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Heat alleviation strategies for athletic performance: A review and practitioner guidelines.

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Heat alleviation strategies

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Abstract

International competition inevitably presents logistical challenges for athletes. Events such as the Tokyo 2020 Olympic Games, require further consideration given historical climate data suggest athletes will experience significant heat stress. Given the expected climate, athletes face major challenges to health and performance. With this in mind, heat alleviation strategies should be a fundamental consideration. This review provides a focused perspective of the relevant literature describing how practitioners can structure male and female athlete preparations for performance in hot, humid conditions. Whilst scientific literature commonly describes experimental work, with a primary focus on maximising magnitudes of adaptive responses, this may sacrifice ecological validity, particularly for athletes whom must balance logistical considerations aligned with integrating environmental preparation around training, tapering and travel plans. Additionally, opportunities for sophisticated interventions may not be possible in the constrained environment of the athlete village or event arenas. This review therefore takes knowledge gained from robust experimental work, interprets it and provides direction on how practitioners/coaches can optimise their athletes' heat alleviation strategies. This review identifies two distinct heat alleviation themes that should be considered to form an individualised strategy for the athlete to enhance thermoregulatory/performance physiology. First, chronic heat alleviation techniques are outlined, these describe interventions such as heat acclimation, which are implemented pre, during and post-training to prepare for the increased heat stress. Second, acute heat alleviation techniques that are implemented immediately prior to, and sometimes during the event are discussed.

Abbreviations

CWI; Cold water immersion
HA; Heat acclimation
HR; Heart rate
HSP; Heat shock protein
HWI; Hot water immersion
LTHA; Long term heat acclimation
MTHA; Medium term heat acclimation
ODHA; Once daily heat acclimation
R.H.; Relative humidity
RPE; Rating of perceived exertion
STHA; Short term heat acclimation
T_{CORE}; Core temperature
TDHA; Twice daily heat acclimation
TS; Thermal sensation
T_{SKIN}; Skin temperature
$\dot{V}O_{2max}$; Maximal oxygen uptake
WGBT; Wet bulb globe temperature

Introduction

Heat stress negatively impacts performance in middle- and long-distance events [1], intermittent sprint activity [2], and during skill-based competition [3]. Strategies to attenuate heat strain i.e. reducing physiological and perceptual disruption prior to and during events such as the Tokyo 2020 Olympic Games, are essential and can be divided into two distinct techniques, chronic heat alleviation and acute heat alleviation. This review details the current state of knowledge in these areas and makes recommendations for practitioners implementing heat alleviation techniques. This review should direct practitioners preparing non-disabled individuals for competition in heat stress to the optimal methods to attenuate the heat-induced performance decrements and to protect athlete health. Whilst many thermophysiology principles are shared, we direct the reader to literature describing techniques to alleviate heat strain in para-athletes, given critical and pertinent nuances should be considered from health and performance perspectives in this cohort [4–7].

The need for this interpretive summary of the literature is borne from data identifying that only 15% of surveyed athletes competing at the 2015 IAAF World Athletics Championships (host city Beijing, China), where heat stress was highly probable (Mean daily temperature and WBGT during the championships were 27±3°C and 24±2°C at 8:00, 31±3°C and 27±2°C at 12:00, and 30±4°C and 25±2°C at 16:00), adopted a recognised chronic heat alleviation strategy. Such strategies include acclimation (physiological or behavioural changes occurring within an organism, which reduces the strain or enhances endurance of strain caused by experimentally induced stressful changes in particular climatic factors.[8]) or acclimatisation [physiological or behavioural changes occurring within the lifetime of an organism that reduce the strain caused by stressful changes in the natural climate [8]). It was also reported that 52% of the surveyed had an acute heat alleviation strategy e.g. pre-cooling [9]. This despite of 48% of competing athletes having previously suffered from symptoms of a heat-related illness/ symptoms which may impact performance e.g. cramping, vomiting, nausea, headache, fainting or fatigue [9]. Further to this, unpublished data collated by the authors, highlight that a barrier to the implementation of heat alleviation strategies arises from an array of logistical issues or being unable to interpret contradictions and ambiguities in the literature effectively. Moreover, an ill-considered notion that athletes are 'protected' from heat stress by virtue of their training status or prior warm weather training, reinforces the avoidance of heat alleviation strategies, despite a lack of empirical evidence to support this [10]. It should not be assumed that an athlete's high aerobic fitness prevents issues related to the heat/heat-related illness risk, with performance data clearly highlighting that heat negatively impacts performance in elite endurance events [1]. Though highly trained endurance athletes are partially heat acclimated (e.g. typically with high sweat rates), they are not excluded from the detrimental effect of heat on performance in the same way that athletes are not protected from altitude related illness or performance detriments because they have greater red cell mass than those who are untrained [11]. Indeed, greater absolute detriments in performance come with increasing altitude in trained *vs.* untrained individuals [12] and even small, relative detrimental effects of heat stress on sports performance will greatly impact individual success at major international tournaments [1,13].

This review will highlight how acute and chronic heat alleviation techniques can be integrated into a preparation strategy through pertinent, applied questions, to prepare for heat stress and enhance thermoregulatory and performance physiology. The aim of chronic heat alleviation strategy/strategies is the induction of heat adaptation, which for many athletes is achieved through the completion of a heat acclimatisation or heat acclimation (HA) protocol. Heat acclimatisation is typically implemented as a training mesocycle immediately prior to competition, with HA a potent intervention which can be implemented as a micro- or mesocycle to induce a myriad of physiological, cellular and perceptual adaptations, which enhances an individual's ability to tolerate heat stress. Heat adaptations can be induced rapidly (e.g. <5 days [14]), and whilst decay occurs over time (e.g. ~1-3 weeks), expedient reinduction is possible [15,16]. HA can be implemented in different ways i.e. passively via resting in heat stress, actively via exercise in hot or hot-humid conditions, or a combination thereof. Acute heat alleviation utilises techniques which provide additional 'protection' against heat stress for the athlete(s) in the immediate hours and minutes prior to competing or indeed during the competition. Acute heat alleviation is similarly centred around optimising the thermoregulatory and performance physiology, with emerging research now realising the importance of improving the perceptual status of the athlete immediately prior to, and if appropriate and regulations permit, during the event [17–19].

Whilst the efficacy of acute techniques is robust, the authors are of the opinion that adopting robust chronic techniques cannot be understated. Indeed, there is good evidence to suggest chronic heat alleviation will be more effective [20,21]. Well-rehearsed, acute techniques to optimise thermoregulatory and performance physiology in the heat and minimise risks to health should not be considered as a "*quick fix*" alternative, but complementary to pre-planned and well considered chronic alleviation strategies. The timeline from publication of this review to Tokyo 2020 will allow for repeated rehearsal and practise of these chronic and acute techniques to maximise their benefit and minimise the disruption to ongoing training.

In keeping with previous work [15,22,23], this review is written with the practitioner in mind and with athlete-centric considerations at the forefront of the content. To that end, the experiences of practitioners working with elite athletes have informed the perspectives within this review. Greater emphasis has been put on content, that to the authors knowledge, has been considered to a lesser extent elsewhere e.g. the time of day of HA, environmental conditions for HA, male *vs*. female differences to HA and, structuring HA around training. The authors direct the research-orientated reader to a number of excellent review articles and meta-analyses that consider specific elements of heat adaptation and/or thermoregulatory function from a mechanistic viewpoint [14,16,24–31].

Chronic heat alleviation

What adjustments are made to the thermoregulatory and performance physiology of the athlete following heat acclimation?

The homoeothermic nature of humans is reflected by the integrated physiological response to maintain an acceptable magnitude of exercise-induced hyperthermia, even when training/competing at performance intensities. The defence of core (deep) body temperature (T_{CORE}) whilst attempting to maintain performance is supported by the multi-systemic adaptations that occur following repeated disruption to an individual's thermal equilibrium. Figure 1 depicts the empirically supported adaptations to thermoregulatory, perceptual and performance physiology which occur following repeated bouts of exercise-heat stress via HA.

Chronic heat alleviation such as HA may induce; reductions in body temperature with lower T_{CORE} and skin temperature (T_{SKIN}) [32,33], sudomotor adaptations which initiate earlier sweat onset (i.e. greater sensitivity and lower temperature thresholds for sweating), greater sweat volume which can enhance heat dissipation via evaporation and more dilute sweat is secreted (i.e. conserved sweat mineral concentration) which preserves electrolyte balance [34–38]. Whilst large sweat volumes are generally a positive adaptation, athletes may already be capable of high sweat volumes such that, particularly in hot-humid environments where evaporation is limited, excess sweating beyond maximal skin wettedness is undesirable, leading to dehydration and/or increased feelings of discomfort. This may be particularly detrimental in prolonged events in heat stress where dehydration is likely to impact performance [39,40]. Strategies to optimise the magnitude of adaptation e.g. by varying the number of HA sessions, are discussed later. Alterations in body water content with heat adaptation are mostly reflected by the hypervolemic response of the extracellular blood plasma over intracellular and interstitial fluid responses[41]. This haematological adaptation improves cardiovascular responses and reduces sensations of thirst sensitivity [42,43], that can combine with dehydration to impair performance [44,45]. Cardiovascular adaptations include reduced heart rate (HR) [46] and greater stroke volume [25,47], facilitating a more stable cardiac output and blood pressure response to the demands of exercise, despite the competing demands for blood between the skin and muscle as an athlete's body temperature rises [48]. The myocardium itself may become more compliant and efficient in its contractions following HA [25,26]. Peripheral cardiovascular adaptations improve skin blood flow via earlier vasodilatory onset thresholds and greater rates of skin blood flow, that improve heat exchange between the skin and the environment [36]. Less well reported, but with important event/athlete specific relevance, are improved thermal perception, in the form of reduced thermal sensation (TS) and improved thermal comfort [49,50], lowered ratings of perceived exertion (RPE) [51,52], and attenuated sensations of fatigue [53]. Metabolic adaptations (albeit reported in non-elite populations), include; lowered metabolic rates, reduced rates of glycolysis associated with a reduction in the relative intensity of exercise [54], and improved muscle contractility [55]. Heat adaptation is associated with elevated heat shock proteins (HSPs) with acute and chronic elevations in HSPs supporting/facilitating heat adaptation [56] and maintaining epithelial tight junctions in the gut, mitigating gastrointestinal distress when an athlete competes in the heat [57,58] and attenuating circulating precursors to heat illness [59]. With the athlete in mind, at a cellular level, the induction of heat adaptation via short- and medium-term HA does not appear to impact circulating markers of immune function negatively [60–63].

When considering the determinants of performance and the performance *per se*, HA has been demonstrated to improve maximal oxygen uptake [48,64–67], facilitate a rightward shift of the anaerobic threshold [48,60,64,68], and most relevantly, improve exercise capacity/tolerance in the heat [46,47,60,69–77], in some cases to levels comparable to temperate conditions [78]. In field-based team-sports, HA also improves intermittent exercise capacity and tolerance to the heat [79–85]. It is of course challenging to prove the erogenicity of HA in elite populations given it is near-impossible to assess this against an ecologically-relevant control condition and thus, is something the practitioner should be mindful of when comparing responses in athletes to experimental data which is commonly collected on less well trained individuals.

Should the athlete undertake acclimatisation or acclimation?

Heat acclimatisation typically occurs in a natural environment, in a location where training activities may combine with mean day time temperatures to provide sufficient stimuli (elevated T_{CORE}, T_{SKIN} and high sweat rates) for adaptation (e.g. >25°C) [26]. This allows athletes to live and most importantly, train in heat stress for extended periods (e.g. 1-4-week mesocycle) prior to competition. In contrast, HA induces heat adaptations in an artificially created environment for shorter durations (e.g. a 4-14-day microcycle), whereby, athletes repeatedly exercise in an environmental chamber as part of an active intervention, or undertake a passive/resting intervention, typically involving post-training saunas or hot baths. To date, no published experimental work has effectively compared acclimatisation with acclimation from an athlete perspective (i.e. using similar exercise intensities and protocol durations), though it has long been known the physiological basis of natural acclimatisation is identical with that of HA [86]. In spite of the lack of specific comparative data in elite athletes, the timeline of performance adaptations is similar when examining endurance performance in individuals during acclimatisation [78,84,87], HA [48,64,88–91], and when examining intermittent-sprint performance following acclimatisation or HA [49,79,80,92–94]. Until experimental work demonstrates that one method is superior, the decision whether to acclimatise or acclimate athletes remains a consideration based upon individual circumstance (e.g. time, cost, logistical challenges, training disruption).

