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LEADING ARTICLE

Adaptation to Hot Environmental Conditions: An Exploration of the Performance Basis, Procedures and Future Directions to Optimise Opportunities for Elite Athletes

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Abstract Extreme environmental conditions present athletes with diverse challenges; however, not all sporting events are limited by thermoregulatory parameters. The purpose of this leading article is to identify specific instances where hot environmental conditions either compromise or augment performance and, where heat acclimation appears justified, evaluate the effectiveness of pre-event acclimation processes. To identify events likely to be receptive to pre-competition heat adaptation protocols, we clustered and quantified the magnitude of difference in performance of elite athletes competing in International Association of Athletics Federations (IAAF) World Championships (1999–2011) in hot environments (>25 °C) with those in cooler temperate conditions (<25 °C). Athletes in endurance events performed worse in hot conditions (~3 % reduction in performance, Cohen's $d > 0.8$; large impairment), while in contrast, performance in short-duration sprint events was augmented in the heat compared with temperate conditions (~1 % improvement, Cohen's $d > 0.8$; large performance gain). As endurance events were identified as compromised by the heat, we evaluated common short-term heat acclimation (≤7 days, STHA) and medium-term heat acclimation (8–14 days, MTHA) protocols. This process identified beneficial effects of heat acclimation on performance using both STHA (2.4 ± 3.5 %) and MTHA protocols (10.2 ± 14.0 %). These effects were differentially greater for MTHA, which also demonstrated larger reductions in both endpoint exercise heart rate (STHA: −3.5 ± 1.8 % vs MTHA: −7.0 ± 1.9 %) and endpoint core temperature (STHA: −0.7 ± 0.7 % vs −0.8 ± 0.3 %). It appears that worthwhile acclimation is achievable for endurance athletes via both short-and medium-length protocols but more is gained using MTHA. Conversely, it is also conceivable that heat acclimation may be counterproductive for sprinters. As high-performance athletes are often time-poor, shorter duration protocols may be of practical preference for endurance athletes where satisfactory outcomes can be achieved.

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Key Points

Elite athletic performance can be influenced both positively (sprint) and negatively (middle—long distance) by hot conditions in comparison with temperate climates, yet this observation has often been anecdotal and rarely been quantified. This leading article provides an evidence-based perspective on the issue.

Elite athletes are often time-poor for event preparations and consequently much conjecture has been provided in the scientific literature about the optimal style and duration of acclimation exposures. This leading article examines the efficacy of short- and medium-duration protocols across heart rate, core temperature and plasma volume and performance variables.

Evidence presented suggests short-term (≤7 days) heat acclimation results in beneficial effects for elite performers, although current findings support medium-term (8–14 days) exposure to a greater extent where this can be incorporated into training and preparation.

1 Introduction

It is popularly perceived that performance in the heat is compromised compared with temperate conditions and that pre-competition adaptation to this environment is a necessity [1, 2]. However, this may not be the case for all events, depending on the intensity and duration of performance. For elite athletes, there are also issues of time efficiencies to be considered when determining event preparation within busy training and performance schedules. Therefore, although some recent articles have added some useful information on this underserved area (e.g., [3, 4]), the purpose of this leading article is to now take this issue forward and describe instances where heat adaptation may be useful, to identify protocols which lead to meaningful adaptations and finally to suggest future directions for this important area of research.

Endurance events in particular have often been described as being compromised in the heat [1, 2]. This effect is most likely mediated as an integrated thermoregulatory response associated with exposure to the heat, including increased exercising heart rate (HR), elevated core (T_c) and skin temperatures, greater perception of effort, thermal strain, thirst, and water loss leading to dehydration (for reviews see [3–5]). It is, therefore, important for athletes to prepare themselves for events that may take place in environmentally challenging conditions. This strategy is particularly important in both team sports [2] and endurance events [6], which require performances to be sustained for extended periods of time potentially increasing the likelihood of athletes developing substantial dehydration, overheating or a potentially critical T_c [7]. This scenario often results in fatigue, down-regulation of effort, performance impairment and, in extreme cases, heat illness [4–6]. However, particular scenarios where heat-induced decrements to performance are most prevalent, and the most effective evidence-based strategies of minimising these effects, are seldom described.

