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Effect of divergent solar radiation exposure with outdoor versus indoor training in the heat: implications for performance

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Introduction

Aerobic exercise when exposed to high ambient temperature (T_a), relative humidity (RH) and solar radiation (SR) elicits detrimental physiological and psychometric effects that limit exercise performance[1-3]. While the thermoregulatory challenges during exercise in hot environments have been well characterized[4], it is a necessity for some athletes residing in many geographical locations to train in hot conditions on a day-to-day basis. For example, winter team-sport athletes are typically required to complete pre-season preparation in the summer months, while the endurance athlete may be required to train and compete during the hottest times of the year. Although training in these environments can convey physiological and performance benefits[5], repeated heat exposure results in increased physiological strain and decreased physical performance[6,7]. Therefore, managing the balance between physiological adaptation to promote optimal performance in the heat and physiological stress can prove challenging for athletic populations.

Exposure to SR increases physiological and perceptual strain in hot environments[8-10]. SR can increase skin temperature (T_{sk}) during exercise above levels associated with high T_a alone, but may not consistently induce a significant effect on core temperature (T_c)[9,10]. When T_{sk} is high, there is a requirement for high skin blood flow for thermoregulatory cooling, which may compromise venous return and cardiac output, increasing cardiovascular strain[11]. From a performance perspective, commencing exercise with increased T_{sk} lowers self-selected exercise intensity[12], and high T_{sk} throughout exercise can compromise work capacity in hot environments[9,10]. Accordingly, team-sport and endurance athletes, training consistently in hot environments with high SR (i.e., outdoors) may experience decreased quality and quantity of work performed during training.

It is common for elite team-sport athletes to complete similar amounts of weekly ‘off-feet’ cross-training (e.g. cycling) load as skills training load during the pre-season preparation phase[13]. The goal of ‘off-feet’ conditioning sessions is to optimize aerobic conditioning while minimizing impact loading associated with running and skills training. Indeed, it is often the aim of these sessions to maximize work capacity to induce the greatest physiological stimulus. As such, training in hot indoor environments may provide the individual or team-sport athlete sufficient stimulus to promote adaptation for athletic performance but reduce the negative impact on training quality associated with SR exposure in hot outdoor environments. However, the practical impact for athletes training in a hot indoor environment and the effect of modified exposure to the individual heat stress variables on physiological responses and performance capacity is currently unknown. Therefore, the primary aim of the current study was to determine the variation in physiological and perceptual responses and performance capacity in heat acclimated, well-trained athletes during high-intensity exercise in hot/humid outdoor versus indoor environmental conditions with contrasting SR exposure. We hypothesized that SR exposure would elicit increases in T_{sk} and thermoregulatory demands and impair the quality and quantity of exercise performance during hot outdoor conditions.

Methods

Experimental approach to the problem

Our within-participant experimental design incorporated two separate but related studies. **Study A** utilized well-trained endurance cyclists (level three[14]), and **Study B** included professional team-sport athletes. Participants completed an outdoor exercise trial followed by a second indoor trial seven days later. This design was necessary to ensure indoor environmental conditions could be matched or manipulated compared to the previous outdoor conditions, including the contrasting SR. Although the exercise protocols were different between Study A and Study B, both incorporated high-intensity intervals. Protocol variation, including constraints on collection of physiological data in Study B, was a result of restrictions on obtrusive protocols (such as gastrointestinal Tc monitoring) placed on the professional athletes and the specificity of training (‘cross-training’ team sport conditioning session). Study A was designed as a proof of principle study to determine differences in physiological and performance responses outdoors compared to indoors. Specifically, given direct sunlight is the major environmental contrast between outdoor and indoor conditions, the aim was to match temperature and humidity and isolate the presence or absence of SR exposure as the primary variable of interest between trials. Consequently, there was a decrease in the relative WBGT during the indoor trial condition in Study A. Study B focused on high external validity as part of the physical preparation for professional team-sport, i.e. the session was regularly completed by the participant cohort in hot indoor conditions and was prescribed to improve team-sport metabolic conditioning. Therefore, the indoor environmental conditions included no SR during Study B but temperature and humidity were not clamped, and there was a resultant increase in RH during indoor exercise and equivalent relative WBGT's between trial conditions.

Subjects

Seven trained male cyclists volunteered to participate in Study A (mean ± standard deviation [SD]; age: 30 ±9 years, height: 182 ±7 cm, body mass: 75 ±7 kg, maximum oxygen uptake [VO_{2peak}]: 58 ±6 $ml^{.}kg^{.}min^{-1}$) and nine male professional team-sport athletes from one Australian Rules Football club volunteered to participate in Study B (age: 24 ±4 years, height: 188 ±9 cm, body mass: 88 ±10 kg, maximal aerobic speed 17.6 ±0.9 $km^{.}h^{-1}$). Participants were accustomed to training in hot and humid conditions in a sub-tropical location (28˚ S, 153˚ E) in Australia for ≥ seven h per week and were deemed to be heat acclimatized. Participants provided written informed consent and studies were approved by the Bond University Human Research Ethics Committee (ID: FO00005, 16171).

