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Ultra-endurance events in tropical environments and countermeasures to optimize performances and health

**Running head:** Aerobic performance in tropical climate

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Abstract

Physical performance in a tropical environment, combining high heat and humidity, is a difficult physiological challenge that requires specific preparation. The elevated humidity of a tropical climate impairs the thermoregulatory mechanisms by limiting the rate of sweat evaporation. Hence, a proper management of whole-body temperature is required to complete an ultra-endurance event in such an environment. In these long-duration events, which can last from 8 to 20 h, held in hot and humid settings, performance is tightly linked to the ability in maintaining an optimal hydration status. Indeed, the rate of withdrawal in these longer races was associated with lower water intake, and the majority of finishers exhibited alterations in electrolyte balance (e.g. sodium).

Hence, this work reviews the effects on performance of high heat and humidity in two representative ultra-endurance sports, ultramarathons and long-distance triathlons, and several countermeasures to counteract the impact of these harsh environmental stresses and maintain a high level of performance, such as hydration, cooling strategies and heat acclimation.

Keywords
Performance, tropical climate, heat, humidity, triathlon, ultra-endurance

Abstract word count: 163
1. Influence of heat on performance and health

It is now well established that aerobic performance and health can be deeply impacted by a hot and humid climate [1]. In particular, long-duration races, such as ultra-marathons or long-distance triathlons, are highly concerned by these environmental stresses due to a much longer exposure to these conditions compared to most events, from short-distance runs or triathlons to marathons.

1.1. Ultra-endurance events: ultramarathon

1.1.1. Ultra-endurance in the heat

Ultramarathon is a running event which lasts more than 6 h and usually presents a high dénivelé, from hundreds to thousands meters elevation [2]. In the past decade, trail running races have become a major ultra-endurance sport. Since the first edition of the ‘Ultra Trail du Mont Blanc’ (160 km and +10,000 m of elevation), the number of finishers has grown from 67 in 2003 to 1685 in 2017. This specific effort involves several physiological and psychological parameters that are modulated by environmental factors. Ultramarathon races are performed in a variety of off-road terrains, elevation profiles (positive: D+ and negative: D- changes) and distances, all of which may greatly complicate the understanding how environmental conditions affect performance. Marathon races present more standardized characteristics, facilitating the comparison of performances in order to study the role played by heat [3]. The analysis of winners’ times in several marathons, evidenced that the optimal ambient temperature for running performance is between 10°C and 12°C for elite athletes [4]. Above this temperature, data from 136 marathons performed between a wet-bulb globe temperature (WBGT) of 5 and 25°C showed a negative correlation between WBGT and running performance (Figure 2) [5]. Interestingly, the same authors also showed that the performance of slower runners, exposed to heat for a longer time than faster runners, are more affected by higher temperatures. In ultramarathon distances, a similar effect of a hot environment on performance was observed in a study that analysed running times in the Western States Endurance Run (161 km and 6000 m D+) [6]. The authors followed 50 runners who completed the race in two consecutive years (2006 and 2007) to investigate the effect of temperature changes, from 7–38°C in 2006 to 2–30°C in 2007 (figure 3). Regardless of their level, athletes were 8% slower during the ‘hot’ year (2006) than during the ‘cooler’ (2007), and the withdrawal rate was 14% higher in 2006. Slower runners did not appear to be more impacted by the hot environment, but this observation was probably due to the longer time running at a comfortable temperature (i.e. during the night).