Almost 50 % of the world's population now live in the Torrid Zone, close to the Earth's equator where temperatures are hotter and more physically challenging than in the Temperate or Frigid Zones [8]. Consequently, many major sporting events are now scheduled to be held in geographical locations that experience hot and humid environmental conditions. These locations include the 2015 International Association of Athletics Federations (IAAF) World Championships (Beijing, summer), the 2016 Olympic Games (Brazil, summer), and the 2022 Fédération Internationale de Football Association (FIFA) World Cup (Qatar). It is, therefore, critical that competitive athletes are adequately prepared for such competitions, particularly individuals more used to living and exercising in temperate environments and unaccustomed to hot conditions. For athletes not living and regularly training in the Torrid Zone, most would likely require some form of preparatory heat training prior to embarking on competition in this region. It is often reported that 10–14 days of heat exposure [3] is ample heat acclimation; however, these extended interventions might not be viable for most sporting programmes. This period may be particularly challenging for time-poor high-performance athletes in terms of availability, timing, training and/or logistical reasons. To combat this, there have been recent efforts to evaluate the effectiveness of shorter heat training programmes of 7 days or shorter duration [4, 5]. The priority for coaches and athletes in such cases is determining the minimum number of days of heat training needed to provide some benefit, within their busy training and performance schedules.

Both short- and medium-term heat adaptation protocols can elicit changes in important physiological parameters such as plasma volume (PV) expansion, reductions to exercising HR, T_c, and sweating commences at a lower T_c with a more dilute concentration of metabolites [9], which could be useful for subsequent performances in the heat and also in cool conditions where potential fluid loss is substantial [10]. It is important to understand how these physiological changes occur, and the potential effects they have on athletes' performances. For example, an expansion of PV can promote improved performance in aerobic events, most likely by reducing plasma protein loss [11, 12] and increasing blood volume, thus mediating a decreased exercising HR in the heat through adaptive gains in central venous return and preload [4, 13, 14]. Consequently, an increase to stroke volume mediated by gains in PV and blood volume lowers cardiac frequency [15, 16]. As heat adaptation increases PV, the body more effectively regulates blood pressure in the face of fluid loss as a consequence of increased levels of sweat [17]. Collectively these adaptations lower HR, promote reduced thermal strain and more efficient transfer of heat [17]. Therefore, as PV expansion plays an important role in extending endurance exercise performance, heat training programmes promoting greater PV expansion are of benefit. Nevertheless, this adaptive response may only be of relevance for athletes undertaking endurance events, where fluid loss and heat dissipation mechanisms play a meaningful role in race or competition performance. For example, athletes competing in events that require only short bursts of anaerobic power (e.g., 100 m sprint) are unlikely to experience a decrement in performance in hot conditions as they are under substantially less sustained thermal load compared with their endurance counterparts.

2 Comparison of Running Performances in Hot and Temperate Conditions: IAAF Track and Field Performances (1999–2011)

Numerous studies have examined the effects of environmental conditions on performance in controlled isolated laboratory experiments. However, to fully ascertain whether or not environmental conditions influence elite field-based performance, it is useful to consider the magnitude of change in outcomes of regularly scheduled events over a longitudinal period performed in different conditions. This type of analysis can be performed by examining secondary data from scheduled major events such as those organised by the IAAF. These data are publicly available and facilitate rapid and meaningful comparisons when appropriately clustered for analysis of data trends. To address the question of where and which events are most affected by environmental conditions, we collated and analysed the mean of the top ten performances in distance events (top 60 % of track events) and top six performances in sprint performances (top 60 %) for males and females in the 100, 200, 400, 800, 1,500, 5,000, 10,000 m and marathon events from seven consecutive IAAF World Championships (1999–2011). Events were categorised as either temperate ($n = 41$) or hot ($n = 44$) conditions, separated using a standardised threshold temperature of 25 °C as an index of comfortable working temperature [18]. It was determined to utilise 25 °C as it further represented the full cohort ($n = 85$) mean temperature (24.5 °C) and resulted in a temperate condition mean ± SD of 18.5 ± 3.2 °C (humidity 59.6 ± 7.0 %) and a hot condition mean ± SD temperature of 30 ± 4.3 °C; (humidity 61.3 ± 4.9 %), which are both in range of common specifications for these conditions. Although 25 °C is a relatively high threshold temperature, outdoor exercise benefits to a greater extent from convective cooling than laboratory exercise, meaning a higher temperature is more comfortable outdoors [19]. Therefore, we sought to recognise this in contrast to laboratory exercise [20].

