

Prolonged self-paced exercise in the heat – environmental factors affecting performance

Nicklas Junge^a, Rasmus Jørgensen^a, Andreas D. Flouris^b, and Lars Nybo^a

^aDepartment of Nutrition, Exercise and Sports, August Krogh Building, University of Copenhagen, Denmark; ^bFAME Laboratory, Department of Exercise Science, University of Thessaly, Trikala, Greece

ABSTRACT

In this review we examine how self-paced performance is affected by environmental heat stress factors during cycling time trial performance as well as considering the effects of exercise mode and heat acclimatization. Mean power output during prolonged cycling time trials in the heat ($\geq 30^{\circ}\text{C}$) was on average reduced by 15% in the 14 studies that fulfilled the inclusion criteria. Ambient temperature per se was a poor predictor of the integrated environmental heat stress and 2 of the prevailing heat stress indices (WBGT and UTCI) failed to predict the environmental influence on performance. The weighing of wind speed appears to be too low for predicting the effect for cycling in trained acclimatized subjects, where performance may be maintained in outdoor time trials at ambient temperatures as high as 36°C (36°C UTCI; 28°C WBGT). Power output during indoor trials may also be maintained with temperatures up to at least 27°C when humidity is modest and wind speed matches the movement speed generated during outdoor cycling, whereas marked reductions are observed when air movement is minimal. For running, representing an exercise mode with lower movement speed and higher heat production for a given metabolic rate, it appears that endurance is affected even at much lower ambient temperatures. On this basis we conclude that environmental heat stress impacts self-paced endurance performance. However, the effect is markedly modified by acclimatization status and exercise mode, as the wind generated by the exercise (movement speed) or the environment (natural or fan air movement) exerts a strong influence.

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Introduction

Humans participating in prolonged physical activity in the heat experience marked homeostatic disturbances that may provoke premature fatigue and affect both occupational work capacity and athletic exercise performance.^{1,2} The etiology of hyperthermia-induced fatigue seems to involve complex interaction between cardiovascular alterations, peripheral (muscular) and central nervous factors (see refs. 3–5 for recent reviews). Independent of the relative importance of the various physiological factors that may limit exercise performance in a given condition, it is clear that the limited ability of the human organism to tolerate excessive increases in internal temperature is a challenge during physical activity in hot conditions, and performance is further deteriorated if air humidity is high,⁶ air movement low or solar radiation is superimposed.^{7–10}

When such adverse ambient conditions are combined with elevated rates of endogenous heat production surpassing the body's heat dissipating capacity, the resulting heat storage and hyperthermia may only be prevented or limited if artificial cooling is provided, or as observed for self-paced exercise, the individuals lower the intensity (i.e. reduced power output and/or speed) and hence reduce the metabolic heat production.^{11–13} While lab experiments with fixed exercise intensity may provide a model for exploring the importance of certain physiological factors,¹⁴ analyzing changes in power output or speed during self-paced exercise in the heat provides an opportunity to evaluate how the integrated physiological response is affected by the environment in real life settings. With this approach, the present review focuses on the influence of elevated environmental heat stress on power output during cycling time trial (TT) performance and compare to changes in pacing during prolonged

CONTACT Lars Nybo  nybo@nexs.ku.dk  Department of Nutrition, Exercise and Sports, Section of Human Physiology, August Krogh Building, University of Copenhagen, Universitetsparken 13, 2100 Copenhagen, Denmark.

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running. Comparison of cycling and running is of interest since they represent exercise modes with differences in heat production for a given metabolic rate and with differences in movement speed when performed in natural settings. Specifically we will focus on A) how the combination of environmental heat stress factors (temperature, humidity, radiation and wind speed) impacts prolonged performance, B) the importance of the participants' training- and acclimatization status and C) the influence of the work/exercise mode - with running and cycling as examples of exercise modalities that elicit different degrees of endogenous heat production for a given metabolic rate and are usually performed with large differences in movement speed, that eventually will influence heat exchange with the environment. In relation to C) it appears that running performance is affected at much lower environmental temperatures than cycling and in addition to the facilitation of heat dissipation, the higher movement speed may also imply that outdoor cycling performance benefits markedly from the lower air density in the heat,¹⁵⁻¹⁸ while reduced air resistance has limited effect for running performance.¹⁹ In relation to B) it has repeatedly been demonstrated that acclimatization may alter the impact of a given heat stress with the largest changes observed in dry environments, whereas the benefit in hot and humid air is modest.²⁰ Furthermore, untrained subjects seem to have a lower heat

