Public Health 28 (2016) 28S–37S.

[17] T. Kjellstrom, I. Holmer, B. Lemke, Workplace heat stress, health and productivity—an increasing challenge for low and middle-income countries during climate change, Global Health Action 2 (2009) 2047.
[18] T. Kjellstrom, R.S. Kovats, S.J. Lloyd, T. Holt, R.S. Tol, The direct impact of climate change on regional labor productivity, Arch. Environ. Occup. Health 64 (2009) 217–227.
[19] T. Kjellstrom, B. Lemke, M. Otto, Climate conditions, workplace heat and occupational health in South-East Asia in the context of climate change, WHO South East Asia J. Public Health 6 (2017) 15–21.
[20] T. Kjellstrom, M. Otto, B. Lemke, O. Hyatt, D. Briggs, C. Freyberg, L. Lines, Climate Change and Labour: Impacts of Heat in the Workplace, in: M. Mckinnon, E. Buckle, K. Gueye, I. Toroitich, D. Ionesco, E. Mach (Eds.), United Nations Development Agency (UNDP), 2016.
[21] A.G. Kwok, J. Reardon, K. Brown, Thermal comfort in tropical classroms/discussion, ASHRAE Trans. 104 (1998) 1031.
[22] K. Lundgren, K. Kuklane, C. Gao, I. Holmer, Effects of heat stress on working populations when facing climate change, Ind. Health 51 (2013) 3–15.
[23] W.D. van Marken Lichtenbelt, H.A.M. Daanen, L. Wouters, R. Fronczek, R.J.E.M. Raymann, N.M.W. Severens, E.J.W. Van Someren, Evaluation of wireless determination of skin temperature using iButtons, Physiol. Behav. 88 (2006) 489–497.
[24] G.A. Meehl, C. Tebaldi, More intense, more frequent, and longer lasting heat waves in the 21st century, Science 305 (2004) 994–997.
[25] C.T. Minson, L.T. Berry, M.J. Joyner, Nitric oxide and neurally mediated regulation of skin blood flow during local heating, J. Appl. Physiol. 91 (2001) 1619–1626.
[26] C. Mora, B. Dousset, I.R. Caldwell, F.E. Powell, R.C. Geronimo, C.R. Bielecki, C.W. Counsell, B.S. Dietrich, E.T. Johnston, L.V. Louis, M.P. Lucas, M.M. Mckenzie, A.G. Shea, H. Tseng, T. Giambelluca, L.R. Leon, E. Hawkins, C. Trauernicht, Global risk of deadly heat, Nat. Clim. Change 7 (2017) 501–506.
[27] D.S. Moran, A. Shitzer, K.B. Pandolf, A physiological strain index to evaluate heat stress, Am. J. Physiol. 275 (1998) R129–R134.
[28] W. Pasut, H. Zhang, E. Arens, Y.C. Zhai, Energy-efficient comfort with a heated/cooled chair: results from human subject tests, Build Environ. 84 (2015) 10–21.
[29] J. Périard, M.N. Cramer, P. Chapman, C. Caillaud, M.W. Thompson, Cardiovascular strain impairs prolonged self-paced exercise in the heat, Exp. Physiol. 96 (2011) 134–144.
[30] J. Périard, S. Racinais, Self-paced exercise in hot and cool conditions is associated with the maintenance of $\%VO_{2peak}$ within a narrow range, J. Appl. Physiol. 118 (2015) 1258–1265.
[31] J.F. Piil, J. Lundbye-Jensen, S.J. Trangmar, L. Nybo, Performance in complex motor tasks deteriorates in hyperthermic humans, Temperature 4 (4) (2017) 420–428.
[32] N.L. Ramanathan, A new weighting system for mean surface temperature of the human body, J. Appl. Physiol. 19 (1964) 531–533.
[33] L.B. Rowell, Cardiovascular aspects of human thermoregulation, Circ. Res. 52 (1983) 367–379.
[34] M.N. Sawka, S.N. Cheuvront, R.W. Kenefick, Hypohydration and human performance: impact of environment and physiological mechanisms, Sports Med. 45 (2015) S51–S60.
[35] M. Sivak, Will AC put a chill on the global energy supply? Am. Sci. 101 (2013) 330–333.
[36] J. Słomko, P. Zalewski, The circadian rhythm of core body temperature (Part I): the use of modern telemetry systems to monitor core body temperature variability, Pol. Hyperb. Res. 55 (2016) 79–83.
[37] V. Venugopal, J.S. Chinnadurai, R.A. Lucas, T. Kjellstrom, Occupational heat stress profiles in selected workplaces in India, Int. J. Environ. Res. Public Health 13 (2015) E89.
[38] World Health Organization, Scientific group on health factors involved in working under conditions of heat stress, Health Factors Involved in Working Under Conditions of Heat Stress; Report of a WHO Scientific Group, World Health Organization, 1969.