Practical application of a mixed active and passive heat acclimation protocol in elite male Olympic team sport athletes

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Original investigation

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Preferred running head: Elite Mixed-Methods Heat Acclimation

Abstract word count: 245
Text-only word count: 4838
Number of tables: 3
Number of figures: 3

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Abstract

To investigate effectiveness and retention of heat acclimation (HA) integrated within an elite rugby sevens team training program, ~~twelve~~ 12 elite male rugby sevens athletes undertook 10-days of mixed active/passive HA across two-weeks of normal training. Physiological and performance variables were assessed using a sport specific, repeated high-intensity heat-response test Pre-HA; after five (Mid-HA) and 10 days (Post-HA); and 16-days post-HA (Decay). Resting, submaximal, and end-exercise core temperature were lower at Mid-HA (≤ -0.26 °C; $d \geq -0.47$), Post-HA (≤ -0.30 °C; $d \geq -0.72$), and Decay (≤ -0.29 °C; $d \geq -0.56$), compared to Pre-HA. Sweat rate was greater Post-HA compared to Pre-HA (0.3 ± 0.3 $L \cdot hr^{-1}$; $d = 0.63$). Submaximal HR was lower at Mid (-9 ±4 bpm; $d = -0.68$) and Post-HA (-11 ± 4 bpm; $d = -0.90$) compared to Pre-HA. Mean and peak 6-s power output improved Mid-HA (83 ± 52 W; 112 ± 67 W; $d \geq 0.47$) and Post-HA (125 ± 62 W; 172 ± 85 W; $d \geq 0.72$) compared to Pre-HA. Improvements in HR and performance persisted at Decay ($d \geq 0.66$). The initial five days of mixed-methods HA elicited many typical HA adaptations, with an additional five days eliciting further thermoregulatory, sudomotor, and performance improvements. Adaptations were well-retained after 16-days of normal training, without any further heat stimulus.

Keywords: Performance; Exercise; Team-sport; Core temperature; Olympic Sport.

1. Introduction

Heat acclimation (HA) is regarded as the best countermeasure to minimise heat-induced physiological strain, lower the incidence of heat-illness, and improve athletic performance in the heat for team sport athletes (Racinais et al., 2015). The general premise of HA involves exposing athletes to a series of increases in core body temperature (T_c) over time (often referred to as thermal impulses) through either passive and active means (Taylor, 2014), with typical physiological adaptations including lowered resting and exercising T_c and heart rate, plasma volume expansion, and a higher exercise sweat rate (Periard et al., 2015). Together, these facilitate a reduction in measures of thermal perception and enhanced exercise performance/capacity in the heat (Tyler et al., 2016). The induction of these physiological adaptations is not uniform however, with ~75% of adaptations in heart rate, T_c, and plasma volume occurring within ~4 to 6 days (Garrett et al., 2009; Pandolf, 1998), while ~~morphological~~ changes ~~such as~~in peak sweat rate can take up to two-weeks of daily heat exposure (Daanen et al., 2018).

In recent times, a plethora of research concerning HA has emerged, largely due to the challenging environmental conditions that were expected at the Tokyo 2020 Olympic Games (Kakamu et al., 2017). In some contexts, this previous research is practically useful for prescribing HA strategies, however, the sustained nature of many of the interventions, along with non-elite populations, make the ecological validity difficult to interpret in an elite team sport context (Casadio et al., 2017). Previous literature clearly indicates the benefits of exercise-based HA; however, competing training priorities (e.g. sport-specific skills, strength training) and logistical/practical burdens (e.g. lack of access to controlled artificially hot environments) can prohibit such HA protocols from being feasible. As a result, passive methods of HA, such as hot water immersion (HWI) have been explored with encouraging results, particularly when used immediately post-exercise (Heathcote et al., 2018; McIntyre et al., 2021; Zurawlew et al., 2018). When a training facility has adequate HWI facilities nearby, passive HA protocols can represent a practical and physiologically beneficial HA strategy; however, sole use of passive exposures may not be as effective as active HA for the development of sport-specific adaptations or performance benefits (Daanen et al., 2018; Gibson et al., 2019). As such, it has been proposed that combining active and passive exposures during a HA protocol may provide the best blend of meaningful physiological, perceptual and performance adaptations in an elite context, without compromising other training priorities (Casadio et al., 2017; Pryor et al., 2019).

The thermal stimulus throughout a HA protocol must be progressively elevated to exceed an individual's threshold for adaptation (Taylor, 2014). There are many approaches to achieve this; including self-paced exercise, constant (set) work-rate exercise, passive heating, post-exercise passive heating, controlled hyperthermia, and controlled heart rate HA (Gibson et al., 2019). Typically, isothermic protocols (i.e. controlled T_c; usually at ~ 38.5 °C) have been utilised in previous literature, as they allow greater workloads to be produced for a set T_c, as adaptation occurs (Garrett et al., 2012; Pethick et al., 2018). Although this approach allows experimental control, its practicality has been questioned in applied sport settings, due to the need to continuously monitor T_c, the need for progressively increased exercise intensities, and typically long exercise exposures (Gibson et al., 2019). As such, the use of heart rate has been proposed to provide a feasible means for regulating HA intensity for elite athletes (Periard et al., 2015; Stephenson et al., 2019), with the notion being that as cardiovascular, thermoregulatory and haematological adaptations occur, greater work output will be possible at any given heart rate range, thus providing a progressive overload with respect to the thermal impulse (Gibson et al., 2019). Furthermore, given that heart rate is a frequently used monitoring and assessment tool in elite sport, heart rate-controlled HA has the benefit of familiarity and ease of use in an applied sport setting.

The retention of adaptations following the removal of heat stimulus is another important consideration for elite teams when preparing to compete in the heat. Adaptation retention is largely dependent on training status and the initial cumulative thermal impulse (factored by time, intensity, mode), with a higher training status and greater initial thermal impulse eliciting greater retention (Gibson et al., 2019; Taylor, 2014). Much of the current evidence suggests that physiological, perceptual, and performance changes can be well-retained across the following ~14 days after the heat stimulus is removed (Daanen et al., 2018; Duvnjak-Zaknich et al., 2019); however, there is a paucity of evidence regarding HA adaptation retention in an elite team sport context.