There are positive and negative aspects to both heat acclimatisation and HA strategies with considerations to this effect outlined in Figure 2. HA proffers less disruption and expense, without diverse weather implications and likely travel fatigue associated with acclimatisation [95]. That said, HA will require specialist facilities, with training often having to be completed on a stationary ergometer (i.e. running, cycling or rowing) [15], though ‘circuit/strength training’ activity can be implemented [91]. The use of ergometry may be considered as a limitation, but this is arguably offset by the ability to individualise the protocol and regulate stimuli more precisely. Further to chamber-based HA protocols, alternate, cheaper and more accessible methods are now acknowledged as methods for passive (e.g. hot water bath) [96–99] and active HA strategies (e.g. overdressing and restricting heat loss during routine training) [100–102]. The authors acknowledge that different athletes will receive different levels of funding/support and this may influence their decision making more greatly than the weight of empirical data, accordingly, discussions of the practicalities of implementing HA for the athlete follow. It is also acknowledged that access to specific facilities immediately prior to competition (e.g. athletics track or rowing lake) are necessary for specific training sessions to determine readiness for competition.

What are my options when implementing heat acclimatisation/acclimation?

Exercise Heat Acclimation Methods

Exercise HA to induce heat adaptation include exercising within naturally hot, hot-humid (e.g. acclimatisation), simulated hot (e.g. acclimation) or temperate conditions with use of additional clothing or restrictive heat loss attire (e.g. alternate acclimation) [16]. For inducing heat adaptations, the type of exercise does not appear to be a relevant consideration (aside from athlete preference) though most protocols utilise either cycling or running ergometry, unless a sport-specific ergometer is available (e.g. rowing), or a large indoor facility can be used to generate hot conditions for running/circuit training. Cycling may be more beneficial than running for athletes seeking general thermoregulatory and performance physiology adaptations, who must manage musculoskeletal load, given the non-weight bearing nature, lowering risk of injury/soreness. Similarly, from a practitioner perspective, cycling ergometry often allows larger groups of athletes to exercise. However, a limitation of ergometry is the inability to utilise sport-specific apparel (e.g. running spikes or protective attire). Typically, higher rates of heat production and storage, resulting from greater muscle mass recruitment and subsequently greater oxygen uptake, occurs with running. This may be advantageous when utilising isothermic techniques (outlined below), expediting the onset of heat strain during training. Nonetheless, practitioners, coaches and athletes may choose their preferred modality (e.g. sport-specific) if available, to ensure maintenance of training and perceptual adaptation specificity, whilst ensuring the primary objective of adequate heat strain is achieved. Active HA strategies are categorized by their prescription method and typically fall into one of following; self-regulated, fixed-intensity or isothermic [16,26].

Fixed-intensity HA

Fixed-intensity HA methods are the most commonly reported in experimental literature, particularly data collected >5 years ago, with this active method requiring athletes to exercise at a pre-selected intensity, which is fixed to elicit a certain cycling or rowing power output or running/walking speeds, relative to maximal aerobic capacity, or absolute/relative HR. The exercise intensity is typically set at ~50% maximal oxygen uptake ($\dot{V}O_{2max}$; i.e. in a moderate intensity domain) which may or may not be possible to prescribe accurately depending on how recently a maximal test has been conducted. Given the same fixed intensity is used for the entire session over the duration of the HA intervention, this method is simple to administer for individuals and groups of athletes alike. However, a critique of this method is that the stimulus for adaptation at the start of the intervention diminishes by the end of the intervention (especially over longer-term protocols), as the athlete enhances their ability to dissipate heat and aerobic capacity improvements are induced [26,103]. Recent data utilising relative HR prescription [82], offer some progression in workload as cardiovascular adaptation occurs and therefore, this administration technique may offer some adaptation advantage despite reduced control over T_{CORE} increase in comparison to other methods [104].

Suggestions have been made to optimise fixed-intensity HA and ensure complete heat adaptations are achieved. These may include progressive physiological strain by increasing the level of heat stress towards the latter stages of the HA intervention [105], increase exercise intensity (~ 5% $\dot{V}O_{2max}$ per week)[106], and/or prolong the duration of exercise (up to 2 mins per HA session) [47,71,72,107]. This is required as athletes adapt to the intervention with day-to-day reductions in T_{CORE} and exercising HR [105,108]. Progressively increasing these aforementioned metrics may not guarantee maintenance of the internal physiological stimuli for adaptation and thus, in spite of increased complexity of the intervention, increased adaptation may not always ensue. This has led to more recent support of independently controlling one of the primary drivers of human thermoregulation, T_{CORE}, via isothermic HA.

Isothermic (Controlled-hyperthermia) HA

Proposed as the current 'optimal' method [109], isothermic HA (also referred to as controlled hyperthermia) involves an active heat stress phase (~30 min), where an elevated T_{CORE} is achieved, followed by a maintenance phase, which is characterised by passive heat stress (e.g. resting in the hot environment) or low intensity exercise to elicit a prolonged period (~60 min) [104] at a targeted T_{CORE} of ≥38.5°C [26,110]. The target T_{CORE} (≥38.5°C) is a primary effector for heat adaptation with athletes maintaining sufficient, sizeable physiological strain for adaptation (e.g. continual elevations in T_{CORE} and T_{SKIN} with concurrent high sweat rates), even as they adapt during HA. It should be noted that experimental data highlights that there is no adaptive advantage to targeting an even higher T_{CORE} (e.g. 39.0°C) [50,106], and therefore, more strain (in this context) is not necessarily more beneficial for the athlete. The primary benefit of the isothermic method is that athletes maintain the same absolute stimuli for adaptation within each session, rather than being exposed to a diminishing stimulus as adaptation occurs (as noted in fixed-intensity strategies).

The prescribed exercise intensity during the active phase of isothermic HA varies and can include; self-regulated intensity (e.g. a rating of perceived exertion [RPE] of 15 [111]), intensity relative to body mass (e.g. 2.0-2.7 $W.kg^{-1}$ [64,104]), or as a percentage of HR_{max}, or $\dot{V}O_{2max}$ (e.g. 50-65% $\dot{V}O_{2max}$ [50,112]), to reach target temperatures within ~30 min. At the current time, recommendations are that relative power provides the best training prescription method given its closer relationship with increases in T_{CORE} (and likely heat production) than perceptual responses, or prescribing exercise based upon relative intensities aligned to physiological responses [104]. Moreover, this approach is simple to administer, negating additional interruption to training by removing the need for an a priori maximal exercise test to derive exercise intensities from. To implement isothermic protocols effectively and safely, T_{CORE} must be continually monitored (e.g. every 5 min). The recommended method is rectal measurement or a gastrointestinal pill, although it is recognised alternative T_{CORE} measurements (e.g. tympanic membrane) may be utilised by experienced practitioners who recognise the limitations of this method. Notably, the tympanic membrane may under-represent deep body temperature absolutely, but should demonstrate similar change [113] and is an approach used safely and effectively [114].

Experimental comparisons have been made between fixed-intensity and isothermic HA protocols, with no difference in the magnitude of physiological adaptation occurring [50,106]. Figure 3 depicts exercise intensity and notional T_{CORE} response to an isothermic HA protocol against a fixed-intensity HA protocol (~50% $\dot{V}O_{2max}$), commencing from a T_{CORE} of 37.0°C. In this figure the isothermic HA protocol commences with a higher exercise intensity (~70% $\dot{V}O_{2max}$), such that T_{CORE} rises rapidly to the endogenous target of 38.5°C during the active phase (~30 min in duration [73,107,115,116]). Following the attainment of the target T_{CORE} in 30 min, the 60 min maintenance phase follows, whereby, seated rest or low intensity exercise effectively maintains the stimuli for adaptation throughout the session (total duration of 90 min). This biphasic method contrasts the fixed-intensity protocol, whereby, a lower exercise intensity elicits a slower increase in body temperature throughout the session. Isothermic protocols benefit from time-efficiency, involving a lower training volume [50], as exercise is closely matched to achieve a specific physiological target. However, the moderate intensity domain training may not be representative a self-selected (performance) intensity, affecting the induction of perceptual adaptations. Higher intensity work in isothermic HA is not necessarily a negative, often it is favourable for an athlete to undertake higher intensity work (similar to regular training or competition intensity for a shorter duration, as opposed to exercising at lower intensities for long durations [50].

Self-regulated HA

Self-regulated HA methods enable athletes to select their own exercise intensity based on their training status and perceived demand of the exercise and environmental conditions [117,118]. This can be achieved by clamping exercise in relation to their RPE, or another athlete-specific self-regulating variable, for all or part of the HA session [111]. Like relative intensity exercise prescription during isothermic HA [104], self-regulated methods may offer the greatest practical application for large groups of athletes training simultaneously, as minimal monitoring equipment is required and when time is restricted, the practitioner can forgo prior physiological assessments commonly required to prescribe relative intensities (e.g. $\dot{V}O_{2max}$ testing). Whilst this method permits athletes to work at sport-specific/self-directed intensities, this method may sacrifice rigour and be subject to greater inter-session variability and therefore, compromise the attainment of precise stimuli for adaptation. This method may also be counterproductive if athletes push themselves too hard and compromise health in pursuit of adaptation.

Passive Strategies

Passive strategies are a desirable intervention given the athlete experiences no additional external training load to accommodate HA, which may be especially important during a taper phase. This "*live cool, train cool, acclimate hot*" method, where HA occurs following training in temperate conditions to maintain training quality is akin to the "*live high, train low*" altitude paradigm. Passive strategies include; residing in simulated heat stress in environmental chambers [16,119–121], wearing restricted heat loss attire (e.g. over dressing in heat stress) [122], wearing water-perfused suits [110,123], sauna exposures [96,124] or hot water immersion (HWI) [97–99,114,125,126], all of which "*raise and maintain*" a moderately high T_{CORE} (e.g. 38.0-38.5°C) alongside high T_{SKIN} (>38.5°C). Passive sessions are typically completed as an individual strategy, independently of training commitments, prescribed prior to [122] or following routine training [99] in hot or temperate conditions. Access to sauna or HWI facilities should be as immediate as possible and practitioners should be mindful of this when planning passive strategies given debriefs, equipment storage and other practicalities are commonplace post-training. Evidence indicates that passive strategies, which provide higher T_{SKIN} than active-only strategies, are effective when implemented in conjunction with active strategies, therefore, athletes may choose to apply a combination of passive and active techniques, as successfully utilised prior to a major sporting competition in heat stress (e.g. World Cup 2014; Rio de Janeiro, Brazil) [114] providing flexibility to ensure that the primary objectives of the overarching physical training programme are met.

A recent review of passive methods [127] concluded that these strategies can be used to induce heat adaptations, such as a reduced resting and/or exercising T_{CORE} [97–99,121,123,126], T_{SKIN} [97,99,123], and HR [97,99,120,128]. Passive methods for HA also improve sweat onset thresholds and enhance sweat capacity [99,129]. Expansion of plasma volume can occur depending on the protocol [96,99,123,124], and improved perceptual responses, such as RPE and TS have been reported [99]. These adaptations to thermoregulatory and performance physiology can also elicit improvements in endurance capacity (e.g. $\dot{V}O_{2max}$) and aerobic performance (e.g. 5 km time trial) [96,99]. Post-exercise HWI appears to be the most well reported intervention to induce adaptations in thermoregulatory and performance physiology associated with HA, with the magnitude of adaptation similar irrespective of training status [98]. To implement this technique, athletes should undertake their normal training in routine environmental conditions, and then seek to immediately submerge themselves to shoulder height in ~40°C water, with immersion times ranging from 10-40 min. The HWI duration will depend on the athletes' preference, tolerance, exposure number and stage of acclimation with an important acknowledgement being that the athlete should "*feel hot*" but cease the intervention if they feel "*too hot, dizzy or lightheaded*". For the novice post-exercise HWI user, supervision and monitoring of T_{CORE} may be desirable. Exposure time will likely increase as the athlete acclimates resulting from reduced T_{CORE}, improved blood pressure regulation and enhanced thermal perception, providing an indication of adaptation in itself. This simple, effective protocol has improved running performance in untrained individuals [99], though performance adaptation has yet to be quantified in well trained individuals. Whilst theoretically simple to implement, assuming access to hot water and a 'bath' to reside in, if HWI is not feasible, sauna exposure is an alternative passive HA technique whereby, post-exercise implementation can lead to performance improvements [96]. The erogenicity of this technique apparently facilitated by haematological adaptation [96]. Observations of performance improvements following post-exercise sauna are not consistent, with others reporting that in spite of physiological adaptation, no performance adaptation occurred [124]. It may be that for athletes to improve exercise performance under heat stress, they potentially need to experience and exercise under heat stress (e.g. active HA), thus, whilst physiological adaptation occurs, performance improvement may be contingent on enhanced pacing which would be observed with exercise-heat stress in accordance with familiarity to a representative sport specific thermal discomfort.