tolerance when exposed to passive heat stress,^{21,22} and performance deteriorates more for slower runners compared to elite trained athletes.¹⁸ Thus, both training- and acclimatization status should be considered when analyzing the environmental impact on exercise. In regard to A) it is clear that temperature is important but also that both humidity and wind speed modify the impact of a given temperature increase,^{6,9,10} and for outdoor exercise the solar radiation should also be considered.^{7,8} Several of the more than 160 existing heat indices attempt to combine the relevant factors into an integrated mathematical model,²³ that may provide a score used for categorizing the environmental heat stress or providing safety limits for occupational workers or competing athletes. E.g. the Wet Bulb Globe Temperature (WBGT) has historically been used in various sport organizations for recommendations of event cancellation or including additional "heat-breaks" if the WBGT surpasses certain thresholds.²⁴⁻²⁶ However, the appropriateness of the prevailing indices to identify thresholds or predicting the impact of a given heat stress on performance has to our knowledge not been systematically analyzed in cycling.²⁷ During the last decade several studies (see Table 1) have reported power output from TT's across a wide span of relevant temperatures with various combinations of humidity levels (consequently changing the environmental vapor

Table 1. Studies with average power output reported for prolonged time trials (TT duration above 30 min.) in the heat (30°C or above) and with a corresponding cool control trial (20°C or below).

Reference	Temperature (°C)	Relative Humidity (and vapor pressure)	Wind speed (m/s)	Peak heart rate HOT (CON)	Sweat rate L/h HOT (CON)	End core temperature HOT (CON)	Power output deficit compared to control
Racinais ¹³ *	39°C	20% (9 mmHg)	9.5	175 (169)	2.1	40.2 (38.5)°C	16%
Racinais ¹³ **	39°C	20% (9 mmHg)	11	177(169)	2.5	40.1 (38.5)°C	2%
Lorenzo ³³ *	38°C	30% (15 mmHg)	0.5	165	—	39.5 (38.8)°C	18%
Lorenzo ³³ **	38°C	30% (15 mmHg)	0.5	150	—	39.4 (38.8)°C	17%
Périard ⁷²	35°C	60% (25 mmHg)	3	184 (179)	1.8 (1.1)	39.8 (38.9)°C	13%
Keiser ³⁴ *	38°C	30% (15 mmHg)	3	183 (182)	1.4 (0.8)	39.7 (39.2)°C	13%
Keiser ³⁴ **	38°C	30% (15 mmHg)	3	186 (177)	1.7 (0.8)	39.6 (38.8)°C	7%
Périard ¹²	35°C	60% (25 mmHg)	4	183(182)	2.3 (1.3)	39.4 (38.6)°C	18%
Périard ⁷³	35°C	60% (25 mmHg)	4	183(180)	2.4 (1.8)	39.6 (38.8)°C	13%
Périard ⁷⁴	35°C	60% (25 mmHg)	3	178 (178)	2.1 (1.3)	39.8 (39.0)°C	13%
Roelands ³⁵	30°C	55% (17 mmHg)	0.5	180 (176)	—	—	11%
Roelands ³⁶	30°C	55% (17 mmHg)	0.5	180 (184)	1.9 (1.6)	39.3 (39.0)°C	25%
Watson ³⁷	30°C	55% (17 mmHg)	0.5	—	1.8 (1.4)	39.7 (39.2)°C	23%
VanHaitsma ⁷⁵	35°C	25 (11 mmHg)	0.5	175 (175)	—	39.2 (38.8)°C	16%
Schlader ⁷⁶	40°C	14 (8 mmHg)	1.5	183 (176)	1.4 (1.0)	38.7 (38.5)°C	22%
Peiffer ³⁸	32°C	40 (14 mmHg)	8.9	172 (168)	—	39.5 (39.1)°C	6%
Romer ⁷⁷	35°C	30 (13 mmHg)	0.5	—	—	—	18%