1.1.2. Hydration requirements during ultra-endurance exercise in the heat

During muscle contraction, only ~25% of the substrate energy is converted to mechanical work, with the other ~75% released as heat. An effective thermoregulation during exercise relies on the balance between the absolute mechanical work generated by the athlete and the heat dissipating process. Ultramarathons, characterized by a low and steady relative exercise intensity over very
long periods, do not significantly challenge the heat balance in temperate environments. However, maintaining mechanical load over a longer time may challenge heat balance in athletes, especially when competing in hot and/or humid environments. Furthermore, environmental heat stress (i.e. temperature) reduces dry heat loss, due to the small (or even negative) temperature gradient between the skin and air, which progressively puts sweat evaporation as the only mechanism available for the organism to dissipate endogenous heat [7,8]. Indeed, in 30°C conditions, a dry heat loss of 75 W is observed whereas it induces a dry heat gain of 75 W at 40°C, increasing the sweating rate required to maintain body core temperature [9]. Thus, ultramarathons performed in a hot environment require greater water intake to compensate increased water losses. During the Badwater Ultramarathon of 2012 (217 km and 4000 m D+), the temperature oscillated from 10.1°C at night to 46.6°C during the day. The follow-up of 4 runners who completed the race in 36±3 h showed a mean water intake of 34±13 [10]. On average, each athlete drank 0.93 L.h⁻¹, whereas on completion of the Biel Ultramarathon in Switzerland (100 km and 645 m D+), in a temperate environment varying from 8 to 28°C, the runners consumed 0.65 L.h⁻¹ [11]. When the distances of these two races were linked to elevation changes (100 m D+ is equivalent to 1 km distance), the adjusted distance for the Biel Ultramarathon was 106.45 km and 257 km for Badwater. Hence, the Badwater runners drank almost twice as much water as the Biel runners (0.13 L.km⁻¹ and 0.069 L.km⁻¹, respectively), despite a higher mechanical workload developed during the Biel Ultramarathon due to its shorter distance and lower elevation change (6.6 min.km⁻¹ vs. 8.5 min.km⁻¹ for Badwater). The characteristics of the 2007 Peninsula Ultra Fun Run (PUFfeR) of South Africa (80 km and 1000 m D+) were close to those of the Biel Ultramarathon, but the participants were subjected to lower environmental temperatures (8–20°C). The runners drank less during this more temperate race than during the Biel Ultramarathon (0.028 L.km⁻¹ and 0.069 L.km⁻¹, respectively) [12]. The analysis of the hydration status of 16 ultramarathon runners (161 km, 7000 m D+) in a hot environment (4.8–37.8°C) showed that finishers (n=6) had drunk significantly more water at the 48th km than non-finishers (n=10) (Stuempfle et al. 2011). However, the authors were unable to determine whether beverage intake was directly linked to finishing capacity or if it was due to other factors, such as runners’ experience or endurance capacity. A second study was focused on a 160-km foot race (positive elevation not known) with temperatures that peaked at 38°C, and followed only runners who had completed at least one previous ultramarathon among the top 50% [13]. The authors showed that, despite their homogenous level and experience, non-finishers also drank significantly less than finishers (-35%, p<0.01). These data confirm the tight relationship between event temperature and water intake, and that hydration strategies remain essential for health and performance. Another study showed an average 0.19 L.km⁻¹ sweat loss in runners during the 2011 Gwada Run, multi-stage race (6 days, 142 km) held in tropical conditions (30 ± 2.4°C and 82 ± 4% RH) [14]. Yet water intake (1.5±0.3 L per stage) was probably distorted by the shortness of the
stages (from 16 to 21 km), which enabled athletes to tolerate transient dehydration during the races (~ $4.2\pm0.9$ L per stage).

### 1.2. Triathlon

Ironman and Challenge triathlon series are trademark brands for long-distance triathlons consisting of a 3.8-km swim, a 180-km cycling leg and a closing full marathon (42.195 km). The best professional triathletes complete the distance under 7 h and 50 min, whereas time of age group athletes may vary from 9 to 13 h and more, making this race one of the longest endurance races. The duration depends on several factors, including terrain (e.g. course route, technicity, elevation) and environmental conditions. For the latter, hot and humid climate impacts the performance and the rate of withdrawal, as observed in the Kona (Hawaii) Ironman World Championships, held every October [15,16]: top age-groupers were slower in Hawaii than in their qualifier races [16], and abandon rate can reach 10%, a high proportion considering the higher fitness level of athletes participating in this particular event, more resistant to heat stress [17,18]. Similarly, more than 25% of the athletes did not reach the finish line at the inaugural Ironman Vichy in 2015, which was held in unusually hot conditions (31~35°C), in contrast to North American races which present a minimum 95% finish rate (Britt 2011).