Rugby sevens is often played in hot environmental conditions, and recent research has demonstrated the regular occurrence of high T_c (>39 °C) during international rugby sevens in hot/humid conditions (Fenemor et al., 2021; Taylor et al., 2019); thus, the inclusion of HA when preparing for international rugby sevens tournaments in hot conditions is well-indicated. Consideration of the multiple factors influencing HA induction and retention, along with practical considerations for integration within an elite training schedule, creates complex questions regarding the optimal design of HA protocols. As a result, the purpose of the current study was to investigate the effectiveness of 10-days of mixed-methods HA, integrated within an elite rugby sevens teams training program. Furthermore, it was investigated whether any resulting physiological, perceptual and performance changes could be retained after 16 days of normal training, without any further heat stimulus. It was hypothesised that 10-days of a mixed active and passive HA protocol would confer physiological, perceptual, and performance benefits that would be well-retained after 16 days of normal training, without any further heat stimulus.

2. Methods

2.1 Participants

Data was collected from 12 male athletes (age 23 ± 2 y; body mass 94.7 ± 6.4 kg; height 187 ± 5 cm) from the same international rugby sevens team (current world champion and Olympic silver medallists). All participants provided informed consent prior to testing, and ethical approval for the study was obtained through the University of Waikato Human Research Ethics Committee (HREC2018#64) in the spirit of the Declaration of Helsinki.

2.2 Design

All subjects undertook a 10-day HA protocol incorporated into two weeks of normal rugby sevens training in local springtime conditions -(six rugby-specific sessions; four gym sessions; no training on weekends). Thermoregulatory, cardiovascular, and perceptual responses to heat stress were assessed using a specifically designed heat response test (HRT), intended to replicate the fixed and maximal intensity demands of a rugby sevens warm up and game (Ross et al., 2015). In total, four HRT were performed: Pre-HA (before the commencement of HA); Mid-HA (after five days of HA); Post-HA (after 10 days of HA); Decay (16 days after the end of HA). All HRTs and active HA sessions were performed in an environmental chamber maintained at 35 °C, 80% relative humidity (RH), replicating a possible scenario at the Tokyo 2020 Olympic Games (Kakamu et al., 2017). Participants refrained from strenuous exercise in the 24-hr before each HRT, and were instructed to arrive to the HRT in a euhydrated state (not thirsty). All HRT's ~~which~~ were ~~all~~ performed on at the same time of day (mornings) to account for circadian rhythms. During the HA protocol, all participants undertook a mixture of active (exercise) and passive (hot water immersion; HWI) heat exposures (see below for details). Participants were asked to undertake permissive dehydration (i.e. refrain from drinking if possible) during the HA sessions, as this has previously been shown to enhance responses to HA (Garrett et al., 2014). During the entire 10-day acclimation process, the total heat exposure for each participant was 7 h 45 min, noting that the Pre-HA and Mid-HA HRTs were considered part of the overall HA thermal stimulus. An overview of the HA timeline is shown in Figure 1.

<<Figure 1 near here >>

2.3 Methodology

2.3.1 Heat response test

All HRTs were performed on a calibrated cycle ergometer (WattBike Ltd, Nottingham, UK) and consisted of a 24-min fixed intensity warm-up, followed by intermittent sprints with the same time structure as a rugby sevens game (2x 7-min halves, with a 2-min halftime break; as described below). The warm-up took the following structure; 7-min cycling at 2.0 W·kg^{-1} (submaximal); 1-min rest; 7-min cycling at 3.0 W·kg^{-1}; 1-min rest; and 3-min cycling at 2.0 W·kg^{-1} with submaximal accelerations during the final 6-s of each minute, followed by a 5-min rest. The repeated intermittent sprint (R-SPRINT) section consisted of 24-s cycling at 3.0 W·kg^{-1}, immediately followed by a 6-s maximal sprint and 40-s rest, repeated 12 times with a 2-min half-time break after interval 6. During rest periods, athletes were permitted to spin their legs (with minimal power output). A cycling power output of 3.0 W·kg^{-1} was chosen as this reflected the individual mean heart rate during maximal aerobic speed running during pilot testing. The design and content of the repeated interval protocol was chosen as it replicates game average high-intensity work: rest ratios [30 s: 40 s; (Ross et al., 2015)] without the increased mechanical load associated with high-intensity running. Peak power output (PPO) and mean power output (MPO) during the 6-s maximal sprints were used as performance measures. Fatigue index percentage (Fatigue%) was also calculated for both PPO and MPO as shown in equation 1.

Equation 1: Calculation of Fatigue Index (Fatigue%) for Peak and ~~Maximal~~ Mean power output (PO)

$$Fatigue\% = \frac{sum\ of PO}{12(\max PO)}$$

Physiological and perceptual measures (as described below) were recorded during seated rest (resting), after each warm-up stage, and after every third interval of the intermittent sprint section. Where necessary, measurements were averaged to be used in the final analysis (i.e. warm-up and R-SPRINT).

2.3.2 Active HA sessions

All participants undertook two active HA sessions per week (four active heat sessions in total), with these sessions being performed within 15 minutes of an on-field training session. The first session (HA1) consisted of ten 2-min intervals performed on a cycle ergometer separated by 2-min rest. During each cycling interval, participants were instructed to rapidly elevate and maintain their heart rate to 85% of their measured maximum. Mean 2-min power output was recorded by a researcher. The second session (HA2) consisted of 10-min fixed intensity cycling (5-min at 2.0 $W{\cdot}kg^{-1}$; 5-min at 3.0 $W{\cdot}kg^{-1}$); six 500 m rowing intervals (Concept 2 Inc., Morrinsville, VT), at a target pace of 1-min 50-s per 500 m, separated by 2-min rest; followed by a 10-min cycling interval where participants were instructed to keep their heart rate at 85% of their measured maximum, with mean power output being recorded. The content of these active HA sessions was chosen for athlete familiarity, and practicality within a sevens squad. Specifically, HA1 (lower intensity) coincided with a high-intensity on-field training session, while HA2 (higher intensity) followed a low-intensity on-field training session.