* Signifies studies with values reported pre-acclimatization (and post acclimatization in the same study marked with **) while subjects in the remaining studies were considered either acclimatized or familiarized with the exercise set-up in the heat prior to testing. Data that wasn't directly extractable was obtained via personal communication with authors or estimated on the basis of provided data (when possible) - "-" indicates that the present value was not reported or possible to estimate/obtain. Columns from left to right: name of lead author and article publication year, temperature in the hot time trial in degrees Celsius, relative humidity and absolute air vapor pressure in the hot time trial, wind speed in meters pr. second (which was set at 0.5 m/s if the time trial was indoor stationary ergometer cycling without artificial airflow generation), highest heart rate in beats per minute observed during the hot and control trials, sweat rate during the hot and controls in liters per minute either directly measured or calculated from body weight changes, core temperature in the hot and control trial at time trial completion in degrees Celsius and percentage power output reduction in the hot trial compared to the control.

pressure and gradient for sweat evaporation) and differences in wind speed that may impact both dry and evaporative heat exchange. Comparing the performance impact (relative decline in power output compared to control [cool-temperate air]) with the reported environmental values for temperature, radiation (when relevant i.e., outdoors), humidity and wind may allow for identifying if existing indices include an appropriate weighing of factors or develop a model that may be used for predicting the environmental impact on performance in conditions with sustained high rates of metabolic heat production.

Methodology

We used cycling TT as a model for this analysis as it is the prevailing exercise mode in scientific studies and as model for reviewing how exercise endurance is affected in the heat, it provides the advantage of direct assessment of power output as a measure of exercise capacity. However, in terms of performance (i.e. speed or time to complete a given distance) it should be acknowledged that air density decreases in the heat, allowing for a faster performance at a given power output or maintained speed at a lower average power.^{13,17} Nevertheless, comparing average power output during prolonged cycling time trials in studies that have been conducted in the heat (30°C or above) with a matched cool/temperate control trial allows for analyzing how work capacity is affected by the absolute temperature, radiation, wind speed and humidity.

Based on the above, the database PubMed was searched during March 2016 in accordance with PRISMA guidelines,^{28,29} using the first-order search terms: 'heat', 'hot' and 'hyperthermia' in conjunction with the second-order search terms 'cycling' and 'time trial', resulting in the retrieval of 2747 articles in total. We excluded reviews, conference proceedings, and interventional studies employing methods such as pre-cooling or pharmacological drug administration (data from placebo trials not excluded), but no other limits were set in the initial screening. Article titles and abstracts were subsequently screened for relevance, resulting in preliminary inclusion of 20 articles for further review. Thereafter, article full texts (retrieved via the University of Copenhagen library) were screened independently by 2 reviewers (N.J. and L.N.) resulting in the inclusion of the 14 studies presented in Table 1, which all fulfilled the inclusion criteria of utilizing a crossover design employing self-paced

prolonged cycling (TT or preloaded TT with total duration of minimum 30 min.), with average power output reported both for trials in the heat (air temperature $\geq 30^\circ\text{C}$) and cool/temperate control ($\leq 20^\circ\text{C}$) and with values for relative humidity, wind speed and solar radiation either reported, obtained via personal communication with authors or estimated/calculated on the basis of reported values (e.g. for indoor trials radiation was estimated to be negligible and when no fanning was provided the wind speed was set to 0.5 m/s, as an estimation of the air flow that is created due to leg movements and heating of still air around the subject.³⁰ Relevant data from interventional studies were extracted and included in the analysis, while data thought to be influenced by the intervention were excluded. The following mean data were extracted for all environmental conditions in the selected studies: temperature, humidity, wind speed, subject acclimatization/acclimation status, familiarity with TT and VO₂max, TT duration, end point criteria and venue, final core temperature, mean and peak heart rate, sweat rate, rating of perceived exertion and mean power output. If not directly reported, thermal indices were calculated; WBGT according to the Liljegren formula,³¹ UTCI via an online calculator on the official UTCI website,³² and a new integrated heat stress index using the formula $\frac{T \cdot RH}{\sqrt{WS}}$ = (T: absolute temperature (°C), RH: relative humidity (%) and WS: wind speed (m/s). Data not numerically reported have carefully been extracted from figures or obtained via communication with corresponding authors. The methodology outlined above was adopted to eliminate bias in our searching and selection procedure since the inclusion (or exclusion) of a study was considered independently by 2 reviewers and was based on content (i.e., study employing self-paced prolonged cycling and providing all relevant data necessary for the purposes of this review), and not on quality, journal or other factors prone to bias.