During long-distance triathlon, heat stress specifically impacts each successive leg: swimming, cycling and running.

#### 1.2.1. Swimming

Most long distance triathlons allow neoprene wetsuits to be worn for the swim leg as long as water temperature does not exceed 24.5°C. Between 24.5°C and 28.8°C, athletes who choose to wear a wetsuit are allowed to participate, but are not eligible for age-group awards or for qualifying slots for the Ironman World Championships; over 28.8°C wetsuits are prohibited (Ironman 2018). Enhancing swimmer’s buoyancy, the neoprene wetsuit reduces ventilation and O$_2$ consumption ($\dot{V}O_2$) at a given swimming speed, and therefore decreases metabolic heat production [19]. However, wetsuits also reduce heat dissipation capacity and may lead to a higher core body temperatures and subsequent dehydration [20,21]. Hence, although proscribing wetsuits in warm water may impair swimming performance, it also might decrease the existing risk of hyperthermia [22].

However, interestingly, Kerr et al. showed in a simulated Olympic triathlon that core temperature was not modified by wearing a wetsuit, thought to limit thermoregulatory mechanisms through heat-insulating properties of neoprene [20], as excess heat was still transferred to the periphery, leading to a higher skin temperature. Some field studies confirmed that core temperature remained around 38°C in well-trained athletes wearing a wetsuit in 20.5°C water during a 3.8 km swim [21], and in triathletes completing a long-distance Ironman, whose core temperature was
continuously monitored [23]. In 29.5°C water, another study showed that the core temperature in moderately trained athletes increased by an average 0.7°C but remained under 38°C during a non-wetsuit half-Ironman (Figure 1). Thus, to this day, no study evidenced a critical elevation of core temperature during the swim leg of long-distance triathlon events. Moreover, while 13 of the 14 documented deaths in triathlon races from 2006 to 2008 occurred during the swim leg, pre-existing cardiovascular abnormalities seem to have been the major factor, ruling out hyperthermia as a potential cause [24].

1.2.2. Cycling

During cycling, some of the heat produced by the muscles is dissipated via air convection around the body. This, however, depends on a sufficient temperature gradient between the skin and ambient air. Convection mechanisms are therefore limited in hot conditions when air temperature exceeds 35°C. Heat is also dissipated during cycling via sweat evaporation, itself depending on the pressure gradient of water vapor between air and skin surface. Like convection, this mechanism is reduced in a humid environment, making performance more challenging as thermoregulatory efficiency is dramatically reduced [25]. In a tropical climate (31-33°C, 70-75% RH), one-hour of pedalling at a submaximal intensity increases core temperature, heart rate, sweat rate and water loss [26–28]. These results can be extrapolated to describe the physiological impact of 4–6-h events, especially if the cycling course includes hills, where the diminished air speed reduces heat dissipation by convection [25]. Laboratory-controlled studies showed that increasing ambient temperature impaired cycling capacity when relative humidity was clamped at 70% [29,30]. During a 9-day (2.5 h/day) cycling race held in Guadeloupe (31.1°C, 75.6% RH), tympanic temperatures measured immediately after the stages never exceeded a 2°C rise compared to resting pre-race values [31]. In contrast to the intrinsic variability associated with stage racing in a peloton, triathletes usually adopt a much steadier pace during non-drafting racing to “save the legs” for the following marathon [32]. Interestingly, Baillot et al showed a negative correlation between body mass and the evolution of core temperature throughout the cycling leg, illustrating greater heat storage and inertia in larger athletes [33]. Thus, a larger body presents a larger surface which allow to preserve heat exchange at high velocity, even in a hot and humid environment [34].

