Investigating passive heating as a heat acclimation strategy for endurance athletes

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Southern Cross University

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Investigating Passive Heating as a Heat Acclimation Strategy for Endurance Athletes

A thesis submitted for the degree

Master of Science

2019

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Declaration

I certify that the work presented in this thesis is, to the best of my knowledge and belief, original, except as acknowledged in the text, and that the material has not been submitted, either in whole or in part, for a degree at this or any other university. I acknowledge that I have read and understood the University's rules, requirements, procedures and policy relating to my higher degree research award and to my thesis. I certify that I have complied with the rules, requirements, procedures and policy of the University (as they may be from time to time).

Storme Louise Heathcote
ABSTRACT

The purpose of this thesis was to examine the effects of passive heating by hot-water immersion (HWI) as a heat acclimation (HA) strategy for endurance athletes residing in cool environments. Heat acclimation/acclimatization involves the repeated exposure to hot conditions to induce physiological and perceptual adaptations that contribute to preventing premature fatigue and reducing the risk of heat illness when exercising in the heat. Successful interventions may induce lower core temperature ($T_{core}$) and heart rate responses and increased sweat responses with subsequent heat exposure. Unlike active HA protocols (i.e., exercising in the heat), passive HA involves heat exposure at rest, and may also improve exercise performance in the heat, as reported by some studies. Therefore, more extensive passive HA research may be valuable to athletes preparing for events held in hot conditions. An acute study with a randomised cross-over design (Study 1) was conducted to determine the most effective out of three time delays (10 min, 1 hr or 8 hr) between exercise and HWI (~39°C; 30 min) for maximising thermoregulatory responses to heat (necessary for HA). A pilot study with a performance-matched parallel-group controlled trial design (Study 2) was also conducted to explore the effects of daily HWI (39°C; duration increased from 15 to 56 min) conducted at home in an ecologically valid 2-week training intervention. In Study 1, the highest delta ($\Delta$, post - pre) $T_{core}$ values accompanied HWI conducted 10 min after exercise, compared to other delays. Additionally, similar absolute $T_{core}$ values were noted with 10 min and 8 h delays, both higher than with a 1 h delay. In Study 2, “large effects” of differences between $\Delta$ values for measurements of resting and exercising heart rate, mean skin temperature change after exercise and thermal comfort between experimental and control groups were noted. Such differences were not large enough to reach the level of significance in a small sample pilot study. To maximise the heat load of this strategy, HWI should be conducted immediately after exercise.
If this is not possible, athletes should bath in the late afternoon in line with natural circadian elevation of core and skin temperatures. Finally, two weeks of normal training with post-exercise HWI (39°C) of increasing duration did not induce heat adaptations in recreationally-trained male runners, however, a larger sample sized study may be warranted, considering large effect sizes were noted for a number of physiological and perceptual responses in the current study.
STRUCTURE OF THE THESIS

The thesis consists of five chapters. Chapter 1 is an introduction to the thesis. It defines and provides the background for the concept of heat acclimation (HA). The relevance of HA for endurance athletes training/living in a cool environment is also highlighted. This chapter also outlines the aims, objectives, limitations and delimitations of the research.

Chapter 2 is a manuscript that reviews the literature covering numerous aspects of HA, with an emphasis on passive HA interventions that have been employed in research to date. Various protocols conducted to date are described, along with their physiological, perceptual and performance outcomes. This chapter identifies evidence that passive HA may be an effective alternate HA strategy for athletes training/living in a cool environment with regards to preparation for events scheduled to be held under hot environmental conditions when financial/logistical factors limit alternate active-based methods. Furthermore, areas that warrant future research are identified. This chapter was published in the journal *Frontiers in Physiology* in December 2018. In an attempt to address some of the gaps in the research that were highlighted during this narrative review, two studies were subsequently designed and are explained in chapters 3 and 4, respectively.

Chapter 3 is a manuscript written after conducting the first study for the thesis. This was an acute study that was designed to provide insight on how different intervals of time between exercise and hot-water immersion (HWI) could affect physiological and perceptual responses that may contribute to heat adaptation for the purpose of HA. The findings of this study were used when constructing the design for the second study of the thesis which is presented in chapter 4.

Chapter 4 is a manuscript written after conducting the second study for the thesis. This was a pilot study with a performance-matched parallel-group controlled trial that was designed
using the findings from the first acute study. Due to time and financial constraints, a pilot study was conducted in order to examine physiological and perceptual response outcomes that could be expected when a larger sample sized study is used, with a two-week training intervention that incorporated daily HWI conducted at home after training, with the intent of passively inducing heat adaptation for endurance runners training in a cool environment.

Chapter 5 provides the discussion and conclusions of the thesis. This chapter highlighted the major findings of the two studies, with suggestions for future research directions.

Appendix A is the ethical approval for the first study. Appendix B is the consent form that participants had to fill out before participating in the first study. Appendix C is a pre-exercise screening questionnaire designed and approved by Exercise & Sport Science Australia, that participants were required to fill in prior to participating in both studies. Appendix D is the thermal comfort scale used for both studies to measure thermal comfort at rest and during exercise. Appendix E in the thermal sensation scale that was used for both studies. Appendix F is the ethical approval for the second study. Appendix G is the consent form used for the second study. Appendix H is the bath protocol used for the second study, participants in the experimental group were given a laminated copy of this document for use during the training period of the study. Appendix I outlines how to safely conduct HWI and relevant safety precautions. This document was also laminated and given to the experimental group in Study 2. Appendix J is the training diary that participants were required to complete for the second study. Appendix K is a document containing current hot bath guidelines proposed (Zurawlew & Walsh, 2016). Appendices L to Y contain raw data from both studies.
PUBLICATIONS INCLUDED IN THE THESIS

I, Storme Heathcote, state that the manuscript appearing in Chapter 2 of the thesis has been peer-reviewed prior to publication in the academic journal ‘Frontiers in Physiology’. I warrant that I have obtained permission from the copyright owners to use my own published work in which the copyright is held by another party (e.g. publisher, co-author).


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Statement of contribution of others to the publication

The statements of contribution signed by co-authors can be found in Appendix Z. The candidate (Storme Heathcote) participated in all stages of the development of this paper. The candidate provided an overall contribution greater than that of any co-author. As primary author, the candidate conducted the literature search and produced the first draft of the manuscript which was revised with feedback from the co-authors.

Signed (candidate):

Signed (lead supervisor): Date: 12/02/2019
STATEMENT OF CONTRIBUTIONS

**Project Support**
Dr Lee Taylor of the ASPETAR Orthopaedic and Sports Medicine Hospital provided the temperature capsules used for both studies.

**Supervision**
All supervisors offered critical feedback for the production of the thesis.
All supervisors offered encouragement and were involved in the resolution of any issues related to their specific areas of expertise and were all extremely approachable and supportive.

Dr Christopher J. Stevens helped propose the concept of the thesis and the design the methodology for the studies, as well as arrange weekly meetings to discuss progress and resolve any issues pertaining to the research. Dr Stevens also helped source the temperature capsules for use in both studies and provided funding for the publishing of the manuscripts. Dr Stevens also helped with the pilot trials for both studies and helped design data and run sheets for the first study, as well as teach me how to use the e-Celsius telemetric capsule software. Dr Stevens contributed to the editing of all thesis chapters.

Professor Peter Hassmén helped with pilot testing for Study 2 and contributed to the editing of all thesis chapters and study designs. He also offered great advice on how to conduct presentations and was present for regular meetings.

Professor Shi Zhou helped with pilot testing for both studies and addressed questions pertaining to statistical models. Professor Zhou contributed to the editing of all thesis chapters and study design.

**External**
Dr Lee Taylor gave input for the editing of the second manuscript (Chapter 3) and also helped with ideas for the experimental design of the second study (Chapter 4). Dr Lee Taylor of the ASPETAR Orthopaedic and Sports Medicine Hospital provided the temperature capsules used for both studies.

Signed (lead supervisor):
ACKNOWLEDGEMENTS

This experience would not have been possible if Chris had not taken me on as an HDR student here at Southern Cross University. The offer to conduct heat acclimation research with endurance athletes was an opportunity I simply could not pass up and was well worth crossing the ocean for. I would therefore like to thank Chris immensely not only for this, but also for his unwavering support through all the pits and troughs that I was faced with during my research experience. Chris played a huge role in helping develop my confidence in my own ability by encouraging me to step outside my comfort zone, present at conferences and submit papers for publication.

I would also like to extend many thanks to my other supervisors, Peter and Shi who were a pleasure to work with. I am extremely grateful for the solid supervisory team I was privileged to have guide me, and would like to acknowledge them all for providing valuable critique and advice over various aspects of my thesis. Their vast range of expertise across different disciplines has enabled me to develop my thesis with a solid foundation.

The running of both ambitious studies would have been difficult to conduct without the dedicated help I received from the head lab technician, Erich Wittstock. I am extremely grateful for Erich’s dedication to the resolution of all technical issues with the utmost haste, which was critical for ensuring that I managed to collect all the data I needed (come hell or hot water) in time for completion between seasons!

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Of course, establishing a life here in Australia would not have been as easy without the support I received from my family. I would like to thank my parents for selflessly encouraging me to leave Africa, despite the difficult circumstances we had faced a year prior to my departure, where sadly we lost my precious brother, Scott, to his battle with cancer. I would like to dedicate this thesis to him. Additionally, I could never extend enough thanks to my family here in Australia, who welcomed me into their home during my initial stay and helped me settle into Australian life, and also to my adopted Australian family (the Collies), for their love and support.

In conclusion, I have learnt and incredible amount throughout the past two years and would like to thank everyone who took steps alongside me during the journey. I am definitely not the same 21-year old that landed her little African feet on Australian soil with no idea what lay ahead of me, and I look forward to the next chapter in my life.
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<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tbody>
<tr>
<td>°C</td>
<td>Degrees Celsius</td>
</tr>
<tr>
<td>%</td>
<td>Percentage</td>
</tr>
<tr>
<td>&gt;</td>
<td>Greater than</td>
</tr>
<tr>
<td>&lt;</td>
<td>Less than</td>
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<tr>
<td>+</td>
<td>Plus</td>
</tr>
<tr>
<td>min</td>
<td>Minute</td>
</tr>
<tr>
<td>↔</td>
<td>No change</td>
</tr>
<tr>
<td>Alb</td>
<td>Albumin</td>
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<tr>
<td>AM</td>
<td>Morning</td>
</tr>
<tr>
<td>BM</td>
<td>Body mass</td>
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<tr>
<td>bpm</td>
<td>Beats per minute</td>
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<tr>
<td>CARI</td>
<td>Central activation ratio index</td>
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<tr>
<td>CH</td>
<td>Controlled hyperthermia</td>
</tr>
<tr>
<td>CN</td>
<td>Control</td>
</tr>
<tr>
<td>d</td>
<td>Day(s)</td>
</tr>
<tr>
<td>ex</td>
<td>Exercise</td>
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<tr>
<td>Exp</td>
<td>Experiment</td>
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<tr>
<td>F</td>
<td>Female</td>
</tr>
<tr>
<td>HA</td>
<td>Heat acclimation/acclimatization</td>
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<tr>
<td>Abbreviation</td>
<td>Definition</td>
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<tr>
<td>--------------</td>
<td>-----------------------------------------------</td>
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<tr>
<td>RER</td>
<td>Respiratory exchange ratio</td>
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<tr>
<td>RH</td>
<td>Relative humidity</td>
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<tr>
<td>RLBM</td>
<td>Relative loss of body mass</td>
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<tr>
<td>RPE</td>
<td>Rating of perceived exertion</td>
</tr>
<tr>
<td>S</td>
<td>Sweat</td>
</tr>
<tr>
<td>S_{Lat}</td>
<td>Sweating latency</td>
</tr>
<tr>
<td>S_{Na}</td>
<td>Sweat Sodium concentration</td>
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<tr>
<td>SC</td>
<td>Sweating capacity</td>
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<tr>
<td>SD</td>
<td>Standard deviation</td>
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<td>SL</td>
<td>Sweat loss</td>
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<td>Sweat output</td>
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<td>SR</td>
<td>Sweat rate</td>
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<tr>
<td>T_{core}</td>
<td>Core body temperature</td>
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<tr>
<td>T_{es}</td>
<td>Oesophageal temperature</td>
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<tr>
<td>T_{re}</td>
<td>Rectal temperature</td>
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<tr>
<td>T_{sk}</td>
<td>Skin temperature</td>
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<tr>
<td>T_{tymp}</td>
<td>Tympanic temperature</td>
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<tr>
<td>TBV</td>
<td>Total blood volume</td>
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<tr>
<td>TC</td>
<td>Thermal comfort</td>
</tr>
<tr>
<td>Temp</td>
<td>Temperature</td>
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<tr>
<td>T_{ms}</td>
<td>Mean skin temperature</td>
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<td>TP</td>
<td>Total protein</td>
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<tr>
<td>Abbreviation</td>
<td>Description</td>
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</tr>
<tr>
<td>TS</td>
<td>Thermal sensation</td>
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<tr>
<td>TT</td>
<td>Time trial</td>
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<tr>
<td>TTE</td>
<td>Time to exhaustion</td>
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<tr>
<td>VO₂</td>
<td>Oxygen consumption</td>
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<tr>
<td>WVP</td>
<td>Water vapour pressure</td>
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<td>WT</td>
<td>Water tank</td>
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CHAPTER 1
INTRODUCTION

1.0 Background

Major sporting events including the Summer Olympics, the FIFA World Cup, and the Tour de France are often held under hot ambient conditions during the hottest part of the day in summer periods (Casadio, Kilding, Cotter, & Laursen, 2016; Racinais, Alonso, Coutts, Flouris, Girard, Gonzalez-Alonso, et al., 2015; Wendt, Van Loon, & Van Marken Lichtenbelt, 2007), which may negatively influence performance and pose a risk to athlete safety (Chalmers, Esterman, Eston, Bowering, & Norton, 2014). Notably, in comparison to those who competed in cooler temperate conditions (<25 °C), performance decrements of ~3 % in hot conditions (>25 °C) were identified in elite endurance athletes who competed in International Association of Athletics Federations (IAAF) World Championships (1999-2011) (Guy, Deakin, Edwards, Miller, & Pyne, 2015). HA is the principal counter-measure to improve endurance performance in the heat, and involves repeated exposure to hot conditions either during exercise (active HA), or rest (passive HA), to elicit physiological adaptations which ameliorate heat loss mechanisms (Taylor, 2006). Heat acclimatization involves natural heat exposure (exercise outdoors), while heat acclimation entails exposure to heat produced artificially/in a laboratory setting (Périard, Racinais, & Sawka, 2015). Notably, conducting HA sessions in a natural outdoor setting enables highly specific response outcomes, since it involves exposure to environmental conditions similar to those expected in competition (Périard, Travers, Racinais, & Sawka, 2016). The passive strategies explored to date include resting in heat chambers, saunas or hot-
water immersion (HWI). Some of the protocols have included exercise beforehand (Scoon, Hopkins, Mayhew, & Cotter, 2007; Stanley, Halliday, D'Auria, Buchheit, & Leicht, 2015; Zurawlew, Walsh, Fortes, & Potter, 2016) and others have included the use of vapour-impermeable suits (Beaudin, Clegg, Walsh, & White, 2009; Fox, Goldsmith, Hampton, & Lewis, 1964).

Research has identified that the stimulation of sweating and heightened core and skin temperature are important stimuli for inducing heat adaptations (Regan, Macfarlane, & Taylor, 1996; Wendt et al., 2007), and that applying the heat stress after exercise may lead to a larger thermoregulatory-adaptive response than application of heat stress alone, since it can elicit larger rises in core temperature, a major contributing factor to heat adaptation (Casadio et al., 2016). Importantly, passive strategies have demonstrated improvements in athletic performance in some cases (in both club-level (sub elite) runners and untrained runners, respectively) (Scoon et al., 2007; Zurawlew et al., 2016), and may present an alternative method of preparation for those training during winter months for competitions scheduled in hot environments, if they lack the funds to travel or if they do not have access to a heat chamber. Notably, performance data following passive heating in elite level runners is limited and may be beneficial for practitioners in this particular field.

Of the few studies that have made use of post-exercise heat stress for HA, the heat-stress has been applied immediately after the exercise (Scoon et al., 2007; Stanley et al., 2015; Zurawlew & Walsh, 2018; Zurawlew et al., 2016). However, it is unknown whether other time delays between exercise and immersion (i.e. what would happen in an athlete’s normal training environment) would be as effective for maximising the heat load that could stimulate heat adaptations, when using such a strategy. Knowledge obtained from comparing the effect of different intervals between exercise and heat application may have practical value for athletes/coaches wanting to implement optimal HA strategies into training programs in terms of
structuring the timing and location of training sessions (i.e. so they finish close to HWI facilities).

Insight on the physiological and thermoregulatory changes that occur during post-exercise HWI is important when considering the implications on the health of the athletes, since exposure to heat stress and possible limitations in sweating capacity when submerged in water may place substantial strain on the cardiovascular and thermoregulatory systems (Kenney, DeGroot, & Alexander, 2004). More specifically, the disruption of thermal balance that may occur consequent of the limitation that submersion places on evaporative heat loss mechanisms, could result in the continuous rise in $T_{core}$, which should be avoided and therefore investigated further.

Additively, the perception of heat can contribute to premature fatigue and negatively influence performance (Tyler, Reeve, Hodges, & Cheung, 2016), yet few studies have reported the perceptual responses following such interventions, leaving gaps for more research in this area.

1.1 Significance of the research

Effective HA strategies can improve endurance performance and reduce the risks of heat illnesses when competing in hot conditions (Casadio et al., 2016). However, most strategies may present limitations for athletes living in a cold environment and training in winter, such as; a) the expense that accompanies travel to a naturally hot environment; b) the interference between specific training/tapering sessions if exercise in the heat is warranted, and c) the logistics around gaining access to a heat chamber.

Study 1 was conducted in controlled laboratory conditions to determine the impact of waiting different lengths of time between finishing an exercise session and commencing a bath
on the thermoregulatory and heart rate responses during submersion for post-exercise HWI. The purpose of this was to be able to provide athletes with guidelines on how quickly to immerse when implementing such a protocol into their training (and subsequently, the consequences of delaying immersion). The aim of Study 2 was to determine if the addition of HWI to a 2-week endurance training program could induce HA adaptations when athletes were expected to train outdoors and bath in a normal training scenario (outside the lab). Knowledge obtained from such a study could contribute to specific recommendations for to athletes and coaches regarding any effects that can be expected with subsequent exercise performance in the heat. This research has direct outcomes for endurance athletes, as it is based on effective strategies that can be applied in the field, are cost effective, and can be easily incorporated into a training program.

1.2 Statement of the problem

Successful athletic performance under hot ambient conditions requires HA. The adaptations can be induced by several strategies and contribute to the prevention of premature fatigue, reduce the risks of heat illness, improve thermoregulation and attenuate physiological strain when exercising in hot conditions (Casadio et al., 2016; Périard et al., 2015). Adequate preparation for performance in the heat can be difficult for athletes living in places where temperatures do not reach the levels elicited by the environments that they aim to compete in, especially during the winter months. It can be difficult for these athletes to prepare sufficiently if they do not have access to a heat chamber with the capacity to simulate the predicted environmental conditions of competition, or if they prefer training outdoors. To date, research has focussed heavily on active HA strategies which require exercising in a hot environment to achieve heat adaptations, and less on the passive strategies which may be a practical alternative HA strategy for athletes. Furthermore, it is unclear how such passive strategies affect endurance
performance, which is the most important outcome for athletes, and research to date has not extensively examined the perceptual responses accompanying such strategies, with most emphasis being based on the physiological responses to passive heating. The current literature has demonstrated that lowered thermal perception can have a powerful effect on exercise, and that along with thermal state, thermal sensation can also influence endurance exercise performance in the heat (Cheung, 2010; Stevens et al., 2016), and therefore information regarding the perceptual responses to passive HA strategies is warranted. Consequently, the current research aims to address the gaps in knowledge that remain regarding the extent of various adaptations accompanying passive HA strategies (Tyler et al., 2016).

1.3 Purposes of the research

The purposes of the research presented in this thesis were to conduct two studies that explored practical aspects of implementing HWI in the field. More specifically, the intention was to advance the knowledge regarding HWI as a passive HA strategy for endurance athletes. Physiological and perceptual responses were analysed. The second study was a pilot training study that was moulded after information gained from the first study which explored appropriate and effective time lapses between exercise and HWI, part of a passive HA protocol. Such insight could benefit athletes and coaches looking to implement practical HA protocols into training programs.

More specifically the purposes of the thesis were as below.

1. To describe the acute physiological and perceptual responses to post-exercise HWI. Such responses included: body temperatures, sweating, heart rate and the perception of thermal sensation and comfort.
2. To examine the potential cost of delays, that are likely to occur between training and HWI conducted in an ecologically valid training scenario. More specifically, to determine the most effective out of three chosen time intervals between exercise and HWI to maximise the thermoregulatory response to the heat and to address the following question:

Could bathing an hour after the exercise session or in the afternoon of the same day be as effective as immediate hot bath following training session, in terms of raising core temperature to stimulate heat adaptations?

3. To assess the effect of an intervention that involved two weeks of daily HWI in combination with normal training to prepare endurance athletes for competition in the heat in a pilot study. Hot baths following exercise in cool conditions were prescribed in a training intervention and the results were compared with a group who did the same training without HWI after exercise (control group). Perceptual and physiological responses at rest and during exercise in hot conditions were analysed to give an indication of response outcomes that may occur in a larger scale study using such a protocol.

1.4 Research hypotheses

The following hypotheses were tested in the research.

**Study 1:** Immediate post-exercise HWI at 38.5-39°C would be more effective to stimulate heat adaptation responses by eliciting larger sweat responses, higher heart rate responses and a heightened core temperature for longer, in comparison to waiting an hour after a training session or performing HWI 8 h later on the same day.

**Study 2:** In comparison to a control group, participants who added HWI to their training program would experience physiological (expansion of plasma volume, lower resting and exercising core temperature and heart rate, and increased sweat rate) and perceptual (report
lower ratings of thermal sensation and improved thermal comfort ratings) markers of HA in post intervention testing.