The environmental influence of temperature, humidity and wind

As illustrated in Figure 1A, ambient temperature as a stand-alone factor is a poor predictor of the integrated environmental heat stress and apparently 2 of the prevailing heat stress indices, WBGT and UTCI (see Fig. 1C and D), also fail to predict the impact of environmental heat stress on TT performance. However, in studies where wind speed, humidity and radiation are controlled

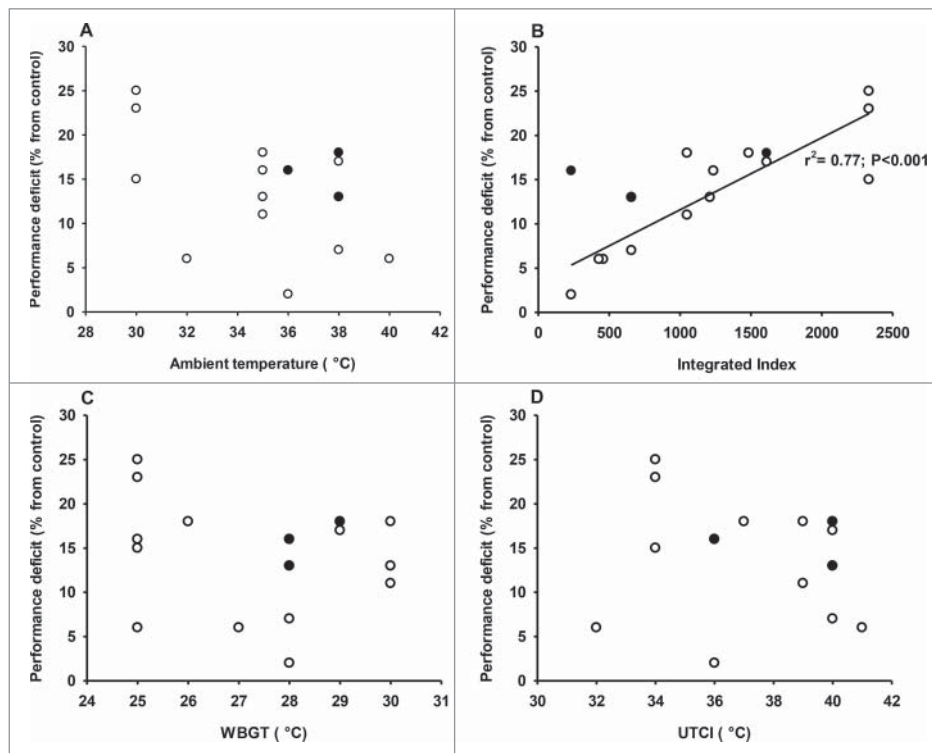


Figure 1. Performance deficit (percentage reduction in power output during hot TT compared to cool control TT for all studies in Table 1 meeting the inclusion criteria specified in text and Table 1 description) vs. ambient temperature (panel A); integrated index (panel B; with the index calculated as absolute air temperature [= dry bulb temperature for indoor studies and $0.7 \times \text{dry bulb} + 0.3 \times \text{black globe}$ for outdoor studies] multiplied with the relative humidity and divided by the square root of the wind speed); Wet Bulb Globe Temperature (WBGT; panel C) and Universal Thermal Climate Index (UTCI; panel D). Black filled circles represent values from studies with unacclimatized subjects (specified in the study description and subsequently acclimatized in the study as specified in Table 1) while the open circles are from studies with acclimatized subjects or trained subjects partly accustomed with exercise in the heat.