Study A

Preliminary Testing

Participants completed an initial maximal exercise test to determine VO_{2peak} and peak power output (PPO). The test was completed in a thermoneutral environment (22 °C and 40-50% RH) on a cycle ergometer (Lode Excalibur Sport, Lode, Netherlands) as described previously[15]. Expired gasses were continuously recorded by a metabolic cart (Quark C-PET, Cosmed, Italy). Data from the maximal exercise test was used to determine values corresponding to 40% PPO, 63% PPO and 80% PPO.

Pre-trial Diet and Exercise Control

Participants provided an exercise and diet recall in the 48 h before the first trial and were instructed to replicate diet and exercise in the subsequent trial; this was confirmed by diet and exercise recall. Participants reported to the laboratory at 0600 h on trial days, in a fasted state, and provided a mid-stream urine sample for urine specific gravity (USG) assessment, recorded nude body-mass (BM) and consumed a standardized breakfast containing two $g \cdot kg^{-1}$ BM carbohydrate. Participants were required to abstain from caffeine and further food intake but consumed water ad-libitum. A standardized snack was provided 90 min before exercise and a second urine sample was collected and analyzed 60 mins before exercise to ensure participants were euhydrated before commencing exercise. All participants USG recordings were <1.020.

Physiological Monitoring

A T_c capsule (e-Celsius, BodyCap, France) was ingested at 0600 h on the morning of each trial. Approximately 1 h before exercise, surface T_{sk} monitors (iButton, Maxim Integrated Products, Inc., USA) were attached with adhesive tape (Fixomull, BSN Medical, Germany) to four sites (sternum, bicep, thigh, calf) in order to calculate mean skin temperature[16] during exercise. Heart rate (HR) was obtained (Polar t31, Polar Electro, Finland) during exercise and mean HR (HR_{mean}) was recorded.

Environmental Monitoring

T_a (°C), RH (%) and wind speed ($km \cdot h^{-1}$) were measured via a portable weather station (Kestrel 5000, Kestrel Instruments, USA), and SR (W/m^2) was recorded via pyranometer (MP-100, Apogee Instruments, USA) at 30 s intervals during each experimental trial. The initial exercise trial was conducted in an outdoors environment with full exposure to the sun, in a sub-tropical location (28º S, 153º E). The second trial was conducted in an indoor heat chamber (Coolmaster, Australia). The recorded T_a and RH was matched indoors from the previous outdoor trial. Subsequently, outdoor wet-bulb globe temperature (WBGTo) was calculated using the Lilijegren method[17], and indoor wet-bulb globe temperature (WBGTi) was calculated using the Bernard method[18].

Exercise Trial

Participants entered the exercise environment at 1130 h and remained passively seated for 10 min before beginning exercise. At the commencement of exercise participants cycled on a stationary ergometer that was deemed to be valid and reliable for the protocol[19] (WattBike, Pro, UK) at ~63% PPO for 10 min, followed by 5 × 4 min at ~80% PPO interspersed with two min recovery at ~40% PPO. Participants then completed a 20 km self-paced ride, with the instruction to complete the ride in the shortest time possible. Participants were not provided with fluid during the exercise protocol and they were blinded to elapsed time during the self-paced ride.

Perceptual Monitoring

Ratings of perceived exertion (Borg 6-20)[20] and both thermal comfort and thermal sensation[21] were recorded after the completion of the initial 10 min at 63% PPO, after each 4 min interval at 80% PPO and after each five km during the 20 km self-paced ride.

Study B

Preliminary Testing

Participants completed an initial exercise test to determine mean four-minute power output[22] a maximum of four weeks before the experimental period. The test was undertaken in a thermoneutral environment (~22 °C Ta and 40-50 % RH) on a stationary cycle ergometer (Watt Bike, Pro, UK).

Pre-trial Diet and Exercise Control

A standard training session was completed by all participants 24 h before experimental trials and was prescribed as part of the professional sporting clubs training schedule. Participants reported to the training facility at 0600 h on trial days where they provided a urine sample for USG assessment and were supplied with a standardized breakfast consisting of two $g{\cdot}kg^{-1}$ BM carbohydrate. A standardized snack was supplied 90 min pre-exercise. Participants were required to abstain from caffeine ingestion throughout the morning of the trial but consumed water ad-libitum. A second urine sample was collected and analyzed 60 min pre-exercise to ensure participants were euhydrated. All participants USG recordings were <1.020.

Environmental and Perceptual Monitoring

Dependent variable monitoring during Study B was undertaken using the equivalent methods of Study A.

Exercise Trial

Participants in Study B cycled at steady state on a stationary ergometer (WattBike, Pro, UK) at ~65% of mean four-minute power output for 20 min followed by 5 × 2 min self-paced *'maximal effort'* intervals interspersed with two min self-selected intensity recovery intervals. During exercise, mean PO, HR, RPE, TC and TS were recorded following the initial 20 min steady-state ride, and at the completion of each two min interval. During the exercise trial, participants consumed a standardized water intake of 200 ml every 10 min.