2.3.3 Hot water immersion (HWI) sessions

All participants undertook four passive HWI sessions (two per week). HWI1 was performed without any prior exercise, as this coincided with a scheduled mid-week non-training day, while HWI2 was performed within 15 min of an on-field training session. All HWI were undertaken in an upright tub for 40 min in 40 °C water. Participants were instructed to stand, immersed to the top of the chest (including arms) for the first 25 min of each exposure, after which time they could elevate to the mammillary line, and bring their arms out of the water.

2.3.4 Physiological measurements

During all HRT's, T_c was measured using a rectal thermistor (U thermistor, Grant Instruments Ltd., Cambridge, United Kingdom), self-inserted to a depth of 10 cm beyond the anal sphincter. T_c was recorded at 1-min intervals on a portable data logger (2020 series data logger, Grant Instruments Ltd., Cambridge, United Kingdom) and averaged over each measurement period. Heart rate (HR; Polar H10, Polar Electro Oy, Kempele, Finland) was monitored throughout each HRT as well as during the active HA sessions to prescribe exercise intensity. To estimate sweat loss, towel-dried, nude body mass (NBM) was recorded to 0.1 kg using digital scales (Tanita HD-351, Tanita Health Equipment H.K. Limited) before and immediately after each HRT and each HA session, this value was adjusted for a standardised amount of ingested liquid during the HRT (640 mL). Sweat loss was converted to sweat rate ($L \cdot hr^{-1}$), for subsequent analysis.

2.3.5 Perceptual Measurements

Rating of perceived exertion [RPE: 6-20 scale; (Borg, 1970)], thermal sensation [1-13 point scale; (Gagge et al., 1967)], thermal comfort [1-10-point scale; (Gagge et al., 1967)], and thirst sensation [Thirst: 1-9 point scale; (Riebe et al., 1997)] were collected at the same time points described above. Additionally, RPE, thermal sensation and thermal comfort were collected at the end of each HA session (RPE during active sessions only).

3. Statistical analysis

One-way repeated measures ANOVA was used to determine main effects for all variables between Pre-HA, Mid-HA, Post-HA, and Decay, along with interaction over time for all dependent measures using IBM SPSS Statistics for Windows, Version 26.0. Normality was assessed using the Shapiro-Wilk test at each time point and Mauchly's test was used to test that sphericity had not been violated. On occasions where sphericity had been violated, the Greenhouse-Geisser correction was used. Where there was a main effect, magnitudes between each measurement period were determined and expressed as both mean differences ± 90% confidence limits (CL) and standardised effect sizes (Cohen's d). If the 90% CL for Cohen's d overlapped positive and negative trivial (± 0.20) d values, the effect was deemed *unclear*; 90% CL were used due to the small sample size as suggested by Turner et al. (2021). Substantial clear effects were described using standard thresholds of < 0.20 *trivial*, 0.20 – 0.49 *small*, 0.50 – 0.79 *moderate*, and > 0.80 *large* (Cohen, 1988). A p-value of ≤ 0.05 was deemed to be statistically significant. The smallest worthwhile change (SWC) for rectal temperature (as depicted in Figure 2) was determined from a recent meta-analysis (Tyler et al., 2016), while the SWC for all performance metrics (as depicted in Figure 3) was calculated as one third of the pre-test coefficient of variation (%) (Hopkins, 2004).

4. Results

Group mean (±SD) physiological and perceptual variables for each HRT are presented in Table 1; Both the raw mean (± 90% CL) and standardised mean differences for each comparison are presented in Table 2. All comparisons were normally distributed, as assessed by Shapiro-Wilk's tests ($p > 0.05$). Group mean (±SD) and standardised mean differences for power output, RPE, thermal sensation, thermal comfort, and sweat rate during each active and passive heat acclimation session are presented in Table 3.

<<Table 1 near here >>

<<Table 2 near here >>

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4.1.1 Physiological measurements

The HA intervention elicited statistically significant changes in resting T_c [$F_{(2, 22)} = 12.158$, $p < 0.001$], submaximal T_c [$F_{(2, 22)} = 8.946$, $p = 0.001$] and end exercise T_c [$F_{(2, 22)} = 10.476$, $p = 0.001$] over time. Resting, submaximal and end exercise T_c were lower at Mid-HA (all $p < 0.05$; $d \geq -0.47$) and Post-HA compared to Pre-HA (all $p < 0.01$; $d \geq -0.72$), while there were no differences in resting, submaximal or end exercise T_c Post-HA compared to Mid-HA. At the Decay test, resting, submaximal and end exercise T_c were all lower, compared to Pre-HA (all $p < 0.01$; $d \geq -0.56$), while there were no significant differences in T_c between Decay and Post-HA. See Figure 2, Table 1, and Table 2 for full descriptions of T_c change across each HRT.

The HA intervention elicited statistically significant changes in submaximal HR [$F_{(2, 22)} = 12.893$, $p < 0.001$] over time, however, there was no statistically significant changes in R-SPRINT HR. Submaximal HR was lower at Mid ($p = 0.003$; $d = -0.68$) and Post-HA ($p = 0.001$; $d = -0.90$) compared to Pre-HA, while submaximal HR was still lower at Decay compared to Pre-HA (*p* = 0.001; *d* = -0.86; see Tables 1 and 2). Sweat rate was greater Post-HA compared to Pre-HA (*p* = 0.05; *d* =0.63), and further increased at Decay compared to Post-HA (*p* = 0.03; *d* = 0.37; see Tables 1 and 2).

<<Figure 2 near here >>

4.1.2 Perceptual measurements

The HA intervention did not lead to any statistically significant changes in ~~submaximal~~ warm-up and R-SPRINT thermal sensation or thermal comfort over time. The HA intervention elicited statistically significant changes in submaximal Thirst [$F_{(2, 22)}$ = 3.820, *p* = 0.038] and R-SPRINT Thirst [$F_{(2, 22)}$ = 9.177, *p* = 0.001] over time. There were some *small-moderate* changes in these perceptual measures between HRTs, as outlined in Tables 1 and 2.