Passive strategies are beneficial (e.g. inexpensive and limit training disruption), induce heat adaptations (e.g. reduced T_{CORE} and HR), improve exercise performance [99] and therefore, address limitations associated with active strategies. For the practitioner, passive strategies still require considerable planning giving limited access to baths and hot water at training facilities at training camps/venues. At the current time, no data has compared passive and active HA. Cross examination of studies investigating these methods independently identifies that the most measurable difference between passive, and exercising adaptation appears to be plasma volume expansion [130] and enhanced sudomotor responses [131], that are common in active strategies, but not so clearly evidenced in passive strategies. As a direct comparison of active *vs.* passive HA interventions has yet to be conducted, it is not possible to identify whether one is preferential, thus, both must be considered based upon their respective merits, or combined to suit the athlete(s) [114,132]. For athletes who struggle to train effectively in the heat, or those who do not wish for tactical or technical training to be impacted by exercise HA, passive HA could be implemented as a preliminary strategy to establish thermoregulatory adaptations prior to a commencing an active HA intervention. Similarly, for athletes who already sweat high volumes of unevaporated fluid, passive HA such as HWI, may effectively induce central adaptations e.g. reduced T_{CORE}, without inducing excessive peripheral responses.

Can we utilise excess or specific clothing to restrict heat loss, and induce adaptation?

Another simple and inexpensive technique to inducing some elements of heat adaptation is to have athletes overdress (i.e. wear more clothing than typically required for the task), or wear a vinyl sauna/sweat suit (which restricts heat loss/evaporation, creating a hot-humid microclimate close to the skins' surface) to increase T_{CORE} and T_{SKIN} above that of training in normal clothing in temperate conditions, and promote greater sweating. Whilst greater sweating occurs, from the outset the authors affirm sentiments from others that this should not be used as a tool to reduce body mass rapidly (e.g. prior to weight category competition) and well considered plans to meet weight (mass) should be implemented [133–135]. In spite of many studies showing an acute session of 'overdressing' provides some thermal strain for adaptation [101,102], experimental work conducted indoors in temperate conditions utilising this method, suggests that this is unlikely to be as effective as a hot air/water HA interventions [136]. It may however, prove partially effective for those who are unable to access genuine heat stress (simulated or natural), or be combined with established HA interventions to provide flexibility [122,137] and affordability. Overdressing during outdoor cycling exercise appears to be ineffective, reflecting the greater cooling air flow experienced when cycling outdoors (*vs.* stationary ergometry) and concurrent minimal changes in physiological/thermoregulatory strain, with no adaptations observed during an applied study [100].

At present, experimental data supports the use of active isothermic HA or passive post-exercise heat exposures to induce adaptation and manage training disruption. A greater volume of data supports improvements in exercise performance following active HA and accordingly we encourage practitioners to consider this the optimal technique to induce adaptation in athletes. Post-exercise passive heat exposures e.g. HWI, may be considered a viable alternative when access to hot environmental facilities for active HA is not possible, for those who are intolerant of exercise in the heat, those wishing to make initial adaptations as a precursor to exercise training, and those who wish to combine chronic heat alleviation methods to fit an intervention around complex training and logistical plans.

How long does heat acclimation take to induce, and how long is a typical heat acclimation session?

In line with conventional training programmes, HA must consider the overall timescale, session duration, session frequency and exercise prescription [26], but additionally, the heat stress mode and magnitude, as well as the option for passive heat exposures. The primary categorisation is the intervention duration, with short-term ([STHA] ≤5-days), medium-term ([MTHA] 6-10-days) and long-term HA ([LTHA] >10-days) being common demarcations, though these are somewhat arbitrary. Within these timescales, individual sessions during HA vary in duration (from 30-120 min), reflecting the specific needs of the athlete and circumstances (e.g. aerobic fitness, time, training cycle, cost, facilities and equipment). A concern when prescribing HA based upon the number of sessions alone, is that this can lead to markedly different HA doses. STHA may require 2-10 hours of athlete time, with MTHA ranging from 2.5-20 hours and LTHA lasting 5-40 hours, thus, whilst two studies may report STHA, the training volume eliciting potentiating stimuli for adaptation may be vastly different (e.g. 5 x 30 min sessions *vs.* 5 x 120 min sessions). Experimental work has seldom considered the heat dose or volume, in this way (i.e. HA-minutes as proposed elsewhere for hypoxic exposures [138]), thus, the minimum time required to induce adaptation is not well known and experimental work often cites mixed findings without effectively controlling this. Practitioners should be mindful of this when interpreting research findings as the variable HA dose may explain the wide range in magnitudes of adaptation, particularly following STHA [14]. In reality, the deciding factor when considering the duration of an acclimation intervention for athletes is likely to be their training schedule and whilst more exposures typically lead to a larger magnitude of adaptation, this may not be optimal given the diminishing returns in adaptation that occur at the latter stages of a HA intervention. The necessary training volume during MTHA/LTHA, rationalises the desire to minimise additional exercise training volume during HA and the greater interest in isothermic or post-exercise techniques that help to mitigate increases in external training load.

The adaptive effects of MTHA (>6-10 days) and LTHA (>10 days) have received much research attention, historically as a means for determining ‘maximal’ adaptation [47,75,77,116,139]. Recent reviews have considered the application of STHA (≤5 days) [23,140] as a highly desirable intervention timescale for the athlete, particularly when training load is already high, or implementation of HA may require careful consideration prior to competition [141,142]. Central adaptations, such as reduced HR and T_{CORE}, appear to be augmented during STHA timescales, with MTHA/LTHA maintaining or improving the HR and T_{CORE} adaptation whilst eliciting greater sudomotor and haematological (e.g. increased plasma volume) responses [140,143–146]. The practitioner should consider the individual needs of the athlete when prescribing the number of HA sessions rather than pursue maximal adaptations. As stated earlier in this review, excessive sweating beyond the evaporative capacity of the environment may be more likely following MTHA/LTHA *vs.* STHA. This could be undesirable and leader to greater deficits of body water content which confound other HA adaptations.

Effective HA interventions have typically implemented minimum daily heat exposures which are combined with aerobic exercise of between 90-120 min in duration, irrespective of the precise method used [27]. However, considerable supportive evidence exists for shorter sessional protocols (e.g. 60 min), demonstrating effective heat adaptation [23,60,140]. Whilst HA sessions of 30 min continuous exercise have demonstrated adaptation [147], several studies have also demonstrated a minimal response for this duration (particularly over STHA) [52,148] and in this regard, even if exercise durations are minimised, the heat exposure duration should be prolonged, likely by implementing an extended maintenance phase post-exercise or combining exercise with a passive HA technique.

What are the Optimal Environmental Conditions for HA?

Athletes will benefit from HA performed in the expected environmental conditions that the competition will occur within [109], with the reader directed to a recent review outlining anticipated heat stress, and indices to describe heat stress in Tokyo [149]. This strategy has been widely implemented and it is beneficial given athletes can specifically understand how they will respond to a representative environment to which they will compete in [150]. Whilst it might be logical for athletes to prepare in conditions which represent the mean environmental conditions in which they will be competing, for example, mean air conditions for Tokyo in August are 30-31°C, ~70% R.H., the authors (and others) recommend that as a minimum, athletes train in the maximum/upper limit of environmental conditions which are forecast for the location at the time of year, for instance maximum air conditions for Tokyo in August are >34°C, >80% R.H. [149]. Indeed, it has been proposed that HA temperatures should be 5-10°C higher than the mean of the event location [151], in keeping with conventional training programmes that mimic '*worst-case scenario*' game demands [152–154]. Athletes and practitioners should also be cautious of being reliant on mean temperatures, particularly given within day differences of ~5°C are likely and events/heats may be scheduled at different times of the day [149]. As part of a '*prepare for the worst, hope for the best'* mantra, this should evoke condition specific adaptations, while optimising HA towards the expected most oppressive conditions [146]. As such athletes and practitioners should also be cautious in relying on natural acclimatisation upon arrival as the environmental conditions preceding the event may not reflect the conditions during the event.

As well as replicating event demands, athletes may also benefit from training in greater heat stress conditions than the expected environment [150]. The majority of experimental HA occurs in 40°C and 40% R.H. [14] to improve the efficiency of adaptation particularly when implementing isothermic HA, where external heat stress is a vehicle to achieve high internal heat strain (e.g. T_{CORE}). A proposed modification to the aforementioned 40°C and 40% R.H. consensus, would be to reduce the rate of evaporative heat dissipation, by increasing the relative humidity of the ambient conditions or prolonging the restriction of heat loss via other means (e.g. additional clothing or passive HA). It has been observed that under fixed workloads and absolute ambient temperature (~30°C), cycling time to achieve a fixed T_{CORE} is reduced with increasing relative humidity, highlighting the effectiveness of elevated humidity in the earlier attainment of a target T_{CORE} for isothermic HA due to impaired evaporative heat loss [155]. In simple terms, increasing humidity of the HA environment would inhibit heat loss via evaporation to a greater extent and reduce the time taken to achieve a targeted elevated body temperature e.g. target 70% R.H., rather than 50% R.H. will expedite the attainment of a T_{CORE} of 38.5°C. When matched for relative heat stress, no difference exists in performance, or acute physiological responses to exercise in hot-dry *vs.* hot-wet environments [156]. However, adaptation to HA between hot-dry and hot-wet environments may differ subtly [157,158]. To enhance adaptation, or at least improve the efficiency of the intervention by reducing the required training volume at the same absolute temperature, humidity could be increased, enhancing the relative heat stress. Given passive heat stress following exercise is a component of the maintenance phase of isothermic HA, a hotter/more humid environment would be more favourable for maintaining heat storage. Clearly, this flaws experimental comparisons between conditions due to differences in wet bulb globe temperature (WGBT) at an air temperature of 40°C, however, from an applied perspective for the athlete this is favourable. For athletes with a history of poor response to exercising under heat stress, dry heat stress may be preferable at the start of HA followed by progressive humid heat stress at the latter stages, to further stress cardiovascular and thermoregulatory function [109]. The initial dry heat stress being more tolerable and will allow heat adaptions to be made prior to the more stressful hot-humid section of the intervention to further refine adaptation later in the intervention. Similarly, progressive increases in simulated environmental conditions for HA are recommended for those who cannot maintain training quality, or for individuals whom health may be compromised should unfamiliar heat strain be experienced.

A critique of much of the experimental work in HA, is that it fails to account for radiative heat gain from the sun and competition surfaces [159], which athletes experience when exercising outdoors, and this may be an important consideration for pacing strategies and the performance intensity adopted [160]. The authors acknowledge this and recommend that athletes who undertake much of their chronic heat alleviation work indoors, should spend time exercising outdoors in hot environments with direct sun exposure to understand their physiological and perceptual responses, and better plan/practice their pacing/event strategy more comprehensively. Practitioners should be mindful that events may take place in the day and evening, and thus prepare athletes for both. Furthermore, appropriate protective clothing must be identified, in combination with appropriate sun-block [161]. Part of this planning should acknowledge HA can be implemented as a microcycle around training in the weeks and months leading up to competition. Whilst previously it has been recommended that HA should be performed immediately prior to competition, physiological adaptations to HA are induced potentially alongside a molecular memory, with researchers speculating that a more rapid re-induction occurs as a result of this [28,162,163], this concept has yet to be effectively examined mechanistically in humans/athletes. Based upon this understanding, we and others support the notion of undertaking dedicated HA microcyles periodically in the lead up to competition [16]. This means that prior to competition rapid re-induction/retention of HA can be obtained whilst experiencing actual competition conditions and may be appealing particularly for athletes/teams for whom extended periods at hot weather holding camps are not possible. Data supporting this concept is discussed in the section entitled "*How long do the adaptations last and how can they be retained?*".

Do athletes need to train in the heat every day?