Statistical Analysis

Data were analyzed using two-way (trial × time) analysis of variance (ANOVA) with repeated measures and Bonferroni post-hoc testing. Paired t-tests were used to compare mean data between trial conditions, and for T_c and T_{sk} area under the curve (AUC). Confidence intervals (95%) and Cohen's effect size (d) were calculated and *d* defined as: 0.2 small effects, 0.5 moderate effects, and 0.8 large effects[23]. Statistical analyses were conducted using GraphPad Prism (8.0.2, GraphPad Software), and significance was set at $p<0.05$. All data are presented as mean ± standard deviation.

Results

Mean environmental conditions during the outdoor trial in Study A were 30.7 ± 0.5 °C, 66 ± 3% RH, 847 ± 72 W/m^2 SR and 4.3 ± 1.7 km$\cdot$h^{-1} WS (WBGTo = 29.6 °C) compared with indoor trial 29.8 ± 0.5 °C, 61 ± 2% RH, 0 ±0 W/m^2 SR and 0 ±0 km/h WS (WBGTi = 26.0 °C). Study B conditions were 30.0 ± 0.6 °C, 41 ± 2% RH, 1068 ± 10 W/m^2 SR and 4.0 ± 1.3 km$\cdot$h^{-1} WS (WBGTo = 26.7 °C) outdoors and

30.6 ± 0.2 °C, 57.2 ± 4.2% RH, 0 ± 0 W/m^2 SR and 0 ± 0 km$\cdot$h^{-1} WS (WBGTi = 26.8 °C) during the indoors trial. Pre-exercise body mass (75.5 ± 8.2 kg vs 75.6 ± 7.9 kg) and USG (1.015 ± 0.01 vs. 1.013 ± 0.01) were not different between trial conditions in Study A or Study B (BM 87.3 ± 9.9 kg vs. 87.4 ± 10 kg, USG 1.011 ± 0.01 vs. 1.009 ± 0.01) suggesting participants began exercise in a similar physiological state. Total exercise and environmental exposure time during Study A was ~75 min and ~45 min during Study B which represent exercise durations that athletes in each cohort were accustomed to completing. Percent body mass loss was not different between trial conditions in Study A (2.6 ± 0.5 % outdoors vs. 2.5 ± 0.8 % indoors) or Study B (0.2 ± 0.4 % outdoors vs. 0.4 ± 0.4 % indoors).

Study A

Exercise Performance

There was a significant effect of time (p<0.0001), but not trial, on PO during exercise. Mean PO was not different when directly comparing the warm-up, 5 × 4 min intervals or 20 km self-paced ride components of the exercise protocol between outdoor and indoor conditions. There were trivial to moderate decreases in PO during the 20 km self-paced ride in the outdoors compared with the indoor trial (d = -0.13–-0.52), but these differences failed to reach statistical significance (Table 1). No statistical difference in time to complete the 20 km self-paced ride existed between trial conditions (Outdoors 00:33:36 ± 00:03:32 vs. Indoors 00:32:05 ± 00:02:46, p = 0.33) despite a moderate effect for the greater time to completion during the outdoors trial (d = 0.62).

INSERT TABLE 1 HERE

Core and Skin Temperature

There were main effects of time (p<0.0001) and trial (p = 0.03) for T_c such that T_c AUC was greater (p<0.0001) during outdoors exercise (Figure 1). There were moderate effects for differences at the completion of warm up (Outdoor, 36.9 ± 0.3 °C vs Indoor, 36.7 ± 0.4 °C, d = 0.51) and Interval Two (Outdoor, 37.7 ± 0.3 °C vs Indoor, 37.4 ± 0.4 °C, d = 0.75), large effects for differences at the completion of Interval Three (Outdoor, 38.0 ± 0.2 °C vs Indoor, 37.8 ± 0.3 °C, d = 0.92), Interval Four

(Outdoor, 38.3 ± 0.3 °C vs Indoor, 38.0 ± 0.3 °C, *d* = 0.96) and Interval Five (38.5 ± 0.3 °C outdoor vs 38.3 ± 0.3 °C indoor, *d* = 0.91), and small effects for differences throughout the 20 km self-paced ride (Outdoor, 39.2 ± 0.4 °C vs Indoor, 39.0 ± 0.5 °C, *d* = 0.44).

There was also an effect of time ($p<0.0001$) and trial ($p = 0.03$) and an interaction effect between time and trial ($p<0.0001$) for T_{sk} during exercise (Figure 2) with T_{sk} AUC greater outdoors ($p<0.0001$). After the initial 10 min before exercise, and following warm-up and Interval One, there were large increases in T_{sk} outdoors compared to indoors (p<0.001; *d* = 1.37–1.99). At the completion of exercise, T_{sk} was moderately higher outdoors ($p = 0.006$, *d* = 0.51).