4.1.3 Performance measurements

MPO and PPO significantly increased Mid-HA compared to Pre-HA by 83 ± 52 W and 112 ± 67 W respectively (both *p* =0.01; *d* = 0.47 and 0.60). Compared to Pre-HA, MPO and PPO were significantly increased Post-HA by 125 ± 62 W and 172 ± 85 W (both *p* = 0.004; *d* = 0.72 and 0.80). This significant increase in MPO and PPO persisted at Decay compared to Pre-HA by 129 ± 58 W and 214 ± 81 W (*p* = 0.002 and 0.001; *d* = 0.66 and 0.90).

Compared to Pre-HA, both MPO and PPO Fatigue% decreased (improved) at Mid-HA by 13 ± 6% and 9 ± 4% and respectively (both *p* = 0.01; *d* = 1.25 and 0.80); at Post-HA by 14 ± 6% and 11 ± 6% and respectively (both *p* = 0.001; *d* = 1.37 and 1.14); and at Decay by 11 ± 3% and 8 ± 4% and respectively (*p* = 0.001 and 0.01; *d* = 0.96 and 0.67). All absolute mean (± 90~~5~~% CL) performance data and standardised effects (Cohen's *d*) are presented in Figure 3.

5. Discussion

In support of our hypothesis, five days of mixed-methods HA integrated into one-week of an elite team's training program elicited some typical physiological, perceptual, and performance adaptations, with an additional five days eliciting further improvements in T_c, sweat rate, and performance during an intermittent sprint HRT. Furthermore, most adaptations were retained after 16-days of normal training with no additional heat exposure, with only R-SPRINT HR and peak power Fatigue% showing small decay profiles.

The thermoregulatory adaptations described herein are in line with those expected, particularly changes in HR and T_c. In the current study, HR was decreased during submaximal exercise, possibly indicating an improvement in central hemodynamics in response to the demands of exercising in the heat (Gibson et al., 2019; Periard et al., 2016). Similarly, resting (-0.42 °C), submaximal (-0.29 °C), and end exercise T_c (-0.40 °C) were reduced as a result of HA. These thermoregulatory adaptations represent functional physiological changes that are likely to contribute to increased exercise capacity, and consequently performance improvements (Lorenzo et al., 2010). Fenemor and colleagues (2021) recently demonstrated that T_c during warm-ups and games can regularly exceed 39 °C during an international rugby sevens tournament played in hot/humid conditions. Such elevated T_c are known to be detrimental for repeated-sprint performance (Beaven et al., 2018); hence, are indicative of the inclusion of HA when preparing for international rugby sevens tournaments in hot conditions. The performance improvements observed in MPO and PPO in the current study were well above the *a priori* SWC following five (12% and 14%, respectively) and ten (18% and 20%) days of HA, which is in line with performance improvements shown in previous research with similar HA durations [~7% following short term-HA; ~22%

following long-term HA (Tyler et al., 2016)]. It should be considered that the current study involved elite repeated high-intensity team sport athletes; hence, even though the athletes were familiar with this HRT, there may be some training effect present, due to the (relative) unfamiliarity of repeated high-intensity exercise on a cycle ergometer. This possible training effect may explain part of the large performance increase demonstrated in the current study.

Moderate decreases in thirst sensation alongside *moderate* increases in sweat rate were shown as a result of HA. This relationship seems paradoxical, and may be a remnant of general perceptual acclimation, rather than of thirst adaptation *per se* (Akerman et al., 2016). Alternatively, the *moderate* reduction in thirst sensation could be related to permissive dehydration during HA sessions, resulting in athletes becoming familiar with consuming less fluid during exercise in hot environmental conditions. When extrapolated to a post-HA competition setting, practitioners should be aware that not proportionally increasing fluid replacement to match HA-induced increases in sweat rate will result in greater dehydration, particularly in humid environments (Periard et al., 2015).

The separate use of exercise-based and passive heat exposures has been extensively described and reviewed (Heathcote et al., 2018; Tyler et al., 2016). However, the use of a practical, combined approach that incorporates both active and passive heat exposures around concurrent training is currently confined to a case-study with a football referee (Ruddock et al., 2016), and one study in para- and able-bodied triathletes (Stephenson et al., 2019). In both cases, normal training was replaced with active HA sessions, which is not likely to be feasible in an elite team sport context. In turn, it has been recently demonstrated that heat re-acclimation using HWI is comparable to exercise-based methods (Gerrett et al., 2021). Together, these previous investigations indicate that a mixed active and passive HA protocol can be effective at stimulating thermoregulatory adaptations in endurance trained athletes and officials. While this approach is practical in an endurance context where normal trainings can be replaced by heat exposure sessions, within an elite team sport context, this is not practical due to concurrent on-field training that often focusses on technical and tactical training methods (Henderson et al., 2018; Marrier et al., 2018). Therefore, the current mixed-methods protocol represents a time-efficient stimulus for heat adaptation, presenting the first evidence of a realistic and ecologically valid solution to overcome the demands of elite training schedules.

The positive thermoregulatory adaptations from the current mixed-methods HA approach were achieved by prescribing a readily accessible and practical heart rate metric during exercise-based sessions. It has previously been suggested that using heart rate to regulate HA session intensity will provide a constant cardiovascular stimulus, and hence a constant thermoregulatory adaptation stimulus, across an acclimation block (Periard et al., 2015). However, this concept has received limited use in the literature, despite previous work showing a constant heart rate during isothermic HA sessions (Garrett et al., 2012; Pethick et al., 2018; Zurawlew et al., 2016). While isothermic HA protocols provide a ~~important mechanistic information regarding adaptations to heat as a result of a constant~~ progressively-increasing thermal stimulus, such an approach may not be practical in an applied team sport environment due to the need for constant temperature monitoring. Therefore, the current study provides further evidence for the efficacy of using heart rate to regulate HA intensity in such a context. In the current study, athletes were able to maintain a constant relative intensity across each heat training session, exhibited via the lack of change in RPE and thermal comfort, and only small changes in TS between active HA sessions (Table 3). Furthermore, progression was indicated as athletes were able to produce greater external workload during active HA sessions on

Week Two, which is in line with isothermic HA protocols, whereby greater workloads are produced across the course of a HA block.