A long-standing consensus is that to optimise thermoregulatory adaptations, daily heat exposures are the priority HA technique, with minimal adaptation occurring when training includes regular 'rest' days or without heat exposures ('intermittent' exposures). i.e. whilst end-exercise T_{CORE} reduced during intermittent (every other day) HA, the reduction was lesser than a consecutive day method, this also being true of final exercise HR or T_{SKIN}, suggesting inferiority. A theoretical model of the adaptation stimulus [164], proposes that intermittent exposures fail to stimulate adaptive pathways continually and potentially initiate a decay in adaptations, which is not observed with daily exposures. As eluded to previously, a critique of this study is the use of 30 min HA sessions, with a longer session more likely to induce greater strain and thus greater adaptation. It is noteworthy that when team-sport athletes perform longer HA sessions (>40 min), it appears irrelevant whether eight HA sessions consisting of intermittent sprint activity are performed on consecutive or intermittent/alternate days as comparable adaptation occurs with either method [83]. More recently it has been shown that four 45 min HA sessions, administered over two consecutive days (i.e. twice-daily HA; TDHA), demonstrated similar adaptations to four consecutive once-daily HA sessions (ODHA), typical of a STHA intervention [89]. A follow up study examined the magnitudes of adaptation within a MTHA intervention (ten x 60 min sessions) performed on alternative days, but in a twice-daily technique. Equivalent heat adaptations and enhanced exercise performance (e.g. reduced T_{CORE} HR, plasma volume expansion, perceptual responses, sweat setpoint and sweat gain, $\dot{V}O_{2max}$ and power at the lactate threshold) in the heat were induced by ODHA and TDHA, compared with equivalent temperate exercise [60]. Most importantly, no difference in the magnitude of adaptation and enhanced exercise performance were observed between either non-consecutive twice-daily, or consecutive once-daily HA when protocols were matched for volume and intensity. This highlights that non-consecutive twice-daily HA provides an alternate method to consecutive once-daily HA to induce adaptation without requiring consecutive day training [60]. That said, it is essential that if athletes undergo two sessions of HA in one day (e.g. TDHA), emphasis towards recovery strategies (e.g. rehydration and nutrition) is imperative, with ~6 hours spent in cool conditions recommended between successive bouts of exercise-heat stress (e.g. 08:00 and 16:00 hrs) to reduce any residual effects of the previous physiological strain [165]. The TDHA approach lends itself to the athlete who is familiar with training multiple times in the same day (e.g. endurance athletes), and practitioners should be carefully manage increases training time/volume in individuals who are unfamiliar with this. Conceptually, these findings suggest the dose of HA (e.g. matched weekly exposure and intensity) is most important for the mechanisms which underpin adaptation, as opposed to the structure of HA (e.g. frequency [once- or twice-daily] and timing [morning or afternoon]) and therefore, athletes are able to adjust the integration of HA sessions around their training, travel and recovery commitments [60]. This has also been implemented well in an intermittent sprint application without compromising the taper or competition performance [114].

Is the time of day when HA is performed a relevant consideration?

Whilst the implementation of a HA intervention itself can be modified to suit individual circumstances, it has previously been proposed that HA adaptations are time-of-day/clock time specific, and in some instances, it has been explicitly recommended that HA be performed at the same clock time as the impending competition/event [140]. In reality, this would be hugely challenging for practitioners to achieve given variable event times during the day, as many athletes will travel across multiple time zones to compete. As discussed below, fortunately it may not be as relevant consideration as initially perceived.

Recommendations for ensuring clock time for HA interventions and the subsequent task are equal, are predominantly attributable to data highlighting that, prolonged passive HA (sitting in a hot room) reduced sweat latency and decreased the T_{CORE} threshold for sweating [166]. These authors concluded the autonomic and behavioural thermoregulatory systems may be activated during, or just before the specific clock time of HA, so that their heat tolerance ability is improved to prepare for a foreseen heat stress at a fixed time-of-day. More recent experimental data suggest clock time appears unlikely to have a strong influence on subsequent exercise heat stress as HA induces a myriad of multi-systemic adaptations [27,146], some of which are governed by autonomic control (which may be somewhat clock time specific) [25], yet others likely remain stable irrespective of clock time (e.g. plasma volume expansion) [116]. Contrary to the notion of a fixed clock time for adaptation, it has been reported that when implementing a post-exercise HWI model for inducing HA, morning HA induced adaptations at rest and during exercise-heat stress in both the morning and mid-afternoon [97]. It was noted that adaptation to the T_{CORE} threshold for sweating onset was similar in the morning and afternoon, this was alongside reductions in resting and exercising T_{CORE}, HR, RPE and TS of a similar magnitude, irrespective of the time-of-day. In support of this lack of time-of-day-dependent adaptation, an isothermic exercise HA model with 40% of the HA taking place in the late afternoon (the remaining 60% taking place in the morning within a TDHA model) observed participants adapted to the intervention to the same extent as those undertaking ODHA (100% of sessions taking place in the morning) [60]. Collectively, these recent data suggest that HA is not as time-of-day dependent as previously thought and athletes should seek to implement HA in a manner which complements their existing training schedule, rather than make wholesale training adjustments to coincide with an event or avoid scheduling HA at all.

The time of day for HA may be of relevance depending on the type of intervention. Whilst fixed-intensity and isothermic HA interventions generally elicit similar magnitudes of adaptation when performed at the same time-of-day [50,106], isothermic HA has been proposed as superior/more efficient given they induce equal adaptations for a reduced workload [15]. It is in this regard, that the time-of-day may greatly impact the exercise requirements to achieve the endogenous stimuli for adaptation (the change in T_{CORE}) in an isothermic protocol, given typical fluctuations in circadian rhythm and thus, starting T_{CORE}. To illustrate this, figure 4 depicts isothermic and fixed-intensity protocols performed in the morning (starting T_{CORE} of 36.5°C) *vs.* afternoon/evening (starting T_{CORE} of 37.5°C [113]). In the fixed-intensity protocol, the increase in T_{CORE} is equal (+1.8°C), but the mean/end T_{CORE} is greater given the elevated starting temperature (AM = 38.3°C; PM = 39.0°C), suggesting the time-of-day is impacting upon the magnitude of endogenous stimuli experienced. The clock time for HA has a greater impact on the isothermic HA protocol. This is because the higher basal T_{CORE} in the afternoon/evening requires a reduced volume of exercise to attain the isothermic T_{CORE} target of 38.5°C (e.g. morning = +2°C, 40 min exercise duration; afternoon/evening = +1°C, 20 min exercise duration) further improving the 'efficiency' of this type of intervention for those who wish to minimise training volume. The differences between morning and afternoon HA may be amplified towards the end of isothermic HA, given the lowering of T_{CORE} is an expected adaptation. This has been demonstrated empirically with an increased exercise duration from 29 to 39 min in trained cyclists undertaking a 8 day isothermic protocol [111]. Accordingly, the notional T_{CORE} responses (Figure 4) described as AM and PM, could also be classified as post-acclimation, and pre-acclimation respectively, to illustrate the need to adjust workloads as adaptation ensues if matched exercise duration is required [113]. A caveat to both of these points are data indicating that the rate of T_{CORE} increase may be slightly (but not significantly) greater in the AM *vs.* PM [167]. However, even accounting for the difference in the rate of change, the time to achieve a +1.5°C increase in T_{CORE} is <5 min slower, later in the day, which still supports the efficiency of adjusting the time of day for HA to suit the individual.

To enhance experimental rigour, the time-of-day is an important consideration when examining the effects of HA on performance and physiological response pre-post intervention, largely due to the impact of circadian rhythm on T_{CORE} and the concurrent changes in physiological responses/adaptations resulting from it. Researchers and practitioners should be mindful of the impact time-of-day may have on the implementation of HA interventions and the magnitude of adaptation attained. At the current time it is not known with certainty whether time-of-day is a beneficial, negligible or inconsequential consideration in this regard. Importantly however, the need to be consistent in the time–of-day of a HA intervention for athletes appears debateable, therefore, difficulty in committing to a precise clock time for HA training should not preclude its use as a heat alleviation strategy altogether.

Do trained individuals adapt as much as untrained?

The effect of training status on the magnitude of adaptation has not been widely reported. It is commonly noted that individuals of a higher training status (i.e. higher aerobic capacity/power) demonstrate ‘partial HA’ adaptations/characteristics from their habitual training (where they routinely experience elevated T_{CORE},T_{SKIN} and sweat rates as a result of high absolute intensities). Recent work has suggested that improved aerobic fitness is a key predictor in mitigating against undesirable change in T_{CORE} during exercise [168]. Seminal work (from an occupational rather than athletic setting) noted that higher aerobic fitness ($\dot{V}O_{2max}$ ~60 $mL.kg^{-1}.min^{-1}$) from long-term training, is of benefit during fixed-intensity exercise in the heat and that the magnitude of improvements in physiological strain with HA are greater in those with high aerobic fitness i.e. those who are more well trained adapt better) [75]. This however, should be taken in context given these findings are drawn from a study where trained individuals demonstrate an improved thermoregulatory response to the same absolute intensity exercise task i.e. exercising at the same treadmill speed (but therefore different relative intensities), in comparison to those less well trained ($\dot{V}O_{2max}$ ~46 $mL.kg^{-1}.min^{-1}$). When trained and untrained individuals exercise at the same absolute heat production, this effect is likely diminished [169,170]. An enhanced sudomotor response to equivalent tasks/heat production partially offsets the increase in temperature and cardiovascular strain more greatly in higher trained individuals for the same absolute speed/power/intensity. With regards to the magnitude of adaptation, more recently classical markers of HA, such as alterations in T_{CORE} and HR, appear to respond equally to both isothermic exercise HA [171] and post-exercise HWI interventions [98] in recreationally active and endurance trained individuals. Thus, the merits of the intervention are apparent for many individuals and the individual variability in the adaptation is likely of greater magnitude and unrelated to aerobic capacity [172].

Do females adapt at the same rate as males?

Given elevations in T_{CORE} during the luteal phase of the menstrual cycle, and subsequent shifts in vascular and sudomotor heat loss pathways during this time [173,174], as already outlined by others [175], it has been proposed that in spite of similar absolute changes in T_{CORE} when performing in the heat during the luteal phase, females face a greater performance detriment. This detriment resulting from a higher baseline at this stage of their menstrual cycle in comparison to the follicular phase. The concerns around performance in the heat during the luteal phase have recently been partially appeased, given that autonomic heat loss responses at rest and during fixed-intensity exercise in well-trained women, are not affected by menstrual cycle phase [176]. Similarly, though individuals report greater physiological/perceptual strain at different phases, exercise performance does not ubiquitously differ across the menstrual cycle [176], although a) manipulation of menstruation is common in athletes as a way of regulating performance [177], and b) for some individuals, menstruation is highly (negatively) impactful on training and performance. Together these points make it a necessity to tailor strategies to optimise thermoregulatory, physiological, and perceptual responses to training and performance in the heat at an individual athlete level. Data indicates that between 50% [177] and 80% [178] of female athletes take hormonal contraception, which is known to increase resting T_{CORE} by ~0.3°C [179,180] and is likely to have other physiological consequences, although elucidation of this mechanism needs further investigation. Individual variability to athletic performance in the heat throughout the menstrual cycle should of course be at the forefront of the mind of the practitioner. All practitioners and female athletes should be mindful that hot-humid conditions, will reduce evaporative cooling and therefore, present a greater performance detriment and risk of heat-related illness in comparison to hot-dry conditions [176]. This is particularly pertinent given thermoregulation is less effective in females *vs.* males at higher rates of heat production that are associated with performance intensities [181]. Specifically, females exhibit a reduced sudomotor response to exercise heat stress, that ultimately limits evaporative heat loss in comparison to males [181]. Challenges to thermoregulation and performance may be even more greatly compromised in amenorrhoeic athletes via direct and indirect means [182], with little currently known of the impact of amenorrhea on thermoregulation in athletes.

The majority of the literature describing chronic heat alleviation techniques is collected in male participants and accordingly, this raises doubts as to the confidence with which these findings can be directly applied to females. Recent work has begun to address the disparity in data examining sex specific responses to HA as it is known that oral contraceptive users likely have an altered sweat response [183] and there are notional effects of oestrogen on the HSP response [184]; both hallmark adaptations of HA [27,146]. In a study examining the magnitude and temporal patterning of HA between males and females using an isothermic HA protocol [112], it was noted that while STHA may be effective in achieving partial adaptation in females, females require LTHA to establish reductions in cardiovascular and thermoregulatory strain that are comparable to males. This is despite similar within-session stimuli for adaptation (e.g. change in T_{CORE}). It should be noted that this was observed in an experiment during which females exercised at lower absolute exercise intensities and therefore lower rates of absolute heat production which may account for differences [185]. More recent work is also supportive of the need for MTHA *vs.* STHA interventions in females, particularly those moderately trained ($\dot{V}O_{2max}$ ~47 mL.kg^{-1}.min^{-1}) who are seeking performance adaptations [186], although due to the duration of the experimental design adopted in these HA studies [112,186], responses were invariably evaluated across different phases of the menstrual cycle in both eumenorrheic and oral contraceptive users, which in part explain their findings. HA protocols should therefore be tailored to target sex differences, as although STHA within one menstrual phase can effectively induce typical HA responses [80,122,187], sex determines the temporal patterning of HA [112]. Therefore, instead of additional HA training sessions or utilising a more humid HA environment (e.g. mist sprays to achieve >60% RH), sudomotor priming can be used, to ensure earlier (and therefore greater total) sweating in females. This has been achieved through over-dressing in vinyl suits and passive heat exposure (50°C) prior to HA training, to improve the magnitude of adaptation in females [122]. Practitioners working with less aerobically trained individuals (e.g. some games players), may also consider this to induce adaptation prior to commencing more well-established HA protocols. When administered effectively, heat adaptation can be induced as effectively in females as males, with improvements in endurance [112,122,185] and intermittent sprint tasks [80] in both sexes, though data in elite female athletes remains scarce. The current literature suggests in order to ensure that appropriate magnitudes of adaptation take place, when working with female athletes, additional exposures should be considered to allow for any differences in temporal patterning be ameliorated in females. The use of additional thermal stress such as pre-HA warming, or extended heat stress after or between HA as part of a multi-mixed/alternate model (e.g. sauna, hot water or prolonged maintenance phases of isothermic HA) may also be considered across the menstrual cycle/when amenorrhea is identified/around contraceptive use to improve the efficiency of HA.