INSERT FIGURE 1 HERE

INSERT FIGURE 2 HERE

RPE, Thermal Sensation, Thermal Comfort

There was a significant effect of time ($p<0.0001$) on TS, TC (Table 1) and RPE. Trivial to small effects were evident between outdoors and indoors exercise during the warm-up and high-intensity intervals (CI = -3.34 to 2.19, *d* = -0.15–0.26) on RPE, and trivial to moderate increases were evident during the outdoors trial condition in the 20 km self-paced ride (CI = -0.86 to 2.31, *d* = 0.00–0.58). However, these effects were not statistically significant. Despite large effects after Interval Three and at 10 km of the self-paced ride for increases in TS during the outdoors trial condition (*d* = 0.88–1.31) and trivial to moderate differences across the remaining time points (*d* = 0.00–0.66) there were no significant effects. Large increases in TC were evident after the warm-up, and the completion of 10 km of the 20 km self-paced ride (*d* = 0.85–0.92) during outdoor exercise and trivial to moderate differences were evident at other timepoints during exercise between trial conditions (*d* = 0.00–0.60).

Heart Rate

There were significant effects of time ($p<0.0001$) and verged on main effect for trial ($p = 0.05$) for HR_{mean} attained during outdoor exercise (Outdoor, 173 ± 12 beats$\cdot$min^{-1} vs Indoor, 169 ± 15 beats$\cdot$min^{-1}), however, post-hoc analysis failed to identify differences between trials. Large effects were apparent during the warm-up (Outdoor, 151 ± 10 beats$\cdot$min^{-1} vs Indoor, 141 ± 10 beats$\cdot$min^{-1}, *d* = 1.00) and moderate effects were apparent for the 5 × 4 min intervals (Outdoor, 175 ± 8 beats$\cdot$min^{-1} vs Indoor, 169 ± 13 beats$\cdot$min^{-1}, *d* = 0.56). Only trivial/small differences were apparent during the 20 km self-paced ride (Outdoor, 177 ± 11 beats$\cdot$min^{-1} vs Indoor, 177 ± 10 beats$\cdot$min^{-1}, *d* = -0.25-0.18).

Study B

Exercise Performance

There was a significant effect of time ($p<0.0001$) and trial ($p = 0.04$) on PO during exercise (Table 2). Specifically, there was a small increase in PO ($p = 0.03$, $d = 0.23$) following Interval Four during the outdoors trial. No differences in PO were evident at any other time point during the exercise trial with trivial to small effects (*d* = 0.03–0.21).

INSERT TABLE 2 HERE

Heart Rate

There was a significant effect of time ($p<0.0001$) but not trial on HR_{mean} during the exercise session. However, there was a significant, moderate increase in HR_{mean} following Warm-Up during the outdoors trial condition (Outdoor, 143 ± 14 vs Indoor, 135 ± 13 beats$\cdot$min^{-1}, $p = 0.04$, $d = 0.61$). Throughout the *maximal effort* intervals, there was a range of trivial to moderate effects (*d* = -0.02–0.75) for the differences between trial conditions that were not significant.

RPE and Thermal Sensation

There was a significant effect of time but not trial condition on RPE and TS (both $p<0.0001$) across the duration of exercise. RPE was not different during exercise between trials despite small to moderate effects between outdoor and indoor conditions (CI = -1.15 to 1.62, *d* = -0.27–0.41). Trivial to moderate effects (*d* = -0.53–0.00) for differences in TS were evident at various time points during exercise between trial conditions, but these failed to reach significance (Table 2).

Discussion

These studies aimed to determine the variation in physiological and perceptual responses and performance capacity in heat acclimatized, well-trained athletes during exercise with contrasting SR exposure. Most notable, lower T_{sk} and T_c was observed during the indoor exercise with no SR exposure during Study A. The lower T_{sk} and T_c was associated with a moderate effect size for increases in self-selected power output and improved time-to-completion during a 20 km self-paced ride in well-trained cyclists. However, when professional team sport athletes completed self-paced *maximal effort* intervals, removing SR had little impact on performance when WBGT was matched for indoor and outdoor conditions.

Our novel data show increases in T_{sk} during the early (~25 min) exposure to high SR (Figure 2). The initial difference in T_{sk} between outdoor and indoor trials in cyclists was not sustained throughout the exercise session. Our findings are in contrast to previous studies in untrained participants showing increased T_{sk} throughout the duration of exercise when undertaking moderate-intensity protocols[8-10]. It seems plausible that the substantially higher exercise intensities undertaken by trained cyclists (Study A) augmented metabolic heat production,[24] muscle temperatures,[25] skin blood flow and heart rate[4]. During the outdoor trial participants were exposed to greater air movement/velocity across the skin's surface, which is similar to previous research comparing indoor and outdoor exercise[26]. Evaporative potential improves with increasing air velocity and typically reduces the rate at which T_c and T_{sk} increase during exercise [27]. While the rate of increase in T_{sk} may have been attenuated outdoors as a result of increased air velocity compared to indoor exercise, the interaction between different environmental exposures and the physiological response for indoor and outdoor sessions is a key consideration for training prescription. The metabolic heat production during repetitive, high-intensity intervals, in conjunction with the increased evaporative and convective cooling capacity during outdoor exercise in the cyclists, likely equilibrated the early differences in T_{sk} between trials as exercise duration extended despite exposure to high SR outdoors.