(remain constant across trials),³³⁻³⁸ performance and the physiological responses are directly influenced by elevated air temperature, as it will limit dry heat loss and either 1) restrict the upper limit for heat dissipation thereby restricting the exercise intensity that may be endured due to constrained ability to maintain heat balance (i.e. storage and elevated body temperature become the limiting factors for the metabolic heat production that the athlete in the given temperature setting may sustain) or 2) it will elevate the skin temperature thereby superimposing a cardiovascular restraint on the ability to support the increased need for skin perfusion and maintenance of stroke volume and arterial oxygen delivery to the exercising muscles (for a detailed discussion of fatigue mechanisms and the impact of hyperthermia-induced cardiovascular versus central nervous temperature changes, please see ref. 39). The temperature threshold where endurance performance becomes limited by the environmental setting is clearly affected by the combination of humidity (vapor pressure) and wind speed, as they in combination determine the upper limit for

evaporative heat loss, while air movement also influences dry heat loss. The direct and independent effects of humidity,⁶ wind speed,^{9,10,40} and radiation on exercise endurance and physiological responses have been verified in laboratory studies with fixed intensity,^{7,8} and the integrative influence of air temperature, humidity and wind speed on performance is illustrated in Figure 1B.

During outdoor cycling in flat terrain the movement speed is usually well above 10 m/s in trained subjects.^{13,41} However, as illustrated in Table 1, most indoor studies employ artificial wind speeds much lower during simulated time trials, resulting in a distorted picture of the influence of air temperature on natural road cycling performance.^{42,43} On the condition that the cyclists are well acclimatized (see discussion below) they may complete prolonged TT's in rather hot conditions (36°C dry air) with maintained performance (i.e., similar or slightly increased average speed) as the lower air density in the heat more than compensates for minor reductions in power output during such conditions.¹³ In accordance, power output during indoor trials may also be

maintained at temperatures up to at least 27 °C when humidity is modest (40% relative humidity) and wind speed corresponds to the movement speed generated during outdoor cycling,³⁸ whereas marked reductions are observed when air movement is minimal (see Table 1). For prediction of the environmental influence of heat stress on exercise performance (i.e. measured as power output) in acclimatized subjects with very high rates of sweat- and endogenous heat production, it appears that none of the environmental heat indices that we have tested (Humidex, apparent temperature, effective temperature or standardized effective temperature; see ref. 44 for a comparison of the different indices) and illustrated in Figure 1 with WBGT and UCTI, are weighing the impact of wind speed sufficiently. E.g. with an air temperature of 40 °C and humidity of 50% the WBGT is almost unaffected by changes in wind speed,³¹ while the UCTI-index will increase if the wind speed increases, as the UCTI-index correctly takes increased convective heat gain into consideration when the skin to air temperature gradient is reversed,³² but overlooks that increased air movement will markedly benefit evaporation which may become restricted at low wind speeds.

For predictions of heat exposure in occupational settings where the workers' metabolic rate is much lower compared to that of trained cyclists and if the wind speed does not vary too much across conditions, it appears that the UCTI and WBGT may be useful.⁴⁵⁻⁴⁷ However, it is important to note that these indices have important limitations,^{26,48,49} the main being lack of consideration of differences in metabolic heat production. Indeed, the UCTI includes a fixed metabolic rate and is not intended for interpretation in relation to different work rates, while the WBGT does not include metabolic rate in the measure or calculation when derived from climate service data. In this light, for predicting the environmental heat stress in athletes or occupational workers with high metabolic rates and substantial reliance on evaporative heat loss, we propose a much larger weighing of wind speed, as exemplified by the new integrated index. In this index, the product of the absolute air temperature (with similar weighing of dry air and black globe temperature as the WBGT) and the relative humidity will integrate the environmental factors of importance for dry heat exchange and also incorporate the impact of increasing vapor pressure, as this is affected both by the relative humidity and temperature. Furthermore, dividing this product by the square root of the wind speed allows for the index to include the facilitating effect on evaporation, which

across the environmental conditions represented in the included exercise studies, seems to be far more important than the interfering effects on dry heat exchange.