1.5 Delimitations of the research

Participants were specifically recreational male runners (who had performed a 10 km run in <50 min, 6 months prior to the study, and were currently training 3-4 times a week). The inclusion of males only removed the effects of fluctuations in core temperature due to menstrual cycle patterns presented in women (Mee, Peters, Doust, & Maxwell, 2017; Wendt et al., 2007). Considering that weather variability, temperatures experienced and how cool conditions are defined differs across the globe, the scope of this research is most applicable to endurance athletes residing in places where average temperatures range between 7°C and 16°C (especially during the HA phase of their periodisation plan), due to the fact that it took into account environmental conditions experienced during the winter months in the state of New South Wales, Australia, where the average minimum and maximum temperatures during the winter months are 7°C and 16°C, respectively (Weatherzone.com.au). Therefore this research may not be as applicable to athletes living in regions with very different climates. In the second study no thermoneutral bath used as a control. The reason for this was that the aim of this particular study was to compare the use of post-exercise HWI against the current practice of athletes (i.e. no water immersion), therefore, if baths had been implemented in the control condition, the primary research question would not have been addressed and there would be no practical outcome for athletes, reducing the impact of this research. Lastly, this research focused on methods of achieving HA for endurance athletes and may not be as applicable to athletes who do not typically compete in endurance events, such as sprinters.
1.6 Limitations of the research

Both studies were limited to the number of participants who could complete the protocols within the time available when accounting for the fluctuations in ambient temperatures that accompanied seasonal weather changes, as well as the requirement of trained athletes.

1.6.1 Study 1

A limitation of this study was that food/caloric intake prior to exercise and HWI was not controlled for between subjects, which might have an effect on the core body temperature. Subjects were also not retained in the lab during the 8 h interval, and therefore apart from having given the instruction to avoid any strenuous exercise/activity, their activity during this period was not strictly controlled.

1.6.2 Study 2

It would have been preferable to have the researcher supervise the training sessions, as well as HWI’s to quantify the heat load of training sessions for participants, however time and resources did not enable the researcher to do this. Technical issues were also experienced during performance tests, leading to a loss of some performance-related data. Significant differences in the responses to the intervention might not be detected using traditional statistical analysis due to the relatively small sample size in the pilot study.
CHAPTER 2

REVIEW OF THE LITERATURE

The following chapter was published in the Journal ‘Frontiers in Physiology’ in December 2018 (Heathcote, Hassmén, Zhou, & Stevens, 2018).

Passive Heating: Reviewing Practical Heat Acclimation Strategies for Endurance Athletes

Abstract

Heat acclimation protocols—both active and passive—have been employed by athletes in an effort to attenuate the detrimental effects of heat stress on physical capacities and sports performance. Active strategies have been extensively reviewed, but have various practical and economic limitations. The purpose of this narrative review was therefore to provide an overview of the passive strategies that have received less attention, yet may be more practical or economically viable; recommendations for athletes are also provided. With a systematic search of the relevant databases ending in June 2018, 16 articles on passive heat acclimation that met the inclusion criteria were included in the review. The review highlighted that passive heat acclimation strategies can successfully induce heat adaptations, evident by reports of improved exercise performance, thermoregulatory, cardiovascular, and perceptual responses accompanying such interventions. Based on the review it is apparent that the use of sauna, hot-water immersion and environmental chambers may be used to provide heat stress under passive conditions, for the purpose of acclimation. To maximize the thermoregulatory-adaptive responses, exercise bouts should be employed prior to passive heat stress, rather than passive heating alone, with a minimal delay between exercise and the application of heat stress. Heating bouts should have a minimum duration of 30 min per session and be employed on consecutive
days, when possible, with a minimum of 6–7 exposures to induce adaptation. This review identified that information regarding the magnitude of performance changes that can occur, as well as the perceptual responses to passive heating protocols is limited. Future research should investigate the use of passive heat exposures before and/or after repeated heat training sessions, to assess if a further boost to heat adaptation can be achieved with this strategy.

**Key words:** Passive heating, heat acclimation, hot-water immersion, thermal adaptation, hot bath, sauna, athletes

### 2.0 Introduction

A hot (30–40°C) and humid (>60%) environment can pose a significant thermoregulatory and perceptual challenge for an endurance athlete, while also elevating their risk of experiencing heat illnesses, especially in individuals unaccustomed to such conditions (Casadio et al., 2016; Racinais, Wilson, Gaoua, & Périard, 2017). Athletes may also be at increased risk of dehydration when performing in the heat due to the thermoregulatory adjustments that allow for increased heat dissipation, for example, enhanced sweat rate (Racinais, Alonso, Coutts, Flouris, Girard, González-Alonso, et al., 2015). As such, exercise performance may be compromised when conducted in hot ambient conditions, while heat acclimatization (exposure to natural outdoor heat) or acclimation training (exposure to simulated environmental heat; both abbreviated to HA) can attenuate the performance decrements (Costa, Crockford, Moore, & Walsh, 2014; Racinais, Alonso, Coutts, Flouris, Girard, González-Alonso, et al., 2015). Effective HA protocols result in numerous physiological adaptations, e.g., decreasing exercising and resting core temperature and heart rate, plasma volume expansion, earlier onset of sweating and higher sweat output. These adaptations contribute to improvements in cardiovascular stability, sweating capacity and
thermoregulation, processes that work in combination to improve physical capacities and sports performance in the heat (Costa et al., 2014; Garrett, Rehrer, & Patterson, 2011; Périard et al., 2015). To date, HA has been achieved via both active strategies, using various modes of exercise outdoors or in a heat chamber (Lorenzo, Halliwill, Sawka, & Minson, 2010), and passive strategies which do not require exercise in the heat, but use heat exposures during rest after training in cool/temperate conditions (Zurawlew & Walsh, 2018).

There are three most commonly used active strategies explored within the literature, including (1) thermal clamping, commonly referred to as the “controlled hyperthermia technique”, where a target core temperature is maintained; (2) exercising at a constant predetermined workload in hot and/or humid conditions, referred to as the “constant work rate technique”; and (3) the “self-regulated technique”, where the individual selects their own work rate during exercise heat exposure (Périard et al., 2015; Taylor, 2006). The duration of these protocols has been categorised as short term (<7 days), medium term (8-14 days) and long term (>14 days) (Garrett et al., 2011). Short term protocols are more convenient for athletes with heavy training regimens (Zurawlew et al., 2016), while medium term protocols elicit greater physiological adaptations and performance improvements (Guy et al., 2015). However, the long term regimes offer the greatest adaptations (Tyler et al., 2016). Despite the absence of a clear consensus on the precise session duration per heat exposure (Daanen, Racinais, & Periard, 2018), current recommendations state that in order to achieve the physiological and performance benefits, athletes should train on consecutive days, across 1-2 weeks and begin preparations at least 2-weeks before the major event prior to tapering (Daanen et al., 2018; Périard et al., 2015; Racinais, Alonso, Coutts, Flouris, Girard, Gonzalez-Alonso, et al., 2015; Tyler et al., 2016). Furthermore, protocols can be made more effective by using the same exercise mode as employed in competition, mimicking competition ambient temperatures, ensuring specific humidity exposure, considering individual differences in athletes’ responses.
to HA, as well as adjusting intensity according to the training phase and time available to the individual (Casadio et al., 2016; Guy et al., 2015; Taylor, 2006; Tyler et al., 2016).

The active strategies have been widely used and extensively reviewed in the literature (Tyler et al., 2016). For athletes residing in cool/temperate environments, the use of these active protocols would require travel to a hot outdoor environment or exercise in a heat chamber, which may be logistically difficult and impractical (Casadio et al., 2016). Such methods may also interfere with both normal training and/or specific taper sessions, perhaps making them dangerous to an athlete’s training outcome. In contrast, the use of passive strategies may be more practical and cost effective, especially for those living in a cool climate. The main stimulus for individuals to experience heat adaptation, is repeated episodes of elevated core temperature, therefore passive HA interventions may present an effective alternative to traditional active-based strategies, since repeated physical exercise in the heat may not be necessary for HA (Brazaitis & Skurvydas, 2010; Regan et al., 1996). This review will summarise the current passive heating literature, including performance, physiological and perceptual adaptations that can be induced, and provide recommendations for athletes.

2.1 Passive heat acclimation strategies

2.1.1 Literature search methods and retrieval

This review was based on searches conducted in relevant databases (Medline, Science Direct Freedom Collection, Highwire Press American Physiological Society, SAGE journals, ProQuest Science Journals, SPORTDiscus and Google Scholar) ending in June 2018, in the areas of HA strategies and the various methods that have been used/ tested, the resultant benefits for athletes and the responses that occur following HA. Database search terms included “heat acclimation,” “heat-acclimatization,” “thermal adaptation,” “hot-water immersion,” “hot
bath,” “sauna,” “heat chamber,” “exercise,” “performance,” “perception,” “heat stress,” and their various truncations. Inclusion criteria stipulated that articles were written in English and investigated humans. A total of 16 articles met these criteria, which are summarised in Table 1 which presents sauna study data first, followed by heat chamber study data and finally HWI study data.
Table 1: Summary of the performance, physiological and perceptual responses to passive strategies for heat acclimation.

<table>
<thead>
<tr>
<th>Investigation</th>
<th>Environmental conditions</th>
<th>Subjects</th>
<th>Heat acclimation method</th>
<th>Performance response</th>
<th>Physiological and perceptual responses</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stanley et al., 2015</td>
<td>Not reported by authors</td>
<td>Number: 7 (no CN) Sex: Male Training status: well-trained cyclists</td>
<td>Post-exercise sauna bathing (30min) Conditions: 87°C, 11% RH (sauna) Duration: 35 days.</td>
<td>↔ Peak PO in a graded cycling test, starting at 175 W, increasing by 25 W/min</td>
<td>↑PV and HR(ex) ↓HRR60s ↔ HR(Peak) ↓HR(wake) (Trivial to moderate)</td>
</tr>
<tr>
<td>Scoon et al., 2007</td>
<td>Not reported by authors</td>
<td>Number: 6 (same group was CN) Sex: Male Training status: competitive distance runners/ triathletes</td>
<td>Post-running sauna bathing (31 min) Conditions: 89.9°C (sauna) (12 sessions) Duration: 21 d (alternate).</td>
<td>↑TTE in a treadmill run at constant speed (runner’s best speed over 5 km) (+32%)</td>
<td>↑PV, RCV, BM and TBV</td>
</tr>
<tr>
<td>Leppaluoto et al., 1986</td>
<td>Not reported by authors</td>
<td>Number: 10 Sex: Male</td>
<td>Finnish sauna dry heat exposure (60 min) twice daily Conditions: 80°C (sauna) Duration: 7 d.</td>
<td></td>
<td>↓HR(rest) and T(rest) ↓Serum K, Na and Fe ↔ ECG recordings</td>
</tr>
<tr>
<td>Shido et al., 1999</td>
<td>Exp1: 27°C, 50% RH (24 h) Exp2: 28°C, 40% RH (1 h), 42.0°C HWI after 30 min (legs) repeated pm.</td>
<td>Number: 6 in each Exp Sex: Male and Female</td>
<td>Seated rest in HC (4 h) Conditions: 46.0°C, 20% RH (HC) Duration: 9-10 d. CN measures: Exp1- Before or after HA, Exp2- All before HA</td>
<td>Exp1: ↓T(rest) after HA ↔ T(sleep), Tsk(rest) and HR(rest) Exp2: ↓T(rest) (pm) ↔ Tsk(rest), HR and BP ↓S(Lat) after HA (pm test) ↑S(Lat) (for CN, pm compared to am test) ↓mean T at S onset (pm) ↔Plasma Na, K, Cl, TP, Alb</td>
<td></td>
</tr>
<tr>
<td>Beaudin et al., 2009</td>
<td>HA: 23.78°C, 29.42% RH CN: 24.2°C, 33.5% RH</td>
<td>Number: 12 Sex: Male</td>
<td>CH, seated in HC with vapour-impermeable suit (2 h) Conditions: 50°C, 20% RH (HC) Duration: 10 d. Subjects: 12M (8HA, 4CN)</td>
<td>↓T(es) (rest) and mean T(es) threshold for S onset ↔Tsk(rest) ↑PV and S (for given T(es))</td>
<td></td>
</tr>
<tr>
<td>Study</td>
<td>Details</td>
<td>Number</td>
<td>Sex</td>
<td>Training status</td>
<td>Conditions</td>
</tr>
<tr>
<td>-------------------------------------------</td>
<td>------------------------------------------------------------------------</td>
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<tr>
<td>Fox et al., 1964</td>
<td>HA groups: 38.5°C (CH) Arms were not immersed, plastic bags enclosed both arms</td>
<td>12</td>
<td>Male</td>
<td>army volunteers</td>
<td>37.9°C (CH and Room), 43°C, 100% RH (air stream), WT temps at 13°C (G1), 37°C (G2), 43°C (G3)</td>
</tr>
<tr>
<td>Henane et al., 1973</td>
<td>Heat sessions had varying stages with maximum temp of 55°C</td>
<td>9 (no CN)</td>
<td>Male</td>
<td>fit, young</td>
<td>48-50°C, 50% RH</td>
</tr>
<tr>
<td>Racinais et al., 2017</td>
<td>HYP, 44-50°C, 50% RH CON, 24°C, 40% RH</td>
<td>14</td>
<td>Male</td>
<td></td>
<td>33°C, 22% RH</td>
</tr>
<tr>
<td>Pallubinsky et al., 2017</td>
<td>Heat exposure with a temperature ramp 29°C for 60 min 37.5°C for 90 min 26 ± 7% RH</td>
<td>11</td>
<td>Male</td>
<td>healthy</td>
<td>33°C, 22% RH</td>
</tr>
<tr>
<td>Zurawlew et al., 2016</td>
<td>Temperate: 18°C, 40% RH Hot: 33°C, 40% RH</td>
<td>17</td>
<td>Male</td>
<td>active</td>
<td>18°C (Run), 40°C (HWI) to neck</td>
</tr>
<tr>
<td>Zurawlew et al., 2018</td>
<td>33°C, 40% RH</td>
<td>10</td>
<td>Male</td>
<td></td>
<td>20°C (Run), 40°C (HWI) to neck</td>
</tr>
<tr>
<td>Study</td>
<td>Condition</td>
<td>Number</td>
<td>Sex</td>
<td>Training status</td>
<td>Procedures</td>
</tr>
<tr>
<td>-------------------------------</td>
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<td>-----------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Brazaitis et al., 2010</td>
<td>23°C, 40% RH</td>
<td>25</td>
<td>Male and Female</td>
<td>Healthy</td>
<td>Passive lower body heating via 7HWI (45 min to waist)</td>
</tr>
<tr>
<td>Kanikowska et al., 2012</td>
<td>26°C, 50% RH (HC), rest 30 min then leg HWI (42°C) for 30 min</td>
<td>6</td>
<td>Male</td>
<td>Healthy</td>
<td>CH at 37.5°C, HWI to chest (10 min), HC with blanket (90 min)</td>
</tr>
<tr>
<td>Allan et al., 1971</td>
<td>40°C (Bath) maintaining T&lt;sub&gt;(tymp)&lt;/sub&gt; between 37.6 and 38.6°C</td>
<td>3</td>
<td>NR</td>
<td>Healthy</td>
<td>Daily HWI (60 min) maintaining T&lt;sub&gt;core&lt;/sub&gt; ≥38°C (bath)</td>
</tr>
<tr>
<td>Shin et al., 2013</td>
<td>Not reported by authors</td>
<td>9</td>
<td>Male</td>
<td>Healthy</td>
<td>Half body HWI (30 min) for 10 sessions in a HC</td>
</tr>
<tr>
<td>Bonner et al., 1976</td>
<td>Seated rest in 48°C db, 33°C wb, 36% RH (HC) 1.5 m/s&lt;sup&gt;−1&lt;/sup&gt; air movement for 155 min, then cycling at 50 rpm for 30 min</td>
<td>5</td>
<td>Male</td>
<td>Healthy</td>
<td>Hot bath in a HC, with CH at 38.5 ± 0.2°C for 60 min</td>
</tr>
</tbody>
</table>

↔, no change; Alb, Albumin; am, morning; BM, body mass; bpm, beats per minute; CH, controlled hyperthermia; CN, control; CON, normothermic state; ; d, day(s); db, dry bulb thermometer; ex, exercise; Exp, experiment; HA, heat acclimated group; HC, heat chamber; Hct, haematocrit; HR, heart rate; h, hour(s); HRe<sub>ex</sub>, Heart rate during submaximal exercise; HR60s, Heart rate recovery at 60s post-exercise; HT, heat transfer; HWI, hot water immersion; HYP, hyperthermic state; MR, metabolic rate; MVC, maximal voluntary contraction; NR, not reported; Perf, performance; PhS, physiological strain; PhS<sub>(ex)</sub>, physiological strain during submaximal exercise; pm, afternoon; PMHA, passive mile heat acclimation; POMS, profile of mood states; PP, plasma protein; RCV, red cell volume; RER, respiratory exchange ratio; RH, relative humidity; RLBM, relative loss of body mass; RPE, rating of perceived exertion; RPE<sub>(ex)</sub>, rating of perceived exertion during submaximal exercise; rpm, revolutions per minute; S, sweat; S(Lat), sweat latency; S[Na], sweat Sodium concentration; SC, sweat capacity; SL, sweat loss; SO, sweat output; SR, sweat rate; Tcore, core body temperature; T(es), esophageal temperature; Tre, rectal temperature; Tre<sub>(ex)</sub>, rectal temperature during submaximal exercise; Tsk, skin temperature; T(tymp), tympanic temperature; TBV, total blood volume; TC, thermal comfort; Temp, temperature; TP, total protein; TS, thermal sensation; TT, time-trial; TTE, time to exhaustion; VO₂, oxygen consumption; W, Watts; wb, wet bulb thermometer; WBSR, whole body sweat rate; WT, water tank; WVP, water vapour pressure.
2.1.2 Protocols

The passive HA strategies used within the literature to date have included resting in a heat chamber (Beaudin et al., 2009; Henane & Valatx, 1973), sauna (Leppaluoto, Tuominen, Vaananen, Karpakka, & Vuori, 1986; Scoon et al., 2007; Stanley et al., 2015), or hot bath (Allan & Wilson, 1971; Brazaitis & Skurvydas, 2010; Zurawlew & Walsh, 2018; Zurawlew et al., 2016). Some protocols had included exercise beforehand (Scoon et al., 2007; Stanley et al., 2015; Zurawlew & Walsh, 2018; Zurawlew et al., 2016) and others had not included any exercise (Allan & Wilson, 1971; Beaudin et al., 2009; Brazaitis & Skurvydas, 2010; Fox et al., 1964; Henane & Valatx, 1973; Kanikowska et al., 2012; Leppaluoto et al., 1986; Shido, Sugimoto, Tanabe, & Sakurada, 1999).

Heat chamber protocols ranged from 9-15 days in duration, some of which included the use of vapour impermeable suits (Beaudin et al., 2009; Fox et al., 1964) or blankets (Kanikowska et al., 2012) to reduce sweat evaporation, heat loss and/or promote achievement of a target core temperature. Sauna (i.e., Finnish bath) protocols typically entailed exposure to dry heat (with a relative humidity ranging between 10 and 20%) and high temperatures elicited by an electric heater with hot rocks in a wooden floored and panelled room (Hannuksela & Ellahham, 2001) either once (Stanley et al., 2015), or twice daily (Leppaluoto et al., 1986), by itself (Shido et al., 1999) or following exercise (Scoon et al., 2007), for a period of anywhere between 7 and 21 days. Sauna suits have also been used to replicate sauna conditions (Mee et al., 2017).

Hot-water immersion (HWI) protocols used hot baths to the level of the neck (Allan & Wilson, 1971; Zurawlew & Walsh, 2018; Zurawlew et al., 2016), chest (Kanikowska et al., 2012) or waist (Brazaitis & Skurvydas, 2010) to maintain a specific body temperature typically over a set duration, anywhere from 6 to 21 days, consecutively (Zurawlew & Walsh, 2018;
Zurawlew et al., 2016), or on every other day (Brazaitis & Skurvydas, 2010). The HWI’s were either carried out following exercise at a controlled workload in a laboratory (temperate conditions) (Zurawlew & Walsh, 2018; Zurawlew et al., 2016), preceding rest in a heat chamber (Kanikowska et al., 2012), or with no other added intervention (Allan & Wilson, 1971; Brazaitis & Skurvydas, 2010; Shin, Lee, Min, & Yang, 2013). Water temperatures were controlled by adding or removing water, and when the controlled hyperthermia technique was used, the target core temperature was kept constant by adjusting the degree of immersion in the water (Allan & Wilson, 1971). The duration of heat stimulus per session for the different types of protocols were typically around 2-4 h for heat chambers (Beaudin et al., 2009; Fox et al., 1964; Henane & Valatx, 1973; Shido et al., 1999), 30-60 min for saunas (Leppaluoto et al., 1986; Scoon et al., 2007; Stanley et al., 2015) and around 30-60 min for HWI (Allan & Wilson, 1971; Brazaitis & Skurvydas, 2010; Kanikowska et al., 2012; Zurawlew et al., 2016). The temperatures used were generally the lowest in the HWI protocols (water temp: ~40°C), followed by heat chamber protocols (ambient temp: ~50°C), with the highest ambient temperatures typically being provided by saunas (ambient temp: ~80°C). Following an HA program, newly acclimated individuals typically displayed several performance, perceptual and physiological adaptations.

2.1.3 Performance responses

Within the HA literature, performance responses have been measured by an improvement in a progressive exercise test (i.e., VO$_{2\text{max}}$ and/or peak power test), exercise duration at a fixed workload (i.e., time to exhaustion), or performance time or power output over a set exercise duration or distance (i.e., time-trial). A 32% improvement in running time to exhaustion (at the runners’ best speed over 5 km) was observed after 12 sauna bathing sessions at 90°C for 30 min following exercise training bouts in a cool environment, across a 21-day protocol (Scoon et al., 2007). This was reported to be equivalent to a 1.9% improvement
in an endurance-based time trial (Scoon et al., 2007). In contrast, no ergogenic effect was demonstrated in peak power output during a graded cycling test to exhaustion following 10 x 30 min sauna exposures (87°C, 11% RH) following or during the warm down of a training session, despite improved physiological markers of heat adaptation (Stanley et al., 2015). Both protocols used similar duration, number and intensity of sauna exposures following exercise, as well as male subjects with similar training status. However, the differences described by Stanley and colleagues may be explained by the fact that athletes completed the second maximal cycling performance test the week following the monitoring period (~15 days after the sauna period). Some adaptations may have been lost during the period prior to the maximal performance test, since research has highlighted that HA benefits can be lost over time without continued repeated heat exposure, with 1 day of acclimation potentially lost with every 2 days lacking heat stress exposure (Daanen et al., 2018). Furthermore, both studies used seven or less participants, and did not use the same type of performance test.