Whether the initial increase in T_{sk} outdoors due to SR exposure contributed to a commensurate increase in T_c throughout prolonged exercise (~75 min) in the current data is intriguing. Indeed, the effect of SR on T_{sk} is clear[3,8-10,28,29], but the relationship between SR and a cause and effect on changes in exercise

T_c remains unresolved. As T_{sk} increases in environments characterized by high relative humidity, and thermoregulatory cooling becomes progressively more challenging, body temperatures continue to rise[2]. However, while associations between increasing SR and tympanic temperature have been observed[8,30] the same relationships have not been apparent between SR and rectal temperature[9,10]. In the present study, the increase in T_c during outdoor (high SR) compared with indoor exercise (no SR) was modest (Figure 1). Nevertheless, it was evident for the duration of the exercise trial. Furthermore, the elevations in T_c were associated with increased heart rates during the warm-up and high-intensity interval training components of the outdoor trial undertaken by cyclists. Together with the moderate effect for improved 20 km cycling time, the data indicate that reducing exposure to the SR component of heat stress may have a small beneficial effect on multiple variables contributing to physiological strain and improve performance capacity during strenuous exercise in thermally challenging environments.

Contrary to our hypothesis, there was no effect of SR on self-selected exercise intensity undertaken by AFL players (Study B). Our findings are in contrast to Otani and colleagues[8,30] showing SR exposure elicited detrimental effects on self-selected exercise intensity and running distance in baseball and soccer players training in hot environments. However, an important difference in the present study was the inclusion of professional team sport athletes compared with the adolescent athletes in previous studies[8,30]. The interval training protocol employed in Study B is typical of a professional team sport 'cross-training' conditioning session, and the study aimed to ensure WBGT between trial conditions for the AFL players was equivalent. Consequently, greater relative humidity during the indoor trial was required to off-set the absence of SR and match outdoor WBGT. Previous studies show that when varying environmental conditions generate similar WBGT's, the work performed in a hot environment[31] and the rate of acclimation to heat stress[32] is comparable. Moreover, participants were exposed to air velocity during outdoor exercise, and as a result, the thermoregulatory capacity of the outdoor exercise environment may have been enhanced[27]. As such, our data are similar to Jeffries et.al.[33] who showed no differences between outdoor and indoor exercise performance, despite greater air velocities during the outdoor trial. Taken together, this may explain, at least in part, the apparent lack of effect of SR and similar performance capacity outdoors versus indoors in the AFL players. In addition, the self-pacing capabilities of team sport players are likely inferior to cyclists more familiar with undertaking high-intensity intervals and constant power cycling during training and competition. As such, individual training history and/or exercise modality may be factors that alter the potential for SR to impact work capacity and quality of training.

Perceptions of effort and thermal tolerance are strongly related to exercise heat strain and performance in the heat[12]. In the early stages of exercise completed by the cyclists, the perceptual response of participants varied, but there were persistent small-large effects for higher ratings of exertion and thermal sensation/comfort outdoors, an effect that was sustained during the self-paced exercise. These perceptual effects are congruent with the increases in T_{sk} during the early stages of exercise and are similar to findings of previous studies[12,34]. Otani and colleagues[9] also report SR exposure may negatively affect thermal tolerance during exercise, however, as with the present study, the responses were variable. In contrast, under matched WBGT conditions, a corresponding difference in perceptual response was not evident for the AFL players, where the higher relative humidity and lack of circulating air velocity appear to have increased perceptual responses during indoor interval training. In summary, it appears there are a multiplicity of factors with the potential to alter perceptions of effort and thermal tolerance during exercise in the heat and further research is required to elucidate relationships between perceptual responses and solar radiation and humidity.

Practical Applications

The term ‘off-feet’ training reflects the use of an alternate exercise mode, typically cycling, to develop or maintain metabolic conditioning in team sport athletes. The indoor training environment for off-feet training can be manipulated and the use of hypoxic and/or heat training methods during indoor exercise sessions has become commonplace. The rationale for indoor training in the heat includes the desire to promote positive adaptations such as integrated thermoregulatory, cardiovascular, and fluid-electrolyte responses. Our data indicate training in hot outdoor environments with exposure to high SR may have the potential to decrease the performance capacity of athletes undertaking high-intensity exercise. Therefore, where the aim of an exercise session is to maximize work capacity while promoting or accelerating physiological adaptation by training in the heat, practitioners can program indoor heat training sessions to mitigate SR exposure. Moreover, the absence of SR should not be off-set by increased humidity which may equilibrate WBGT of the indoor training environment, rather the aim should be to ensure a modest decrease in the relative WBGT through the removal of SR. This approach to indoor training has the potential to convey beneficial effects for enhancing the quality and quantity of work performed in the heat.