How long do the adaptations last and how can they be retained?

An extensive overview of the retention, decay and reinduction of heat adaptations has highlighted that in spite of a plethora of data describing the induction of thermoregulatory and performance physiology that follows HA, understanding of responses in the days and weeks following HA cessation is limited [16]. Indeed, data tracking the decay in athletic performance responses following HA is particularly limited. Consensus viewpoints highlight that once robust adaptations have been induced following MTHA/LTHA, that they are well retained, with similar physiological responses occurring 1 week after the cessation of the HA training [109]. From this point onwards, heat adaptations reduce in magnitude unless an additional heat stimulus is introduction. The typical rate of decay in adaptation has historically been described as "*for every day of HA undertaken, the adaptation will be retained for two days*" [188]. Accordingly, an athlete who undertakes 7 daily sessions of HA can expect to retain benefits for 14 days thereafter, though as with all physiological adaptations, a gradual decay rather than immediate withdrawal occurs. More recently, data examining fundamental HA adaptations, such as reduced T_{CORE} and HR, alongside improved sweating capacity, have calculated that after STHA, a decay of 2.5% of adaptation made to T_{CORE} and HR are lost daily thereafter [16]. This more recent analysis indicates that adaptations are retained effectively for some time after a dedicated HA intervention. Data examining the retention of passive HA decay is even more limited than that of exercise HA, however a recent study examining the retention of adaptations following post-exercise HWI suggests that the time course is similar to active HA and that reduced T_{CORE}, HR and perceptual benefits are still present 2 weeks following the final HA session [189]. With the team-sport athlete in mind, prolonged repeat-sprint exercise in the heat is improved after HA with performance well-maintained over the subsequent 2 weeks, despite removal of the heat stimulus [83]. One aspect of the research on decay of HA that complicates the issue is the training programme following HA and how this influences the decay observed in key physiology. Essentially, research suggests low physical activity levels post-HA accelerate the loss of adaptation, but maintenance of high physical activity levels prolongs the adaptation; an artefact in the favour of the athlete [15] and a concept that could be further supported by having athletes overdress during training within a warm weather holding camp.

Given challenges of scheduling HA prior to competitions, we and others propose that individuals competing in the heat would benefit from undertaking a dedicated micro- or mesocycle of HA, well in advance of the competition, up to 4 weeks prior. This could then be 'topped up' with intermittent single or repeated HA sessions in the lead up to competition. Examples of this approach suggest it is possible to maintain thermoregulatory and performance physiology when individual heat exposures occur 5-7 days following a HA micro-cycle [190–192]. This concept mitigates the need to schedule prolonged HA immediately before competing i.e. within the taper [191]. It is also noteworthy that HA reinduction occurs at a faster rate following multiple cycles of HA [16,193,194]. This is advantageous to the athlete in two regards. First, an athlete may benefit from inducing the same magnitude of thermoregulatory and performance physiology adaption in a shorter duration (e.g. number of sessions) in subsequent cycles. Second, it could be decided that the athlete will undertake the same number of sessions in a subsequent cycle in order to elicit a greater adaptation. See figure 5 for a suggested integration of HA into the final sixteen weeks of preparation prior to a major championship (e.g. Tokyo 2020 Olympic Games) with our proposed timeline avoiding the need to implement HA within the taper period.

Are there hydration and nutritional considerations associated with HA?

The nutritional considerations for HA can be subdivided into fluid and macro/micronutrient considerations. From a fluid demand perspective, it has been proposed that permissively dehydrating (i.e. not drinking during HA sessions), may facilitate a greater magnitude of adaptation [195]. Despite data reporting that this may be evident during STHA [144], more recent data in both STHA/MTHA interventions highlight that irrespective of whether participants drink to retain body mass, or dehydrate intentionally during exercise-HA, the adaptive response is equivocal [107,115,196]. Rehydration following HA should include fluid and sodium given high sweat rates. It is recommended that isotonic beverages totalling 150% of the mass of fluid lost are consumed to replace the volume and composition of sweat lost more effectively [197].

Exercising in hot conditions has been reported to elevate substrate utilisation in favour of glycolysis for a given activity [198], with HA subsequently reducing rates of glycolysis in favour of lipolysis at the same absolute intensity [199]. This is a result of the increased relative intensity of the task and is facilitated by elevated rates of glycolysis at submaximal intensities [200]. Accordingly, athletes, particularly those who are tightly regulating macronutrient intake, should seek to provide sufficient energy via this substrate during and after a HA session. Protein is also an important macronutrient to consider to aid adaptation, both given the established importance in supporting muscular recovery from exercise [201–203], but also given the mechanistic role of the plasma protein albumin in increasing plasma volume [116]. L-glutamine has also been implicated as an important amino acid in facilitating elevations in HSPs, and in maintaining gut function under heat stress [204–206]. These proteins have been evidenced as important in attenuating gastrointestinal (GI) permeability during heat stress which may improve symptoms of gastrointestinal distress [57,58], heat-related illness [59], and facilitating heat adaptation in general via HSPs [56]. Though proposed as beneficial, as yet, probiotic intake has not been evidenced as beneficial during repeated exercise in the heat [207]. The reader is directed to a recent comprehensive overview of the effects of nutrients on gastrointestinal distress in the heat for further information in this regard [208].

Considering the above, athletes may experience favourable adaptation and enhanced recovery from HA if they consume fluids containing both sodium and carbohydrate post-training [209], whilst also seeking to ingest L-glutamine rich protein following HA sessions [210]. Precise intakes for HA mediated benefits associated with protein/amino acid consumption are yet to be explored in a controlled research experiment, however, the authors recommend adhering to guidelines allied to post-exercise recovery using nutritional protein [211].

Acute Heat Alleviation

The training volume associated with chronic heat training inevitably interferes with periodised training programmes and has led to considerable research into heat-alleviating strategies that can be implemented on the day of performance. There are two predominant acute approaches to help combat this problem, pre-cooling and per/mid-cooling. Pre-cooling targets the reduction of T_{SKIN} and/or T_{CORE} before the event begins, theoretically delaying the progressive, adverse effects of heat stress. Per/mid cooling may be used as a complementary, or independent strategy, which involves cooling during the event. In addition to a distinction for timing of cooling i.e. per/mid-cooling (referred to as mid-cooling hereafter), cooling studies are often further differentiated into internal or external cooling, depending upon where the cooling impulse is delivered. External cooling can be simplified as cooling the body from the '*outside in*', predominantly through the lowering of T_{SKIN}. Intuitively, internal cooling acts from the '*inside out*', typically having been ingested prior too, or during competition.

The subsequent sections will discuss internal and external techniques in greater detail; however, some broad recommendations can be made irrespective of the strategy adopted. A number of reviews of cooling and athletic performance are now available [212–221], providing detailed discussions of mechanisms and likely performance benefits of different strategies. It is not within the scope of this review to examine each of these areas, therefore, interested readers are directed to these significant citations. The focus of this section will be to summarise key findings and translate this information as key messages for practitioners who will support athletes competing in the heat.

Are there acute heat alleviation techniques that can be implemented on the day?

Despite the plethora of literature concerning pre/mid-cooling techniques, systematic interpretation is often hampered by divergence in experimental methodologies, notably concerning the timing that cooling occurs before the event, inclusion of representative warm-up, the type of exercise test implemented (i.e. open/closed loop, intensity, duration), heat strain experienced prior to cooling (both of which potentiate active and passive heat transfer), and a lack of true environmental simulation (e.g. representative air flow and solar/radiative heat exchange). Moreover, study findings may be impacted upon by the population used, with the participants' biophysical and physiological profiles having direct influences on the magnitude of heat strain, for example, as a result of body size and/or mass [222], or fitness and therefore absolute energy expenditure [170,223]. Finally, whilst studies often report an absence of heat exposures preceding experimental trials, this does not ensure that these individuals are not partially heat acclimated, with fitter individuals often having a partial acclimation state, which may influence their response to acute interventions [168]. Thus, we recommend practitioners critically interpret study findings with regard to the potentially confounding variables highlighted above.

The mechanistic basis for elevated body temperature impairing sporting performance is multi-factorial [224], but the consequences may be crudely simplified to; reduced performance/thermoregulatory capacities, and feelings of extreme discomfort from the heat. Clearly such symptoms are interlinked, and it is intuitive therefore, that any acute heat alleviation intervention should consider addressing both of these elements, with two clear objectives, first, reduce body temperature or allow greater heat loss and second, ensure that the individual perceives themselves to be cooler/feel better immediately prior too, and during competition [212,225]. The effectiveness of pre-cooling is often a consequence of the degree of heat strain and magnitude of cooling. However, the importance of thermal comfort and sensation in determining athletic performance in the heat is now being realised [19,226,227], such that strategies which target only alleviated perceptual strain, for example menthol application or mouth rinsing, may elicit an ergogenic effect in some types of activity (e.g. during self-paced endurance exercise in untrained individuals [228]), but not other (e.g. intermittent sprint/team-sport activity [229]). It is pertinent however, to remind practitioners of the intuitive heat-related illness risk that may follow, from creating a dissociation between an individual's TS and body temperature, and that excessive cooling may inhibit sweating and delay heat loss [230]. Together these comments reinforce our philosophy, that acute techniques should be well-rehearsed and complementary to chronic heat alleviation, ideally in an event requiring utmost motivation to most closely reflect circumstances akin to the Tokyo 2020 Olympic Games. Given changes in perception of heat stress during competition [18], trialling thermoregulatory responses, with and without cooling during competitive preliminary events would be desirable.

What are external cooling techniques?

Principles of heat exchange determine that a greater amount of heat energy will be lost from the body when a large temperature gradient (i.e. difference) with an external material/environment exists and there is a large skin surface area (i.e. volume) for heat exchange to occur [231]. Thus, whole-body cold-water immersion (CWI) is considered the most effective external cooling method [232], reflecting the ability of cold water to contact with virtually all the skin, and water temperatures below 20°C providing a significant temperature gradient relative to typical T_{CORE} (~36-40°C) and T_{SKIN} (~28-37°C). CWI can be implemented either before an event or when an individual is already hot (i.e. between performance/exercise bouts). Typical protocols involve water of 15-25°C for a period of 10-20 min, with likely reductions in T_{SKIN} in the region of 9°C, but may not elicit a visible reduction in T_{CORE} within this duration [233,234]. A similar water temperature can be used for partial body water immersion, although a longer duration will be required to elicit the same magnitude of total body cooling.

Despite the proliferation of portable and inflatable ice-baths, water immersion still provides significant logistical challenges for implementation across many sporting environments. Water and ice supplies will be required to fill and maintain bath temperatures, whilst the athletes will be required to dry off, change, as well as warm-up prior to competing. Consequently, practical combinations of cold clothing and partial/localised body water immersion (e.g. just hands or feet) appear preferable for athletes [200,235–237]. When cold water is not available or feasible at events, other approaches such as cold, wet clothing/towels or ice packs can also lower body temperature, the effectiveness of which again will be determined by a combination of the temperature gradient, skin surface area coverage and cooling capacity [212]. Logically, research has identified both volume and duration-dependent relationships for pre-cooling strategies utilising multiple garments [235,236], such that most research adopts 'mixed-methods' cooling, targeting many body sites, with a cooling period of 20-30 min [212,214]. Cooling garments (e.g. ice-vest/cooling shorts) are typically applied frozen (0°C) and worn for over 20 min, similarly, cold/frozen/wet towels (0-20°C) which can be placed on the body (e.g. neck, back and torso [238–240]) until no longer cool. An applied cooling example, combining cooling techniques may include wet, iced towels (3°C) covering the head, neck and trapezius muscles, forearm and hand immersion in cold water (9°C), and an ice vest on the torso. On this point, the authors note that practitioners may wish to trial/avoid cooling specific areas of the body in a sport-dependent manner, such as in sports requiring dexterity of hands (e.g. field hockey, rugby, sailing, rowing) and/or optimised lower limb major muscle group temperature (e.g. most team-sports) as cooling these regions may be counter-productive. Consideration may also be given to cooling areas that heavily influence TS and comfort, due to the distribution of localised thermoreceptor (e.g. found in the hands and face), which theoretically will help to attenuate or delay subsequent behavioural thermoregulation arising from perceived discomfort [227]. Purpose-made cooling garments, such as ice-vests or ice shorts are now available, though cooling shorts can also be improvised using ice packs or bags of ice and temporary bandages or cling film [241]. Indeed, loosely bagged ice is commonly seen attached to the limbs, neck, back and torso or axilla in many sporting situations for recovery purposes, this same approach can be applied prior to competition.