In the only study performed to date to measure endurance performance in an externally valid time trial performance test, the use of post-exercise HWI to the level of the neck improved endurance performance in a hot environment (Zurawlew et al. (2016). The authors reported a 4.9% improvement in a 5 km treadmill time-trial test conducted in hot (33°C) conditions after a 6-day protocol consisting of daily 40 min HWI exposures at 40°C following training, which comprised of 40 min of treadmill running at 65% VO2max in temperate (18°C) conditions. Interestingly, the ergogenic effect was not transferred to performance of the same test under cool conditions (18°C). The notion that HA performance benefits (achieved via active/passive interventions) can be observed in temperate/cool conditions remains debatable (Minson & Cotter, 2016). Active-HA based research has indicted that performance benefits following acclimation/ acclimatization interventions may be elicited in cool/temperate conditions (Lorenzo et al., 2010), while others reported contradictory findings (Karlsen et al., 2015).
Importantly, there seems to be no clear evidence that HA could be detrimental to performance in cool environments, thus HA strategies are still recommended when anticipated environmental conditions for competition are hot/unknown (Minson & Cotter, 2016).

Most of the studies included in this review focused on physiological responses to HA, as presented below, while only three studies measured endurance performance following passive HA protocols. Such research suggests performance can be significantly improved. Future studies could include more performance tests, specifically time trials, in order to provide a clearer consensus regarding the performance benefits of such interventions.

2.1.4 Physiological responses

Changes in several physiological variables have been identified following HA protocols. These have included a reduction in metabolic rate, heightened skin blood flow and sweat responses, increased plasma volume, improved cardiovascular stability and fluid balance and improved thermal tolerance, which are all contributors to the benefits of HA (Périard et al., 2015). Furthermore, the physiological responses that typically occur earliest are reductions in heart rate, skin and core temperature, as well as a rise in sweat rate and work capacity, generally occurring within the first week of HA, following which other cardiovascular and sudomotor adaptations are likely to occur (Racinais, Alonso, Coutts, Flouris, Girard, González-Alonso, et al., 2015). The thermoregulatory, cardiovascular and other physiological alterations that have occurred following passive HA will be discussed in the following sections.

2.1.4.1 Temperature responses

Increased core and/or skin temperatures that accompany exercise in hot conditions can indirectly reduce maximal oxygen uptake and thus negatively influence aerobic performance (Cheuvront, Kenefick, Montain, & Sawka, 2010). Core temperature responses when humans are exposed to hot environmental temperatures are influenced by hydration status, if hypo-
hydration accompanies compensatory increase of sweat outputs, elevations in core temperature and heat storage generally occur in consequence (Kenney et al., 2004). Heat adaptation creates a shift in the “critical environment” (a range of environmental conditions beyond which core temperature cannot be maintained within the normal range), improving the ability to effectively withstand hot environmental temperatures (Kenney et al., 2004). Importantly, effective passive HA interventions have reduced core temperature at rest, during exercise and upon cessation of exercise (Bonner, Harrison, Hall, & Edwards, 1976; Leppaluoto et al., 1986; Shido et al., 1999; Zurawlew & Walsh, 2018; Zurawlew et al., 2016). Reductions in resting core (oesophageal/rectal) temperature (~0.26°C reduction on average), have been noted following 10-11 day passive HA regimes that used 1-h, 2-h or 4-h heat exposures per day. These involved rest in a heat chamber either with (Beaudin et al., 2009), or without (Racinais et al., 2017; Shido et al., 1999) the application of vapour impermeable suits, respectively, as well as a 7-day protocol involving 1-h exposures twice a day to dry heat in a Finnish sauna (Leppaluoto et al., 1986) and HWI with/without exercise beforehand (Bonner et al., 1976; Brazaitis & Skurvydas, 2010; Shin et al., 2013; Zurawlew & Walsh, 2018; Zurawlew et al., 2016). Similarly, the time to reach a specific target core temperature has been increased (~9 min increase) following an 11-day heat chamber protocol using 1-h per day passive heat exposures (Racinais et al., 2017).

The main stimulus for individuals to achieve a lower resting core temperature, and thus heat adaptation, is repeated episodes of elevated core temperature, suggesting that repeated physical exercise in the heat may not be necessary for HA (Brazaitis & Skurvydas, 2010; Regan et al., 1996). Furthermore, simply subjecting individuals to significant heat stress can improve tolerance to greater doses of heat stress by stimulating heat shock protein production and enabling greater cell protection against the adverse effects of high temperatures (Lim, Byrne, & Lee, 2008). Passively induced HA can also reduce the end-exercise core temperature significantly, as demonstrated by two 6-day interventions involving repeated 40 min HWI at
40°C following running in temperate (18°C and 20°C) conditions on consecutive days, which lead to lower final rectal temperatures in both hot (33°C) (~0.36°C mean reduction), and temperate (18°C) (~0.28°C mean reduction) environments, at the end of treadmill running (Zurawlew & Walsh, 2018; Zurawlew et al., 2016). Such reductions in core temperature can be attributed to a reduced heat storage resulting from improved heat loss mechanisms (Buono, Heaney, & Canine, 1998) which typically accompany HA, as shown by Henane and Valatx (1973) who reported a heightened heat transfer between the core and periphery, as well as improved sweat responses during 3 h of controlled hyperthermia in a heat chamber (refer to Table 1).

Lower core temperatures have also accompanied exposure to 27°C and 50% relative humidity in a heat chamber at the same time of previous heat exposure, suggesting a timed memory of heat exposure following a passive HA intervention (Shido et al., 1999). These were observed in acclimated individuals who followed a protocol that involved rest in a heat chamber at 46°C, with 20% relative humidity for 4 h on 9-10 consecutive days, to analyse how the thermoregulatory responses differed between the time period when the individuals were exposed to heat stress and the rest of the day. In contrast, a recent study that used post-exercise HWI conducted in the morning, advanced such findings and reported the presence of physiological adaptions gained from the intervention (resting and during exercise in the heat) in both the morning and mid-afternoon (Zurawlew & Walsh, 2018). Additive research is required to provide more robust conclusions with regards to whether HA adaptions (physiological/perceptual) are more apparent at the time of dosage of heat stress in an HA intervention, or if they can be observed similarly throughout the day after HA is complete.

Skin temperature is influenced by environmental temperatures as well as thermoregulatory responses (Cheuvront et al., 2010). Passive HA can reduce skin temperature during submaximal exercise in both hot and cool conditions, as demonstrated by a 6-day post
exercise HWI interventions (Zurawlew & Walsh, 2018; Zurawlew et al., 2016). This adaptation could have high relevance for athletes, since previous research has identified that high skin temperatures that accompany exercise in hot conditions, without the presence of considerably high core temperatures, are associated with earlier exercise cessation at light/moderate exercise intensities (Cheuvront et al., 2010). The mechanism of how high skin temperatures contribute to compromised exercise performance can be explained by the fact that the skin blood flow is increased in an attempt to dissipate heat, contributing to the distribution of blood to the periphery, thereby reducing cardiac filling and cardiac output, which in turn contributes to a reduced maximal oxygen uptake (Cheuvront et al., 2010). Additionally, skin temperature influences perceptual comfort, which could impact pacing strategies and performance (Bulcao, Frank, Raja, Tran, & Goldstein, 2000). With regards to resting skin temperatures, three studies using an either 7 or 10-day protocols with 20 or 26% relative humidity in a heat chamber, with (ambient temperature at 50°C) or without vapour-impermeable suits (ambient temperature at 37.5 or 46°C), reported no significant changes in skin temperatures that were measured post-acclimation from the resting skin temperatures measured prior to the acclimation (Beaudin et al., 2009; Pallubinsky et al., 2017; Shido et al., 1999).

2.1.4.2 Sweat responses

Evaporative heat loss is the primary means of heat dissipation from the body during physical activity accompanied by significant environmental heat stress, accounting for almost 80% of heat loss, highlighting the importance of the ability to sweat under such conditions to enable adequate thermoregulation (Kenney et al., 2004; Lim et al., 2008). As such, enhanced sweating responses are important physiological adaptations acquired from HA, since sweat evaporation aids the maintenance of thermal balance and the ability to avoid thermal overload (Henane & Valatx, 1973). The time to sweat onset (sweat latency) during resting exposure to heat has decreased (~4 min) following protocols involving seated rest in a heat chamber for 9-
10 days (Henane & Valatx, 1973; Shido et al., 1999). Furthermore, sweat onset has commenced at lower associated core temperature following heat chamber protocols at rest (~0.31°C mean reduction) (Beaudin et al., 2009; Henane & Valatx, 1973), and also following HWI protocols (Zurawlew & Walsh, 2018; Zurawlew et al., 2016), where the response has been noted following HA within performance tests conducted in both temperate and hot conditions (Zurawlew et al., 2016). Earlier sweat onset may be attributed to a number of factors including greater thermal input, enhanced sensitivity of the central nervous system, higher skin temperatures at measurement sites, and/or enhanced sensitivity of the sweat gland to a given level of central drive (Shido et al., 1999).

Enhanced sweating capacities, demonstrated by increased sweat outputs and sweat rates, have also been observed following various passive HA protocols. Increased sweat outputs have accompanied controlled hyperthermia heat chamber protocols either with (Beaudin et al., 2009; Fox et al., 1964) or without (Henane & Valatx, 1973) the application of rain/vapour-barrier suits. Additively, enhanced sweat rate responses have accompanied heat chamber protocols that entailed exposure to incremental heat stress (Henane & Valatx, 1973; Racinais et al., 2017) or application of a vapour impermeable suit (Fox et al., 1964), as well as HWI protocols using either daily HWI following exercise (Zurawlew et al., 2016), HWI prior to passive heating in a climate chamber (Kanikowska et al., 2012), or the controlled hyperthermia technique without exercise (Allan & Wilson, 1971; Bonner et al., 1976). The enhanced sweat rate responses following acclimation protocols have occurred at rest upon exposure to heat (Allan & Wilson, 1971; Henane & Valatx, 1973), as well as during exercise in hot and temperate conditions (Zurawlew et al., 2016). Furthermore, enhanced body fluid loss as demonstrated by larger relative reductions in body mass and an increase in whole body sweat loss have accompanied alternate day HWI protocols (Bonner et al., 1976; Brazaitis & Skurvydas, 2010; Shin et al., 2013). Enhanced sweat loss can be beneficial for athletes,
provided that it is further accompanied by increases in heat loss via evaporative mechanisms and that athletes maintain adequate hydration in order to prevent a rise in thermal strain, since increased fluid loss from the body can result in progressive dehydration and cardiovascular strain, and a prolonged dehydration can reduce performance and be harmful to health (Kenney et al., 2004; Tyler et al., 2016).

Consequently, the requirement for fluid replacement is greater once heat adaptations have been achieved, due to the enhanced sweat responses. Dehydration has a significant influence on sweat latency and also results in core temperature responses that are the same as if acclimation had not been achieved, further highlighting the importance of ensuring proper hydration status (Shido et al., 1999; Wendt et al., 2007). However, heat-adapted individuals are generally better at maintaining adequate hydration status via improved fluid replacement, noted by reduced voluntary dehydration and improved relationships between thirst and body water requirements in these individuals (Périard et al., 2016). More dilute sweat, potentially achieved via increased reabsorption of electrolytes, can evaporate easier from the skin and is therefore a beneficial response accompanying HA (Tyler et al., 2016). As such, sweat concentration has been reduced after passive HA, as demonstrated by decreased sweat sodium content over a variety of sweat rates following controlled hyperthermia using 40°C HWI (Allan & Wilson, 1971). This, along with a reduction in time to sweat onset, is a common feature of HA (Allan & Wilson, 1971; Henane & Valatx, 1973; Leppaluoto et al., 1986).

2.1.4.3 Haematological responses

The expansion of plasma volume (hypervolemia) has been induced in men of various training statuses (healthy, active, well-trained and competitive) following heat chamber, sauna and HWI protocols with 40-120 min heat exposures (~11.08% mean increase) (Beaudin et al., 2009; Bonner et al., 1976; Scoon et al., 2007; Stanley et al., 2015; Zurawlew et al., 2016). Importantly, plasma volume expansion can improve maximal oxygen uptake (Davies, 1979)
and contribute to improved cardiovascular stability, by allowing for a reduction in heart rate (via contribution to an improved distribution of blood flow during exercise and improved ventricular filling) and an increase in stroke volume (Périard et al., 2016; Racinais, Alonso, Coutts, Flouris, Girard, González-Alonso, et al., 2015; Wendt et al., 2007). Plasma volume expansion may also contribute to improved heat transfer between exercising muscle and skin by raising the specific heat capacity of the blood (Casa, 2018). Reductions in serum potassium, sodium and iron levels have been reported after a sauna bathing protocol involving rest for an hour, twice daily in 80°C conditions (Leppaluoto et al., 1986); as well as reduced plasma osmolarity, plasma protein concentration and absolute values of haematocrit, with no significant changes in plasma cortisol or aldosterone levels after a protocol involving 1-h of HWI (41°C) for 13 days (Bonner et al., 1976). However, no significant changes in plasma sodium, potassium, total protein and albumin levels were noted after a heat chamber involving rest for 4 h at 46°C and 20% relative humidity (Shido et al., 1999). Both protocols used healthy men and did not include exercise, but made use of different heat stimuli temperatures, duration and methods that could potentially explain the conflicting observations. Other cardiovascular adaptations such as increased red cell volume, body mass and total blood volume have accompanied post exercise sauna bathing in long distance runners (Scoon et al., 2007). Despite limited information regarding skin blood flow changes with passive HA interventions, there is general consensus that following HA maximal skin blood flow is unchanged (Périard et al., 2015). However, skin blood flow responses may improve (redistribution and reduced requirements) as a result of enhanced sweating capacity and thus reduced skin temperature responses (Schmit, Duffield, Hausswirth, Brisswalter, & Le Meur, 2018). Additively, the expansion of blood volume allows more blood to be pumped, as required, to muscles, organs and the skin. Evidently, the cardiovascular adaptations acquired following HA contribute to
improved cardiovascular stability accompanying physical exercise under hot conditions (Garrett et al., 2011).

2.1.4.4 Heart rate responses

A recent systematic review on the effects of active HA on physiology, perception and exercise performance in the heat stipulated a lowered heart rate during exercise, but less of an impact on reducing resting values (Tyler et al., 2016). In opposition, the passive HA protocols explored in this review have noted significant changes in resting heart rate values (Kanikowska et al., 2012; Leppaluoto et al., 1986; Racinais et al., 2017). Sauna bathing for 30 min following training lead to trivial-to-moderate reductions in heart rate upon waking, but no change in the peak heart rate values for well-trained cyclists (Stanley et al., 2015); and similarly, Finnish sauna dry heat exposure for 1-h, twice per day (Leppaluoto et al., 1986), HWI either following exercise (Zurawlew & Walsh, 2018; Zurawlew et al., 2016), or preceding rest with a blanket in a heat chamber (Kanikowska et al., 2012), and passive heat exposure using a heat chamber (Racinais et al., 2017) have all successfully lowered resting heart rate values. Similarly, following a HA protocol that made use of passive lower body heating achieved by HWI, the reading for heart rate after 45 min of passive heating had decreased (Brazaitis & Skurvydas, 2010), demonstrating successful HA in the participating individuals. In contrast, no significant changes in resting heart rate values were noted after a 7 or 9-day interventions where individuals rested in a heat chamber for 4-6 h per day (Pallubinsky et al., 2017; Shido et al., 1999).

Exercising heart rate values have also shown a reduction after HWI protocols (Bonner et al., 1976; Kanikowska et al., 2012; Zurawlew & Walsh, 2018; Zurawlew et al., 2016). Importantly, only four studies used exercise tests, with only two that measured end-exercise heart rate values (Zurawlew & Walsh, 2018; Zurawlew et al., 2016), and one that measured heart rate during submaximal exercise (Stanley et al., 2015), but this study reported equipment
malfunction and loss of some heart rate related data (0-13%). Consequently, there is limited information on the exercising heart rate responses during performance testing after passive HA protocols.

2.1.4.5 Thermoregulatory strain responses

Thermoregulatory strain can be calculated using rectal temperature and heart rate during submaximal exercise where the information is converted to a scale ranging from 0 to 10. Reduced physiological strain indexes (Moran, Shitzer, & Pandolf, 1998) in hot conditions have been reported after HWI of the lower body (Brazaitis & Skurvydas, 2010), and HWI following exercise in temperate conditions (Zurawlew et al., 2016). Such changes may decrease negative contributions to performance including lowered muscle recruitment, excess fluid loss from the body, feelings of discomfort and a disturbed relationship between oxygen consumption and heart rate (Tyler et al., 2016).

2.1.5 Perceptual responses

Hyperthermia and heat stress contribute to the increased perception of exertion during submaximal exercise in hot ambient conditions, highlighting the benefit of improved ability of the human body to dissipate heat following HA for athletes (Armada-da-Silva, Woods, & Jones, 2004; Cheuvront et al., 2010; Pandolf, 2001). The implications for athletes of a higher perceived exertion as a result of increased heat stress is that it may influence other factors associated with exercise performance, such as behaviour and motor neural firing that is driven by motivation (Cheuvront et al., 2010). Consequently, perception of heat can contribute to premature fatigue and negatively influence performance (Stevens, Mauger, Hassmén, & Taylor, 2018; Tyler et al., 2016), and as such, athletes may perform better with improved perception of thermal load (Chalmers et al., 2014).

There are a number of perceptual responses that have been examined in the literature,
for example, mood (Kanikowska et al., 2012), thermal sensation (Racinais et al., 2017; Schulze et al., 2015; Young, Sawka, Epstein, Decristofano, & Pandolf, 1987; Zurawlew et al., 2016), thermal comfort (Bulcao et al., 2000; Kelly, Gastin, Dwyer, S, & Snow, 2016; Racinais et al., 2017; Schulze et al., 2015; Young et al., 1987), and perceived exertion (Zurawlew et al., 2016). Some of these studies investigated the effect of HA on perceptual responses (i.e., POMS, thermal sensation, thermal comfort and perceived exertion) (Kanikowska et al., 2012; Kelly et al., 2016; Racinais et al., 2017; Zurawlew et al., 2016). Others investigated perceptual responses during heat stress tests (Bulcao et al., 2000; Schulze et al., 2015; Young et al., 1987).

Thermal sensation refers to the recognition of how hot or cold the body feels, whereas thermal comfort is a measure of how the individual interprets their thermal state, and could have a larger influence on exercise regulation in the heat than the actual thermal state, since it is thought to be the initiator of behavioural thermoregulation (Bulcao et al., 2000; Mee et al., 2017; Schulze et al., 2015). Thermal comfort in hot environments can be improved with the adaptations gained following repeated exposure to hot conditions (Périard et al., 2016). Different scales have been used to assess thermal sensation and thermal comfort in previous research, with some scales not clearly distinguishing between the two variables (Schweiker et al., 2017). The use of a seven-point ASHRAE scale to measure thermal sensation, and a different four-point scale to assess thermal comfort was proposed by Gagge, Stolwijk, and Hardy (1967). Interventions using HWI have lowered ratings of perceived exertion during and after exercise in both hot (33°C) and temperate (18°C or 20°C) conditions for participants who followed a 6-day protocol (Zurawlew & Walsh, 2018; Zurawlew et al., 2016). In the same studies, reductions in thermal sensation were observed during exercise in the hot conditions, and at the end of exercise in temperate conditions, respectively (Zurawlew & Walsh, 2018; Zurawlew et al., 2016). In contrast, another recent study reported no changes in either thermal sensation or comfort measures reported by male participants after an 11-day heat chamber.
protocol (Racinais et al., 2017). Improvements in perceptual responses following HA protocols may allow up-regulated self-paced exercise, and therefore are worth investigating further. Kanikowska et al. (2012) made use of a Japanese version of the profile of mood states questionnaire at test sessions to analyse feelings during a HWI followed by blanket resting in a heat chamber protocol, and reported higher scores on the anger-hostility subscale from the six healthy male participants, indicating mood decrements after HA.

2.2 Practical applications and recommendations for athletes

Based on the research described herein, it is evident that passive strategies using hot rooms/HWI can be employed to induce heat adaptations, as per measured improvements in performance, thermoregulatory, cardiovascular and perceptual responses. Exercise is not necessary for the physiological adaptations to occur following passive protocols, however including exercise under temperate ambient conditions in the regime may lead to larger thermoregulatory-adaptive responses than application of heat stress alone, since it can elicit larger rises in core temperature, a major contributing factor to heat adaptation (Casadio et al., 2016). Additively, combining exercise and passive heating in the intervention may induce greater heat shock protein synthesis than utilizing either method alone (Casa, 2018). Importantly, research has highlighted that the magnitude of heat adaptations can depend on the method of induction, the initial heat exposure status and also the number, duration and frequency of heat exposures involved in the HA protocol (Périard et al., 2016; Tyler et al., 2016). Research has also indicated that individual training status could influence the magnitude and timeframe of acclimation in response to HA interventions, (Daanen et al., 2018; Sawka, Périard, & Racinais, 2015) although information regarding passive HA is limited. The rationale for this suggestion is that well-trained individuals may naturally be partially heat adapted, thus acclimate faster, as they are likely to already have higher aerobic capacity than untrained
individuals. In contrast, a recent study concluded that the inter-individual adaptive responses to a 10-day active HA intervention was not related to baseline maximal oxygen uptake (Corbett, Rendell, Massey, Costello, & Tipton, 2018), as such we cannot conclude whether untrained individuals may experience greater HA benefits in comparison to trained individuals.

The application of post-exercise heat stress can induce numerous physiological adaptations and may improve endurance performance (Scoon et al., 2007; Stanley et al., 2015; M. J. Zurawlew et al., 2016). It is important to note that such performance improvements have only been demonstrated under hot but not temperate conditions (M. J. Zurawlew et al., 2016). For these passive protocols which used post-exercise application of heat stress, exercise in temperate conditions has typically been performed immediately before entering a sauna or bath. Importantly, while passive strategies may be logistically easier to incorporate into complex training programs and schedules of elite athletes, passive heat exposures alone may not be as effective for the development of sport-specific adaptations in comparison to active/exercise-induced HA (Daanen et al., 2018). Based on the information gathered from this review, for successful passive HA, the heat stimulus should ideally have a minimum duration of 30 min per session, employed on consecutive days, when possible, and the time of day for heat application may not be important for adaptation. Furthermore, the ambient temperatures that have been used are at least 80°C for sauna, 45-50°C for heat chambers and around 40°C for HWI (see Table 1). If the controlled hyperthermia technique is used, the target core temperature should be around 38.5°C, which has been shown to be effective (Patterson, Stocks, & Taylor, 2004). Furthermore, other research has suggested that elevating core temperature beyond 38.5°C during HA is not necessary, as it does not further enhance the acclimation benefits (Gibson et al., 2015). Only 6-7 exposures are required to induce beneficial physiological and performance responses (Brazaitis & Skurvydas, 2010; M. J. Zurawlew et al., 2016) but most protocols have used the medium term duration of 8-14 days (Beaudin et al., 2009; Scoon et al.,
Despite the fact that most complete adaptations accompany long term interventions, thus may be best practice for ultra-endurance events (Périard et al., 2015), successful medium term protocols may be more favourable for endurance athletes, since they are slightly less time-consuming and can induce complete thermoregulatory benefits as well as more extensive protective effects than short term protocols (Casadio et al., 2016). Current recommendations state that HA protocols should be conducted immediately prior to competition in order to limit the decay of adaptations (Casa, 2018). Passive heating could also be combined with active HA protocols when time is limiting and active HA is possible, as demonstrated by Mee et al. (2017), who reported accelerated thermal, cardiovascular and perceptual adaptations in females who were passively heated prior training in the heat.