References

1. Galloway SD, Maughan RJ. Effects of ambient temperature on the capacity to perform prolonged cycle exercise in man. *Med Sci Sports Exerc.* 1997;29(9):1240-1249.
2. Maughan RJ, Otani H, Watson P. Influence of relative humidity on prolonged exercise capacity in a warm environment. *Eur J Appl Physiol.* 2012;112(6):2313-2321.
3. Nielsen B, Kassow K, Aschengreen FE. Heat balance during exercise in the sun. *Eur J Appl Physiol Occup Physiol.* 1988;58(1-2):189-196.
4. Sawka MN, Wenger CB, Pandolf KB. Thermoregulatory Responses to Acute Exercise-Heat Stress and Heat Acclimation. In: *Comprehensive Physiology.* John Wiley & Sons, Inc.; 2010.
5. Lorenzo S, Halliwill JR, Sawka MN, Minson CT. Heat acclimation improves exercise performance. *Journal of applied physiology (Bethesda, Md : 1985).* 2010;109(4):1140-1147.
6. Maunder E, Kilding AE, Stevens CJ, Plews DJ. Heat Stress Training Camps for Endurance Sport: A Descriptive Case Study of Successful Monitoring in Two Ironman Triathletes. 2019:1.
7. Pryor RR, Pryor JL, Vandermark LW, et al. Exacerbated heat strain during consecutive days of repeated exercise sessions in heat. *J Sci Med Sport.* 2019.
8. Otani H, Goto T, Goto H, Shirato M. Time-of-day effects of exposure to solar radiation on thermoregulation during outdoor exercise in the heat. *Chronobiol Int.* 2017:1-15.
9. Otani H, Kaya M, Tamaki A, Goto H, Maughan RJ. Exposure to high solar radiation reduces self-regulated exercise intensity in the heat outdoors. *Physiol Behav.* 2019;199:191-199.
10. Otani H, Kaya M, Tamaki A, Watson P, Maughan RJ. Effects of solar radiation on endurance exercise capacity in a hot environment. *Eur J Appl Physiol.* 2016;116(4):769-779.
11. Ely BR, Cheuvront SN, Kenefick RW, Sawka MN. Aerobic performance is degraded, despite modest hyperthermia, in hot environments. *Med Sci Sports Exerc.* 2010;42(1):135-141.
12. Schlader ZJ, Simmons SE, Stannard SR, Mundel T. Skin temperature as a thermal controller of exercise intensity. *Eur J Appl Physiol.* 2011;111(8):1631-1639.
13. Ritchie D, Hopkins WG, Buchheit M, Cordy J, Bartlett JD. Quantification of Training and Competition Load Across a Season in an Elite Australian Football Club. *Int J Sports Physiol Perform.* 2016;11(4):474-479.
14. De Pauw K, Roelands B, Cheung SS, de Geus B, Rietjens G, Meeusen R. Guidelines to classify subject groups in sport-science research. *Int J Sports Physiol Perform.* 2013;8(2):111-122.
15. Hawley JA, Noakes TD. Peak power output predicts maximal oxygen uptake and performance time in trained cyclists. *Eur J Appl Physiol Occup Physiol.* 1992;65(1):79-83.
16. Ramanathan NL. A NEW WEIGHTING SYSTEM FOR MEAN SURFACE TEMPERATURE OF THE HUMAN BODY. *J Appl Physiol.* 1964;19:531-533.
17. Liljegren JC, Carhart RA, Lawday P, Tschopp S, Sharp R. Modeling the Wet Bulb Globe Temperature Using Standard Meteorological Measurements. *J Occup Environ Hyg.* 2008;5(10):645-655.
18. E. Bernard T, Pourmoghani M. *Prediction of Workplace Wet Bulb Global Temperature.* Vol 141999.
19. Borg DN, Osborne JO, Stewart IB, Costello JT, Sims JNL, Minett GM. The reproducibility of 10 and 20km time trial cycling performance in recreational cyclists, runners and team sport athletes. *J Sci Med Sport.* 2018;21(8):858-863.
20. Borg GA. Psychophysical bases of perceived exertion. *Medicine and science in sports and exercise.* 1982;14(5):377-381.
21. ISO. Ergonomics of the physical environment - Subjective judgment scales for assessing physical environments. *International Organization for Standardization, 10551:2019.* 2019.
22. Quod MJ, Martin DT, Martin JC, Laursen PB. The power profile predicts road cycling MMP. *Int J Sports Med.* 2010;31(6):397-401.
23. Cohen J. *Statistical power analysis for the behavioral sciences.* New York, NY: Academic Press; 1977.