Compared with internal cooling, external cooling will not always demonstrate a reduction in pre-exercise T_{CORE}, especially when delivered to a static individual [200,235]. However, an '*after-drop*' may occur following external cooling, whereby T_{CORE} falls following the onset of exercise as vasoconstriction reduces and warm blood is subsequently cooled in the periphery [242]. T_{SKIN} may be lowered by 7°C when weighted averages from the chest, upper arm, quadriceps and calf are used to estimate mean T_{SKIN} [200,243]. It is this systematic reduction in peripheral T_{SKIN}, thereby enhancing the T_{CORE}:T_{SKIN} gradient [244] and likely reducing the cutaneous blood flow demand [245], that in turn mediates cardiovascular strain [246] and underpins the physiological alleviation afforded by external cooling. Furthermore, there is evidence that external cooling maintains improved thermal sensation for longer, compared with internal cooling [200]. In summary, in addition to meaningful reductions in T_{SKIN}, the benefits of external cooling are such that it can be easily adapted for different individuals or sports, requiring only cooling garments to be frozen at the team hotel or athletes' village and then transported in ice boxes to the event; transit time is therefore a relevant consideration for the practitioner to ensure the efficacy of this technique.

Internal cooling

Principles of heat exchange determine that a larger transfer of heat energy is required to complete the phase change of ice into water, than to heat cold water. Thus, ingesting ice is preferable to ingesting liquids, because an equivalent cooling magnitude can be delivered from a smaller absolute dosage. Whilst colder drinks provide a greater temperature gradient and cooling effect, the optimal drink temperature may ultimately be determined by the individual. Athletes should seek to consume cold drinks (5-15°C) *ad libitum*, and if well tolerated, ice-slurry drinks (0°C). The benefits of cold water and ice-slurry ingestion can be summarised into directly cooling of core organs and circulating blood, enhanced thermal sensation through thermoreceptors in the mouth and gut, and can be complementary to existing pre-event hydration or nutrition supplementation strategies (e.g. combine with CHO and minerals) [200,247]. The use of internal cooling is not without risk and rehearsal of techniques should be trialled in event simulations to determine erogenicity at an individual level and understand whether gastrointestinal or elevated urination issues may occur. Mechanistically, the thermal stimulus to elicit a phase change from ice to water draws heat from internal tissue, reducing temperatures proximal to the gut directly and indirectly cools other regions, as blood of a lower temperature circulates the body. Therefore, unlike external cooling, internal cooling often displays minimal changes in T_{SKIN}, but prompt changes in T_{CORE}, reflecting the cooling site proximity to core organs and typical T_{CORE} measurements in the gut (e.g. pill) or rectum (e.g. thermistor probe). Cooling via the mouth and gut may also positively influence indices of perceived thermal strain (i.e. thermal comfort and sensation), as a consequence of the relative prominence of thermoreceptors in these regions [248,249]. The systemic nature of cooling the periphery through the blood stream however does not lead to the same concerns around localised external cooling, with the maintenance of dexterity and muscle temperature.

Ice ingestion alone enhances the likelihood of sphenopalatine ganglioneuralgia ('*brain freeze'*) and carries a choking risk, therefore, a mixture of liquid and crushed ice (i.e. slurry/slushy) is more suitable. A typical ice slurry drink may elicit a 0.2-0.6°C reduction in T_{CORE}, when ingested over 20 min [200,234,250,251]. Despite the large reduction in T_{CORE}, evidence exists that ice-slurry ingestion will likely inhibit with the sudomotor response, resulting in reduced evaporative heat loss [234,252,253]. This leads to increased heat storage during the initial phase of exercise, which may help explain the elevated finishing T_{CORE} that has been observed following ice-slurry ingestion [234]. Despite this observation, ice-slurry ingestion is likely to benefit exercise performance in the heat particularly when environmental conditions or protective equipment (e.g. hockey goalkeeper) limit evaporative heat loss potential [254] and given reported reductions in brain temperature, cognition and decision making may also be improved [255].

Notwithstanding the benefits of internal cooling, questions remain concerning the optimal quantity and ingestion time before performance. A balance must be found between delivering a large cooling impulse (typically in the region of ~500-700 mL) and athlete comfort, ensuring feelings of being bloated and gastrointestinal complaints are avoided [251]. To this effect, it is recommended that smaller doses, made relative to the athlete's body mass (7.5 $g.kg^{-1}BM$ = e.g. 525 g (or 525 mL) for a 70 kg individual) are used. Spreading this out in small doses (1.25 $g.kg^{-1}BM$ per 5 min = e.g. 100 g (or 100 mL) for a 70 kg individual), rather than drinking a single bolus, appears to offer greater cooling and is likely to be better tolerated by athletes [256].

What practical cooling guidelines should I follow?

As with all competition day strategies, cooling must be meticulously planned and practiced from both athlete and practitioner perspectives. Anecdotally, athletes take time to identify a preferred pacing strategy within endurance events, not always utilising the apparent alleviated physiological strain [20,21] and find the transition from cool to ‘very hot’ is expedited when pre-cooled, challenging planned pacing strategies. Whilst ‘*more is better’* may be a pertinent cooling mantra, some is also better than none. Athletes and practitioners should therefore not discount apparently less effective cooling techniques, if these are easily integrated with other preparation priorities and are easy to use (e.g. ice-vests and/or electric fans).

Cooling strategies often require electrical power in the field, a local ice supply and/or effective storage of cooling devices, all of which should be discussed with event organisers prior to travel. It is also important for practitioners to note that 24 h supervision of ice slurry machines may be necessary to avoid contamination and robust hygiene protocols are required. We also emphasise that heat stress does not only affect the performance, but also affects the rest of pre and post-competition routines. For example, increased sweat loss whilst travelling to the venue should be expected, as well as greater perceived exertion from activation and/or warm-up activities. Therefore, whilst this review focusses on competitive performance, athletes may also wish to utilise simple cooling methods, such as cold drinks, handheld electric fans and/or mist sprays throughout the day. Whilst such cooling practices may offer limited physiological impact during the performance, they are likely to maintain feelings of comfort and relaxation prior to the event, especially if the individual has to spend prolonged periods outside waiting where air conditioning is not available.

Guiding principles to be mindful of when implementing acute heat alleviation strategies include; 1) covering as much of the body (i.e. skin) surface area as possible and doing so as close to the performance as possible, and 2) practicing the routine in its entirety, including warm-up and event simulation from both athlete and practitioner perspectives. Pre-cooling is not going to remove thermal sensation as athletes will still feel hot after 10-15 min throughout most competitions, but these will likely be less than would otherwise have been the case. It is important to acknowledge that some individuals find the transition from feeling ‘cold’ to ‘very hot’ occurs quickly and they should familiarise to this. It is not advisable to neglect an effective technical, skill-based warm-up in lieu of staying cool, as there are a range of other beneficial consequences from a proper warm-up. Finally, 3) the athlete and practitioner should beware of ‘evaporative cooling’ garments and not solely rely on these. Garments of this nature utilise moisture to enhance natural heat loss (via sweat evaporation), but do not deliver a cooling impulse as a phase-change/ice cooling product will, and the efficiency of these aids will be considerably reduced in humid climates that impair sweat evaporation.

Example pre-cooling approaches include implementing external cooling only, via 20 min of cold water immersion (10-20°C) in an inflatable pool, finishing just before the warm-up, or implementing internal cooling only via ice-slurry drinks (~500 mL) between arrival at venue and during warm up (100 mL every 5 min). Superior to these approaches is the implementation of combined cooling approaches involving pre-travel CWI (20 min), upon arrival 20 min wearing ice-vest, cooling shorts, cold wet towels around head and neck, finishing just before warm-up. Many athletes, across multiple sports can wear an ice-vest during warm-up and then use electric fans and drink an ice-slurry (containing CHO, electrolytes and caffeine) post warm-up, until their event starts. The implementation of combined approaches is often dictated by the environment, as such a more pragmatic combined cooling would involve a ~500 mL ice-slurry drink prior to arrival at venue followed by a complete warm-up wearing ice-vest, neck cooling collar, cooling wrist wraps. Figure 6 provides a suggested pre- and mid-cooling schematic to be implemented in the build-up to and during a team-sport (field hockey) fixture.

Can cooling be used effectively mid event?

There is strong evidence that cooling during exercise in the heat (mid-cooling or per-cooling) will elicit beneficial performance effects [215] and can be used additively with pre-cooling [218]. Mid-cooling techniques are directly informed by pre-cooling techniques and the similar importance of cooling magnitude (i.e. temperatures, duration and surface area), as well as alleviated perceptual strain should be noted, to benefit performance [214,215]. However, sporting regulations and/or practicalities associated with movement, will ultimately determine how sport-specific strategies are implemented. In long distance events, the most prevalent mid-cooling strategies are reliant upon the event organiser (e.g. feed stations / mist sprays) and/or team members (e.g. domestiques / staff members lining the route). Any benefits afforded by wearing additional cooling garments or carrying additional cold drinks may be offset by increased weight. Thus, simple recommendations include using cold water sprays, sipping or pouring a cold drink [257], cold/wet/frozen towels or bags of ice. Whilst such techniques may be less effective for pre-cooling, during exercise the thermal strain is greater, with a likely greater perceived benefit from localised (otherwise underpowered) cooling, if they alleviate thermal discomfort [212,218]. For sports that have short breaks in play, such as team-sports (e.g. hockey), industrial fans with mist sprays are probably the simplest method of providing effective cooling to a large number of athletes in a short period of time. As with pre-cooling, the use of cooling vests [258] and vests/jackets with gloves [259], may also be considered during breaks in play (e.g. half time). To summarise, practitioners should consider a '*toolbox*', containing ice-slurry/cool drinks in thermos flasks, ice packs, ice cubes (loose or wrapped in towels to form a cooling cylinder), with replacement clothing cooling inside the box to fit the individual needs of the athlete.

Combined Chronic and Acute Heat Alleviation Strategies

Can we combine and conquer?

The benefit of combining chronic and acute heat alleviation interventions is yet to be convincingly demonstrated experimentally. In two studies utilising intermittent sprint protocols, HA alone was sufficient to negate the effect of heat strain, leaving pre-cooling unnecessary [79,92]. Pre-cooling typically elicits larger effects on endurance performance, compared with intermittent sprinting [214]. The two studies to combine techniques in endurance performance revealed encouraging findings, although no performance advantage. Utilising an ice-vest prior to a 20 km cycling time trial, following 10-days of acclimatisation did not improve overall performance above acclimatisation alone, although transient, beneficial pacing alterations were observed until the dissipation of pre-cooling effects indicating a more aggressive cooling approach may prolong this effect [20]. Implementing a 20 min mixed-method external pre-cooling following five days of STHA, afforded large differences in T_{CORE}, T_{SKIN}, T_{CORE}:T_{SKIN} gradient, TS and HR during the first half of a 5 km running trial, but without any change in initial self-selected running speed [21]. This alludes to a sub-optimal 'flat' pacing strategy, which appears to prevail when individuals familiarise to exercising in the heat [246]. Thus, whilst an insensitivity or 'ceiling effect' following HA has been proposed [79], when an aggressive pre-cooling technique is adopted and heat strain remains severe, these data indicate small, meaningful changes, notably in HR and T_{SKIN}, that have the potential to benefit performance. Therefore, further familiarisation to combined chronic and acute heat alleviation interventions appears necessary to ensure pacing and performance is optimised at an individual level.

Summary

To prepare for elite international competition, quality training, individualised nutrition, and appropriate recovery will always be fundamental. Events such as the Tokyo 2020 Olympics also require athletes to prepare for the demands of the climate in a manner that does not unduly impact or detract from these factors. Whilst it is optimistic, unrealistic even, to envisage all of the potential detriments associated with performing under heat stress can be ameliorated, well-structured, individualised heat alleviation strategies have the potential to moderate the thermal challenge. Key messages arising from this review include

- HA provides a robust opportunity to improve thermoregulatory and performance physiology, alongside thermal perception, for athletes who are likely to be impacted by the predicted climate.
- Athletes may utilise a singular or combined method HA strategy that includes exercise-heat stress and/or post exercise heat stress e.g. hot water/sauna, to fit individual needs and circumstances.
- Once or twice daily HA sessions of 30-90 min may be used to optimise the magnitudes of adaptation in a manner that compliments training.
- Athletes should 'prepare for the worst' by preparing too perform in environments equal too, or greater than maximum anticipated climatic conditions including radiative (solar) heat.
- Female athletes, or those who are lesser trained (irrespective of sex), may require additional exposures than males, or those who are more aerobically trained to achieve optimal magnitudes of adaptation.
- Female athletes should be familiarised to exercising at performance intensities under anticipated heat stress across the menstrual cycle.
- Structured HA may be performed weeks prior to the competition, with subsequent 'top-up' sessions implemented closer to individual events.
- Athletes should rehydrate post HA and will benefit from carbohydrate and protein consumption to aid recovery and adaptation.