In summary, the higher velocity and the intrinsic non-drafting nature of cycling in triathlon promotes heat dissipation by convection only if air temperature is lower than skin’s. In a thermally challenging environment, sweat evaporation remains the main process for heat dissipation but is limited by the high humidity of a tropical environment. Nevertheless, triathletes appear to show adequate thermoregulatory capability to prevent excessive hyperthermia, mainly through intensity management and pacing strategies [33].
1.2.3. Running

Of the three sports in the triathlon, running may carry the greatest risk of hyperthermia for triathletes competing in a tropical climate. Several factors and stressors come into play. Firstly, although running is faster than swimming, air possesses neither the heat capacity nor the transfer celerity of water, hence limiting the quantity of heat energy dissipated from the body. Secondly, unlike in cycling, the lower speed of running does not allow excess heat dissipation via air convection around the body [34]. These factors may have a strong negative impact on running performance [35], particularly in a marathon [5]. Furthermore, this negative impact is amplified under two additional factors: (i) a heavier body mass, at a given pace, requires more energy for running locomotion and therefore produces a larger quantity of metabolic-related heat; and (ii) heat exchange by convection and evaporation is limited in heavier athletes running in a hot/humid environment, who display a greater imbalance between heat production and dissipation, even at slower paces [36].

While the core temperature data of professional triathletes in the Hawaii Ironman or other hot/humid locations are not available, a few studies in moderately to very well trained age group athletes pointed out that they did not suffer from heat-related illness and excessive increases in core temperature [21] (Figure 1). Laursen et al showed, in 7 out of 10 well trained triathletes racing a high-level sub-10-hour performance at Ironman Western Australia in temperate but humid conditions (23.3°C, 60% RH), that the average core body temperature remained close to 38°C [21]. Despite a much hotter and more humid environment in Guadeloupe (27.2°C, 80% RH), the average body temperature of moderately trained athletes during a half-Ironman run was 38.2°C and none of them reached 40°C [33]. These values are coherent with the relatively lower intensity and absolute workload at which most long-distance triathlon races are performed, in contrast with shorter events at a higher intensity and thus inducing a higher heat production [33,37]. The key role of exercise intensity on core temperature was confirmed in dryer conditions in a study showing that the fastest athletes exhibited the highest core temperatures [38].

2. Countermeasures to optimize performance and health

2.1. Hydration

Limiting dehydration during triathlons and ultramarathons in hot environments seems to be essential in order to maintain a mechanical workload over 6~7 hours. The key role of hydration strategy in a tropical climate is critical since it has been shown that combined hyperthermia and dehydration are worse than hyperthermia alone [39,40]. Despite contradictory observations on thermoregulatory mechanisms and core temperature [41,42], it seems that hyperhydration can delay the development of dehydration [41,43,44]. However, hyperhydration did not lead to enhanced
performances during a laboratory-controlled 46 km cycling time trial by elite cyclists [42] or a 60 min run by trained runners [45]. As hyperhydration results in non-negligible added body weight, it may not be an advantage for running performance, greatly impacted by extra weight [46]. In addition, it does not enhance thermoregulation in a hot and humid climate and augments the risk of hyponatremia [47].

In triathlon, although hydration depends very much on beverage availability provided by race organization, descriptive papers report that no triathlete has suffered from dehydration symptoms in hot and humid events, despite occasional significant water losses [21,33,38,48]. This suggests that hydration strategies used by athletes meet the body’s water requirements [49].

Maintaining an optimal hydration level is more complicated in ultramarathon. Indeed, analysis of the hydration status of ultramarathon runners in two different races showed that finishers drank significantly more water than non-finishers, even if the runners’ experience was taken into account [13,50]. In contrast, slower runners became over-hydrated because they feared dehydration, potentially leading to hyponatremia [51,52]. Hyponatremia however, is not only due to over-hydration, but may be the consequence of insufficient sodium intake during the race [13,50]. In a hot environment, hyponatremia affected 30–50% of ultramarathon finishers, reflecting the inadequate or incorrect hydration strategies of numerous runners [13,53,54]. Thus, additional sodium intake during ultramarathons could contribute to faster performances by stimulating thirst, increasing voluntary fluid intake, enhancing intestinal glucose and water absorption, optimizing extracellular and intracellular fluid balance, and potentially mitigating the occurrence of clinically significant episodes of hyponatremia [55–58].