Use of HWI protocols for endurance athletes who train in a cool environment may offer the most practical benefits, since they do not demand lengthy heat exposures (as required by heat chamber protocols), or extremely high ambient temperatures (as are the nature of sauna protocols). Furthermore, hot baths following physical training in temperate conditions can successfully raise core and skin temperatures necessary for heat adaptations to be initiated, and have improved exercise performance, highlighting the relevance for athletes. Despite clear consensus as to whether most of the resting and exercising physiological adaptations acquired could be transferred to performance in a cool environment, there is no evidence to suggest that HA interventions are detrimental to subsequent performance in a cool environment (Minson & Cotter, 2016). While we can suggest that athletes should commence HWI immediately after exercise, it is unclear how long the window is between finishing a session and commencing HWI to obtain the additional benefit. Most studies that have implemented heat exposure after training (via HWI/saunas) have commenced heating immediately following the exercise (Scoon et al., 2007; Stanley et al., 2015; M. J. Zurawlew et al., 2016).
In order to improve safety when utilizing such protocols, consideration should be geared toward the timing of induction and the environmental/ambient conditions, with pre-disposing factors for heat illness having been identified before implementation of any kind of HA intervention (Casa, 2018). Individuals must keep in mind that heat transfer/dissipation is also influenced by the surface area of the body, with faster rates of heat dissipation generally occurring in conjunction with larger body surface area to volume ratios (West, Sill, York, & Kaplan, 2015). Other research has noted that lower absolute metabolic heat production occurs in runners of lower body mass compared to heavier individuals, therefore coaches must monitor heavier athletes during the HA process, as these individuals may be at increased risk of heat illness (Dennis & Noakes, 1999). Importantly, heating sessions should not be undertaken by athletes who have acute injuries, oedema, vascular disease, wounds or infections (Wilcock, Cronin, & H., 2006).

Notably, when water temperatures are higher than core temperatures, the thermal gradient changes from external to internal, leading to progressive heat influx which could contribute to hyperthermia (Taylor, 2006). However, if conducted in a controlled manner, the resultant heat influx can be beneficial, since repeated episodes of elevated core temperature are necessary for heat adaptation (Brazaitis & Skurvydas, 2010). Some successful HWI interventions have even made use of water temperatures above 40°C (Allan & Wilson, 1971; Bonner et al., 1976; Brazaitis & Skurvydas, 2010; Kanikowska et al., 2012; Shin et al., 2013; M. J Zurawlew & Walsh, 2018; M. J. Zurawlew et al., 2016). Naturally, it is important to consider that when submerged in water with a temperature greater than that of body temperature, avenues for heat loss via sweating are limited, and consequently, the body will progressively gain heat. Hence, HWI (especially after exercise) could potentially cause heat illness and therefore important safety measures should be implemented. Such safety measures should include using thermal scales to monitor perceptions of hotness, continuous measurement of water temperatures and/or supervision of immersions and monitoring the signs
of hyperthermia. Furthermore, drinking water/fluids must be available before, during and after heat sessions, and athletes should discontinue heat sessions accompanied by signs of heat illness, light-headedness, nausea or extreme discomfort (Casa, 2018). Finally, most athletes are likely to have access to a bath in their own home, and as such, employing the HWI strategy may work in favour of time, convenience, comfort and cost, enabling use in a practical setting.

2.3 Conclusion and future research directions

Extensive research has been conducted on HA, with the majority geared toward active rather than passive strategies. Passive strategies can be used to induce heat adaptation, as measured by improvements in endurance capacity and performance, reduced resting and exercising core temperature, lower skin temperature at sweat onset, enhanced sweat capacity, expansion of plasma volume, reduced resting and exercising heart rate, as well as lowered physiological strain index, rating of perceived exertion and thermal sensation (Casadio et al., 2016; Shin et al., 2013; Tyler et al., 2016). Such changes have been noted in participants of different sex, training status and sport disciplines. Passive heat stress can be provided by saunas, HWI or environmental chambers. If possible, exercise bouts should be employed prior to heat sessions, rather than passive heating alone, with minimal delay between training and the application of heat stress, for optimal thermoregulatory-adaptive response. Heating bouts should have a minimum duration of 30 min per session and be employed on consecutive days, when possible with interventions having a minimum of 6-7 exposures for successful adaptations.

Passive HA strategies may be more practical than active strategies for athletes training in winter months, residing in cool environments, or with financial constraints (Casadio et al., 2016). The passive strategies that have been explored to date have focused heavily on the
physiological responses acquired, while few studies have measured changes in exercise performance which is highly relevant to athletes and practitioners (Wilcock et al., 2006). Additional investigations are needed to provide information regarding the magnitude of performance changes that can occur following passive HA interventions by testing trained athletes in ecologically valid performance tests (i.e., time-trial protocols). Different time intervals, and comparisons between effects of pre- as opposed to post-exercise application of heat stress should also be explored in order to provide more robust recommendations for athletes using these strategies, who likely have delays between completing a training session and commencing HWI for several logistical reasons. Furthermore, future research could examine the combination of active and passive protocols (i.e., passive heat exposure following exercise in the heat) to investigate if this double heat training technique could provide a further boost to the performance, physiological and perceptual adaptations. Additively, research directed towards heat adaptation with consideration for sport specificity is warranted (i.e., protocols tailored to the specific demands of the chosen sport). The review has also identified that perceptual responses to HA achieved via protocols that involve rest in environmental chambers/saunas have not been explored thoroughly within the literature to date. This has also been highlighted by Tyler et al. (2016), who found limited data with regards to perceptual measures, including ratings of perceived exertion and thermal sensation, accompanying HA studies in a recent systematic review. As such, future research should employ more perceptual measurements accompanying HA strategies for athletes, since reducing the perception of heat stress may delay the onset of fatigue during exercise performance (Armada-da-Silva et al., 2004). This information could help lower the incidence of heat stress and improve performance for individuals competing in the heat.
CHAPTER 3
STUDY 1

Post-exercise hot-water immersion for heat acclimation: Is timing everything?

Abstract

Purpose: To assess physiological responses central to the stimulation of heat adaptation during hot-water immersion (HWI) of a set duration that was conducted with different time delays after exercise conducted in cool conditions. Methods: Core temperature (T<sub>core</sub>), mean skin temperature (T<sub>ms</sub>), heart rate (HR), sweat rate (SR), and perceptual responses were collected from twelve trained recreational male runners, who completed three sessions in a randomised counterbalanced cross-over design. Sessions included a 40 min treadmill run (18.0 ± 0.9°C and 64.5 ± 4.7% RH), followed by a delay of 10 min (C0), 1 h (C1) or 8 h (C8) before a 30 min HWI (38.9 ± 0.1°C). Effect of condition on all responses was modelled. One-way repeated measures ANOVA were conducted to identify significant main effects for run data, SR, T<sub>core</sub> and pre and post T<sub>ms</sub> data during HWI. Perceptual data, HR and ΔT<sub>ms</sub> during HWI were analysed using non-parametric Friedman’s two-way ANOVA with follow up pairwise comparisons. Effects were described as “small” (r = .1), “medium” (r = .3) or “large” (r = .5).

Results: T<sub>core</sub> (absolute) during HWI were similar between C0 (37.83 ± 0.24°C) and C8 (37.74 ± 0.19°C), yet delta values were significantly higher in C0 (0.83 ± 0.25°C) than C1 (0.47 ± 0.17°C; p = 0.003) and C8 (0.56 ± 0.14°C; p = 0.031). The T<sub>ms</sub> changes were significantly higher in C0, despite similar SR and perceptual responses during HWI between conditions.

Conclusions: Athletes can maximise T<sub>core</sub> and T<sub>ms</sub> responses (key stimuli for heat acclimation) by commencing HWI immediately after exercise. If unviable, athletes could use HWI in the
afternoon when natural circadian body temperature is highest to maximise the heat load of the immersion

**Keywords:** Heat acclimation; heat stress; hot bath; passive heating; endurance athletes.

### 3.0 Introduction

Endurance performance is compromised in the heat through elevated thermoregulatory/physiological strain (Daanen et al., 2018; Schmit et al., 2017) and unpleasant thermal sensations (TS) (Stevens et al., 2018). The Tokyo 2020 Summer Olympics are expected to be held under extremely hot conditions (Kakamu, Wada, Smith, Endo, & Fukushima, 2017). Therefore, endurance athletes should employ heat acclimatisation (training within a hot outdoor environment) or acclimation (heat produced artificially) strategies (both abbreviated to HA) to negate heat-mediated performance decrements and provide protection against exertional heat illnesses (Kakamu et al., 2017; Racinais, Alonso, Coutts, Flouris, Girard, Gonzalez-Alonso, et al., 2015). Active (heat stress during exercise) and passive (heat stress at rest) HA strategies have varying efficacy to procure a heat adapted phenotype (Daanen et al., 2018; Périard et al., 2016).

Factors central for heat adaptation are increased sweating and heightened core temperature ($T_{\text{core}}$) and skin temperatures ($T_{\text{skin}}$) (Neal, Corbett, Massey, & Tipton, 2016; Périard et al., 2015; Wendt et al., 2007). Effective HA elicits increased plasma volume (PV) and whole body sweat rate (SR), and lower $T_{\text{core}}$ and heart rate (HR) responses at rest and during exercise in the heat (Buono et al., 2018; Pallubinsky et al., 2017; Tyler et al., 2016). Adaptations can occur in 4 to 5 days (with sudomotor adaptations typically present after HR and $T_{\text{core}}$ changes), but their magnitude and retention are greater with longer protocols (Daanen et al., 2018). The benefits of HA are clear (Daanen et al., 2018; Tyler et al., 2016), yet evidence-
based active protocols, typically involving specialised facilities and/or relocation, may be logistically difficult to incorporate into complex training programs and schedules of elite athletes (Casadio et al., 2016). The training sessions themselves are also onerous, generally involving exercise in the heat for approximately 100 min at intensities greater than 50% of maximal oxygen uptake, preferably on consecutive days for a minimum duration of one week (Casadio et al., 2016; Périard et al., 2015). Despite the ergogenic potential, during the International Association of Athletics Federations (IAAF) World Athletics Championships in Beijing in 2015, where hot and humid conditions were predicted, only 15% of athletes engaged in HA training (Kakamu et al., 2017).

In response to these challenges, practically compatible passive HA strategies have been employed, including sauna bathing and HWI (Scoon et al., 2007; Stanley et al., 2015; M. J. Zurawlew et al., 2016). Post-exercise HWI has improved endurance performance in the heat after 6 days (M. J. Zurawlew et al., 2016), presenting a practical HA method for athletes residing in cooler climates, compared to expensive alternatives requiring artificial heat chambers and/or expensive relocation. Typically, heat stress is applied immediately following training (Scoon et al., 2007; Stanley et al., 2015; M. J. Zurawlew et al., 2016), with exercise conducted in laboratory settings in some cases, enabling easy access to heating facilities. Practically however, the ability to undergo HWI immediately after exercise could be challenging for athletes who lack such facilities near training locations. Indeed, a delay of up to 1 h between training and HWI is not unlikely, whilst other athletes may only have time to immerse later that evening following morning training. The challenges that may accompany conducting heating sessions immediately after training include; the access to facilities and the travel time to reach their locations. Furthermore, athletes could also have other commitments and only have time available to conduct heating sessions (e.g. HWI) later in the day.
Mechanistically, delays that could occur between training and heat exposure may elicit decays in potentiating stimuli for adaptation and should therefore be explored further.

Coaches and athletes who consider the use of HWI after training as a HA intervention would benefit from additional knowledge pertaining to the cost (if any) of delaying immersion on the adaptation potential, for example, when structuring training sessions. Predictably, post-exercise HWI with different time periods between administration and exercise cessation will likely alter the physiological responses to the HWI exposure, however, currently no data exist in these regards.

Therefore, the aim of this study was to assess physiological responses central to procurement of a heat acclimated (T\text{core} and T\text{skin}, and SR) phenotype during a 30 min HWI (~39°C) administered 10 min, 1 h or 8 h after a 40 min treadmill run in a temperate environment. It was hypothesized that the greatest physiological responses and heat load would be seen in the 10 min condition.

### 3.1 Methods

#### 3.1.1 Participants

Twelve male, recreational (performance level two) (De Pauw et al., 2013) long distance runners (mean ± SD; age: 38 ± 13 y, height: 180 ± 7 cm, body mass: 81 ± 13.7 kg, body fat: 13.9 ± 3.5%) volunteered for the study. Females were actively excluded to avoid the confounding influence of menstrual cycle mediated T\text{core} fluctuations (Mee et al., 2017; Wendt et al., 2007). Inclusion criteria stipulated that the participants had performed a 10 km time trial within 6 months prior to the study in ≤ 50 min (mean time: 47 ± 3 min, range: 42-49 min). Exclusion criteria included any contra-indications to exercise as per the Exercise & Sports Science Australia Adult Pre-exercise Screening Tool (Coombes & Skinner, 2014) (see
Appendix C), previous diagnosis of low blood pressure, history of heat illness or use of prescribed medication during the time of the study. Approval for the project was granted by The Human Research Ethics Committee at Southern Cross University, Australia (ECN-17-121) (see Appendix A), and written informed consent was obtained before commencing any testing procedures (see Appendix B).

3.1.2 Experimental design

A randomised and counter-balanced cross-over design was employed at the end of winter to control for natural HA. Participants completed three experimental sessions separated by 7 to 10 days each. Sessions included a 40 min treadmill run (Trackmaster TMX425 CP, Carrollton Texas, USA), a specified duration of time before HWI and then 30 min of HWI. Participants were instructed to avoid alcohol and caffeine during testing days and to ensure adequate hydration by ingesting 500 mL of water 2 h prior to arrival.

3.1.2 Exercise protocol

A 40 min treadmill run [climate controlled laboratory; 18.0 ± 0.9°C; relative humidity (RH) 64.5 ± 4.7 %] commenced in the morning (between 06:00 and 07:30; time held consistent after first laboratory visit), to control for circadian variation of internal body temperature (Slomko & Zalewski, 2016). A pedestal fan (Dynabreeze, China) set at a wind speed of 10 km h⁻¹ was placed 2.5 m in front of the treadmill to replicate the convective cooling of running outdoors. During the first trial, running intensity was based on ratings of perceived exertion (RPE; 6-20 scale) (Borg, 1998). Participants were instructed to run at self-selected speeds, including 10 min at “light” intensity (RPE = 11), 20 min at “hard” intensity (RPE = 15) and further 10 min at “light” intensity. The treadmill speeds were recorded and replicated in subsequent trials so that each participant ran at the same speeds in all trials. Participants consumed drinking water at 33°C ad libitum during the run. The HWI was administered
following a 10 min (C0), 1 h (C1) or 8 h (C8) time interval as illustrated in Figure 3.1. During C1 and C8, participants were permitted to leave the lab after the run and conduct their normal daily activities, but were instructed to avoid any physical activity.
Figure 3.1: Schematic of the study design.
3.1.3 Immersion protocol

Immersion was administered using a bathtub (2.3 m long x 1.1 m wide x 0.5 m high) located within a bathroom (8 m²; 24.2 ± 2.3°C, RH 76.3 ± 8.1%), with water temperature (38.9 ± 0.1°C) and flow maintained using a two-tap mechanism. While HWI termination criteria was set according to ethical requirements (i.e., reaching a $T_{core}$ >39.4°C, rapid increase in HR, light headedness or reporting a thermal comfort rating that reached “very uncomfortable”), all participants completed the full 30 min HWI protocol. Consumption of fluids during HWI was not permitted.

3.1.4 Anthropometry

Before the each initial experimental trial, participants underwent anthropometrical measurements including body mass by an electronic scale (Charder MS3200, Taichung City 412, Taiwan), stature (S+M Height Measure 2m, Rosepark, SA) and skin-fold measurement by calliper (Harpenden Calipers, Baty International, West Sussex, United Kingdom) at seven sites including the bicep, tricep, subscapular, supraspinalae, abdominal, mid-thigh and medial calf, following the International Society for the Advancement of Kinanthropometry (ISAK) recommended protocol (Marfell-Jones, Stewart, & De Ridder, 2012)

3.1.5 Temperature measurement

$T_{core}$ was measured continuously using an e-Celsius ingestible telemetric capsule (BodyCap, Caen, France). Participants were instructed to ingest the capsule with water just before going to sleep the night before testing (approximately 8 h prior to each trial). Measurements of $T_{skin}$ were taken using a dermal thermal scanner (DermaTemp, Exergen Corporation, MA, USA), at four sites (forehead, right calf, right hand and lower back) before and after exercise/immersion on the right side of the body, to estimate mean skin temperature ($T_{ms}$) according to the following equation (Nielsen & Nielsen, 1984):
Mean skin temperature \( (T_{ms}) = 9.429 + (0.137 \times \text{Forehead temp}) + (0.102 \times \text{Hand temp}) + \\
(0.29 \times \text{Back temp}) + (0.173 \times \text{Calf temp}) \)

The skin was wiped dry before measurements. Delta (\( \Delta \)) \( T_{ms} \) was calculated using pre and post values for exercise and immersion.

3.1.6 Fluid ingestion and sweat loss

Nude, dry body mass (accurate to 10 g) was recorded prior to the run after emptying the bladder. Water bottles were also weighed before and after the exercise to calculate fluid intake during the run. Body mass was recorded prior to and after HWI following the same procedure which allowed SR to be estimated with the following equation;

\[
\text{Sweat rate (SR)} = \frac{[(\text{change in body mass} + \text{fluid ingested}) / \text{time}]}{\text{[body mass (initial)]}}
\]

3.1.7 Heart rate

HR responses were measured continuously using a Garmin Forerunner 920XT heart rate monitor (Garmin, Neuhausen am Rheinfall, Switzerland). Average HR was recorded every 5 min during exercise and HWI.

3.1.8 Perceptual thermal comfort (TC) and thermal sensation (TS)

Measurements of TC and TS were recorded at 5 min intervals during exercise and HWI. A four-point scale (1-4) proposed by Gagge et al. (1967) (see Appendix D) was used to assess TC and a seventeen-point scale (0.0-8.0) was used to assess TS (Young et al., 1987) (see Appendix E).
3.2 Statistical analyses

Statistical procedures were performed within the Statistical Package for the Social Sciences (IBM SPSS, Version 22). Data are represented as mean ± standard deviation, unless stated otherwise. All assumptions of normality, homogeneity of variance and sphericity were met according to results of the Shapiro-Wilk, $F_{max}$ and Mauchly’s tests, respectively. The HR, $\Delta T_{ms}$, TC and TS measured during immersion were not normally distributed, and thus analysed using non-parametric Friedman’s two-way analysis of variance (ANOVA) to identify the any significant main effects for the relevant comparisons, with follow up pairwise comparisons using the Wilcoxon Signed Rank test and a Bonferroni adjusted alpha of .017. For these tests, effect sizes for the pairwise comparisons were described as “small” (r = .1), “medium” (r = .3) or “large” (r = .5) (Cohen, 1988). Effect of condition on all responses across the trials was modelled. Modelling of $T_{core}$ data included both absolute and change from baseline ($\Delta$) values. Baseline $T_{core}$ values were taken as 5 min prior to the run in C0, whilst in C1 and C8 $T_{core}$ over the 5 min prior to immersion. One-way repeated measures ANOVA tests were conducted to identify significant main effects for the data collected during treadmill runs as well as sweat, $T_{core}$ and pre and post $T_{ms}$ data during immersion.

3.3 Results

3.3.1 Treadmill Run

All measured variables were similar during the treadmill runs between trials, with no significant main effects observed in any case for the three different conditions.
3.3.2 HWI

Tcore data was not retrieved for one participant during immersion in C8 and thus statistics for the Tcore data was analysed using 11 participants. The absolute Tcore and Δ Tcore and responses to HWI are illustrated in Figure 3.2A and 3.2B, respectively. A significant main effect of condition on the absolute Tcore during immersion was identified, p < .001. Pairwise comparisons further indicated that absolute Tcore was significantly higher for C0 (37.83 ± 0.24°C), and C8 (37.74 ± 0.19°C), compared to C1 (37.39 ± 0.30°C; p < .05). The C8 condition resulted in similar absolute Tcore responses to C0.

A significant main effect was also identified when analysing the effect of condition on Δ Tcore during immersion p < .05. Pairwise comparisons further indicated that Δ Tcore during HWI was significantly higher for C0 (0.83 ± 0.25°C), compared to C1 (0.47 ± 0.17°C; p = .003) and C8 (0.56 ± 0.14°C; p = .031). However, C8 did not result in a statistically significant difference to Δ Tcore in comparison to C1.

The time course of changes for Tcore and Tms across the trial are illustrated in Figure 3.3. Complete Tcore data were not retrieved for two subjects, thus statistics for this data were analysed using 10 subjects.
Figure 3.2: Absolute (A) and delta (B) mean $T_{core}$ (core temperature) for each condition; 10 min (C0), 1 h (C1) and 8 h (C8) intervals ($n = 11$). **significantly different to C1, *significantly different to C0. The circles represent the individual responses.
Figure 3.3: $T_{\text{core}}$ (core temperature) (A) and $T_{\text{ms}}$ (mean skin temperature) (B) across the different conditions; 10 min (C0), 1 h (C1) and 8 h (C8) intervals ($n = 10$). *significantly different to C0 for
The $T_{ms}$ responses pre and post-exercise and HWI are illustrated in Figure 3(B). The $\Delta T_{ms}$ data during HWI was not normally distributed. Immersions increased skin temperatures for all three conditions, noted by higher $T_{ms}$ values at the end of HWI in comparison to pre-HWI values. Furthermore, the $\Delta T_{ms}$ varied significantly across the three conditions, as identified by a Friedman two-way ANOVA test, $X^2_F = 13.5$, $df = 2$, $N = 12$, $p = .001$. Follow up pairwise comparisons with the Wilcoxon Signed Rank test and a Bonferroni adjusted alpha of .017 indicated that C0 ($\text{Mean Rank} = 2.75$) induced significantly higher $\Delta T_{ms}$ compared to C8 ($\text{Mean Rank} = 1.25$) $T = 78$, $z = -3.059$ (corrected for ties), $N – Ties = 12$, $p = .002$. This effect can be described as “large”, $r = .88$. The difference in $\Delta T_{ms}$ for C0 ($\text{Mean Rank} = 2.75$), compared to C1 ($\text{Mean Rank} = 2.00$) approached significance ($p = .041$, $r = .59$), whereas the differences between C1 and C8 was not significant ($p = .050$, $r = .56$). No significant main effect was identified for sweat loss responses between conditions.