Brief analysis of performances identified that the temperate conditions (<25 °C) resulted in faster performances in endurance events (>5,000 m) (~2 % mean gain, medium effect) (Fig. 1; Table 1). Conversely, the sprint events (≤200 m) demonstrated the opposite effect with athletes performing better in hot conditions (~2 % mean gain, medium to large effect) compared with the events in temperate climates. As might be expected, middle-distance events were less affected by ambient conditions and considerable variation between performance gains and losses were observed for males and females, probably due to the influence of other factors such as race tactics (Fig. 1).

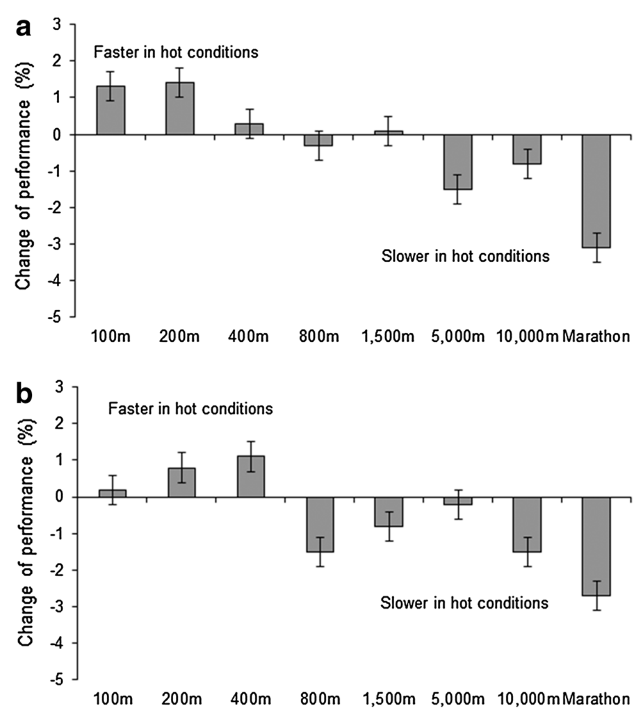

Fig. 1 Comparative mean ± 95 % CL percentage change of performance in temperate (<25 °C) vs hot (≥25 °C) conditions from International Association of Athletics Federation (IAAF) World Championship track events from 1999–2011 for **a** males and **b** females. Positive percentage indicates faster performance, and negative percentage indicates slower performance in hot conditions

Table 1 Effect size (mean Cohen's *d*) of performance in temperate (<25 °C) vs hot (≥25 °C) conditions from IAAF World Championship track events from 1999 to 2011

IAAF event (m)	Men	Women
100	Large ↑ (2.4)	Medium ↑ (0.7)
200	Large ↑ (2.3)	Large ↑ (0.9)
400	Trivial ↓ (−0.1)	Large ↑ (1.0)
800	Small ↓ (−0.4)	Large ↓ (1.4)
1,500	Medium ↑ (0.6)	Medium ↓ (−0.7)
5,000	Medium ↓ (−0.7)	Medium ↓ (−0.5)
10,000	Medium ↓ (−0.6)	Medium ↓ (−0.7)
Marathon	Large ↓ (−2.0)	Large ↓ (−2.4)

IAAF International Association of Athletics Federation

Effect sizes are reported as: trivial (≤0.19), small (0.2–0.49), medium (0.5–0.79), or large (≥0.8). ↑ (positive effect) indicates faster performance, and ↓ (negative effect) indicates slower performance in hot (≥25 °C) conditions

The marathon exhibited the largest performance impairment in the heat, with a mean reduction of 3.1 % for males (also a large effect; effect size [ES] = −2.0) and 2.7 % mean change for females (large effect; ES = −2.4) (Table 1). Although inferences from this observation were limited due to absence of knowledge in relation to race tactics, it is most likely that these reductions in performance were primarily related to the ambient temperature and absolute humidity in which the athletes were competing.

There are logical physiological and behavioural explanations for the differential effects of environment on performance variations in endurance and sprint events which have been detailed previously [8]. However, the underlying observation that hot conditions do not necessarily compromise all events is an important consideration for athletes and coaches in their preparation for competition based in the heat. This information should be useful for evidence-based decisions on prescribing appropriate pre-event acclimation for endurance-type activities where performance is most likely to be impeded in the heat.