- Acute heat alleviation such as pre, and mid event cooling should compliment chronic HA strategies.
- Acute strategies should be individualised, and well rehearsed prior to competition to optimise responses.

Figure legends

Figure 1. Summary of adaptations to thermoregulatory and performance physiology following exercise heat acclimation

Figure 2. Advantages and disadvantages of using heat acclimatization or heat acclimation interventions with athletes. Note ✓ depicts positive, ✓✓ depicts very positive, X depicts negative, XX depicts very negative

Figure 3. Notional core temperature responses to a fixed intensity protocol (filled circles [T_{CORE}]/triangles [Exercise intensity]) and isothermic HA protocol (open circles [T_{CORE}]/triangles [Exercise intensity]) performed on a cycle ergometer in 40°C and 40% R.H. Change in temperature based upon an individual exercising at 1.3 W.kg^{-1} (Fixed intensity) or 2.7 W.kg^{-1} (Isothermic) [96].

Figure 4. Notional core temperature responses to a fixed intensity protocol (filled circles/triangles) and isothermic HA protocol (open circles/triangles) performed during the morning (~08:00; circles) or evening (~18:00; triangles) on a cycle ergometer in 40°C and 40% R.H. Change in temperature based upon an individual exercising at 1.3 W.kg^{-1} (Fixed intensity) or 2.7 W.kg^{-1} (Isothermic) from [96]. Resting morning and evening core temperature based upon data from [104].

Figure 5. Proposed sixteen-week chronic heat preparation approach which includes MTHA (ten one day HA sessions) commencing sixteen weeks prior too competition start, followed by STHA in the form of five one day HA (twelve weeks prior to competition start) and TDHA (eight and five weeks prior to competition start). Weekly adaptation retention sessions using established exercise heat acclimation approaches e.g. isothermic method (HA) or alternative approaches (HA-ALT) e.g. over-dressing or post exercise HWI/Sauna, punctuate these interventions. Days with no notation are regular training/recovery days. Athletes may consider implementing double sessions e.g. strength and conditioning or similar activity on acclimation days.

Figure 6. Practical cooling strategies for use before and during a Field Hockey game. Note. Field Hockey permits unlimited substitutions, so cooling strategies can be implemented throughout the game.

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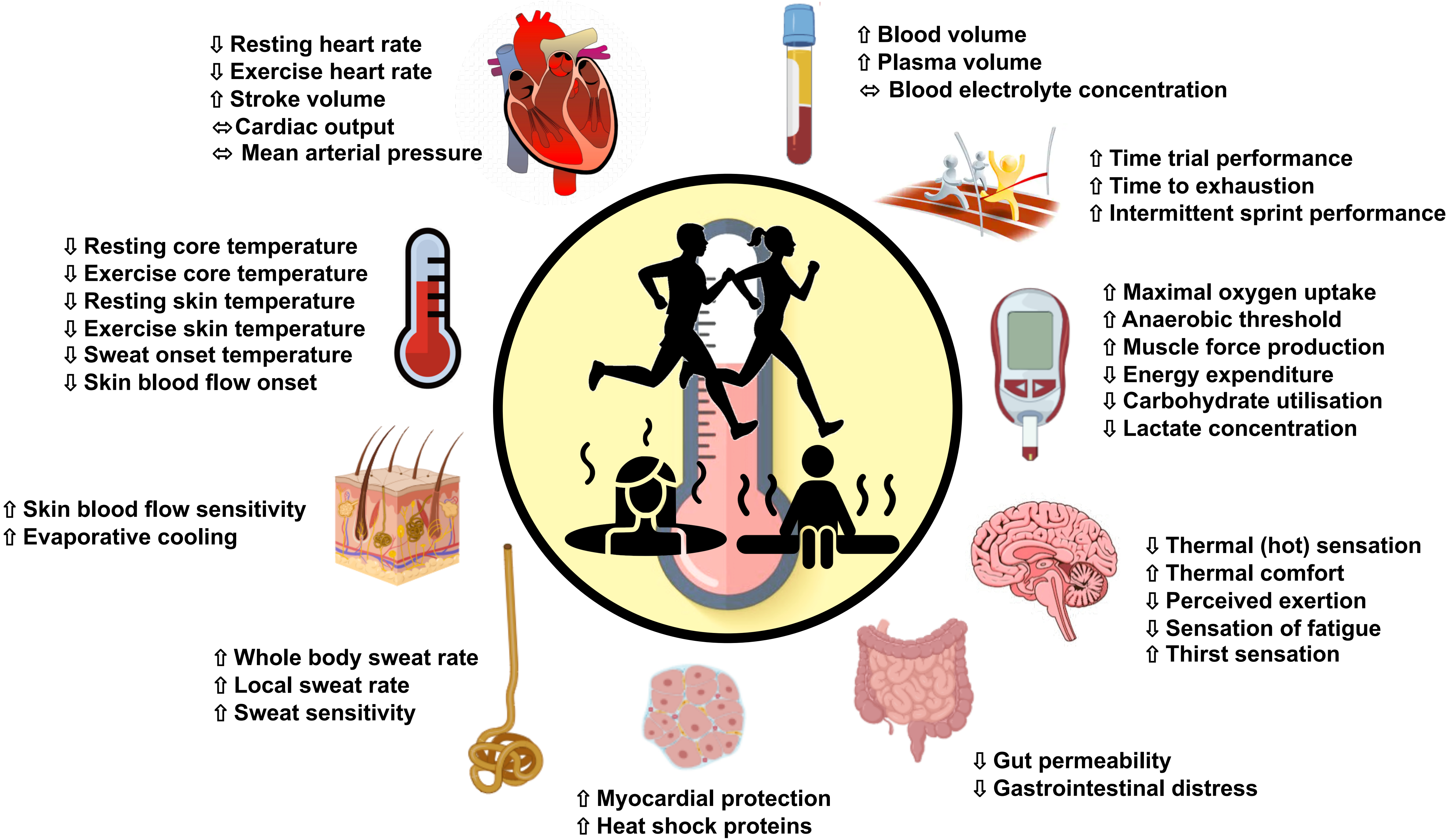


⇩ Resting heart rate
⇩ Exercise heart rate
⇧ Stroke volume
⇔ Cardiac output
⇔ Mean arterial pressure

⇧ Blood volume
⇧ Plasma volume
⇔ Blood electrolyte concentration

⇧ Time trial performance
⇧ Time to exhaustion
⇧ Intermittent sprint performance

⇧ Maximal oxygen uptake
⇧ Anaerobic threshold
⇧ Muscle force production
⇩ Energy expenditure
⇩ Carbohydrate utilisation
⇩ Lactate concentration

⇩ Thermal (hot) sensation
⇧ Thermal comfort
⇩ Perceived exertion
⇩ Sensation of fatigue
⇧ Thirst sensation

⇩ Gut permeability
⇩ Gastrointestinal distress

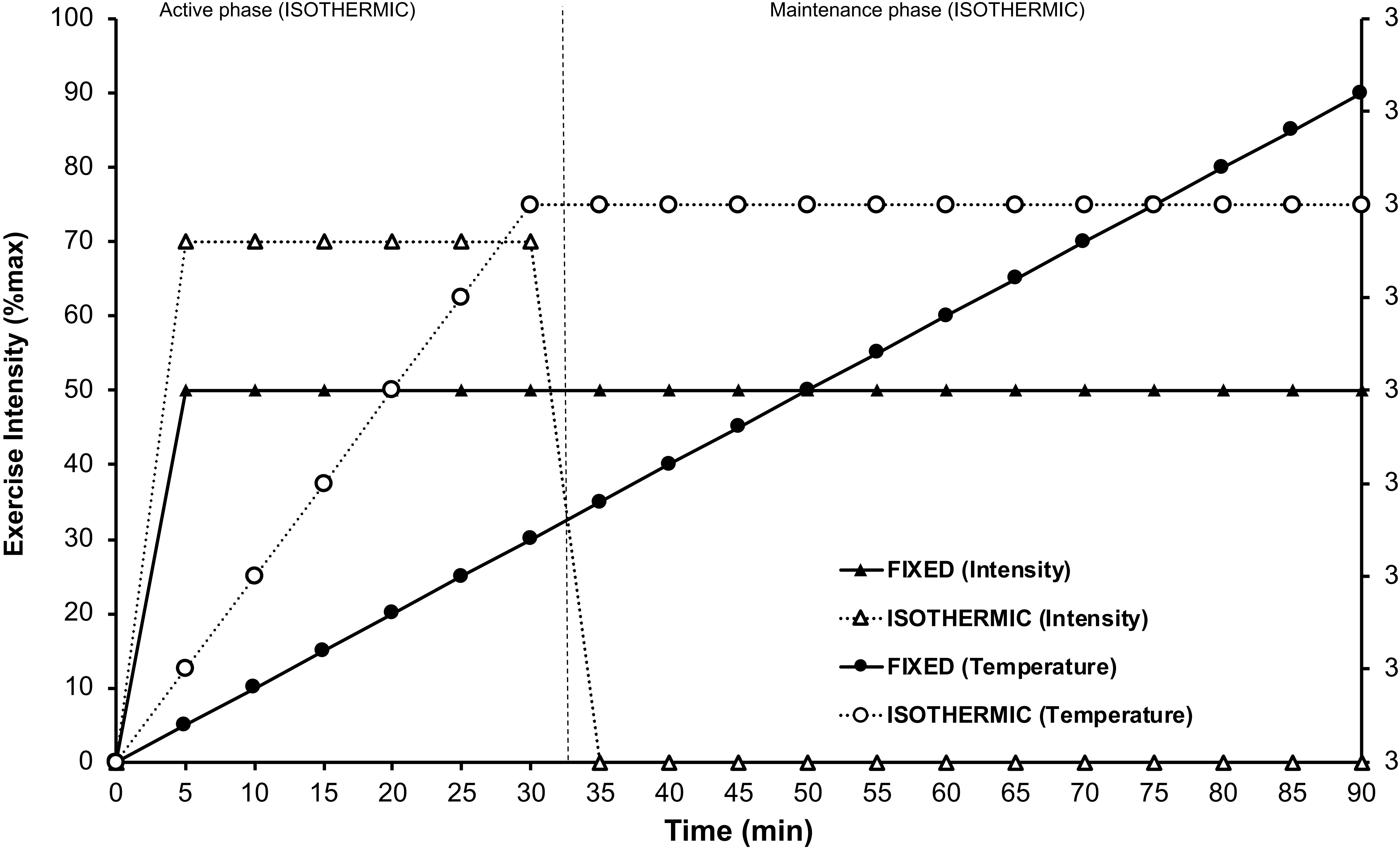
⇧ Myocardial protection
⇧ Heat shock proteins

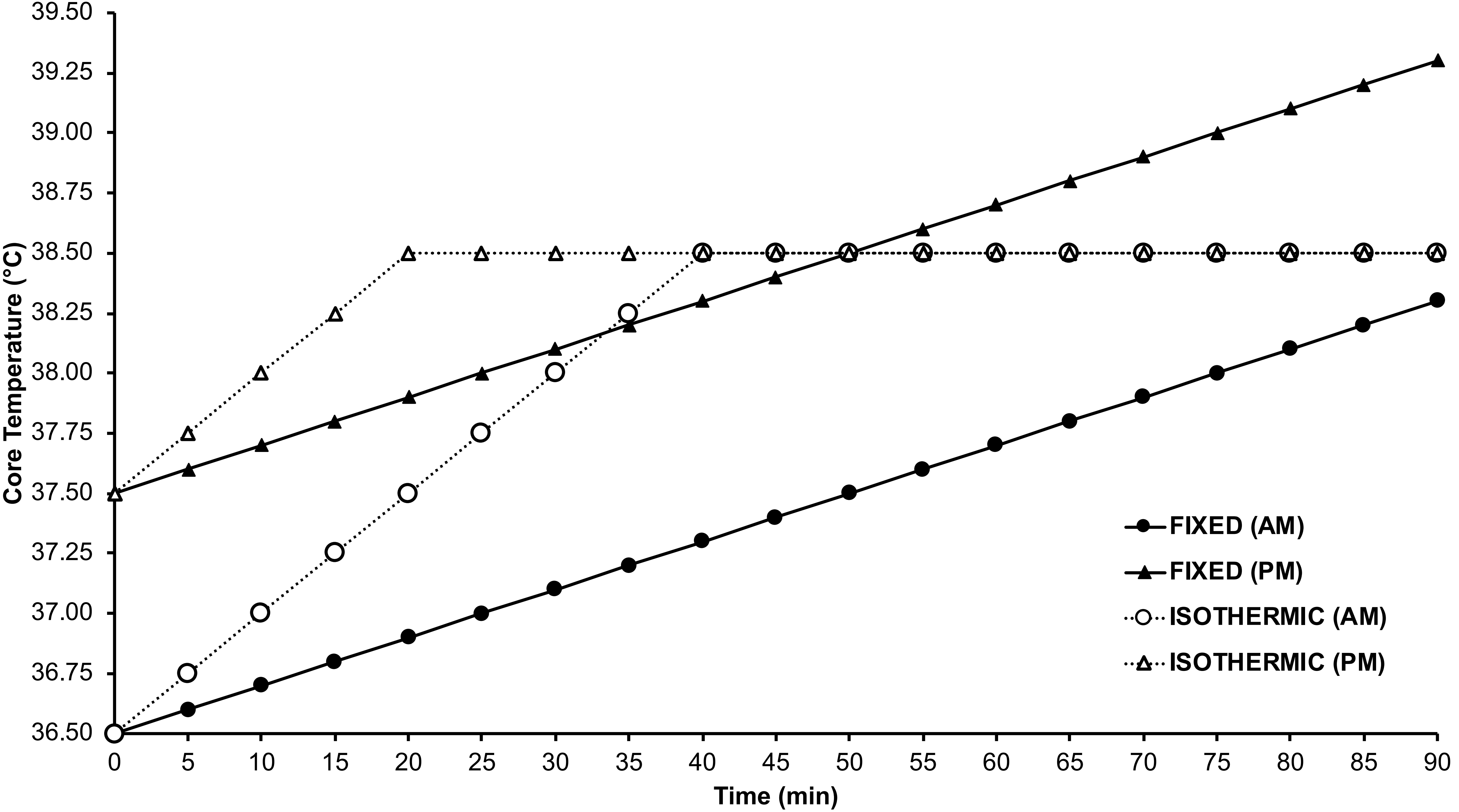
⇧ Whole body sweat rate
⇧ Local sweat rate
⇧ Sweat sensitivity