Due to technical problems, HR data was missing for one participant during C8 and therefore data for 11 participants was analysed. Main effects also identified by a Friedman two-way ANOVA demonstrated that average and maximal HR’s during immersion varied significantly across the 3 conditions, $X^2_F = 17.64$, $df = 2$, $N = 11$, $p = .000$, and $X^2_F = 19.19$, $df = 2$, $N = 11$, $p = .000$, respectively. Follow up pairwise comparisons indicated that C0 induced significantly higher average and maximal HR’s than C1, and also compared to C8, all “large effects”. However, differences between observed average HR values for C1 and C8 only approached significance, while significant differences were identified for maximal HR values between C1 and C8 (“large” effect, $r = .083$).

The mean perceptual and sweat responses during the 30 min HWI and 40 min run are summarised in Table 2. Data are represented as mean ± standard deviation.
Table 2: Summary of the mean perceptual and sweat responses to the 30 min HWI and 40 min run for 12 participants.

<table>
<thead>
<tr>
<th></th>
<th>HWI</th>
<th>RUN</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>C0</td>
<td>C1</td>
</tr>
<tr>
<td>TC</td>
<td>1.82 ± 0.52</td>
<td>1.92 ± 0.47</td>
</tr>
<tr>
<td>TS</td>
<td>5.11 ± 0.57</td>
<td>5.16 ± 0.85</td>
</tr>
<tr>
<td>SL (ml)</td>
<td>700 ± 376</td>
<td>482 ± 259</td>
</tr>
<tr>
<td>SR (ml/min/kg)</td>
<td>0.29 ± 0.16</td>
<td>0.20 ± 0.10</td>
</tr>
<tr>
<td></td>
<td>1.75 ± 0.53</td>
<td>1.87 ± 0.32</td>
</tr>
<tr>
<td></td>
<td>4.03 ± 0.52</td>
<td>4.05 ± 0.74</td>
</tr>
<tr>
<td></td>
<td>635 ± 143</td>
<td>645 ± 150</td>
</tr>
<tr>
<td></td>
<td>0.20 ± 0.03</td>
<td>0.20 ± 0.03</td>
</tr>
</tbody>
</table>

HWI = hot-water immersion, C0 = the condition where immersion was applied 10 min after exercise, C1 = the condition where immersion was applied 1 h after exercise, C8 = the condition where immersion was applied 8 h after exercise, TC = thermal comfort, TS = thermal sensation, SL = total sweat loss, SR = sweat rate.

No significant main effect was observed for TC during immersion for C0 (1.8 ± 0.5), C1 (1.9 ± 0.5) or C8 (2.0 ± 0.5) for the different conditions. However, a significant main effect for TS values was observed for the different treatments $X^2_f = 6.50$, df = 2, N = 12, $p = .039$. Follow up pairwise comparisons indicated that differences in TS during immersion for C8 (Mean Rank = 2.58) compared to C0 (Mean Rank = 1.58), approached significance ($p = .04$, $r = .59$), however differences between C8 versus C1 (Mean Rank = 1.83) were not significant ($p = .146$, $r = .42$), nor were the differences for C0 versus C1 ($p = .665$, $r = .13$)

### 3.4 Discussion

The major finding was that significantly lower absolute and $\Delta T_{core}$ values were measured during HWI when conducted 1 h after exercise (C1), compared to a 10 min delay (C0). The second major finding was that the absolute $T_{core}$ values were similar between C0 and an 8 h delay (C8), likely due to a circadian rhythm influence. Such findings support the
hypothesis of the study, despite similar sweating and perceptual responses during immersion observed for all three conditions.

In the current study, C0 induced significantly higher Δ $T_{\text{core}}$ responses in comparison to C1 and C8. More specifically, the mean Δ $T_{\text{core}}$ during 30 min HWI conducted within 10 min of exercise (C0) was $0.83 \pm 0.25 ^\circ \text{C}$, slightly lower than the mean rectal temperature increase (1.01 ± 0.31 °C) reported during ≤40 min HWI conducted immediately after exercise in a successful 6 day passive HA intervention (Zurawlew et al., 2016). Notably, the reported study used a training intervention and immersion duration was increased by the end of the intervention. This finding supports methodology of other studies where ‘immediate’ post-exercise heating accompanied training in cool/temperate environments. Such studies implemented HWI/sauna sessions soon after/during the warm down of, or within a few minutes of preceding exercise (Scoon et al., 2007; Stanley et al., 2015; M. J. Zurawlew et al., 2016). The data supports current recommendations (Scoon et al., 2007; Stanley et al., 2015; M. J. Zurawlew et al., 2016) that HWI within 10 min of exercise is best practice (for HA purposes) and why athletes should avoid delays between exercise and immersion, that could reduce the magnitude of the desired thermal stress.

Absolute $T_{\text{core}}$ at initiation of HWI was highest within C0. The progressive $T_{\text{core}}$ increase during HWI with longer delays (C1 or C8) was evident from the start of immersion, yet was only seen after 15 min of HWI during C0. Likely due to higher $T_{\text{core}}$ values at the beginning of C0 compared to other conditions. Absolute $T_{\text{core}}$ responses were similar in CO and C8 (8 h delay of HWI post-exercise; 2:00-3:30 PM). This could be due to circadian rhythm where $T_{\text{core}}$ peaked later in the day (between 3:00 and 5:00 PM) for most individuals, according to natural variations (Slomko & Zalewski, 2016). Therefore, athletes could alternatively wait until the afternoon to immerse to attempt to maximise $T_{\text{core}}$ responses, when they cannot immerse immediately after a morning training session.
The sweat responses and mean perceptual ratings were similar for all conditions. As immersion time progressed, higher TS and TC ratings were reported for all conditions, despite water temperature remaining constant. Likely a consequence of negating heat-loss when subjects were submerged in hot water (i.e., an uncompensable heat-loss environment).

The primary objective of the study design was to maximise the external validity of utilising a post-exercise HWI protocol for inducing heat stress. With this approach, the aim was to provide clear recommendations for endurance athletes using this strategy outside of the laboratory setting. Including a trial without HWI (i.e., exercise alone) acting as a pure ‘control’ would have strengthened the outcomes of the study. Notably, in the current study, only three time delays were implemented. More research could explore the use of other time intervals. A potential limitation of the study was that fluid intake was not controlled during the 40 min run during the intervention. Finally, the participants had commitments which limited their retainment in the lab during C1 and C8 time delays, which would have increased internal validity albeit at the cost of external validity.

3.5 Practical application

In order to achieve a larger thermoregulatory-adaptive responses than those induced by passive exposure to heat stress alone (e.g. 8 h after exercise), passively exposing athletes to heat following training may elicit larger rises in core temperature, a major contributing factor to heat adaptations (Casadio et al., 2016). Athletes should utilise immediate post-exercise HWI for the effective initiation of heat adaptations to induce HA, rather than allowing for delays of 1 or 8 h after training. We base this recommendation off observations of the largest core (0.83 ± 0.25°C), and $T_{ms}$ changes (2.00 ± 0.45°C), which occurred when baths were conducted in C0, in comparison to other conditions. Alternatively, if immediate immersion is not possible,
athletes should bath in the late afternoon when core and skin temperatures are naturally elevated (Yosipovitch et al., 1998). Future research could employ protocols combining immediate post-exercise HWI with afternoon exercise when T_{core} is naturally elevated according to circadian rhythm, or following training in additional clothing (Stevens, Plews, Laursen, Kittel, & Taylor, 2017) to investigate if Δ T_{core} values can be elevated further. Additionally, it may be worth including measurements of blood pressure and plasma volume to enable more robust conclusions from the outcomes of similar studies. Finally, transitions of 20 to 50 min should be investigated.

### 3.6 Conclusion

The findings of the present study produced new evidence that supports the suggestions in the literature that passive heat exposure applied after exercise should be initiated as soon as possible after the cessation of physical activity, for the purpose of HA. In the current study, significantly lower absolute and Δ T_{core} values were observed when HWI was conducted 1 h after exercise, compared to a 10 min delay. Additionally, when delays of 10 min or 8 h were used, similar absolute T_{core} values were achieved. These key findings suggest that athletes can maximise T_{core} responses necessary for HA by immersing directly (within 10 min) after exercise, and delays of 1 h should be avoided when implementing such interventions. If this is not practical, athletes should wait until the afternoon to immerse, when T_{core} is naturally elevated under the influence of circadian rhythm (Słomko & Zalewski, 2016). A protocol of 30 min at 39°C (waist-level immersion) is safe and appropriate. However, immersed athletes should be given clear instructions to discontinue HWI when they become uncomfortably hot or experience any symptoms of heat illness.
CHAPTER 4

STUDY 2

Can two weeks of daily hot-water immersion induce heat acclimation when training in a cool environment? A pilot study

Abstract

The aim of this study was to assess the effect of daily self-administered hot-water immersion (HWI), in addition to endurance training conducted in the field on physiological (lower body temperatures and increased sweat rate responses) and perceptual markers of heat acclimation (HA). Twelve recreationally-trained male endurance runners participated in a performance-matched parallel-group controlled trial that involved two weeks of outdoor training in cool conditions (16.7 ± 4.0°C; 58.8 ± 19.5 % relative humidity) either with (HWI; n = 6); or without (control, CN; n = 6) daily waist-level HWI at 39°C after the outdoor training. The HWI was performed unsupervised in the participant’s home, with a progressively increasing duration of 15 min to 56 min across the two weeks. No statistically significant differences were observed between groups (by independent sample t test or Shapiro Wilk test) for any delta (post - pre) values for the physiological (resting and average core temperature and heart rate during exercise, mean skin temperature change after exercise, sweat rate, and plasma volume) or perceptual (average thermal comfort and sensation and ratings of perceived exertion during exercise) responses measured between HWI and CN groups. Despite this, large effects (Cohen’s D effect sizes) were present for differences between delta values for resting and exercising heart rate, mean skin temperature change after exercise and thermal comfort between groups. In summary, the two weeks of daily HWI conducted outside the lab in a
training intervention did not significantly induce HA within a small sample. The current intervention showed promise for successful HA (evident by a number of large effects present in a number of responses); however, a similar study with a larger sample size may be warranted for more robust conclusions.

**Keywords:** Heat acclimation, passive heat acclimation, hot-water immersion, endurance, athletes.

### 4.0 Introduction

Adequate preparations are pivotal prior to competing in sport events that are scheduled to be held under high ambient temperatures. Consequently, endurance athletes may be looking for a competitive advantage for events like the Tokyo 2020 Olympic Games (Kakamu et al., 2017). Hot and humid environmental conditions contribute to physiological strain, and may consequently result in sub-optimal athletic performance (Akerman, Tipton, Minson, & Cotter, 2016). Training with repeated heat exposures is the primary countermeasure to maintain performance and combat associated physiological strain in the heat (Racinais, Alonso, Coutts, Flouris, Girard, Gonzalez-Alonso, et al., 2015), and the benefits of HA have been well documented (Daanen et al., 2018; Périard et al., 2015). Classic HA comprises 4 to 21 days of regular heat exposures (>30°C, >40% RH) with or without exercise at submaximal intensities in ambient temperatures sufficient to induce ample sweating and elevated body temperatures (Périard et al., 2015; Schmit et al., 2018; Willmott et al., 2017). HA may be active or passive. Active protocols involve combining heat stress with exercise, whilst passive HA involves heat exposure at rest. Physiological and psychological adaptations that typically accompany HA include reduced resting and exercising body temperatures and heart rates (HR), earlier onset and higher rates of sweating and skin blood flow, increased plasma volume (PV) and improved thermal comfort (TC) (Sawka et al., 2015). These integrated adaptations may contribute to
reduced risk of experiencing heat illnesses and improved physical performance in the presence of high heat stress. Athletes who train during winter months or in cooler climates, may opt to implement passive HA interventions, as they negate the need for exposure to high ambient temperatures (outdoors/simulated using specialized facilities) during training, and may thus be easier to implement and more affordable than active HA interventions. As such, knowledge gained from passive HA studies where routine outdoor training sessions are followed by heating interventions is required.

To date, passive HA strategies employed in research studies have implemented heating sessions using environmental chambers (Pallubinsky et al., 2017; Shido et al., 1999), saunas (Leppaluoto et al., 1986; Scoon et al., 2007; Stanley et al., 2015) and HWI (Brazaitis & Skurvydas, 2010; M. J Zurawlew & Walsh, 2018; M. J. Zurawlew et al., 2016). Most studies have focused on the physiological adaptations accompanying the interventions and have been conducted under controlled laboratory conditions. Some passive HA studies have implemented the post-exercise application of heat stress (between 30 and 40 min in duration) via use of saunas (87-89.9°C) / HWI (40°C) on 6 to 35 alternate or consecutive days. Such lab-based studies have reported improvements in a number of physiological and perceptual responses in subsequent heating tests (Scoon et al., 2007; Stanley et al., 2015; M. J. Zurawlew et al., 2016).

Interventions that have high ecological validity may be both more applicable for use in training programs and be of more interest to athletes who have limited access to a laboratory with an environmental chamber and/or other specialised facilities. As such, athletes and coaches may benefit from knowledge acquired from studies where HA interventions are both easy to implement and affordable in an ecologically valid training scenario, which could provide additional insight and enable recommendations for ease of incorporation of passive heating sessions into training regimes.

Therefore, the aim of this pilot study was to examine the effects of daily self-
administered HWI with or without preceding exercise across a two-week ecologically valid training intervention in runners, on physiological and perceptual markers of HA, compared to a control group.

4.1 Methods

4.1.1 Design

This pilot study was a performance-matched parallel-group controlled trial where trained runners each completed a familiarisation session, a pre-intervention testing session and a post-intervention testing session. Runners were assigned to one of two groups (HWI or CN) after the familiarisation session, where they were matched for performance and body fat percentage. Both groups completed two weeks of normal training between pre- and post-intervention testing. Additionally, the experimental group (HWI) was instructed to include self-administered daily HWI of increasing duration over the training period. A schematic of the study design is represented in Figure 4.1.
Figure 4.1: Study design. HWI = hot water immersion group, CN = control group.
Training sessions during the interventions were performed in the field (i.e., outdoors), and HWI was conducted at the participants’ homes, to investigate the real-world effect of using this strategy and enhance the ecological validity of the research.

4.1.2 Participants

Volunteer participants were recruited against the inclusion criteria: male runners over 18 years of age, training at least four times per week in the three months prior to the study. Individuals were not allowed to participate in the study if they had been diagnosed with low blood pressure, previous history of heat illness or displayed/reported any contra-indications to exercise as per the Exercise & Sport Science Australia Adult Pre-exercise Screening Questionnaire (Coombes & Skinner, 2014) (see Appendix C). Written informed consent was obtained before commencing any testing procedures using an institutionally approved consent form (see Appendix G). Females were excluded due to menstrual cycle mediated core temperature (T\text{core}) fluctuation (Mee, Peters, Doust, & Maxwell, 2017; Wendt et al., 2007).

Twelve participants were recruited and paired for their endurance running performance and body composition, then each in the pair was randomly allocated to either the HWI or CN group that was assessed in a pre-intervention performance test. The runner’s baseline performance was determined by the treadmill distance achieved in 20 min in an environmental chamber during the familiarisation maximal run. The body fat percentage was assessed by skinfolds by calliper and associated calculations. The HWI group had \( n = 6; \) (mean SD) age 39 ± 14 years; body mass 82.2 ± 16.3 kg; body fat 15.93 ± 3.16 %; distance achieved in the 20-min trial 3.87 ± 0.43 km; and the CN had \( n = 6; \) age 38 ± 13 years; body mass 85.2 ± 8.7 kg; body fat 15.05 ± 3.58 %; distance in the 20-min trial 3.85 ± 0.61 km. Participants were asked to continue with their usual training (checked by the researcher) for two weeks following the initial pre-program test and an initial rest day. Each group had specific requirements as presented below.
4.1.2.1 Hot-water immersion group

Participants in this group performed HWI every day for two weeks. A total of 14 baths with 557 min of immersion at waist-level, at water temperature of 39°C, were prescribed for each participant. Instructions to immerse immediately following exercise on training days; or if unable to do so, to conduct immersion in the evening of the training day were given. Initial immersion duration was set at 15 min, with additional 5 min increment in each subsequent day up to the 40 min mark, followed by a progressive 2 min daily increment for the remaining intervention days, since research has suggested heat exposure duration should be increased each day of HA for enhanced core temperature adaptations (Daanen et al., 2018). The bath protocol was designed based off current recommendations (Sawka et al., 2015; Zurawlew & Walsh, 2016) (see Appendix K) and stipulated that participants had to bath every day after the initial rest day that followed the pre-intervention test. On non-training days participants were asked to conduct HWI in the evening. They were given a thermometer (Coralife, Walnut Creek, United States), a laminated bath protocol (see Appendix H) and safety instructions (see Appendix I).

4.1.2.2 Control group

Participants in this group followed the same procedures for the intervention as the HWI group, apart from avoiding baths and saunas for the duration of the training program.

4.1.3 Familiarisation session

The familiarisation session was used to inform the participants about all procedures during the study, allowing the opportunity for participants to ask questions and familiarise themselves with the treadmill (Trackmaster TMX425 CP, Carrollton Texas, USA) and the custom-built environmental chamber (2.8 m x 2.8 m x 2.3 m).

Each participant was measured for body mass (Charder MS3200, Taichung City 412
Taiwan), stature (S+M Height Measure 2m Rosepark, SA) and seven skinfolds by caliper (Harpenden Calipers, Baty International, West Sussex, United Kingdom) with subjects wearing only running shorts to estimate body fat percentage following the International Society for the Advancement of Kinanthropometry (ISAK) recommended protocol (Marfell-Jones et al., 2012) the body fat percentage was estimated using the formula below (Siri, 1956).

\[
\text{Male Body Density} = 1.0988 - 0.0004(X_1)
\]

\[
\% \text{ Body Fat} = \frac{4.95}{\text{Body Density} - 4.5} \times 100
\]

Each participant was asked to provide details of their typical training week prior to the study. Participants then completed a 40 min run (preload) at approximately 75% effort (self-selected treadmill speed) in the environmental chamber [33.3 ± 0.5°C; relative humidity (RH) 45.6 ± 2.3 %]. Following this, they had a 10 min rest outside the heat chamber and then re-entered the chamber to complete a 20 min distance trial at their best effort at a self-selected speed. The distance for the 20 min trial was kept private from the participants, recorded and used to calculate the speed to be prescribed for the 40 min preload segment of the remaining experimental trials.

4.1.4 Pre-intervention testing

This test took place one week after the familiarisation session. Prior to attending the lab for their pre-intervention testing session, participants were asked to avoid caffeine and alcohol for a minimum of 24 h and to consume their usual pre-exercise meal (recorded and replicated for the post-test) as well as sip on water ad libitum for 2 h prior to attending the lab to ensure they are well-hydrated.

Upon arrival at the lab, participants self-inserted an e-Celsius ingestible telemetric capsule (BodyCap, Caen, France) to the depth of one finger for the continuous measurement of core temperature (T\text{core}). This technique has greater agreement with core body temperature
measured by rectal probe, compared with measurements of intestinal temperature measured via an ingested capsule (Kenefick et al., 2009). They also provided a midstream urine sample for analyses of hydration status using a portable osmometer (Pocket PAL-OSMO, Tokyo, Japan). Participants were deemed adequately hydrated if urine osmolality was <700 mOsm/kg of water, in line with previous research (Sawka et al., 2007). Finger-prick capillary blood sampling was also implemented to analyse haematocrit (Centurion Scientific K3 Series, Sussex, U.K.) and haemoglobin levels (HemoCue Hb 301, Angelholm, Sweden) in order to calculate plasma volume changes using the formulas below (Dill & Costill, 1974).

\[
\text{Blood volume}_{\text{pre}} = \text{Blood volume}_{\text{post}} \left( \frac{\text{haemoglobin}_{\text{post}}}{\text{haemoglobin}_{\text{pre}}} \right)
\]

\[
\text{Red cell volume}_{\text{pre}} = \text{Blood volume}_{\text{pre}} \left( \text{haematocrit}_{\text{pre}} \right)
\]

\[
\text{Plasma volume}_{\text{pre}} = \text{Blood volume}_{\text{pre}} - \text{red cell volume}_{\text{pre}}
\]

\[
\Delta \text{Plasma volume} (\%) = 100 \left( \frac{\text{Plasma volume}_{\text{pre}} - \text{plasma volume}_{\text{post}}}{\text{plasma volume}_{\text{post}}} \right)
\]

Participants were then weighed after emptying the bladder on electronic scales (OHAUS Defender 3000, Parsippany, USA) wearing only running shorts. Drinking water was adjusted to 30°C (to avoid cooling effects) and bottles were weighed to allow calculations for sweat rate (SR) and fluid intake. Participants were then fitted with a Garmin Forerunner 920XT heart rate monitor (Garmin, Neuhausen am Rheinfall, Switzerland) and ran in standardised footwear and clothing.

The test during this session was a 40 min run at a set intensity (75% average speed during distance trial in familiarisation session) on a treadmill in the environmental chamber with hot and humid conditions [33.3 ± 0.5°C; relative humidity (RH) 45.6 ± 2.3%]. Baseline measurements were taken prior to exercise, and a 5 min adjustment period was implemented inside the chamber before exercise. A pedestal fan (Dynabreeze, China) set at 10 km·h⁻¹ inside
the chamber was used to simulate the convection load of running outdoors during exercise, and participants had access to water at 30°C *ad libitum* in line with previous research (Stevens et al., 2017).