3 Comparison of Short- and Medium-Term Heat Acclimation Models

Defining the optimum length of a heat acclimation protocol will be influenced by two factors: first, in physiological performance terms, the number of sessions needed to attain appropriate adaptations, and, second, the practical issues of logistics related to the competition such as a one-off tournament or an ongoing seasonal competition combined with player availability. Research has primarily focused on the acute effects in response to a single stressor, or in preparation for a one-off event, with little practical recognition of preparatory time restrictions commonly experienced by athletes across a competitive season. In most sports, teams and athletes need to compete in various conditions across a season, and hot condition events might only constitute a short period within the competitive cycle [21]. As such, it is important to consider both the acute effects of acclimation and secondary (residual) factors which might influence the magnitude and time course of benefits.

The majority of heat acclimation research to date has examined either short-term heat acclimation (≤7 days, STHA) (Table 2), or medium-term heat acclimation (8–14 days, MTHA) (Table 3) protocols. Clearly, for elite athletes performing in a congested competitive season, a shorter acclimation period would be advantageous and less disruptive to routine training. Therefore, we have made a brief practical comparative analysis to identify the degree of benefit derived from both STHA and MTHA protocols [21]. A representative sample of relevant research papers were included on the basis of acclimation or acclimatisation occurring in conjunction with exercise as well as the reporting of either a performance variable such as a time trial or time to exhaustion, HR, T_c or PV. From these data, pooled percentage change (mean ± 90 % confidence limits [CL]) as well as ES size was calculated.

From this brief comparison of available data, it is evident that there are merits to both STHA and MTHA strategies. Both strategies appear to result in some positive effects on subsequent performance outcome, HR adaptations, and reductions to exercising T_c (Table 2). However, it is also evident that MTHA protocols are more beneficial for eliciting plasma volume expansion (∼7 % mean gain) when compared with STHA (∼3.5 % mean gain) (Tables 2, 3, 4). This is also supported by changes in performance outcomes which demonstrate greater gains in response to MTHA compared with STHA protocols. The extent of any possible gain will be acutely meaningful among high-performance athletes for whom the smallest advantage represents a competitive edge (Table 4). It is plausible that elite athletes may also adapt more rapidly to a hot environment and several studies [2, 4] indicate short-term protocols are capable of evoking beneficial adaptations to athletic performance, but greater consistency of protocol design and a considerably larger volume of data is required to fully elucidate this area of athletic preparation. The balance between time effectiveness of the protocol and gaining meaningful adaptation should be the focus of future investigations. Nevertheless, it is important for a leading article such as this to identify important current deficiencies in contemporary practice and research literature, and propose areas in which more empirical data is required.

Table 2 Representation of studies that investigated short-term heat acclimation protocols (≤7 days)

Study/participants/design	Training status	Days/sessions	Heat training protocol	Reported outcome measures
Aoyagi et al. [29] $n = 16$, no CON	Trained and untrained	6 days	60 min walking or running (40 °C, 30 %)	Walk TTE in NBC (T: 2 % ↑, UT: 2 % ↑) PV (T: 1 % ↑, UT: 8 % ↑)
Aoyagi et al. [30] $n = 8$, no CON	Moderately trained	6 days	60 min walking (40 °C, 30 %)	Walk TTE in NBC (15 % ↑), PV (7 % ↑)
Brade et al. [31] $n = 10$	Moderately trained	5 days	50 min cycling (35 °C, 60 %)	Cycle work (J kg^{-1}) (5 % ↑), endpoint T_c (1 % ↓)
Buchheit et al. [32] $n = 15$, no CON	Well trained	7 days (acclimatisation)	60–90 min soccer training (35 °C, 25 %)	YoYo IR1 (6 % ↑), endpoint HR (1 % ↓)
Buono et al. [33] $n = 9$, no CON	Moderately trained	7 days	120 min walking and cycling (35 °C, 70 %)	HST endpoint HR (2 % ↓) and T_c (2 % ↓)
Chen et al. [34] $n = 14$	Moderately trained	5 days	25–45 min cycle (39 °C, 52 %)	TTE cycle, (TN: 5 % ↑, HT: 7 % ↑), endpoint HR (TN: 5 % ↓, HT: 5 % ↓)
Cotter et al. [35] $n = 8$, no CON	Healthy	5 days	70 min cycling (40 °C, 60 %)	Cycle work (kJ) (1 % ↑), endpoint HR (6 % ↓)
Garrett et al. [36] $n = 10$, no CON	Moderately trained	5 days	90 min cycling (40 °C, 60 %)	Cycle TTE (14 % ↑), endpoint HR (9 % ↓) PV (4 % ↑)
Garrett et al. [21] $n = 8$, no CON	Highly trained	5 days	90 min cycling (40 °C, 60 %)	Rowing TT (1 % ↓), endpoint HR (1 % ↓) PV (4% ↑)
Marshall et al. [37] $n = 7$	Healthy	3 days	120 min cycling (38 °C, 60 %)	HST endpoint HR (0.5 % ↓), T_c (0.5 % ↓)
Petersen et al. [38] $n = 12$	Moderately trained	4 days	30 min cycling (30 °C, 60 %)	Repeat sprint test (no change)
Sunderland et al. [39] $n = 6$ (F)	Well trained	9 days, 4 sessions	30–45 min of LIST (30 °C, 24 %)	LIST run to volitional exhaustion (33 % ↑), endpoint HR (3 % ↓) and T_c (1 % ↓)