The retention of thermoregulatory adaptations has significant implications for scheduling HA prior to competition, particularly in the current team sport context where specific training demands and travel often take precedence in the taper period (Casadio et al., 2017). In the current study, thermoregulatory changes between the Post-HA and Decay HRTs were either *unclear*, *trivial or small* (Tables 1 and 2), indicating that the adaptations resulting from HA were well-retained after 16-days of normal training, with no environmental heat stimulus. Indeed, the rates of decay within the current study are well within the bounds described in a previous meta-analysis (Daanen et al., 2018). This notion is further supported by only *trivial* changes in peak and average R-SPRINT power output at decay compared to Post-HA, combined with a *small* decrease in peak blood lactate, indicating little change in anaerobic capacity across the decay period. The increased sweat rate described after 16-days with no heat stimulus in the current study is an example of a morphological change with a longer time course than other physiological and cardiovascular adaptations (Periard et al., 2016; Sato et al., 1990). The initial magnitude of adaptation ~~, and favourable retention shown in the current study,~~ is likely a result of a combination of the high baseline training status of the population, the duration and type of activities within the HA, and the progressive overload approach (i.e. controlled HR) contributing to a sufficiently strong cumulative thermal impulse (Daanen et al., 2018; Taylor, 2014). In turn, the maintenance of high levels of physical activity [i.e. normal training weeks, characteristic of an international elite rugby sevens team (Marrier et al., 2018)] in the post-HA period likely ~~helped~~ contributed to the favourable adaptation retention shown in the current study ~~prolong the adaptations~~ (Gibson et al., 2019).

5.1 Practical Applications

The current study is the first to demonstrate the efficacy of a practical mixed active/ passive, heart-rate controlled HA protocol, integrated into an elite teams' training program. These findings are of particular interest to practitioners who have limited access to hot environments pre-competition. Furthermore, the described HA framework is generalisable to other ~~invasion~~ team sports, and/ or sports that include similar weekly training models. In turn, similar HA protocols could facilitate readiness for deployment to hot climates in military personnel {Ashworth, 2020 #475}. Given that the athletes in the current study predominantly undertake repeated high-intensity running exercise as part of their normal training, there may have been some training effect resulting from the repeated high-intensity cycle ergometer exercise protocol. The ecological validity and high calibre of athletes are strengths of the current study; however, research in such a setting precludes the use of a control group engaging in thermoneutral exercise. Nonetheless, due to the calibre of athletes involved it is unlikely that any meaningful non-HA related adaptation occurred during this time (Lorenzo et al., 2010). Future research should test practical re-acclimation protocols 3-4 weeks after a similar HA protocol, giving further information to practitioners to support HA periodisation within a pre-competition schedule.

6. Conclusion

The current study provided initial evidence for the efficacy of a practical, and ecologically valid, mixed-methods HA protocol within an elite teams training program. While the integration of one week of such an HA protocol elicited many typical physiological, perceptual and performance adaptations, an additional week elicited further thermoregulatory, sudomotor and performance improvements. Furthermore, these adaptations were well-retained after 16-days with no additional heat exposure. These novel findings have distinct implications for practitioners aiming to schedule HA into the pre-competition period.

7. Acknowledgements

The authors would like to thank the athletes, coaches and management of the All Blacks sevens team for engaging in this research project. We also acknowledge the contribution to data collection from Lucy Jacobs, Lauren Keaney, and Lorenz Kissling from High Performance Sport New Zealand, along with volunteers from the University of Waikato; Francesco Sella, Kelly Walsh, Courtney Davie, Jade Wharemate, Menso van der Laan, Drew Carson, and Josh Olsen.

8. Author contributions

SF and CMB conceived and designed the research, conducted the research protocols, and processed / analysed the data; MD, NG and JR helped design the research; BM conceived and designed the research, and conducted the research protocols. All authors contributed to the final editing and revision of the manuscript. All authors have read and approved the final manuscript.

9. Statements and Declarations

The authors declare that they have no competing interests.

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11. Tables

Table 1: Mean ± SD for variables during heat response tests (HRT) pre-, mid-, post-, heat acclimation (HA) and +16 days (decay).

		Heat Response Test			
Variable	**Timepoint**	**Pre-HA**	**Mid-HA**	**Post-HA**	**Decay**
Core temperature (°C)	*Resting*	37.03 ± 0.33	36.75 ± 0.33*	36.61 ± 0.22***	36.70 ± 0.31**
	Sub-max	37.15 ± 0.32	36.84 ± 0.26**	36.86 ± 0.24**	36.87 ± 0.30**
	End Exercise	38.96 ± 0.52	38.70 ± 0.51*	38.56 ± 0.52***	38.67 ± 0.46**
Heart rate (bpm)	*Sub-max*	154 ± 12	144 ± 15*	142 ± 12***	141 ± 16***
	R-SPRINT	174 ± 11	172 ± 12	170 ± 9	173 ± 9
RPE (AU)	*Warm Up*	15.7 ± 1.5	15.1 ± 1.5	15.5 ± 1.3	15.4 ± 1.5
	R-SPRINT	19.2 ± 0.8	18.9 ± 0.7	19.0 ± 0.6	19.3 ± 0.7
Thermal sensation (AU)	*Warm Up*	10.8 ± 0.7	10.6 ± 0.9	10.9 ± 0.6	10.6 ± 0.9
	R-SPRINT	12.1 ± 0.6	11.9 ± 0.8	12.2 ± 0.7#	12.1 ± 0.8
Thermal comfort (AU)	*Warm Up*	6.6 ± 1.0	6.2 ± 1.5	6.3 ± 1.4	5.6 ± 1.5*^
	R-SPRINT	8.9 ± 0.9	8.6 ± 1.2	8.6 ± 1.4	8.7 ± 1.3
Thirst (AU)	*Warm Up*	4.1 ± 1.2	3.2 ± 1.6*	3.1 ± 1.8*	3.0 ± 1.4*
	R-SPRINT	6.0 ± 2.3	4.4 ± 2.3*	4.2 ± 2.7**	4.0 ± 2.3**
Sweat rate ($L \cdot hr^{-1}$)	*Mean*	1.9 ± 0.5	2.0 ± 0.5	2.2 ± 0.5*	2.3 ± 0.4**^
Peak blood $[La^+]$ $mmol \cdot L^{-1}$	*Mean*	10.3 ± 3.1	10.5 ± 2.9	11.0 ± 3.1	10.0 ± 2.7

* = different to Pre; # = different to mid; ^ = different to post. The number of symbols represent the significance level; 1 = $p \leq 0.05$, 2 = $p \leq 0.01$, and 3 = $p \leq 0.001$; AU = Arbitrary Units; RPE = Ratinge of perceived exertion.