Physiological and perceptual measurements were taken from the participants during experimental sessions. These included continuous measurement of $T_{core}$ and HR as described in Study 1. Skin temperature measurements were taken at four sites on the right side of the body (forehead, right hand, lower back and right calf) using a dermal scanner (DermaTemp, Exergen Corporation, MA, USA) inside the chamber prior to and following exercise bouts to estimate mean skin temperature ($T_{ms}$) changes (Nielsen & Nielsen, 1984):

$$Mean \ skin \ temperature \ (T_{ms}) = 9.429 + (0.137 \times \text{Forehead temp}) + (0.102 \times \text{Hand temp}) + (0.29 \times \text{Back temp}) + (0.173 \times \text{Calf temp})$$

Perceptual measurements of thermal sensation (TS) (Young et al., 1987), thermal comfort (TC) (Gagge et al., 1967; Schweiker et al., 2017) and rating of perceived exertion (RPE) (Borg, 1998) were taken every five minutes during exercise using appropriate scales (see Appendices E & D). Body mass was measured prior to and after exercise, after towel-drying as best as possible, and water bottles were weighed in the same manner to calculate fluid consumption. Sweat rates were estimated via the following equation:

$$Sweat \ rate = [\frac{(\text{change in body mass + fluid ingested})}{\text{time}}]/[\text{body mass (initial)}]$$

All equipment was used according to its operating instructions.

4.1.5 Training

After initial testing, the participants matched their “typical training week” (as reported to the researcher prior to the start of the study) for two weeks outdoors in cool conditions ($16.7 \pm 4.0°C, 58.8 \pm 19.5\% \ RH$). The participants were unsupervised during the sessions, but
monitored online by the researcher with Strava training management software and a daily written training log (see Appendix J) which included notes on the baths (duration, time delay between training and immersion and temperature) and training sessions conducted each day (average heart rate and outside temperature and humidity). Compliance was also checked via weekly phone calls.

4.1.6 Post-intervention testing

The post intervention test replicated and took place at the same time of the day, 16 days after the ‘pre-intervention testing’ protocol. Pre-test meals were also replicated and individuals followed the same instructions prior to arrival for the test.

4.2 Statistical analyses

Statistical procedures were performed within the Statistical Package for the Social Sciences (IBM SPSS, Version 22). Data are represented as delta (Δ) ± standard deviation, unless stated otherwise. For statistical analyses, the data of two participants were removed due to experiencing injuries prior to post-intervention testing. Performance outcome was not included in the analyses due to technical issues with the treadmill in several participants’ post-test. Independent samples t tests were used to compare delta (Δ) (i.e., post – pre) values for all other variables (perceptual and physiological) measured for participants in the CN group (n = 5) to the values for the HWI group (n = 5). Levene’s tests for the equality of variances were all non-significant, apart from the RPE variable (for which the Shapiro Wilk statistic was non-significant, meaning normality assumption was not violated), thus equal variances were assumed. Due to the small sample size of the pilot study, Cohen’s D effect sizes were utilized to give an indication of the magnitude of differences observed (Cohen, 1988).
4.3 Results

Four out of the six participants in the HWI group completed all 14 baths, three of them followed the exact prescribed durations (total duration = 557 min), with the fourth participant reducing the duration of two baths (total time lost = 49 min). The remaining two participants were unable to conduct one bath each (44 min and 30 min) but otherwise followed the protocol as instructed, with total immersion durations of 513 and 527 min across the two-week intervention. When participants managed to immerse soon after training, the average time lapse between exercise and immersion reported was 11.2 ± 2.23 min. For the duration of the entire intervention, three participants reported more evening (14, 10 and 9) than immediate (1, 2 and 5) baths and the other three participants reported more immediate (9, 8 and 8) than evening (5, 5 and 6) baths. With regards to only training days of the intervention, the total number of immediate baths (total = 33) surpassed that of the total number evening baths (total = 19), as reported by participants.

The physiological responses to the intervention are illustrated in Figure 4.2.
Figure 4.2: Physiological response changes for HWI and CN groups after the intervention.

Delta values (Δ) are reported (post-pre) for (a) resting $T_{\text{core}}$; (b) average $T_{\text{core}}$ during exercise; (c) resting HR; (d) average HR during exercise; (e) average SR during exercise and (f) average $T_{\text{ms}}$ change after exercise. The circles represent the individual responses.
4.3.1 Temperature

Changes (post compared to pre-values) in resting $T_{core}$ (average $T_{core}$ over 5 min prior to exercise) were not significantly different for the HWI group ($M = -0.11$, $SD = 0.30^\circ C$) compared to the CN group ($M = -0.02$, $SD = 0.16^\circ C$), $t(8) = 0.570$, $p = 0.584$, two-tailed, with only a “small” effect present $d = 0.36$. Similarly, no significant differences were observed between HWI ($M = -0.02$, $SD = 0.24^\circ C$) and CN ($M = 0.03$, $SD = 0.18^\circ C$) for changes in exercising $T_{core}$ (average $T_{core}$ during 40 min of running at a set workload) values, $t(8) = 0.389$, $p = 0.707$, two-tailed, $d = 0.25$ (“small” effect size).

Mean skin temperature changes after exercise were lower for the HWI group ($M = -0.22$, $SD = 0.43^\circ C$) and higher for the CN group ($M = 0.31$, $SD = 0.50^\circ C$) after the intervention. These differences were non-significant $t(8) = 1.780$, $p = 0.113$, two-tailed, with a “large” effect size, $d = 1.13$.

4.3.2 Heart rate

No statistically significant differences were observed between changes (post-pre) for measures of both resting and average exercising HR for both groups. However, for resting HR, the HWI group had a larger reduction ($M = -7$, $SD = 11$ bpm) than the CN group ($M = 0$, $SD = 8$ bpm), $t(8) = 1.179$, $p = 0.272$, two-tailed, with a “large” effect size identified, $d = 0.75$. Similarly, the exercising HR was reduced by a larger amount for the HWI group ($M = -6$, $SD = 6$ bpm) compared to the CN group ($M = 1$, $SD = 5$ bpm). The differences between the two groups was not statistically significant, $t(8) = 2.172$, $p = 0.062$, two-tailed, with a “large” effect size, $d = 1.37$.

4.3.3 Sweat rate

The difference in SR ($L^1/min^1/kg^1$) changes (post - pre) during exercise between HWI ($M = 0.000012$, $SD = 0.00005$) and CN ($M = -0.000026$, $SD = 0.00004$) groups was not
statistically significant, $t(8) = -1.281, p = 0.236$, two-tailed, and the effect size was “large” $d = 0.81$.

4.3.4 Plasma volume

No significant differences were observed for resting PV changes between HWI ($M = -1.14, SD = 4.64 \%$) and CN ($M = -3.74, SD = 12.41 \%$) groups, $t(8) = 0.439, p = 0.672$, two-tailed, with a “small” effect size, $d = 0.28$.

4.3.5 Perceptual responses

The perceptual responses to the intervention are illustrated in Figure 4.3.
Figure 4.3: Perceptual response changes during exercise for HWI and CN groups after the intervention. Delta values (Δ) are reported (post-pre) for (a) average TS; (b) average TC and (c) average RPE. The circles represent the individual responses.
The TC during exercise improved for the HWI group (\( M = -0.23, \ SD = 0.48 \) AU), but not for the CN group (\( M = 0.09, \ SD = 0.22 \) AU). A “large” effect size \( d = 0.85 \) was present, with the difference between groups lacking statistical significance \( t(8) = 1.346, \ p = 0.215 \), two-tailed. Similarly, TS changes were not statistically significant between HWI (\( M = 0.16, \ SD = 0.33 \) AU) and the CN (\( M = 0.22, \ SD = 0.34 \) AU), \( t(8) = 0.270, \ p = 0.794 \), two-tailed, with only a “small” effect present, \( d = 0.17 \). Additionally, no significant differences were observed for RPE between HWI (\( M = -0.20, \ SD = 1.05 \) AU) and CN (\( M = -0.13, \ SD = 0.19 \) AU), \( t(8) = 0.146, \ p = 0.887 \), two-tailed.

### 4.4. Discussion

The objective of this pilot investigation was to examine the effects of implementing an ecologically valid 2-week daily HWI intervention for endurance athletes training in a cool environment. A range of physiological and perceptual responses were measured to determine HA status. There were two major findings of the current pilot study. The first was the absence of significant differences identified between HWI and CN for all of the mean Δ values (post - pre) of the physiological/perceptual responses measured. The second was the presence of “large effects” of differences between Δ values (post minus pre) for measurements of both resting and exercising HR, \( T_ms \) change after exercise and TC between HWI and CN groups. As such, a larger study is warranted to determine if these effects could be significant with more participants.

The resting and exercising HR values were lower for the HWI group in the post compared to pre-test values, unlike the CN group, with “large effects” of differences between groups noted for both measures. This finding is similar to those reported following passive HA lab-based studies that implemented similar designs with the immediate application of heat.
stress using HWI and saunas (Stanley et al., 2015; M. J. Zurawlew et al., 2016). These other studies reported a reduction in HR values measured at the end of running performance tests held in a heat chamber after a post-exercise HWI intervention (Zurawlew & Walsh, 2018; Zurawlew et al., 2016), or reduced resting HR (trivial to moderate amount) and HR recovery after exercise in cyclists after a post-exercise sauna intervention (Stanley et al., 2015). Notably, HR reduction is identified as the most rapid adaptation resulting from HA training, and occurs within 4–5 days and achieved after only one week (Périard et al., 2015). This adaptation may contribute to maintenance of cardiac output and blood pressure during submaximal exercise, when additionally accompanied by increased stroke volume (Périard et al., 2016).

There were “small effects” observed for the differences in delta PV between groups after the intervention. Changes occurred for HWI group that were similar to the CN group, a finding dissimilar to those reported by post-exercise sauna bathing HA studies that were lab-based (Scoon et al., 2007; Stanley et al., 2015). This finding opposes previous research that has identified PV expansion as an early adaptive HA response typically apparent in the first 3-4 days of HA, which is accompanied by HR-based response changes as consequence (Périard et al., 2016; Taylor & Cotter., 2006). Expansion of PV may benefit endurance athletes via the possible contribution to improved maximal cardiac output and capacity in thermoregulation by sweating, potentially enabling better exercise performance (Lorenzo et al., 2010).

A “large effect” was identified for the differences between groups for T_{ms} changes after exercise between groups, with the HWI group displaying reductions after the intervention unlike the CN group, despite no statistical significance. Lower skin temperature responses after HA could benefit athletes by enabling a larger thermogradient between the core and periphery facilitating heat loss and by aiding the redistribution of blood from peripheral to central circulation, possibly a result of earlier sweating responses (Périard et al., 2015).
Additionally, a “large effect” was identified for the difference between delta TC values between groups following the intervention. The findings from the current study support research that has indicated that TC is influenced largely by skin temperature, with $T_{core}$ primarily determining physiological responses (Bulcao et al., 2000; Mower, 1976), since we did not observe large effects of differences between groups for $T_{core}$ following the intervention. As such, findings from the current study are less in favour of other research that has reported that $T_{core}$ and skin temperature contribute equally to TC (Frank, Raja, Bulcao, & Goldstein, 1999). Whilst some research suggests thermal perception does not primarily influence pacing strategy in trained athletes (Barwood, Corbett, White, & James, 2012), other research has highlighted that improved perceptual responses in the heat during exercise may benefit athletes competing in ultra-endurance based events via the influence it may have on pacing strategies (McCormick, Meijen, & Marcora, 2015). The mechanism by which such improvements may influence pacing strategies (and potentially improve endurance performance in hot conditions) could be that subjects may subsequently increase voluntary workloads to match previous levels of psychophysiological strain that were present before adaptation occurred (Cheung, 2010).

The information gathered from this pilot intervention indicates that while immediate post-exercise application is recommended (Scoon et al., 2007; Stanley et al., 2015; M. J. Zurawlew et al., 2016) rather than allowing for greater time delays between training and heating sessions, it may be difficult to consistently immerse directly after exercise in an ecologically valid training scenario when HWI is conducted external to the lab. More specifically, in the current study, when instructed to immerse immediately after training, or in the evening when immediate HWI was not possible, runners conducted 64% of their HWI’s immediately (~10 min) after training sessions, and the remainder in the evenings on training days.
The lack of significant differences between groups for responses measured in the study does not allow us to conclude that the 2-week daily self-administered HWI intervention with may effectively induce HA. These results differ from other investigations of similar nature that implemented 40 minutes of daily post-exercise HWI (Zurawlew & Walsh, 2018; Zurawlew et al., 2016), where significant changes in the markers of successful HA were identified after 6 days. However, these studies were conducted in controlled environments and not in the field (Zurawlew & Walsh, 2018; Zurawlew et al., 2016). In this pilot investigation, no significant differences were found using null hypothesis significance testing (as expected with a small sample size ($n = 12$) that could increase the probability of type 1 error), however, several large effect sizes were demonstrated, therefore, a similar intervention with an expanded sample size is recommended to enable more robust conclusions and evidence of outcomes. Notably, using G*Power 3.0.10 software, a follow up sample size calculation was made after the pilot study and the required group sample size given was 28.

4.5. Conclusion

In this pilot study where two weeks of normal endurance training with additional self-administered waist-level daily HWI at 39°C, no significant changes were found in the physiological and perceptual markers of heat adaptations in a cohort of recreationally-trained male runners. However, a number of “large effects” with regards to classic markers of HA were noted that may warrant further investigations with a larger sample size. Runners reported more post-exercise baths (within ~10 min of training) than evening baths on training days, indicating it may be possible to incorporate aspects of this intervention in an ecologically valid training scenario, when specialist HA facilities are unavailable, provided adequate organisation and prioritisation of heating sessions by athletes. While current HA research recommends traditional active-based HA interventions that replicate expected environmental conditions
when preparing for competition in the heat over passive methods for most effective development of HA adaptations (Périard et al., 2016; Sawka et al., 2015; Taylor, 2006), the current study found no negative implications of employing HWI after training in a cool environment to induce HA adaptations. It may be worth exploring physiological responses prior to and after the intervention by implementing a trial using a fixed heat production, as well as include a performance trial in future areas of research to compliment the findings. Future studies could implement a cross over design training study, where the athlete completes both conditions (with a wash out period), or use more athletes of higher training status who may prioritise training more than recreational runners, in order to identify if any differences could be observed from the current study.
CHAPTER 5

DISCUSSION AND CONCLUSIONS

5.0 Discussion

The aim of the thesis was to examine the effects of passive heating by HWI as a HA strategy for endurance athletes residing in a cool environment. Undertaking HA training is the primary countermeasure to reduce the risk of heat illness and impairment of athletic performance when competing under high ambient temperatures. Unlike traditional active HA, passive HA does not require exercise under high ambient conditions and may be more affordable and practical to incorporate into training programs for athletes training in winter or residing in cooler environments. Passive HA research to date has explored the use of saunas, heat chambers and HWI to provide the heat stimuli necessary to induce desirable heat adaptations. A search of the literature identified that current research has placed a large emphasis on active HA strategies in comparison to passive HA. Furthermore, an extensive amount of research has reported positive HA outcomes, but less is known about the effect of implementing such lab-based (active/passive) strategies into an ecologically valid training scenario. Naturally, in the face of high-profile athletic events that are scheduled to be held in an environment with a high wet-bulb thermometer index, such as the Tokyo 2020 Olympics, coaches and athletes could benefit from research with an ecologically-valid approach.

Two related studies were therefore conducted and presented in this thesis to address the gaps identified after reviewing the literature in passive HA research and to provide more insight on the effect of implementing such programs, using two different models. Both studies were designed to enable more insight on the efficacy of using HWI after training as a passive HA intervention for endurance athletes. Time intervals between exercise and application of heat
stress via hot-water immersion (HWI), and a pilot two-week training intervention, where daily HWI was conducted in the field, were examined to explore the potential for producing heat adaptations when economic and/or logistical factors might limit the application of traditional active-based HA strategies (or access to specific facilities).

Study 1 was designed to determine the most effective out of three specific time intervals between exercise and HWI, to maximise the thermoregulatory responses to heat for the purpose of HA. Further, Study 1 was conducted to address the research question pertaining to whether delaying immersion an hour after exercise cessation, or immersing later in the afternoon of the training day, could be as effective as immediate post-exercise HWI, in terms of raising core temperature ($T_{core}$) to stimulate heat adaptations, and to determine any impact on heart rate, sweat loss and skin temperature responses.

In the Study 2 a pilot training intervention was implemented that involved daily HWI in combination with normal training, and the recommendation to immerse as soon as possible after exercise (which was the timeframe deemed most effective from Study 1). The aim was to assess the effect of two weeks of normal training in cool conditions in combination with daily HWI conducted at home, on the physiological and perceptual adaptive responses to heat in order to give an indication of response outcomes typical of HA that may occur in a larger scale study using such a protocol.

Both studies were conducted to provide more insight on the use of HWI following training as a passive HA strategy for athletes who may have limited access to facilities/outdoor temperatures required by active strategies.

The findings of both studies in the current thesis contribute to knowledge pertaining to the use of the post-exercise HWI as a passive HA strategy for endurance athletes. The outcomes include evidence-based recommendations for athletes/coaches who may want to implement
such a strategy within their program. After noting that immediate immersion may elicit the highest $T_{\text{core}}$ responses in Study 1 (Fig. 3.2), the subsequent training study (Study 2) was designed with the prescription to immerse as soon as possible after training. Notably, similar lab-based sauna and HWI studies conducted to date have also used this prescription in their interventions (Scoon et al., 2007; Stanley et al., 2015; Zurawlew et al., 2016). Study 2 was conducted to test how realistic implementing this strategy in an ecologically valid training scenario could be, and whether bathing after training at home could be effective for inducing markers of HA. The thesis provides evidence that it is possible to implement immediate HWI after training in the field, provided athletes make an effort to prioritise heating sessions. Additively, the research suggests that such a strategy may be effective for inducing HA adaptations since a number of “large effects” were noted for delta (post-pre) values for a number of physiological (Fig. 4.2) and perceptual (Fig. 4.3) responses following the intervention. A larger sample sized study may enable more robust conclusions.

5.1 Major findings

The major findings of the two studies are summarised below;

1. Study 1 identified significantly lower absolute and $\Delta T_{\text{core}}$ values measured during HWI conducted 1 h after exercise (C1), compared to a 10 min delay (C0). The hypothesis of the study is supported by the fact that the $\Delta T_{\text{core}}$ alone was significantly higher for C0 compared to both other conditions, despite similar sweating and perceptual responses during immersion observed for all three conditions.

2. The second major finding of Study 1 was that the absolute $T_{\text{core}}$ values were similar between C0 and an 8 h delay (C8), likely due to a circadian rhythm influence, since core and skin temperatures are naturally higher in the late afternoon. This finding indicates that HWI immediately (>10 min) after exercise or waiting till the late
afternoon/evening may be more effective for inducing HA adaptations compared to immersing 1 h after morning training.

3. Study 2 identified that the addition of daily waist-level HWI at 39°C with increasing duration for two weeks conducted at home did not significantly alter physiological or perceptual responses that typically accompany heat adaptation with a small sample size. Notably, the small sample size of the pilot study was \( n = 6 \) in each of the experimental and control groups, and therefore the potential for significant effects to be observed with a larger sample size should not be ruled out. A suggested sample size of 28 matched pairs was given using calculations made with G*Power 3.0.10 software, and may be used in a larger study.

4. The second major finding of Study 2 was the identification of “large effects” (as per Cohen’s D effect size) of differences between \( \Delta \) values (change scores) for measurements of both resting and exercising heart rate, mean skin temperature change after exercise and thermal comfort between experimental and control groups. This finding may indicate the potential for significant improvements to be identified with a similar study using a larger sample size. Reduced skin temperatures during subsequent exposure to hot conditions may reduce skin blood flow requirements under the same conditions, therefore reducing thermoregulatory strain in the heat. As such, the reduced skin temperature responses may have contributed to the improved perceptual responses after the intervention, since research has identified that thermal comfort is largely dependent on skin temperature (Bulcao et al., 2000). Additionally, improvements in thermal comfort during exertional heat stress may influence pacing strategies for ultra-endurance athletes, linking these physiological and perceptual adaptations to potential improvements in endurance performance in the heat (McCormick et al., 2015).
5. Study 2 also identified that the immediate application of HWI after exercise should not be ruled out as a practical HA strategy for athletes who intend on using baths at home, since participants reported slightly more immediate baths than evening baths on training days, when asked to train and conduct HWI externally on their own accord.

5.2 Practical applications

The current findings indicate that when HWI is to be used for the intent of inducing HA, it should be commenced immediately after exercise with minimal delay, when $T_{\text{core}}$ is already elevated, to maximise the heat load of a training session. If immediate immersion is not possible, athletes should bath in the late afternoon in line with the natural circadian elevation of core and skin temperatures, rather than immersing an hour after training.

With regards to implementation of such a protocol in the field managed by athletes themselves, results of the second study indicate that it may be indeed be possible to conduct immediate post-exercise HWI within the daily training environment using a bath at home, provided adequate organisation and prioritisation of heating sessions are implemented for the intention of achieving HA. Importantly, when coaches and athletes use HWI to induce heat stimuli, athletes and coaches should ideally gauge perceptions of hotness and comfort by using appropriate perceptual scales, and regularly monitor and ensure that water temperatures are within the prescribed range. Furthermore, it is recommended to monitor $T_{\text{core}}$ as often as possible, and the discontinuation of HWI if any feelings of dizziness, nausea, muscle cramps or severe headaches are experienced.

Two weeks of normal training with additional post-exercise waist-level HWI at 39°C with increasing immersion duration did not induce significant heat adaptation in recreationally-trained male runners. Considering that there were no negative consequences from the heat exposure in Study 2, and other studies have demonstrated significant improvements (Zurawlew
& Walsh, 2018; Zurawlew et al., 2016), athletes should experiment with post-exercise hot-water immersion as a HA strategy when active HA is not possible.

5.3 Future research directions

After conducting the research to address the research questions of this thesis, potential future areas of research were identified and are summarised below.

1. Additional research could explore protocols for athletes training in a cool environment that combine immediate post-exercise application of heat stress with afternoon exercise when $T_{core}$ is already elevated under the influence of circadian rhythm, or after training with additional clothing.

2. There may be a potential for significant HA to be induced passively with a larger sample-sized study that implements a design similar to the second study conducted in this thesis (two weeks of waist-level HWI of at 39°C with increasing duration each day combined with normal endurance training in recreationally-trained male runners), as indicated by a number of large effect sizes identified for some HA markers.

3. It may be worth also investigating athletes of higher training status, who may prioritize training more than recreational runners, in such a study, in order to identify if any differences could be observed from the current study with a similar design. Importantly, some research suggests that athletes of higher training status may already display partial heat acclimation characteristics, and therefore may experience less physiological and performance improvements as a result of an HA intervention than those who are less trained (Corbett et al., 2018).