⇧ Skin blood flow sensitivity
⇧ Evaporative cooling

⇩ Resting core temperature
⇩ Exercise core temperature
⇩ Resting skin temperature
⇩ Exercise skin temperature
⇩ Sweat onset temperature
⇩ Skin blood flow onset

Consideration	**Acclimation**	**Acclimatisation**
Control of environmental conditions	✓✓	X
Competition specificity of environmental conditions	X	✓
Control of stimuli for adaptation	✓✓	X
Ability to monitor thermoregulatory responses	✓✓	✓
Specialist facilities required	X	✓
Pre intervention travel implications	✓✓	X
Straightforward logistics	✓ (active) X (passive)	✓
No training interruption (modality/prescription/type)	X (active) ✓ (passive)	✓
Ability to implement with larger groups	X (active) ✓ (passive)	✓


Active phase (ISOTHERMIC)
Maintenance phase (ISOTHERMIC)
Exercise Intensity (%max)
0
10
20
30
40
50
60
70
80
90
100
Core Temperature (°C)
37.00
37.25
37.50
37.75
38.00
38.25
38.50
38.75
39.00
Time (min)
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
75
80
85
90
FIXED (Intensity)
ISOTHERMIC (Intensity)
FIXED (Temperature)
ISOTHERMIC (Temperature)


Core Temperature (°C)
39.50
39.25
39.00
38.75
38.50
38.25
38.00
37.75
37.50
37.25
37.00
36.75
36.50
Time (min)
0
5
10
15
20
25
30
35
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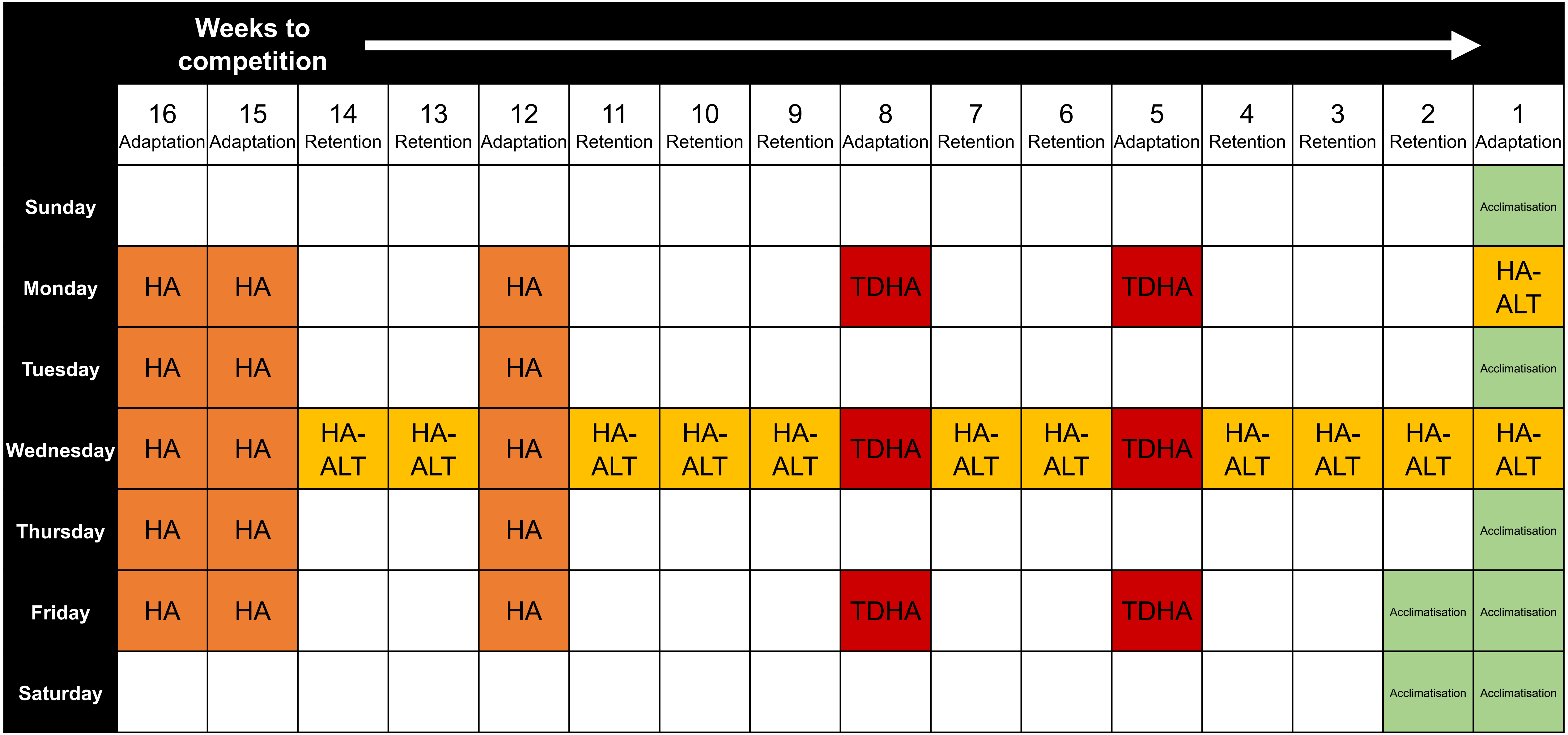
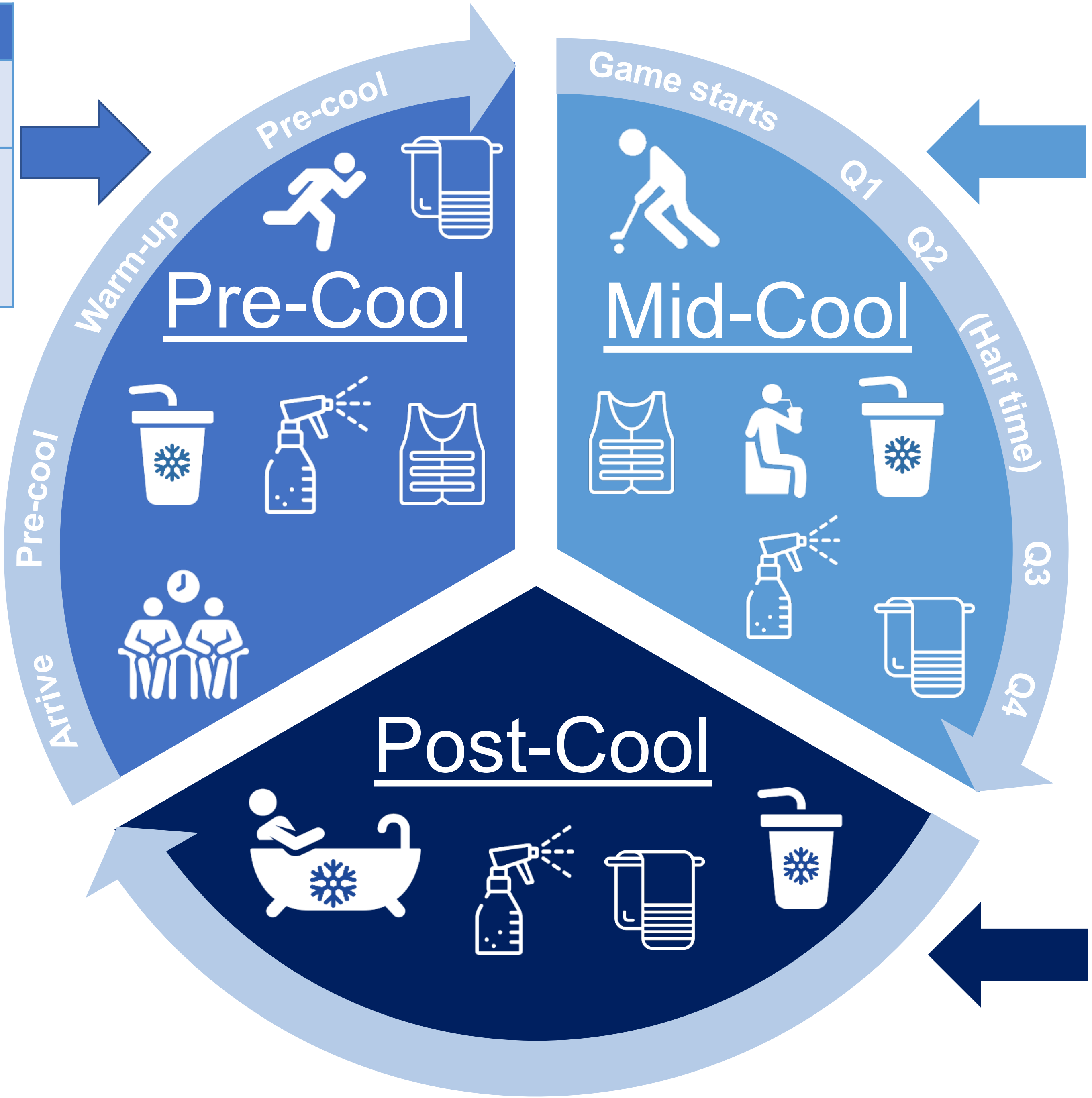
85
90
FIXED (AM)
FIXED (PM)
ISOTHERMIC (AM)
ISOTHERMIC (PM)



Weeks to competition →

	16 Adaptation	15 Adaptation	14 Retention	13 Retention	12 Adaptation	11 Retention	10 Retention	9 Retention	8 Adaptation	7 Retention	6 Retention	5 Adaptation	4 Retention	3 Retention	2 Retention	1 Adaptation
Sunday																Acclimatisation
Monday	HA	HA			HA				TDHA			TDHA				HA-ALT
Tuesday	HA	HA			HA											Acclimatisation
Wednesday	HA	HA	HA-ALT	HA-ALT	HA	HA-ALT	HA-ALT	HA-ALT	TDHA	HA-ALT	HA-ALT	TDHA	HA-ALT	HA-ALT	HA-ALT	HA-ALT
Thursday	HA	HA			HA											Acclimatisation
Friday	HA	HA			HA				TDHA			TDHA			Acclimatisation	Acclimatisation
Saturday															Acclimatisation	Acclimatisation



6:30 PM – Arrive

- Team-Talk
- Players change and wear ice vests
- Drink ~350 mL ice-slurry
- Taping and strapping, usual pre-match routines
- Possible mist spray in order to wet skin*

7:20 PM – Warm-Up

- Physical warm-up (~15 min)
- Technical warm-up (~15 min)

- Players drink ~100 mL ice-slurry *ad libitum* every 5 min
- Handheld mist spray
- Cold, wet towels

8:00 PM – Game Starts

Break between quarters (2 min)

- Drink ice-slurry / cold fluids
- High powered fans with misting spray
- Handheld mist spray available

Half time break (10 min)

- Wear ice vests
- Use cold towels
- Drink ice-slurry / cold fluids
- High powered fans with misting spray
- Handheld mist spray available

Substitutes (throughout game):

- Wear ice vests
- Use cold towels
- Drink ice-slurry / cold fluids
- High powered fans with misting spray on bench

9:15 PM – Game Ends

- Drink ice-slurry / cold fluids
- Handheld mist spray
- Cold, wet towels
- Ice-bath available
- Implement recovery protocols

* Applicable to hot dry conditions (e.g. 35°C, 30% RH).