24. Medicine Io. *Nutritional Needs in Hot Environments: Applications for Military Personnel in Field Operations.* Washington, DC: The National Academies Press; 1993.
25. Kenny GP, Reardon FD, Zaleski W, Reardon ML, Haman F, Ducharme MB. Muscle temperature transients before, during, and after exercise measured using an intramuscular multisensor probe. *Journal of applied physiology (Bethesda, Md : 1985).* 2003;94(6):2350-2357.
26. Mieras ME, Heesch MW, Slivka DR. Physiological and psychological responses to outdoor vs. laboratory cycling. *J Strength Cond Res.* 2014;28(8):2324-2329.
27. Otani H, Kaya M, Tamaki A, Watson P, Maughan RJ. Air velocity influences thermoregulation and endurance exercise capacity in the heat. *Appl Physiol Nutr Metab.* 2018;43(2):131-138.
28. Otani H, Goto T, Goto H, Hosokawa Y, Shirato M. Solar Radiation Exposure Has Diurnal Effects on Thermoregulatory Responses During High-Intensity Exercise in the Heat Outdoors. *Journal of strength and conditioning research.* 2019.
29. Blazejczyk K. Influence of solar radiation on skin temperature in standing and walking subjects outdoors. Paper presented at: Proceedings of the 8th international conference on environmental ergonomics1998.
30. Otani H, Goto T, Goto H, Hosokawa Y, Shirato M. Solar Radiation Exposure Has Diurnal Effects on Thermoregulatory Responses During High-Intensity Exercise in the Heat Outdoors. *J Strength Cond Res.* 2019;33(10):2608-2615.
31. Stapleton JM, Wright HE, Hardcastle SG, Kenny GP. Body heat storage during intermittent work in hot-dry and warm-wet environments. *Appl Physiol Nutr Metab.* 2012;37(5):840-849.
32. Griefahn B. Acclimation to three different hot climates with equivalent wet bulb globe temperatures. *Ergonomics.* 1997;40(2):223-234.
33. Jeffries O, Waldron M, Patterson SD, Galna B. An Analysis of Variability in Power Output During Indoor and Outdoor Cycling Time Trials. *Int J Sports Physiol Perform.* 2019:1273-1279.
34. Vargas NT, Slyer J, Chapman CL, et al. The motivation to behaviorally thermoregulate during passive heat exposure in humans is dependent on the magnitude of increases in skin temperature. *Physiol Behav.* 2018;194:545-551.

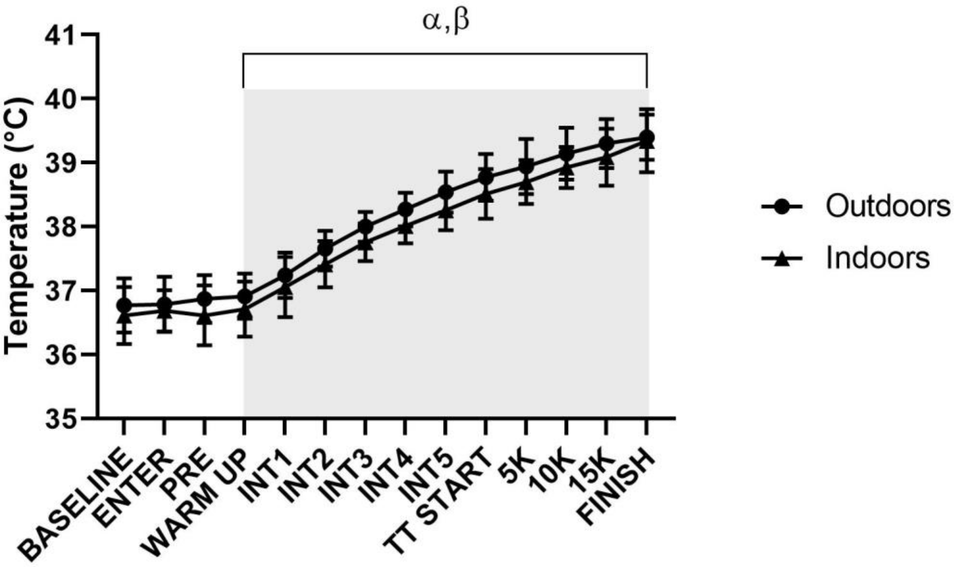

Figure 1. Core temperature response of trained cyclists undertaking high-intensity interval (INT) training and 20 km self-paced cycling during outdoor and indoor trial conditions. Grey shading highlights the exercise period. Data are mean ± standard deviation (n = 7), α denotes a main effect of time, β denotes a main effect of trial, and area under the curve was greater during the outdoors trial ($P<0.0001$). Outdoor WBGT = 29.6 °C, Indoor WBGT = 26.0 °C