2.2. Heat acclimation

Heat acclimation (HA) before a race is an efficient way to limit the decrease of performance in a hot environment [59,60], with physiological adaptations ranging from the fifth day [61] to a two-week span [61,62]. These adaptations of HA lead to better cardiovascular function (output, stroke volume, heart rate) and a decreased core temperature at rest and during exercise, partly due to an enhanced sweat rate and an expanded plasma volume [59]. HA is also known to reduce sodium loss by sweating [63]. However, HA does not fully restore long to ultra-long endurance performance to the level reached by athletes in temperate conditions [62].

If early arrival at the race location is not possible, HA in an environmental chamber remains an alternative strategy that may help preserve ultramarathon performance. Costa et al examined the effects of six 2-h sessions of running at 60% of VO\(_{2\text{max}}\) on a motorized treadmill in an environmental heat chamber at 30°C or 35°C [64]. From the third session onward, mean heart rate was lower at 30°C, whereas mean heart rate and thermal comfort were lower at 35°C. The authors concluded that two bouts of running at 60% of VO\(_{2\text{max}}\) in a 30°C air temperature conditions were
sufficient to induce heat acclimation in ultra-runners, which may enhance their performance in such environments.

2.3. Hydration policy and implementation

In a triathlon field study, oral salt supplementation improved half-Ironman performance through faster cycling (p<0.05) and showed a similar trend in the running leg (p=0.06), with reduced sweat rate and limited electrolyte deficit [65]. Thus, the consensus recommendation is to ingest 0.5 to 0.7 g.L⁻¹.h⁻¹ for long endurance races [66] and up to 1.5 g.L⁻¹.h⁻¹ for athletes prone to develop muscle cramping [67]. However, adding salt to the consumed water is not sufficient to avoid hyponatremia if athletes overhydrate during a race, as 73% of severe symptomatic hyponatremia found after an Ironman [57].

Hoffman et al observed no advantage to sodium-enriched beverages during a 161-km ultramarathon performed by all levels of athletes in heat (38°C) [68]. This result may have been due to a variation in sodium intake from solid food and/or to a better tolerance of faster runners to hypohydration and hyperthermia [14,69].

2.4. Cooling

Cooling strategies such as cold drink ingestion or cold-water immersion in order to reduce the thermal stress may enhance performance in the heat. This effect has been observed in cyclists (Figure 4) [70–72] and runners, illustrated by a longer time to exhaustion [37,73,74]. Wearing cooling garments prior to or during exercise has proven to be performance-effective in hot and humid climate [75–77], but remain difficult and impractical to use, and are often banned in official long-distance events.

Other studies have focused on more direct cooling strategies, but the exercise durations were shorter than ultra-endurance events. Nonetheless, they show interesting results that may be extrapolated for long and ultra-long events. Spraying or pouring water over the face and/or body can improve performance in tropical conditions. For example, pouring cold water over the skin will reduce skin temperature by absorbing the peripherally-transferred heat, before dripping off the body, and transiently improve thermal comfort. Cooling the head in this manner resulted in a 51% increase in cycling time to exhaustion at 75% VO₂max [78], with similar effects recently observed in running [79]. Neck cooling during a 90-min running trial in a hot environment (30.4°C and 53% RH) increased the distance covered by 7.4% with no change in rectal temperature [80]. A similar effect was found with menthol ingestion, as it activates cold dermal sensors [81]. Mixed into a cold beverage, menthol did not lower core body temperature but had a positive effect on thermal sensation and running/cycling performances over various distances in tropical climate [72,82]. Indeed, Stevens et al showed that a menthol mouth rinse every kilometre (25 mL at a concentration of 0.01%) during a running time trial in the heat improved 5-km performance time by 3% [82]. A
cumulative effect of menthol and ice slurry or cold water was observed on performances during a 20-km cycling trial in hot environment (30.7±0.8°C and 78±0.03% RH) [72]. Ultimately, menthol mouth rinsing and ingesting influence thermal perception and thermal comfort, which in turn might contribute to enhance performance in hot climates [82,83].