Table 2: Mean difference ± 90% confidence limits; (Cohen's *d*) for variables during heat response tests (HRT) pre-, mid-, post-, heat acclimation (HA) and +16 days (decay).

Variable	Timepoint	Mid - Pre	Post - Pre	Post - Mid	Decay - Post	Decay - Pre
Core temperature (°C)	*Resting*	-0.27 ± 0.17; (-0.78) ***moderate***	-0.41 ± 0.15; (-1.39) ***very large***	-0.14 ± 0.19 (-0.47) ***small***	0.08 ± 0.14 (0.29) *trivial*	-0.29 ± 0.16 (-0.71) ***moderate***
	Sub-max	-0.32 ± 0.17; (-1.03) ***large***	-0.30 ± 0.14; (-0.97) ***large***	0.02 ± 0.14 (0.08) *unclear*	0.01 ± 0.11 (0.04) *unclear*	-0.30 ± 0.15 (-0.87) ***large***
	End Exercise	-0.26 ± 0.16 (-0.47) ***small***	-0.40 ± 0.12; (-0.72) ***moderate***	-0.14 ± 0.16 (-0.26) *trivial*	0.11 ± 0.15 (0.20) *trivial*	-0.30 ± 0.17 (-0.56) ***moderate***
Heart rate (bpm)	*Sub-max*	-9 ± 4; (-0.68) ***moderate***	-11 ± 4; (-0.90) ***moderate***	-2 ± 5; (-0.12) *unclear*	-1 ± 4; (-0.12) *unclear*	-13 ± 5; (-0.86) ***moderate***
	R-SPRINT	-3 ± 3; (-0.22) *trivial*	-4 ± 4; (-0.38) *trivial*	-1 ± 4; (-0.12) *unclear*	3 ± 3; (0.34) *trivial*	-1 ± 3; (-0.08) *unclear*
RPE (AU)	*Warm Up*	-0.6 ± 0.5; (-0.34) ***small***	-0.2 ± 0.6; (-0.10) *unclear*	0.4 ± 0.6; (0.27) *trivial*	-0.1 ± 0.4; (-0.05) *unclear*	-0.2 ± 0.6; (-0.14) *unclear*
	R-SPRINT	-0.3 ± 0.4; (-0.31) *trivial*	-0.1 ± 0.4; (-0.17) *unclear*	-0.1 ± 0.3; (-0.18) *unclear*	0.2 ± 0.3; (0.28) *trivial*	-0.1 ± 0.4; (0.09) *unclear*
Thermal sensation (AU)	*Warm Up*	-0.2 ± 0.4; (-0.20) *unclear*	0.1 ± 0.3; (0.20) *unclear*	0.3 ± 0.4; (0.39) *trivial*	-0.3 ± 0.4; (-0.41) *trivial*	-0.2 ± 0.3; (-0.23) *trivial*
	R-SPRINT	-0.3 ± 0.2; (-0.33) ***small***	0.1 ± 0.2; (0.08) *unclear*	0.3 ± 0.1; (0.40) ***small***	-0.1 ± 0.2; (-0.08) *unclear*	0.0 ± 0.2; (-0.01) *unclear*
Thermal comfort (AU)	*Warm Up*	-0.4 ± 0.5; (-0.37) *trivial*	-0.3 ± 0.5; (-0.25) *trivial*	0.1 ± 0.4; (0.09) *unclear*	-0.7 ± 0.5; (-0.46) ***small***	-0.9 ± 0.7; (-0.74) ***moderate***
	R-SPRINT	-0.3 ± 0.3; (-0.27) *trivial*	-0.3 ± 0.4; (-0.26) *trivial*	0.0 ± 0.3; (-0.02) *unclear*	0.1 ± 0.4; (0.04) *unclear*	-0.2 ± 0.4; (-0.21) *trivial*
Thirst (AU)	*Warm Up*	-0.9 ± 0.7; (-0.62) ***moderate***	-0.9 ± 0.8; (-0.69) ***moderate***	-0.1 ± 0.3; (-0.10) *unclear*	-0.1 ± 0.4; (0.02) *unclear*	-1.1 ± 0.6; (-0.76) ***moderate***
	R-SPRINT	-1.6 ± 0.9; (-0.63) ***moderate***	-1.9 ± 1.1; (-0.75) ***moderate***	-0.2 ± 0.3; (-0.18) *unclear*	-0.2 ± 0.5; (-0.02) *unclear*	-2.0 ± 0.9; (-0.80) ***large***
Sweat rate (L·hr^{-1})	*Mean*	0.2 ± 0.2; (0.34) ***small***	0.3 ± 0.3; (0.63) ***moderate***	0.1 ± 0.3; (0.30) *trivial*	0.2 ± 0.2; (0.37) ***small***	0.4 ± 0.3; (1.00) ***large***
Peak blood [La$^+$] mmol·L^{-1}	*Mean*	0.2 ± 1.2; (0.09) *unclear*	0.7 ± 1.5; (0.22) *unclear*	0.5 ± 1.2; (0.14) *unclear*	-1.0 ± 0.9; (-0.28) ***small***	-0.3 ± 1.6; (-0.03) *unclear*

Table 3: Mean ± SD power output (W) and thermoregulatory variables during exercise (active) and passive hot-water immersion (HWI) heat acclimation sessions on week one and week two.