CON control group, *F* Female, *HR* heart rate, *HST* heat stress test, *HT* hot environment, *kJ* kilojoules, *LIST* Loughborough intermittent shuttle test, *NBC* nuclear biological and chemical suit, *PV* plasma volume, *T* trained, T_c core temperature, *TN* thermo-neutral environment, *TT* time trial, *TTE* time to exhaustion, *UT* untrained, *YoYo IR1* YoYo intermittent recovery test level 1, ↑ increase, ↓ decrease

Based on current evidence and utilising a limited range of protocols, MTHA acclimation periods (8–14 days) are of more benefit for both performance and physiological indices such as PV expansion, lower exercising T_c, and lower end-point exercise HR. These observations are likely to be particularly meaningful for the preparation of athletes competing in particularly long duration events such as marathon or triathlon, which would be most challenging to heat dissipation mechanisms, or athletes required to continue with high-quality training regimens with minimal disruption. For example, hot environmental conditions may diminish training intensity among non-acclimated athletes if they are still acclimating, which could induce a detraining effect. Therefore, the individualised requirements and periodisation of athletic preparation must be carefully considered.

4 Preparatory Activities that may Optimise Exercise in the Heat

It is often purported that, for exercise-induced heat acclimation to be most effective, athletes should employ the same exercise mode in which they will compete [17]. One way to achieve this is to use high-specification ergometry in a regulated hot and/or humid environment in a sealed heat chamber, utilising the athlete's common exercise modality. Depending on the expected environmental conditions of the targeted athletic event, mere heat exposure in the absence of (elevated) humidity is less appropriate for preparation for hot humid environments [22]. Specific humidity exposure can form part of the acclimation strategy if appropriate for the athlete, as high humidity is an aspect of heat exposure that is both extremely challenging and under researched [22]. Responsiveness to these conditions requires manipulation of training volume and intensity to ensure that the appropriate exercise and recovery strategies are applied. Quantifying the degree of thermal load throughout training sessions through devices such as ingestible T_c pills can complement this process. Simple submaximal heat stress tests that include physiological and performance measures can be used throughout the acclimation process to indicate the level of adaptation reached [23].

Although it has been reported that, following heat acclimation, physiological adaptations may decay after a

Table 3 Representation of studies that investigated medium-term heat acclimation protocols (8–14 days)