With multiple linear regression analysis, using the reduction in mean TT power output from cool control to exercise in the heat as the dependent (output) parameter and dry air, black globe, vapor pressure, relative humidity, and wind speed as independent parameters, we were unable to obtain a better correlation than the one obtained for the new integrated index (presented in Fig. 1B and providing a $R^2 = 0.77$; $P < 0.001$), indicating that the weighing of temperature, humidity and air movements apparently are appropriate. While WBGT in isolation failed to predict cycling performance loss in the heat (see Fig. 1C), we obtained a significant coefficient of determination ($R^2 = 0.55$; $P < 0.05$) when the WBGT-index was divided by the square root of wind speed, again emphasizing the importance of air movement. All of the above analysis only included the studies/trials with acclimatized subjects or athletes accustomed to exercise in the heat (specified in Table 1). As discussed below, acclimatization markedly improves exercise performance in the heat, when all studies/trials in Table 1 were included in the analysis, i.e., mixing unacclimatized and acclimatized subjects, the strength of the correlation between performance and the new integrated index presented in Figure 1B is lowered (R^2 reduced from 0.77 to 0.54). This emphasizes the importance of acclimatization, but besides this parameter, none of the other subject characteristics or reported physiological responses (heart rate, delta change or absolute core temperature response, VO_{2max} or sweat rates) were correlated to the changes in performance or added to the prediction power as evaluated with additional multiple linear regression analyses. Thus for acclimatized athletes, it appears that the loss of work capacity during cycling in the heat to a very large extent is dictated by the ambient conditions and the physical limits these provide for heat dissipation. While athletes' absolute endurance capacity may rely on both cardiovascular and muscular parameters, the relative decline during exercise in the heat seems to be highly dictated by the environmental restraints on heat balance.

Influence of acclimatization

Heat acclimatization increases the capacity for dissipating heat to the environment through increased sweating and improved ability to support an elevated perfusion of the skin in conditions of increased cardiovascular

stress.^{15,33,34,50,51} (see ref. 52 for recent review). Unless the environment is very humid,²⁰ or the wind speed is low and insufficient to allow for the increased sweat rate to evaporate, the acclimatization induced adaptations will improve the endurance capacity in the heat in both trained and untrained individuals.^{50,53-55} During fixed intensity exercise, the improved ability to dissipate heat results in an attenuation of storage and hence a slower rise in the individual's core temperature, prolonging time to exhaustion,⁵⁰ whereas during self-paced exercise, the improved ability to dissipate heat allows for an elevated exercise intensity, as individuals may endure a higher metabolic heat production owing to improved thermoregulatory ability.¹³ E.g. in the outdoor study by Racinais et al.,¹³ 14 d of heat acclimatization increased average power output from 256 to 294 W, improving time required to complete a flat 43 km TT from 77 min in the unacclimatized state to 66 min following acclimatization. The ~40 W increase in average power output post-acclimatization corresponds to an increased metabolic rate of ~190 W and heat production of ~150 W, which was counterbalanced by an increased sweat rate of 0.3 L/h. (corresponding to a ~200 W increase in evaporative cooling power), while the end/peak core temperature and estimated rate of heat storage were unchanged across TT's in the acclimatized and unacclimatized condition. Matching observations are reported from indoor studies by Lorenzo et al.³⁰ and Keiser et al.,³⁴ indicating that trained subjects, both pre- and post-acclimatization, "exhaust" their heat storage capacity during self-paced prolonged exercise in the heat, but utilize the improved capacity for heat dissipation, achieved via acclimatization, to increase their exercise intensity as adaptations have rendered them capable of coping with a higher metabolic heat production in a given environmental heat stress. It has been debated and investigated if the adaptations achieved via heat acclimatization may also transfer to cooler conditions where exercise performance is limited by other factors than heat balance issues,^{13,33,34,56,57} but it is beyond the scope of the present review to explore this complex topic, and we refer the reader to recent cross talk for a detailed discussion (see refs. 58,59). The physiological factors and/or altered perceptual clues that mediate changes in pacing strategy in the heat and subsequent adjustments following acclimatization are not well understood, but may involve integration between afferent feedback from thermal receptors, cardiovascular changes or familiarization,^{60,61} but independent of the underlying mechanisms, it appears that pacing strategies are

intuitively adopted by athletes in individual sports such as cycling and for team sports such as soccer.^{12,62}