4. The intervention used in the second study could also be replicated with a female athletic population. Further to this, a critical comparison between an established active HA
method, and a passive heating protocol to determine equality (or otherwise) of physiological and performance responses to the respective protocols may be warranted in future research.

5. Further research could also explore the comparison between a traditional standard magnitudes of heat load approach with that of progressive overload to see if there are any differences in responses at the end of the intervention.

6. Active HA studies that involve training in the heat may look at adding daily HWI to their protocols to see if any additional beneficial effects may occur as a consequence.

7. After conducting the literature search, it is evident a systematic review or meta-analysis may be a valuable contribution to the field of passive HA in future research.

8. Future studies may also consider testing pre-post intervention responses at both spontaneous (naturally occurring) and identical (clamped) skin temperature
REFERENCE LIST


West, M., Sill, G., York, T., & Kaplan, J. (2015). Surface area to volume ratio affects the rate of thermal heat loss and retention in animals found in cooler environments. JIBI, 2(1).


Appendix A
Ethics approval (Study 1)

SCU HUMAN RESEARCH ETHICS COMMITTEE (SCU HREC)

NOTIFICATION
HREA Application Approval

To: Dr Chris Stevens and Ms Storme Healcoate
From: SCU Human Research Ethics Committee (HREC)
Project name: Acute responses to post-exercise hot water immersion
Approval Date: 4th July 2017
Approval Number: EDN-17-121
Expiry Date: 3rd July 2020

Dear Chris and Storme,

Thank you for the HREA application received 12th June 2015. This was considered by the SCU HREC at the Meeting on 26th June 2017 and is approved. Please note the ethics approval number above.

The nominated participating sites in this project include:

1. Southern Cross University Sport Science Labs, Lismore Campus.

This approval is subject to the following conditions being met:

1. The Coordinating Principal Investigator will immediately report anything that might warrant review of ethical approval of the project on the Adverse Events form.
2. The Coordinating Principal Investigator will immediately notify the SCU HREC, on the appropriate form, of any change in protocol.
3. The Coordinating Principal Investigator will report to the SCU HREC annually in the specified format and notify HREC when the project is completed.
4. The Coordinating Principal Investigator will notify the SCU HREC if the project is discontinued at a participating site before the expected completion date, with reasons provided.
5. The Coordinating Principal Investigator will notify the SCU HREC of any plan to extend the duration of the project past the approval period listed above and will submit any associated required documentation.

A copy of this ethical approval letter must be submitted by all site Principal Investigators to the Research Governance Office or equivalent body or individual at each participating institution in a timely manner to enable the institution to authorise the commencement of the project at its site.

This letter constitutes ethical approval only. This project cannot proceed at any site until separate research governance authorisation has been obtained from the CEO or Delegate of the institution under whose auspices the research will be conducted at that site.

Should you have any queries about the SCU HREC’s consideration of your project please contact ethics.lismore@scu.edu.au. The SCU HREC Terms of Reference, membership and standard forms are available from http://scu.edu.au/research/index.php?did=1120#art1215.

SCU HREC wishes you every success in your research.

Kind Regards,

per
Prof. Bill Boyd
Chair, Human Research Ethics Committee
Appendix B

Consent form (Study 1)

Title of research project: Acute responses to post-exercise hot-water immersion

Name of researcher: MissStorme Heathcote and Dr Chris Stevens

I agree to take part in the Southern Cross University project as specified in the information statement that I have read in full and retained. [Yes ☐ No ☐]

I understand that I should not participate in the above study if I have a health-related condition that restricts my capacity to exert myself or if I have experienced heat exhaustion. [Yes ☐ No ☐]

I agree to have my height, weight, and skinfolds measured. [Yes ☐ No ☐]

I agree to running at a moderate-hard intensities on a treadmill for 40 minutes [Yes ☐ No ☐]

I agree to take a hot water bath at 38-40 degrees Celsius for 30 minutes [Yes ☐ No ☐]

I agree to have sensors placed on my body for the measurement of skin temperature and heart rate [Yes ☐ No ☐]

I agree to ingest a telemetric capsule for the measurement of gastro-intestinal temperature and wear the ‘no-MRI’ wristband for 48 h post ingestion. [Yes ☐ No ☐]

I agree to cease the bath if I feel light-headed, have difficulty breathing, or experience sudden or excessive pain, cramping, nausea, vomiting or severe headache. [Yes ☐ No ☐]

I understand that my participation is voluntary and that I can cease my participation at any time. [Yes ☐ No ☐]

I understand that my participation in this research will be treated with confidentiality. [Yes ☐ No ☐]

I understand that any information that may identify me will be de-identified at the time of analysis of any data and no identifying information will be disclosed or published. [Yes ☐ No ☐]

I understand that all information gathered in this research will be kept confidentially for 7 years at the University. [Yes ☐ No ☐]

I consent to the data collected in this research being used in future research. [Yes ☐ No ☐]

I am aware that I can contact the researchers at any time with any queries. Their contact details have been provided to me. [Yes ☐ No ☐]

I understand that this research project has been approved by the SCU Human Research Ethics Committee [Yes ☐ No ☐]

Participant’s name: _____________________________ Signature _____________________________

Date: __________________________ Email _____________________________

☐ Please tick this box and provide your email or mail address below if you wish to receive feedback about the research
Appendix C

Exercise & Sport Science Australia Pre-exercise Screening Tool

ADULT PRE-EXERCISE SCREENING TOOL

This screening tool does not provide advice on a particular matter, nor does it substitute for advice from an appropriately qualified medical professional. No warranty of safety should result from its use. The screening system in no way guarantees against injury or death. No responsibility or liability whatsoever can be accepted by Exercise and Sports Science Australia, Fitness Australia or Sports Medicine Australia for any loss, damage or injury that may arise from any person acting on any statement or information contained in this tool.

Name: __________________________
Date of Birth: ____________________ Male [ ] Female [ ] Date: ____________________

STAGE 1 (COMPULSORY)

AIM: to identify those individuals with a known disease, or signs or symptoms of disease, who may be at a higher risk of an adverse event during physical activity/exercise. This stage is self-administered and self-evaluated.

Please circle response

1. Has your doctor ever told you that you have a heart condition or have you ever suffered a stroke?  Yes [ ] No [ ]
2. Do you ever experience unexplained pains in your chest at rest or during physical activity/exercise? Yes [ ] No [ ]
3. Do you ever feel faint or have spells of dizziness during physical activity/exercise that causes you to lose balance? Yes [ ] No [ ]
4. Have you had an asthma attack requiring immediate medical attention at any time over the last 12 months? Yes [ ] No [ ]
5. If you have diabetes (type I or type II) have you had trouble controlling your blood glucose in the last 3 months? Yes [ ] No [ ]
6. Do you have any diagnosed muscle, bone or joint problems that you have been told could be made worse by participating in physical activity/exercise? Yes [ ] No [ ]
7. Do you have any other medical condition(s) that may make it dangerous for you to participate in physical activity/exercise? Yes [ ] No [ ]

IF YOU ANSWERED ‘YES’ to any of the 7 questions, please seek guidance from your GP or appropriate allied health professional prior to undertaking physical activity/exercise.

IF YOU ANSWERED ‘NO’ to all of the 7 questions, and you have no other concerns about your health, you may proceed to undertake light-moderate intensity physical activity/exercise.

I believe that to the best of my knowledge, all of the information I have supplied within this tool is correct.

Signature __________________________ Date __________________________

ESSA - EXERCISING & SPORTS SCIENCE AUSTRALIA
Fitness Australia
SPORTS MEDICINE AUSTRALIA
Appendix D

Thermal comfort scale

(Gagge et al., 1967; Schweiker et al., 2017)

*How comfortable do you feel with the temperature of your body?*

<table>
<thead>
<tr>
<th>PERCEIVED THERMAL COMFORT</th>
<th>RATING</th>
</tr>
</thead>
<tbody>
<tr>
<td>COMFORTABLE</td>
<td>1</td>
</tr>
<tr>
<td>SLIGHTLY COMFORTABLE</td>
<td>2</td>
</tr>
<tr>
<td>UNCOMFORTABLE</td>
<td>3</td>
</tr>
<tr>
<td>VERY UNCOMFORTABLE</td>
<td>4</td>
</tr>
</tbody>
</table>
Appendix E

Thermal sensation scale

(Young et al., 1987)

*How does the temperature of your body feel?*

<table>
<thead>
<tr>
<th>PERCEIVED THERMAL SENSATION</th>
<th>RATING</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unbearably Cold</td>
<td>0.0</td>
</tr>
<tr>
<td></td>
<td>0.5</td>
</tr>
<tr>
<td>Very Cold</td>
<td>1.0</td>
</tr>
<tr>
<td></td>
<td>1.5</td>
</tr>
<tr>
<td>Cold</td>
<td>2.0</td>
</tr>
<tr>
<td></td>
<td>2.5</td>
</tr>
<tr>
<td>Cool</td>
<td>3.0</td>
</tr>
<tr>
<td></td>
<td>3.5</td>
</tr>
<tr>
<td>Comfortable</td>
<td>4.0</td>
</tr>
<tr>
<td></td>
<td>4.5</td>
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<tr>
<td>Warm</td>
<td>5.0</td>
</tr>
<tr>
<td></td>
<td>5.5</td>
</tr>
<tr>
<td>Hot</td>
<td>6.0</td>
</tr>
<tr>
<td></td>
<td>6.5</td>
</tr>
<tr>
<td>Very Hot</td>
<td>7.0</td>
</tr>
<tr>
<td></td>
<td>7.5</td>
</tr>
<tr>
<td>Unbearably Hot</td>
<td>8.0</td>
</tr>
</tbody>
</table>
Appendix F

Office of Research

Ethics approval (Study 2)
SOUTHERN CROSS UNIVERSITY HUMAN RESEARCH ETHICS COMMITTEE
(SCU HREC)
NOTIFICATION
Human Research Ethics Application Approval

To: Dr Christopher Stevens, Dr Lee Taylor and Storme Heathcote
From: Professor Colleen Cartwright
Chair, Human Research Ethics Committee (HREC)
Project name: Effects of 2-weeks hot-water immersion on heat acclimation and endurance performance in male runners
Approval Date: 29 May 2018
Approval Number: ECN-18-042
Expiry Date: 28 May 2021

Dear Chris, Lee and Storme,

Thank you for the Human Research Ethics Application (HREA) received 15 March 2018. The Application was considered by the SCU HREC at the meeting on 9 April 2018 and is approved. Please note the ethics approval number above.

The nominated participating site/s in this project is/are:
Site 1: Southern Cross University, Lismore Campus,
Site 2: Southern Cross University, Coffs Harbour Campus

This approval is subject to the following conditions being met:

1. The Coordinating Principal Investigator will immediately report anything that might warrant review of ethical approval of the project on the Adverse Events form.
2. The Coordinating Principal Investigator will immediately notify the SCU HREC, on the appropriate form, of any change in protocol.
3. The Coordinating Principal Investigator will report to the SCU HREC annually in the specified format and notify HREC when the project is completed.
4. The Coordinating Principal Investigator will notify the SCU HREC if the project is discontinued at a participating site before the expected completion date, with reasons provided.
5. The Coordinating Principal Investigator will notify the SCU HREC if any plan to extend the duration of the project past the approval period listed above and will submit any associated required documentation.

A copy of this ethical approval letter must be submitted by all site Principal Investigators to the Research Governance Office or equivalent body or individual at each participating institution in a timely manner to enable the institution to authorise the commencement of the project at its site/s.

This letter constitutes ethical approval only. This project cannot proceed at any site until separate research governance authorisation has been obtained from the CEO or Delegate of the institution under whose auspices the research will be conducted at that site.

Should you have any queries about the SCU HREC’s consideration of your project please contact ethics.lismore@scu.edu.au. The SCU HREC Terms of Reference, membership and standard forms are available from https://www.scu.edu.au/research/forms-and-downloads-document-downloads/.

Office of Research

SCU HREC wishes you every success in your research.

Kind Regards,

for
Professor Colleen Cartwright.
Chair, Human Research Ethics Committee
APPENDIX G

Consent form (Study 2)

**Title of research project:** Effects of 2-weeks hot-water immersion on heat acclimation and endurance performance in male runners

**Name of researchers:** Miss Storme Heathcote, Dr Chris Stevens, Dr Lee Taylor

I agree to take part in this Southern Cross University project as specified in the information statement that I have read in full and retained. Yes ☐ No ☐

I understand that I should not participate in the above study if I have a health-related condition that restricts my capacity to exert myself or if I have experienced heat exhaustion. Yes ☐ No ☐

I agree to have my height, weight, and skinfolds measured. Yes ☐ No ☐

I agree to running at moderate-vigorous intensity on a treadmill in a hot room (33 degrees C) for 60 min on three separate occasions. Yes ☐ No ☐

I agree to completing a 2-week unsupervised running training program and training diary in my own time. Yes ☐ No ☐

I agree to have a hot water bath at 39°C daily for 2-weeks, if I am randomly chosen to do so. Yes ☐ No ☐

I agree to cease hot baths and contact the researchers if I feel extremely hot, dizzy, light-headed or any other unusual symptoms. Yes ☐ No ☐

I agree to provide capillary blood samples, urine samples and have measurements of skin temperature, heart rate and body weight taken. Yes ☐ No ☐

I agree to self-inserting a small telemetric capsule rectally for the measurement of core body temperature and wearing a ‘no-MRI’ wristband until it leaves my body. Yes ☐ No ☐

I understand that my participation is voluntary and that I can cease my participation at any time. Yes ☐ No ☐

I understand that my participation in this research will be treated with confidentiality. Yes ☐ No ☐

I understand that any information that may identify me will be de-identified at the time of analysis of any data and no identifying information will be disclosed or published. Yes ☐ No ☐

I understand that all information gathered in this research will be kept confidentially for 7 years Yes ☐ No ☐

I am aware that I can contact the researchers at any time with any queries. Their contact details have been provided to me. Yes ☐ No ☐

I understand that this research project has been approved by the SCU Human Research Ethics Committee. Yes ☐ No ☐

Participant’s name: _______________________________ Signature __________________________________

Date: ____________________ Email________________________________________________

☐ Please tick this box and provide your email or mail address below if you wish to receive feedback about the research.
APPENDIX H

Bath protocol (Study 2)

You are required to have a hot bath immediately after exercise on training days (preferably within 20 minutes of the session). If this is not possible, wait until the evening when you have your normal bath on the non-training days. Use the Coralife thermometer you were given to monitor the temperature of the bath continuously. Aim for 39°C. The water must remain between 38.5-39.5°C at all times. You must bath with the water at the level of your waist (i.e., just above your belly button). Submerge your arms when possible. Have drinking water nearby, you may drink as much as you like. Monitor your feelings of hotness and comfort on the temperature scales provided. Thermal sensation is a measure of how hot or cold you feel and thermal comfort is a measure of how comfortable you feel with the temperature of your body. If you reach number 4 on the thermal comfort scale (feel very uncomfortable), you should stop the bath immediately.

The recommended durations of the bath are in the table below, please follow these as closely as you can (except if you experience signs of heat illness on the reverse side of this page):

<table>
<thead>
<tr>
<th>Day</th>
<th>Bath duration (minutes)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>15</td>
</tr>
<tr>
<td>2</td>
<td>20</td>
</tr>
<tr>
<td>3</td>
<td>25</td>
</tr>
<tr>
<td>4</td>
<td>30</td>
</tr>
<tr>
<td>5</td>
<td>35</td>
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<tr>
<td>6</td>
<td>40</td>
</tr>
<tr>
<td>7</td>
<td>42</td>
</tr>
<tr>
<td>8</td>
<td>44</td>
</tr>
<tr>
<td>9</td>
<td>46</td>
</tr>
<tr>
<td>10</td>
<td>48</td>
</tr>
<tr>
<td>11</td>
<td>50</td>
</tr>
<tr>
<td>12</td>
<td>52</td>
</tr>
<tr>
<td>13</td>
<td>54</td>
</tr>
<tr>
<td>14</td>
<td>56</td>
</tr>
</tbody>
</table>

Please fill in your training details of your bath on each day in the diary you were given.
APPENDIX I

Safety precautions for bath protocol (Study 2)

If you experience any of the following, please remove the plug immediately and exit the bath slowly, gripping two hands on the edge of the tub and carefully raise yourself out.

- Feelings of ‘very uncomfortably’ on the thermal comfort scale
- Faintness or dizziness
- Nausea or vomiting
- Heavy sweating often accompanied by cold, clammy skin
- Weak, rapid pulse
- Pale or flushed face
- Muscle cramps
- Headache
- Weakness or fatigue

Do not immediately get into a cold shower, rather sit down in a cool room and make sure someone is aware of your condition.

Sit/ lay down and elevate the legs and feet slightly if needed.

Drink cool water and avoid alcohol and caffeine

Call 000 or your local emergency number if the condition deteriorates

Contact and notify the researcher of any signs, symptoms or problems you have with the hot water immersion.
APPENDIX J

Training diary (Study 2)

Pre-test day:

Rest day: Complete: yes / no

Day 1:
Did you train: Yes/No
Date:
Time at start of session:
Time at end of exercise:
Average heart rate:
Starting ambient temp/humidity:
Finishing ambient temp/humidity:
Bath completed:
Time taken to initiate bath after exercise:
Duration of bath (minutes):

Day 2:
Did you train: Yes/No
Date:
Time at start of session:
Time at end of exercise:
Average heart rate:
Starting ambient temp/humidity:
Finishing ambient temp/humidity:
Bath completed:
Time taken to initiate bath after exercise:
Duration of bath (minutes):

Day 3:
Did you train: Yes/No
Date:
Time at start of session:
Time at end of exercise:
Average heart rate:
Starting ambient temp/humidity:
Finishing ambient temp/humidity:
Bath completed:
Time taken to initiate bath after exercise:
Duration of bath (minutes):

Day 4:
Did you train: Yes/No
Date:
Time at start of session:
Time at end of exercise:
Average heart rate:
Starting ambient temp/humidity:
Finishing ambient temp/humidity:
Bath completed:
Time taken to initiate bath after exercise:
Duration of bath (minutes):

Day 5:
Did you train: Yes/No
Date:
Time at start of session:
Time at end of exercise:
Average heart rate:
Starting ambient temp/humidity:
Finishing ambient temp/humidity:
Bath completed:
Time taken to initiate bath after exercise:
Duration of bath (minutes):

Day 6:
Did you train: Yes/No
Date:
Time at start of session:
Time at end of exercise:
Average heart rate:
Starting ambient temp/humidity:
Finishing ambient temp/humidity:
Bath completed:
Time taken to initiate bath after exercise:
Duration of bath (minutes):
Day 7:
Did you train: Yes/No
Date:
Time at start of session:
Time at end of exercise:
Average heart rate:
Starting ambient temp/humidity:
Finishing ambient temp/humidity:
Bath completed:
Time taken to initiate bath after exercise:
Duration of bath (minutes):

Day 8:
Did you train: Yes/No
Date:
Time at start of session:
Time at end of exercise:
Average heart rate:
Starting ambient temp/humidity:
Finishing ambient temp/humidity:
Bath completed:
Time taken to initiate bath after exercise:
Duration of bath (minutes):

Day 9:
Did you train: Yes/No
Date:
Time at start of session:
Time at end of exercise:
Average heart rate:
Starting ambient temp/humidity:
Finishing ambient temp/humidity:
Bath completed:
Time taken to initiate bath after exercise:
Duration of bath (minutes):

Day 10:
Did you train: Yes/No
Date:
Time at start of session:
Time at end of exercise:
Average heart rate:
Starting ambient temp/humidity:
Finishing ambient temp/humidity:
Bath completed:

Day 11:
Did you train: Yes/No
Date:
Time at start of session:
Time at end of exercise:
Average heart rate:
Starting ambient temp/humidity:
Finishing ambient temp/humidity:
Bath completed:
Time taken to initiate bath after exercise:
Duration of bath (minutes):

Day 12:
Did you train: Yes/No
Date:
Time at start of session:
Time at end of exercise:
Average heart rate:
Starting ambient temp/humidity:
Finishing ambient temp/humidity:
Bath completed:
Time taken to initiate bath after exercise:
Duration of bath (minutes):

Day 13:
Did you train: Yes/No
Date:
Time at start of session:
Time at end of exercise:
Average heart rate:
Starting ambient temp/humidity:
Finishing ambient temp/humidity:
Bath completed:
Time taken to initiate bath after exercise:
Duration of bath (minutes):

Day 14: Rest day but still bath
Bath completed:

Day 15: Post Test
APPENDIX K
Current hot-water immersion guidelines

Hot bath and performance - Practical guidelines
June 15, 2016  |  Neil P Walsh and Mike Zurawlew, Bangor University, UK

How to train cool - bathe hot
Practical and safety guidelines

1. Exercise moderately for ~40 min in temperate conditions “feel warm but comfortable”

2. Immediately take a hot bath in 40°C water for 15 min

3. Increase bath duration by ~5 min each day for a total of 6 days

Safety guidelines
- If in doubt, get out!
- Hot bath guidelines - heat acclimation in the bath but NOT “as hot as you can stand”
- Sit for a few min after getting out of the bath to recover/avoid light headedness

APPENDIX L

Subject descriptive data (Study 1)

Table 3. *Raw data for subject age (years), height (cm), body mass (kg), body density, and body fat (%) in Study One.*

<table>
<thead>
<tr>
<th>Subject</th>
<th>Age</th>
<th>Height</th>
<th>Body mass</th>
<th>Body density</th>
<th>Body fat %</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>34</td>
<td>180.5</td>
<td>76.10</td>
<td>1.06</td>
<td>15.68</td>
</tr>
<tr>
<td>2</td>
<td>24</td>
<td>172.6</td>
<td>67.06</td>
<td>1.07</td>
<td>11.39</td>
</tr>
<tr>
<td>3</td>
<td>34</td>
<td>191.3</td>
<td>87.54</td>
<td>1.07</td>
<td>11.70</td>
</tr>
<tr>
<td>4</td>
<td>48</td>
<td>187.0</td>
<td>92.12</td>
<td>1.06</td>
<td>14.81</td>
</tr>
<tr>
<td>5</td>
<td>48</td>
<td>180.1</td>
<td>78.12</td>
<td>1.07</td>
<td>14.37</td>
</tr>
<tr>
<td>6</td>
<td>23</td>
<td>182.6</td>
<td>98.56</td>
<td>1.07</td>
<td>13.81</td>
</tr>
<tr>
<td>7</td>
<td>19</td>
<td>179.4</td>
<td>62.14</td>
<td>1.07</td>
<td>11.56</td>
</tr>
<tr>
<td>8</td>
<td>27</td>
<td>173.2</td>
<td>62.48</td>
<td>1.07</td>
<td>10.98</td>
</tr>
<tr>
<td>9</td>
<td>60</td>
<td>177.2</td>
<td>79.30</td>
<td>1.06</td>
<td>14.98</td>
</tr>
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<td>45</td>
<td>171.2</td>
<td>97.64</td>
<td>1.05</td>
<td>23.18</td>
</tr>
<tr>
<td>11</td>
<td>52</td>
<td>191.3</td>
<td>99.46</td>
<td>1.07</td>
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</tr>
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<td>12</td>
<td>45</td>
<td>176.6</td>
<td>75.44</td>
<td>1.08</td>
<td>9.99</td>
</tr>
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</table>

<table>
<thead>
<tr>
<th></th>
<th>Mean</th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>38.25</td>
<td>180.25</td>
<td>81.33</td>
<td>1.07</td>
<td>13.86</td>
</tr>
<tr>
<td>SD</td>
<td>13.18</td>
<td>6.79</td>
<td>13.65</td>
<td>0.01</td>
<td>3.46</td>
</tr>
</tbody>
</table>

Note: SD = standard deviation
## APPENDIX M

Core temperature raw data (Study 1)

Table 4. Raw data for the core temperature during immersion for 11 participants for the three different conditions in Study One (HWI administered 10 min, 1 h or 8 h after a treadmill run).