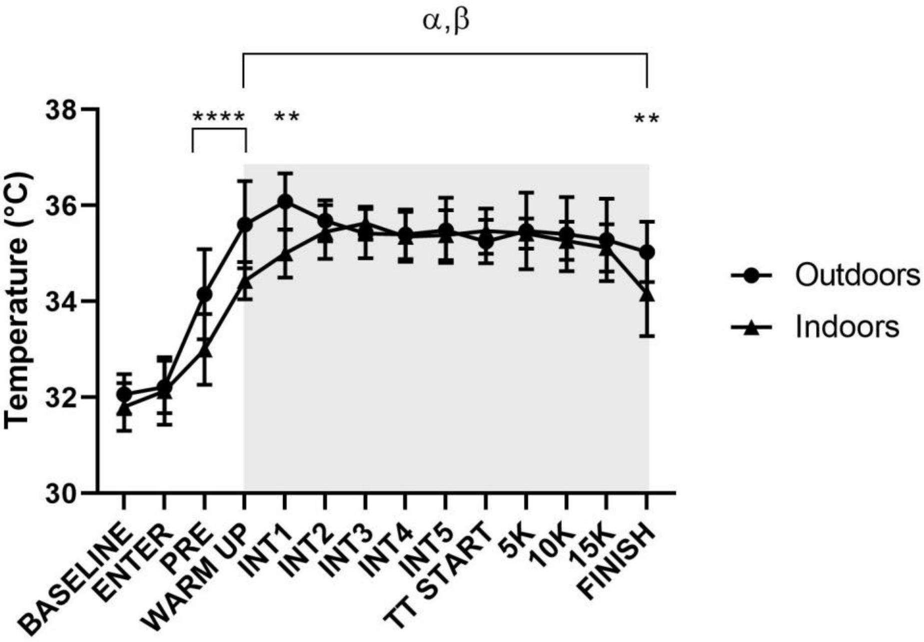

Figure 2. Skin temperature response of trained cyclists undertaking high-intensity interval (INT) training and 20 km self-paced cycling during outdoor and indoor trial conditions. Grey shading highlights the exercise period. Data are mean ± standard deviation (n = 7), α denotes a main effect of time, β denotes a main effect of trial condition. *p <.05, **p <.01, ***p <0.001, ****p <.0001 for outdoors vs. indoors at the equivalent timepoint, and area under the curve was greater outdoors compared to indoors (p<0.0001). Outdoor WBGT = 29.6 °C, Indoor WBGT = 26.0 °C

Table 1. Power output and Perceptual responses of trained cyclists undertaking high-intensity interval training and 20 km self-paced cycling during outdoor compared to indoor trial conditions (n = 7). Data are mean difference (arbitrary units, AU) with 95% confidence intervals (CI) and Cohen's effect size (*d*) statistics. Outdoor WBGT = 29.6 °C, Indoor WBGT = 26.0 °C.

	Outdoors vs. Indoors	Warm Up	Int 1	Int 3	Int 5	5k	10k	15k	20k
PO (W)	Mean Difference (W)	-1.50	-0.71	-0.15	-5.00	-6.6	-14.9	-20.5	-22.9
	95% CI	-31.4 to 28.5	-30.6 to 29.2	-30.0 to 29.8	-34.9 to 24.9	-36.5 to 23.3	-44.8 to 15.0	-50.4 to 9.50	-52.8 to 7.10
	d	-0.05	-0.03	0.00	-0.19	-0.13	-0.37	-0.48	-0.52
TS	Mean Difference (AU)	0.15	0.15	0.50	0.00	0.29	0.50	0.29	0.15
	95% CI	-1.51 to 1.79	-0.93 to 1.21	-0.49 to 1.49	-1.26 to 1.26	-0.47 to 1.04	-0.68 to 1.68	-0.89 to 1.46	-0.44 to 0.73
	d	0.27	0.20	1.31	0.00	0.66	0.88	0.53	0.35
TC	Mean Difference (AU)	0.71	0.15	0.21	0.29	0.15	0.29	0.00	0.00
	95% CI	-0.21 to 1.63	-0.73 to 1.02	-0.54 to 0.98	-0.32 to 0.88	-0.37 to 0.66	-0.17 to 0.74	-	-
	d	0.92	0.27	0.31	0.60	0.44	0.85	-	-

Int, interval; PO, power output; W, watts; TS, rating of thermal sensation; TC, rating of thermal comfort; -, no difference between trial conditions

Table 2. Power output and Perceptual response of professional AFL players undertaking high-intensity interval training cycling preceded by a 20 min steady-state ride during outdoor compared to indoor trial conditions (n=9). Data are mean difference (arbitrary units, AU) with 95% confidence intervals (CI) and Cohen's effect size (*d*) statistics. Outdoor WBGT = 26.7 °C, Indoor WBGT = 26.8 °C

	Outdoors vs. Indoors	Warm Up	Int 1	Int 2	Int 3	Int 4	Int 5
PO (W)	Mean Difference (AU)	1.0	11.9	9.4	11.2	13.1*	9.1
	95% CI	-11.1 to 13.1	-0.25 to 24.0	-2.7 to 21.6	-0.92 to 23.4	0.97 to 25.3	-3.10 to 21.3
	d	0.12	0.03	0.17	0.18	0.21	0.23
TS	Mean Difference (AU)	-0.22	-0.28	-0.33	-0.22	-0.06	0.06
	95% CI	-1.19 to 0.74	-1.24 to 0.68	-1.33 to 0.67	-1.19 to 0.74	-1.07 to 0.96	-0.88 to 0.99
	d	-0.44	-0.53	-0.49	-0.49	-0.16	0.09

Int, interval; PO, power output; W. watts; TS, rating of thermal sensation, *$p < 0.05$

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