2.5. Cooling policy and implementation

According to the existing literature, pre-cooling by ice or cold water has been successfully studied during short duration exercise (<60 min), yet too brief to be a key factor of performance during ultra-endurance trials [73,79]. Conversely, percooling by cold water or ice slurry ingestion during exercise seems to be a very interesting intervention to improve performances in a hot environment and possibly increase fluid intake, particularly for well-trained athletes. Indeed, most high-level runners exhibit the greatest increase of internal temperature, probably due to higher thermogenesis consecutive to higher workloads. Faster trail runners (27 km) [69] and multi-stages trail runners (127 km on 6 days) [14] also present a greater post-race dehydration, which could be reduced by cold water due to its effect on voluntarily increasing water absorption during exercise. The higher temperature and greater dehydration observed in faster trail runners also seem to indicate that performance in heat is associated with a better tolerance to hyperthermia in elite athletes [84].

3. Conclusion

The maintenance of performance in long endurance events such triathlon and ultramarathon held in a hot environment is a considerable challenge which requires meticulous preparation and management before and during the race. To limit performance decrements induced by these harsh environmental conditions, several countermeasures have been proposed, such as cold–water or ice slurry ingestion, external precooling (before exercise) and precooling (during) and/or menthol use. However, the limited duration of exercise performed in these studies does not allow a direct application to an ultra-endurance or ultra-triathlon context. Thus, further studies will be needed to validate these approaches in ultra-endurance events.

Conventionally, one of the most relevant strategies to employ for performing in the heat is to consume adequate fluids: maintaining water availability along different race courses is thus crucial due to the detrimental effects of dehydration on fluid balance and the subsequent heat loss via sweating. Individual sweat rates are highly dependent on athlete’s morphology, the intensity level of exercise and the environmental temperature and humidity. Sweat losses are accompanied by electrolyte losses, mostly sodium, potentially contributing to hyponatremia if not compensated: exogenous intake of sodium-enriched beverages is the most effective strategy to reduce this risk. In addition to the traditional compounds found in most sport drinks (e.g. glucose, magnesium),
ultramarathon beverages should contain about 0.7–1.2 g.L\(^{-1}\) of salt when performing in the heat. However, sodium-enriched beverages remain insufficient if athletes overdrink by fear of dehydration during the race, placing management of water intake as a key determinant of performance.

Heat acclimation remains a relevant strategy that may enhance ultra-endurance performance in hot environments: most of the acclimation benefits occur in the first 14 days of exposure, and a short-term protocol of 5 days will already induce significant early adaptations.

Additional information

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Captions

Figure 1.
Individual and mean values (±SD) of core temperature at each stage of the Guadeloupe half-Ironman held in tropical climate. T1: just before the race; T2: after the swim phase; T3: after the cycle phase; T4: at the end of the run phase. Temperatures were obtained from telemetric intestinal temperature devices ingested at least 6 hours before the race. Modified from [33].

Figure 2.
Nomogram representing the impact of WBGT on the relation between marathon finishing times according to quartiles and relative performance decrement in comparison with WBGT at 5°C. Modified from [5].

Figure 3.
Proportion of runners abandoning the Western States Endurance Run (161 km; 6000m D+) race at each checkpoint along the course (A), and relationship between finish times for the 2006 (7-38°C) and 2007 (2-30°C) edition (B). Modified from [6].

Figure 4.
Trial times for 5 successive blocks (4 km cycling + 1.5 km running.) with the ingestion of Neutral water (orange), Cold water (blue) and Ice-slurry (green). Mean ± SD.

Neutral water vs. Ice-Slurry/Menthol (P<0.05).
Cold vs. Ice-Slurry/Menthol (P<0.05).

β and † denote that block performance was affected by Time Period (β: P<0.007) and the Time Period x Drink Temperature interaction (†: P<0.004), respectively.

Modified from [72].
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