		Cycling power output (W)	**RPE (AU)**	**Thermal sensation (AU)**	**Thermal comfort (AU)**	**Sweat rate ($L \cdot hr^{-1}$)**
Active session one	Week 1	211 ± 22	16.9 ± 1.2	10.3 ± 0.6	7.7 ± 0.9	2.6 ± 0.7
	Week 2	225 ± 26	17.2 ± 1.8	9.8 ± 0.8	7.5 ± 1.3	3.0 ± 0.9
	Cohen's d	*0.50* ***small***	*0.12 unclear*	*-0.53* ***small***	*-0.22 trivial*	*0.40* ***small***
Active session two	Week 1	100 ± 20	18.3 ± 1.3	12.1 ± 0.8	8.6 ± 1.0	2.0 ± 0.5
	Week 2	108 ± 18	17.8 ± 1.6	11.6 ± 1.0	8.3 ± 1.5	2.4 ± 0.7
	Cohen's d	*0.42* ***small***	*-0.31 trivial*	*-0.53* ***small***	*-0.22 trivial*	*0.49* ***small***
HWI session one	Week 1	-	-	12.7 ± 0.5	9.5 ± 0.6	1.7 ± 0.7
	Week 2	-	-	11.7 ± 0.9	7.8 ± 2.1	1.5 ± 0.5
	Cohen's d	-	-	*-1.29* ***large***	*-0.82* ***large***	*-0.23 trivial*
HWI session two	Week 1	-	-	10.8 ± 1.1	6.3 ± 1.5	1.2 ± 0.5
	Week 2	-	-	10.7 ± 1.1	7.3 ± 2.1	1.7 ± 0.6
	Cohen's d	-	-	*-0.14 trivial*	*0.41* ***small***	*0.64* ***moderate***

12. Figures

Week	**Mon**	**Tue**	**Wed**	**Thu**	**Fri**	**Sat**	**Sun**	**Heat exposure *(mins)***
1	Pre-HA HRT *45 min*	HA1 *40 min*	HWI1 *40 min*	HA2 *45 min*	HWI2 *40 min*	*No heat exposure*		*210*
2	Mid-HA HRT *45 min*	HA1 *40 min*	HWI1 *40 min*	HWI2 *40 min*	HA2 *45 min*	*No heat exposure*		*210*
3	Post-HA HRT *45 min*	*Normal training*						*45*
4	*Normal training*							***Total 465 mins***
5				Decay HRT *45 min*				

Figure 1: Overview of the mixed-methods heat acclimation timeline, including weekly mins of heat exposure. HRT = Heat Response Test; HA= Exercise-based heat acclimation session (1 and 2); HWI1 = Passive heat acclimation session involving 40 min hot-water immersion (40 ºC); HWI2 = the same protocol as HWI1, performed immediately after an on-field training session.

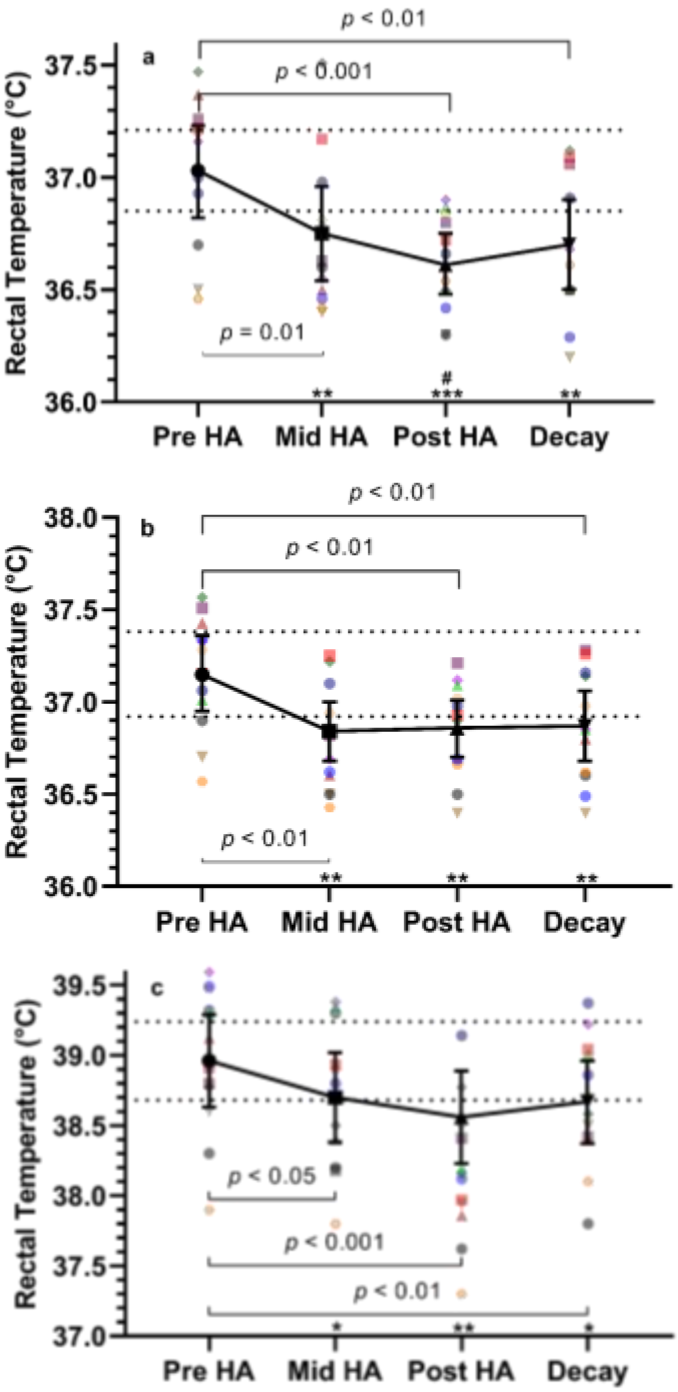

Figure 2: Resting (Figure 2a), Submaximal exercise (Figure 2b) and End exercise (Figure 2c) rectal temperature (°C) during Heat Response Tests Pre-HA, Mid-HA (5 days), Post-HA (10 days) and Decay (+16 days after Post-HA). The area between the dotted lines represents the smallest worthwhile change (± 0.3 °C of Pre-HA). Colour symbols represent individual data; black symbols represent mean ± 90% confidence limits. Where statistical significance occurred, it is indicated. Symbols above the x-axis represent standardised effect sizes (Cohen’s *d*) for the following comparisons: * = compared to Pre-HA; # = compared to Mid-HA. The number of

symbols represent the size of the effect; 1 = *small*, 2 = *moderate*, and 3 = *large*. HA = Heat Acclimation.