Influence of exercise mode – comparison of running and cycling

Running and cycling both represent exercise modalities in which endurance trained individuals may sustain very high metabolic rates and hence endogenous heat productions for prolonged periods, which subsequently may become limiting for performance in thermally challenging conditions as previously discussed and reviewed.^{17,39,63-65} However, running seems to be affected at lower ambient temperatures (less adverse environmental heat stress conditions) for 3 major reasons: 1) During outdoor natural settings the lower exercise movement speed generates less air movement over the skin and is therefore benefited to a lesser degree by the facilitated evaporation as previously discussed. 2) Higher endogenous heat production for a given metabolic rate,⁶⁶⁻⁶⁸ and 3) less benefit from reduced air density and hence air resistance in running compared to cycling, where the temperature effect on air density markedly reduces the aerodynamic drag and improves the speed achieved for a given power output.^{13,69}

In agreement with these considerations, Chan et al.⁷⁰ reported that triathletes tested in hot and temperate conditions in trials of 40 km cycling and 10 km running were 8 minutes slower in the heat, but this was entirely related to a reduced running performance while cycling performance did not differ between conditions. Furthermore Ely et al.¹⁸ analyzed performances from a large number of marathon runners completing the same courses in different years under different environmental conditions, and report that performance for trained runners (with comparable training status to the cyclists in the studies represented in Table 1) already becomes affected when the WBGT surpasses 10 °C (it should however be acknowledged that even the fastest marathon runs differ in terms of time span compared to the included TT's). In agreement, a meta-analysis of ~1.8 million marathon runs indicates that the fastest performances are achieved in air temperatures between 5 and 10 °C for male runners and at ~10 °C in females,⁷¹ while ambient temperatures above this level will impair performance. In the analysis by Ely et al.¹⁸ the average performance time was ~5 % slower for top 3 finishers at a WBGT of 22 °C (compared to 8 °C) while larger performance deteriorations are

apparent for less trained runners. In contrast, Peiffer et al.³⁸ report no difference in performance during cycling TT's across these temperatures (i.e. similar power output at 17, 22 and 27 °C dry air temperature) during indoor cycling when high wind speeds (matching realistic outdoor cycling) are applied. For outdoor cycling where the aerodynamic benefit becomes relevant, acclimatized subjects may, as previously discussed, maintain average TT speed and performance at temperatures as high as 36 °C or 28 °C WBGT,¹³ and these differences between running and cycling highlight the importance of taking the exercise mode into consideration when evaluating the impact of a given environmental heat stress. Several more complex heat strain indices have been developed in attempt to incorporate all relevant heat stress factors (environmental, clothing aspects, individual physical and physiological characteristics; see ref. 23 for an overview), but most are focused on occupational settings and do not allow for calculation of the range of metabolic heat productions or wind speeds addressed in the present review, and the rather large influence of exercise mode illustrated with the differences between running and cycling puts emphasis on the difficulty of predicting and incorporating all factors into one universal heat index.

In conclusion, self-paced endurance performance is markedly influenced by environmental heat stress factors (i.e., the combination of air temperature plus superimposed radiation, humidity and wind speed). However, the performance impact is markedly modified by the individual's acclimatization- and training status and consideration of the exercise mode is of great importance, as the wind generated by the individual's movements or by environmental (either natural or fan generated) air flow over the skin seems to have a strong influence, as illustrated by the integrated index.

Disclosure of potential conflicts of interest

No potential conflicts of interest were disclosed.

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