Study/participants/design	Training status	Days/sessions	Heat training protocol	Reported outcome measures
Aoyagi et al. [30] $n = 8$, no CON	Moderately trained	13 days, 12 sessions	60 min walking (40 °C, 30 %)	Walk TTE in NBC (11 % ↑), PV (1 % ↑)
Burk et al. [40] $n = 16$, no CON	Moderately trained	10 days	110 min walking (32 °C, 18 %)	Walk TTE (83 % ↑), endpoint HR (4 % ↓), PV (11 % ↑)
Castle et al. [41] $n = 8$	Moderately trained	10 days	60 min cycling (33 °C, 53 %)	Cycle PPO (2 % ↑)
Cheung and McLellan [42] $n = 15$, no CON	Moderately and highly fit	14 days, 12 sessions	60 min walking wearing NBC clothing (40 °C, 30 %)	TTE walk (MF, 3 %, HF, 10 % ↑) endpoint HR (MF, 4 % ↓, HF, 6 % ↓) and T_c (MF and HF 0.5 % ↓)
Daanen et al. [43] $n = 15$, no CON	Moderately trained	12 days	120 min cycling (35–41 °C, 29–33 %)	Cycle TTE (24 % ↑) endpoint HR (6 % ↓) and T_c (1 %)
Houmard et al. [44] $n = 9$, no CON	Trained	9 days	60 min running (40 °C, 30 %)	HST run endpoint HR (8.4 % ↓) and T_c (1 % ↓)
Lorenzo et al. [45, 46] $n = 12$ (2 F)	Trained	10 days	90 min cycling (40 °C, 30 %)	Cycle work (kJ) (8 % ↑), LT power (7 % ↑), endpoint HR (9 % ↓) and T_c (1 % ↓), PV (7 % ↑)
Magalhaes et al. [23] $n = 9$, no CON	Healthy	11 days	60 min running (40 °C, 50 %)	HST endpoint HR (7 % ↓) and T_c (1 % ↓)
Nielsen et al. [47] $n = 13$	Well trained	9–12 days	40 min cycling (40 °C, 10 %)	Cycle TTE (67 % ↑), endpoint HR (7 % ↓), PV (13 % ↑)
Nielsen et al. [48] $n = 12$	Trained	8–13 days	45 min cycling (35 °C, 87 %)	Cycle TT (17 % ↑), endpoint HR (4 % ↓), PV (9 % ↑)
Racinais et al. [49] $n = 15$, no CON	Elite	14 days (acclimatisation)	90 min AFL training (29–33 °C, 37–50 %)	YoYo IR2 in temperate conditions (44 % ↑)
Sawka et al. [50] $n = 13$, no CON	Moderately trained	9 days	120 min walking (49 °C, 20 %)	Cycle power output (TN 4 % ↑, HT 2 % ↑), endpoint HR (TN 4 % ↓, HT 2 % ↓)
Voltaire et al. [51] $n = 9$	Highly trained	12 days (acclimatisation)	50 min running and 70 min swimming (33 °C, 78 %)	Maximal anaerobic velocity (4 % ↑), mean HR (16 % ↓) and T_c (1 % ↓)
Weller et al. [24] $n = 16$, no CON	Moderately trained	10 days	110 min walking (32 °C, 18 %)	HST endpoint HR (14 % ↓) and T_c (1 % ↓), PV (1 % ↓)

AFL Australian football, *CON* control group, *F* Female, *HF* highly fit, *HR* heart rate, *HST* heat stress test, *HT* hot environment, *LT* lactate threshold, *MF* moderately fit, *NBC* nuclear biological and chemical suit, *PPO* peak power output, *PV* plasma volume, T_c core temperature, *TN* thermo-neutral environment, *TT* time trial, *TTE* time to exhaustion, *YoYo IR2* YoYo intermittent recovery test level 2, ↑ increase, ↓ decrease

Table 4 The mean change and effect size (mean Cohen's *d*) of short- and medium-term acclimation training derived from protocols in Tables 3 and 4

Acclimation period	TTE	Athletic performance	Heart rate	Core temperature	Plasma volume[a]
STHA (≤7 days)	11 ± 8 % medium ↑ (0.5) ($n = 7$)	2.4 ± 3.5 % small ↑ (0.3) ($n = 5$)	−3.5 ± 1.8 % large ↓ (−1.0) ($n = 9$)	−0.7 ± 0.7 % large ↓ (−0.9) ($n = 5$)	3.5 ± 2.6 % (↑) ($n = 7$)
MTHA (8–14 days)	31 ± 29 % large ↑ (1.0) ($n = 7$)	10.2 ± 14.0 % medium ↑ (0.6) ($n = 7$)	−7.0 ± 1.9 % large ↓ (−1.0) ($n = 14$)	−0.8 ± 0.3 % large ↓ (−1.1) ($n = 12$)	7.1 ± 3.7 % (↑) ($n = 7$)

Data is expressed as mean change ±90 % confidence limits with effect size descriptor and (value). Effect sizes are reported as trivial (≤0.19), small (0.2–0.49), medium (0.5–0.79), or large (≥0.8), unclear = unclear finding

MTHA medium-term heat acclimation, *STHA* short-term heat acclimation, *TTE* time to exhaustion, ↑ increase, ↓ decrease