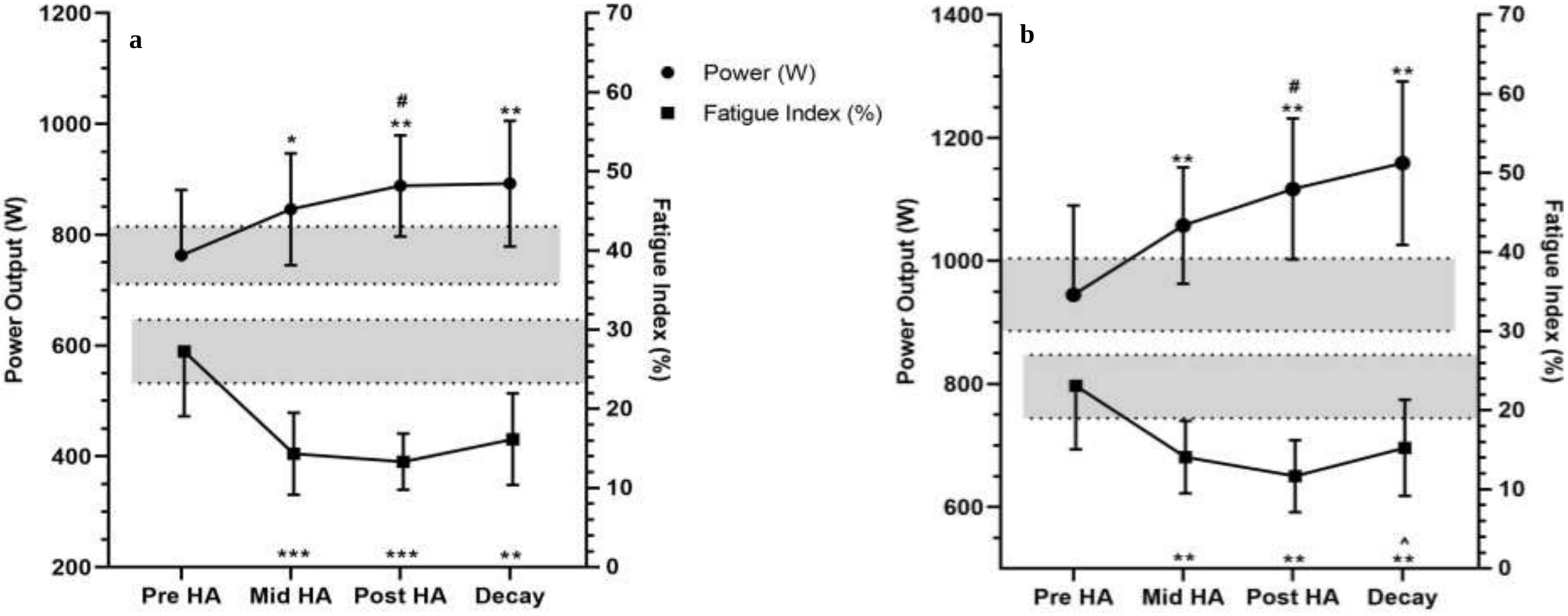

Figure 3: Mean (± 90% confidence limits) Power Output (W; closed circles) and Fatigue Index (%; closed squares) during Heat Response Tests Pre-HA, Mid-HA (5 days), Post-HA (10 days) and Decay (+16 days). Figure 3a represents average 6 s power; Figure 3b represents peak 6 s power. Shaded area represents the smallest worthwhile change for each variable, calculated as 1/3rd of the pre-test CV%. Symbols represent clear differences in standardised effect sizes (Cohen's *d*) for the following comparisons: * = compared to Pre-HA; # = compared to Mid-HA; ^ = compared to Post-HA. The number of symbols represent the size of the effect; 1 = small, 2 = moderate, and 3 = large; HA = Heat Acclimation.

13. Figure Captions

Figure 1: Overview of the mixed-methods heat acclimation (HA) timeline, including weekly mins of heat exposure. HRT = Heat Response Test; HA1 and HA2 = Exercise-based heat acclimation session; HWI1 = Passive heat acclimation session involving 40 min hot-water immersion (40 ºC); HWI2 = the same protocol as HWI1, performed immediately after an on field training session.

Figure 2: Resting (Figure 2a), Submaximal exercise (Figure 2b) and End exercise (Figure 2c) rectal temperature (°C) during Heat Response Tests Pre-HA, Mid-HA (5 days), Post-HA (10 days) and Decay (+16 days after Post-HA). The area between the dotted lines represents the smallest worthwhile change. Colour symbols represent individual data; black symbols represent mean ± 90% confidence limits. Where statistical significance occurred, it is indicated. Symbols above the x-axis represent standardised effect sizes (Cohen's *d*) for the following comparisons: * = compared to Pre-HA; # = compared to Mid-HA. The number of symbols represent the size of the effect; 1 = small, 2 = moderate, and 3 = large. HA = Heat Acclimation.

Figure 3: Mean (± 90% confidence limits) Power Output (W; closed circles) and Fatigue Index (%; closed squares) during Heat Response Tests Pre-HA, Mid-HA (5 days), Post-HA (10 days) and Decay (+16 days). Figure 3a represents average 6 s power; Figure 3b represents peak 6 s power. Shaded area represents the smallest worthwhile change for each variable, calculated as 1/3rd of the pre-test CV%. Symbols represent clear differences in standardised effect sizes (Cohen's *d*) for the following comparisons: * = compared to Pre-HA; # = compared to Mid-HA; ^ = compared to Post-HA. The number of symbols represent the size of the effect; 1 = *small*, 2 = *moderate*, and 3 = *large*; HA = Heat Acclimation.