[a] Effect size not applied as the selected studies did not report pre-post values

period of non-exposure, one walking-based study demonstrated T_c adaptations could be preserved for up to 1 month [24]. However, for elite athletic performance, the period of decay may be much shorter. It is likely that athletes would, therefore, benefit from undertaking 'top-up' or supplementary heat exposure sessions periodically following heat exposure, although there is currently no systematic evidence of this type of strategy being performed. Routine and regular exposure to heat during an acclimation protocol enables the athlete to experience the heat in day-to-day training sessions [17], and athletes can gradually increase passive heat exposure related to daily living as soon as possible (i.e., live hot). Greater research in this area and manipulations of time spent training and passively recovering in hot or cool conditions may help ascertain whether residual effects of heat exposure are retained and, once undertaken, whether and how often it should be repeated.

It is possible that to adapt to the heat optimally and in a time efficient way, short-term protocols may best utilise a combination of active acclimation and passive acclimatisation. This could be achieved by using widely reported and effective heat tolerance training protocols in standardised conditions (acclimation), but also by promoting passive effects of the heat by living in hot conditions over the short- or medium-term period (acclimatisation). Living in the heat could enable athletes to adapt to hot conditions more rapidly while facilitating training in the cooler parts of the day. It has also recently been proposed that heat training may prove a useful preparatory strategy for performance in cool and temperate conditions [10], and consequently the potential gains from STHA and MTHA could be multi-faceted. Therefore, a combined approach could prove effective and achievable in short-duration protocols (<7 days); however, new research is required to clarify the interactions between STHA and MTHA and the extent to which passive exposure to heat might be useful.

Training intensities in hot or humid conditions, certainly in the short term, should not rely solely on HR or personal best times as effective markers of adaptation as these can be misleading [25]. Consequently, the use of scalar methods such as perceived exertion may be more effective in this context. Effective pacing strategies take time to establish in the heat and athletes should expect a degree of performance decrement in events of prolonged duration, especially when still acclimating. Knowing that elite athletic performance can be reduced by as much as 3 % in endurance events such as the marathon (Table 1), athletes can adjust their pacing strategies to ensure maximum possible performance, taking into consideration their current level of acclimation, relevant ambient conditions (temperature and humidity) and other competitor actions. It seems likely that the shorter time spent acclimating, the faster the acquired adaptations may diminish [8] and, therefore, it is probable that undertaking pre-event acclimation, top-up sessions, and living hot as soon as practical could facilitate athletes to compete at greater intensities in hot and humid conditions [26]. Potentially, the combination of all three strategies (heat acclimation, top-up sessions and living hot) may yield greater improvements in performance but this premise remains to be tested and may be best suited to either individual sports or tournament-like competitions that are major features of the athletes' season.

The adaptations underpinning maintenance of performance are likely consequent to the cumulative effect of the necessary heat adaptations for that particular individual or event. As discussed above, a 100 m runner may not require a lowered HR or T_c or other body cooling capabilities for optimal performance. It is plausible that physiological factors associated with being non-acclimated to the heat, such as peripheral vasodilation, coupled with elevated pre-race muscle temperatures may actually be beneficial in the context of sprinting performance although this is a concept rarely considered [27]. Minimising heat acclimation adaptations for these athletes could, therefore, be of benefit as it is possible that acclimation could have the opposite of the intended effect. More data are required to determine if it could be counter-productive for sprint athletes to undertake heat acclimation. It is even conceivable that sprinters may gain more from exaggerating the effects of initial heat exposure by undertaking pre-(hot)event cold acclimation to promote immediate 'fight or flight' style of responsiveness to the heat so as to up-regulate muscle temperature, elevate HR and T_c as a means of readiness for very short duration events [28]. It is one of the purposes of a leading article to challenge existing concepts and stimulate new research; it is our view that new research is required to clarify the issues we have identified.

5 Conclusion

Athletic performance for males and females participating in endurance events is likely to be impaired in very warm to hot environments. The opposite is the case for athletes competing in short-distance sprint events. Short-term heat acclimation programmes of <7 days provide athletes with modest thermoregulatory adaptations and performance benefits but, based on current evidence, more can be gained from medium-term (>8–14 days) acclimation periods. However, considerable recent evidence suggests STHA may be worthwhile [5] as, given the practical considerations of congested training and competition schedules, coaches and athletes will most likely give preference to shorter-term protocols. More efficient shorter-term acclimation may be achieved through strategies such as manipulations of active and passive periods of heat exposure and top-up sessions over the adaptive period.

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