<table>
<thead>
<tr>
<th>Subject</th>
<th>T&lt;sub&gt;core&lt;/sub&gt; (HWI) pre</th>
<th>Mean</th>
<th>∆ T&lt;sub&gt;core&lt;/sub&gt; (HWI) (mean - pre)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>C0</td>
<td>C1</td>
<td>C8</td>
</tr>
<tr>
<td>1</td>
<td>37.1</td>
<td>37.0</td>
<td>37.5</td>
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<tr>
<td>2</td>
<td>37.1</td>
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<td>37.3</td>
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<td>36.9</td>
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</table>

<table>
<thead>
<tr>
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<th>37.2</th>
<th>Mean</th>
<th>37.8</th>
<th>37.4</th>
<th>37.7</th>
<th>Mean</th>
<th>0.8</th>
<th>0.4</th>
<th>0.6</th>
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</thead>
<tbody>
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<td>0.3</td>
<td>0.2</td>
<td>SD</td>
<td>0.2</td>
<td>0.3</td>
<td>0.2</td>
<td>SD</td>
<td>0.3</td>
<td>0.2</td>
<td>0.1</td>
</tr>
</tbody>
</table>

Note: T<sub>core</sub> = core temperature, ∆ = delta (mean – pre), HWI = hot-water immersion, C0 = the condition where immersion was applied 10 min after exercise, C1 = the condition where immersion was applied 1 h after exercise, C8 = the condition where immersion was applied 8 h after exercise, SD = standard deviation.
### APPENDIX N

**Skin temperature raw data (Study 1)**

Table 5. Raw data for skin temperature in Study One before and after immersion for three different conditions (HWI administered 10 min, 1 h or 8 h after a treadmill run).

<table>
<thead>
<tr>
<th>Subject</th>
<th>T&lt;sub&gt;ms&lt;/sub&gt; (HWI) pre</th>
<th>T&lt;sub&gt;ms&lt;/sub&gt; (HWI) post</th>
<th>∆ T&lt;sub&gt;ms&lt;/sub&gt; (HWI)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>C0</td>
<td>C1</td>
<td>C8</td>
</tr>
<tr>
<td>1</td>
<td>29.48</td>
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<td>31.71</td>
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<td>2</td>
<td>30.70</td>
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<tr>
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<td>30.05</td>
<td>31.08</td>
<td>32.48</td>
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</tbody>
</table>

**Mean** 29.99 30.63 31.70  **Mean** 31.98 32.07 32.59  **Mean** 2.00 1.44 0.88

**SD** 0.52 0.90 0.27  **SD** 0.56 0.57 0.41  **SD** 0.45 0.59 0.48

Note: HWI = hot-water immersion, min = minute(s), h = hour(s), T<sub>ms</sub> = mean skin temperature, C0 = the condition where immersion was applied 10 min after exercise, C1 = the condition where immersion was applied 1 h after exercise, C8 = the condition where immersion was applied 8 h after exercise, ∆ = delta (post – pre).
## APPENDIX O

### Heart rate raw data (Study 1)

Table 6. Raw data for heart rate in Study One before during immersion for three different conditions (HWI administered 10 min, 1 h or 8 h after a treadmill run).

<table>
<thead>
<tr>
<th>Subject</th>
<th>HR (HWI) mean</th>
<th></th>
<th></th>
<th>HR (HWI) max</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>C0</td>
<td>C1</td>
<td>C8</td>
<td></td>
<td>C0</td>
<td>C1</td>
</tr>
<tr>
<td>1</td>
<td>132</td>
<td>93</td>
<td>95</td>
<td></td>
<td>140</td>
<td>103</td>
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<td>2</td>
<td>162</td>
<td>96</td>
<td>88</td>
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<td>176</td>
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<td>3</td>
<td>146</td>
<td>92</td>
<td>81</td>
<td></td>
<td>158</td>
<td>97</td>
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<td>4</td>
<td>111</td>
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<td>124</td>
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<td>122</td>
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<td>66</td>
<td></td>
<td>135</td>
<td>69</td>
</tr>
<tr>
<td>6</td>
<td>146</td>
<td>144</td>
<td>96</td>
<td></td>
<td>167</td>
<td>160</td>
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<tr>
<td>8</td>
<td>132</td>
<td>104</td>
<td>86</td>
<td></td>
<td>146</td>
<td>110</td>
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<td>118</td>
<td>92</td>
<td>90</td>
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<td>134</td>
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<td>10</td>
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<td>89</td>
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<td>143</td>
<td>110</td>
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<td>137</td>
<td>101</td>
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<td></td>
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<tr>
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<td>94</td>
<td>92</td>
<td>86</td>
<td></td>
<td>99</td>
<td>99</td>
</tr>
</tbody>
</table>

| Mean    | 129.9 | 94.2 | 84.8 |
| SD      | 17.9  | 20.4 | 10.4 |
| Mean    | 142.6 | 101.7| 90.8 |
| SD      | 19.9  | 23.2 | 11.9 |

Note: HR = heart rate, HWI = hot-water immersion, mean = average, max = maximum, C0 = the condition where immersion was applied 10 min after exercise, C1 = the condition where immersion was applied 1 h after exercise, C8 = the condition where immersion was applied 8 h after exercise, SD = standard deviation.
Table 7. Raw data for the average thermal comfort and thermal sensation during immersion for the three different conditions in Study One (HWI administered 10 min, 1 h or 8 h after a treadmill run)

<table>
<thead>
<tr>
<th>Subject</th>
<th>TC mean (HWI)</th>
<th>TS mean (HWI)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>C0</td>
<td>C1</td>
</tr>
<tr>
<td>1</td>
<td>1.29</td>
<td>2.00</td>
</tr>
<tr>
<td>2</td>
<td>1.71</td>
<td>1.71</td>
</tr>
<tr>
<td>3</td>
<td>2.14</td>
<td>2.43</td>
</tr>
<tr>
<td>4</td>
<td>1.57</td>
<td>1.71</td>
</tr>
<tr>
<td>5</td>
<td>1.14</td>
<td>1.00</td>
</tr>
<tr>
<td>6</td>
<td>3.00</td>
<td>2.57</td>
</tr>
<tr>
<td>7</td>
<td>1.57</td>
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<td>8</td>
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<td>1.86</td>
</tr>
<tr>
<td>9</td>
<td>2.00</td>
<td>2.29</td>
</tr>
<tr>
<td>10</td>
<td>1.43</td>
<td>1.71</td>
</tr>
<tr>
<td>11</td>
<td>2.43</td>
<td>1.57</td>
</tr>
<tr>
<td>12</td>
<td>2.00</td>
<td>1.57</td>
</tr>
</tbody>
</table>

Mean 1.82 1.92 1.99 Mean 5.11 5.16 5.36
SD 0.52 0.47 0.49 SD 0.57 0.85 0.66

Note: HWI = hot-water immersion, min = minute(s), h = hour(s), TC = thermal comfort, TS = thermal sensation, C0 = the condition where immersion was applied 10 min after exercise, C1 = the condition where immersion was applied 1 h after exercise, C8 = the condition where immersion was applied 8 h after exercise.
APPENDIX Q

Subject descriptive data (Study 2)

Table 8. Raw data for subject age (years), height (cm), body mass (kg), body density, body fat (%) and distance achieved in 20 min pre-test distance trial (km).

<table>
<thead>
<tr>
<th>Subject</th>
<th>Group</th>
<th>Age</th>
<th>Height</th>
<th>Body mass</th>
<th>Body density</th>
<th>Body fat %</th>
<th>Distance</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>CN</td>
<td>29</td>
<td>195.3</td>
<td>96.64</td>
<td>1.06</td>
<td>15.02</td>
<td>3.93</td>
</tr>
<tr>
<td>4</td>
<td>CN</td>
<td>47</td>
<td>177.5</td>
<td>74.58</td>
<td>1.07</td>
<td>10.95</td>
<td>4.95</td>
</tr>
<tr>
<td>6</td>
<td>CN</td>
<td>35</td>
<td>194.0</td>
<td>86.07</td>
<td>1.07</td>
<td>10.60</td>
<td>3.65</td>
</tr>
<tr>
<td>7</td>
<td>CN</td>
<td>49</td>
<td>184.0</td>
<td>85.04</td>
<td>1.06</td>
<td>17.95</td>
<td>3.39</td>
</tr>
<tr>
<td>8</td>
<td>CN</td>
<td>49</td>
<td>187.0</td>
<td>92.60</td>
<td>1.06</td>
<td>19.07</td>
<td>3.25</td>
</tr>
<tr>
<td>11</td>
<td>CN</td>
<td>18</td>
<td>182.0</td>
<td>76.42</td>
<td>1.06</td>
<td>16.73</td>
<td>3.93</td>
</tr>
<tr>
<td>Mean</td>
<td></td>
<td></td>
<td>37.83</td>
<td>186.63</td>
<td>85.23</td>
<td>1.06</td>
<td>15.05</td>
</tr>
<tr>
<td>SD</td>
<td></td>
<td></td>
<td>12.75</td>
<td>6.95</td>
<td>8.68</td>
<td>0.01</td>
<td>3.58</td>
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</table>

<table>
<thead>
<tr>
<th>Subject</th>
<th>Group</th>
<th>Age</th>
<th>Height</th>
<th>Body mass</th>
<th>Body density</th>
<th>Body fat %</th>
<th>Distance</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>HWI</td>
<td>46</td>
<td>173.0</td>
<td>95.62</td>
<td>1.05</td>
<td>20.34</td>
<td>3.68</td>
</tr>
<tr>
<td>3</td>
<td>HWI</td>
<td>45</td>
<td>165.0</td>
<td>59.20</td>
<td>1.06</td>
<td>16.52</td>
<td>4.52</td>
</tr>
<tr>
<td>5</td>
<td>HWI</td>
<td>44</td>
<td>180.0</td>
<td>91.30</td>
<td>1.06</td>
<td>18.82</td>
<td>3.36</td>
</tr>
<tr>
<td>9</td>
<td>HWI</td>
<td>20</td>
<td>179.4</td>
<td>63.46</td>
<td>1.07</td>
<td>12.72</td>
<td>4.25</td>
</tr>
<tr>
<td>10</td>
<td>HWI</td>
<td>24</td>
<td>182.0</td>
<td>91.16</td>
<td>1.07</td>
<td>13.08</td>
<td>3.59</td>
</tr>
<tr>
<td>12</td>
<td>HWI</td>
<td>54</td>
<td>191.0</td>
<td>92.46</td>
<td>1.07</td>
<td>14.07</td>
<td>3.83</td>
</tr>
<tr>
<td>Mean</td>
<td></td>
<td></td>
<td>38.83</td>
<td>178.40</td>
<td>82.20</td>
<td>1.06</td>
<td>15.93</td>
</tr>
<tr>
<td>SD</td>
<td></td>
<td></td>
<td>13.57</td>
<td>8.76</td>
<td>16.30</td>
<td>0.01</td>
<td>3.16</td>
</tr>
</tbody>
</table>

Note: CN = control group, HWI = experimental group, SD = standard deviation.
## APPENDIX R

Core temperature raw data (Study 2)

Table 9. Raw data for core temperature (°C) as described in Chapter 4 for 10 subjects (Study Two).

<table>
<thead>
<tr>
<th>Subject</th>
<th>Group</th>
<th>$T_{core}$ (rest) pre</th>
<th>$T_{core}$ (rest) post</th>
<th>$\Delta T_{core}$ (rest)</th>
<th>$T_{core}$ (ex) pre</th>
<th>$T_{core}$ (ex) post</th>
<th>$\Delta T_{core}$ (ex)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>CN</td>
<td>36.74</td>
<td>36.78</td>
<td>0.05</td>
<td>37.75</td>
<td>37.81</td>
<td>0.06</td>
</tr>
<tr>
<td>6</td>
<td>CN</td>
<td>37.26</td>
<td>37.28</td>
<td>0.01</td>
<td>37.95</td>
<td>37.87</td>
<td>-0.08</td>
</tr>
<tr>
<td>7</td>
<td>CN</td>
<td>37.27</td>
<td>37.41</td>
<td>0.14</td>
<td>37.87</td>
<td>37.83</td>
<td>-0.04</td>
</tr>
<tr>
<td>8</td>
<td>CN</td>
<td>36.67</td>
<td>36.63</td>
<td>-0.04</td>
<td>37.68</td>
<td>38.01</td>
<td>0.33</td>
</tr>
<tr>
<td>11</td>
<td>CN</td>
<td>37.50</td>
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<td>-0.27</td>
<td>38.32</td>
<td>38.19</td>
<td>-0.13</td>
</tr>
<tr>
<td>Mean</td>
<td></td>
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<td>37.07</td>
<td>-0.02</td>
<td>37.92</td>
<td>37.94</td>
<td>0.03</td>
</tr>
<tr>
<td>SD</td>
<td></td>
<td>0.36</td>
<td>0.34</td>
<td>0.15</td>
<td>0.25</td>
<td>0.16</td>
<td>0.18</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Subject</th>
<th>Group</th>
<th>$T_{core}$ (rest) pre</th>
<th>$T_{core}$ (rest) post</th>
<th>$\Delta T_{core}$ (rest)</th>
<th>$T_{core}$ (ex) pre</th>
<th>$T_{core}$ (ex) post</th>
<th>$\Delta T_{core}$ (ex)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>HWI</td>
<td>37.26</td>
<td>37.33</td>
<td>0.07</td>
<td>37.97</td>
<td>38.06</td>
<td>0.09</td>
</tr>
<tr>
<td>5</td>
<td>HWI</td>
<td>37.23</td>
<td>37.16</td>
<td>-0.06</td>
<td>37.95</td>
<td>37.85</td>
<td>-0.10</td>
</tr>
<tr>
<td>9</td>
<td>HWI</td>
<td>37.21</td>
<td>36.83</td>
<td>-0.38</td>
<td>38.11</td>
<td>37.72</td>
<td>-0.39</td>
</tr>
<tr>
<td>10</td>
<td>HWI</td>
<td>37.55</td>
<td>37.82</td>
<td>0.27</td>
<td>38.43</td>
<td>38.66</td>
<td>0.23</td>
</tr>
<tr>
<td>12</td>
<td>HWI</td>
<td>36.94</td>
<td>36.50</td>
<td>-0.44</td>
<td>37.67</td>
<td>37.72</td>
<td>0.05</td>
</tr>
<tr>
<td>Mean</td>
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<td>37.24</td>
<td>37.13</td>
<td>-0.11</td>
<td>38.03</td>
<td>38.00</td>
<td>-0.02</td>
</tr>
<tr>
<td>SD</td>
<td></td>
<td>0.22</td>
<td>0.50</td>
<td>0.30</td>
<td>0.28</td>
<td>0.39</td>
<td>0.24</td>
</tr>
</tbody>
</table>

Note: $T_{core}$ = core temperature, CN = control group, HWI = experimental group, $\Delta$ = delta, ex = exercising, SD = standard deviation.
### APPENDIX S

Skin temperature raw data (Study 2)

Table 10. Raw data for skin temperature changes (°C) as described in Chapter 4 for 10 subjects (Study Two).

<table>
<thead>
<tr>
<th>Subjects</th>
<th>T&lt;sub&gt;ms&lt;/sub&gt; change pre</th>
<th>T&lt;sub&gt;ms&lt;/sub&gt; change post</th>
<th>Δ T&lt;sub&gt;ms&lt;/sub&gt; change</th>
<th>Subjects</th>
<th>T&lt;sub&gt;ms&lt;/sub&gt; change pre</th>
<th>T&lt;sub&gt;ms&lt;/sub&gt; change post</th>
<th>Δ T&lt;sub&gt;ms&lt;/sub&gt; change</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>0.48</td>
<td>0.06</td>
<td>-0.42</td>
<td>1</td>
<td>0.71</td>
<td>0.21</td>
<td>-0.50</td>
</tr>
<tr>
<td>5</td>
<td>1.23</td>
<td>0.37</td>
<td>-0.86</td>
<td>6</td>
<td>-0.94</td>
<td>-0.09</td>
<td>0.85</td>
</tr>
<tr>
<td>9</td>
<td>0.30</td>
<td>0.25</td>
<td>-0.05</td>
<td>7</td>
<td>0.53</td>
<td>1.04</td>
<td>0.51</td>
</tr>
<tr>
<td>10</td>
<td>0.34</td>
<td>0.31</td>
<td>-0.03</td>
<td>8</td>
<td>1.32</td>
<td>1.63</td>
<td>0.31</td>
</tr>
<tr>
<td>12</td>
<td>0.81</td>
<td>1.08</td>
<td>0.27</td>
<td>11</td>
<td>0.50</td>
<td>0.89</td>
<td>0.40</td>
</tr>
</tbody>
</table>

| Mean     | 0.63                     | 0.41                      | -0.21                  | Mean     | 0.42                     | 0.74                      | 0.31                   |
| SD       | 0.39                     | 0.39                      | 0.43                   | SD       | 0.83                     | 0.68                      | 0.50                   |

Note: T<sub>ms</sub> = mean skin temperature, T<sub>ms</sub> change = the difference between the mean skin temperature taken pre and post exercise, Δ = delta (post-pre), SD = standard deviation.
**APPENDIX T**

**Heart rate raw data (Study 2)**

Table 11. *Raw data for heart rate (bpm) as described in Chapter 4 for 10 subjects (Study Two).*

<table>
<thead>
<tr>
<th>Subject</th>
<th>Group</th>
<th>HR (rest) pre</th>
<th>HR (rest) post</th>
<th>HR (rest) Δ</th>
<th>HR (ex) pre</th>
<th>HR (ex) post</th>
<th>HR (rest) Δ</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>CN</td>
<td>75</td>
<td>68</td>
<td>-7</td>
<td>139</td>
<td>140</td>
<td>1</td>
</tr>
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<td>6</td>
<td>CN</td>
<td>57</td>
<td>61</td>
<td>4</td>
<td>124</td>
<td>120</td>
<td>-4</td>
</tr>
<tr>
<td>7</td>
<td>CN</td>
<td>76</td>
<td>75</td>
<td>-1</td>
<td>125</td>
<td>124</td>
<td>-2</td>
</tr>
<tr>
<td>8</td>
<td>CN</td>
<td>72</td>
<td>64</td>
<td>-8</td>
<td>110</td>
<td>115</td>
<td>5</td>
</tr>
<tr>
<td>11</td>
<td>CN</td>
<td>75</td>
<td>86</td>
<td>11</td>
<td>143</td>
<td>150</td>
<td>7</td>
</tr>
</tbody>
</table>

| Mean    | 71.00 | 70.80 | -0.20 | 128.23 | 129.68 | 1.45 |
| SD      | 7.97  | 9.98  | 7.92  | 13.17  | 14.52  | 4.60 |

<table>
<thead>
<tr>
<th>Subject</th>
<th>Group</th>
<th>HR (rest) pre</th>
<th>HR (rest) post</th>
<th>HR (rest) Δ</th>
<th>HR (ex) pre</th>
<th>HR (ex) post</th>
<th>HR (rest) Δ</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>HWI</td>
<td>92</td>
<td>68</td>
<td>-24</td>
<td>148</td>
<td>143</td>
<td>-5</td>
</tr>
<tr>
<td>5</td>
<td>HWI</td>
<td>74</td>
<td>67</td>
<td>-7</td>
<td>145</td>
<td>132</td>
<td>-13</td>
</tr>
<tr>
<td>9</td>
<td>HWI</td>
<td>79</td>
<td>70</td>
<td>-9</td>
<td>148</td>
<td>141</td>
<td>-8</td>
</tr>
<tr>
<td>10</td>
<td>HWI</td>
<td>68</td>
<td>70</td>
<td>2</td>
<td>154</td>
<td>151</td>
<td>-4</td>
</tr>
<tr>
<td>12</td>
<td>HWI</td>
<td>75</td>
<td>77</td>
<td>2</td>
<td>125</td>
<td>127</td>
<td>2</td>
</tr>
</tbody>
</table>

| Mean    | 77.60 | 70.40 | -7.20 | 144.18 | 138.65 | -5.53 |
| SD      | 8.96  | 3.91  | 10.66 | 11.03  | 9.15   | 5.51  |

Note: HR = heart rate, CN = control group, HWI = experimental group, Δ = delta (post-pre), ex = exercising, SD = standard deviation.
## APPENDIX U

Sweat rate raw data (Study 2)

Table 12. Raw data for pre and post sweat rate (L\(^{-1}\) min\(^{-1}\) kg\(^{-1}\)) as described in Chapter 4 for 10 subjects (Study Two).

<table>
<thead>
<tr>
<th>HWI subjects</th>
<th>SR Pre</th>
<th>SR Post</th>
<th>∆ SR</th>
</tr>
</thead>
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<td>5</td>
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<td>9</td>
<td>0.000236</td>
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</table>

<table>
<thead>
<tr>
<th>CN Subjects</th>
<th>SR Pre</th>
<th>SR Post</th>
<th>∆ SR</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.000225</td>
<td>0.000242</td>
<td>0.000017</td>
</tr>
<tr>
<td>6</td>
<td>0.000322</td>
<td>0.000290</td>
<td>-0.000033</td>
</tr>
<tr>
<td>7</td>
<td>0.000188</td>
<td>0.000190</td>
<td>0.000002</td>
</tr>
<tr>
<td>8</td>
<td>0.000221</td>
<td>0.000126</td>
<td>-0.000096</td>
</tr>
<tr>
<td>11</td>
<td>0.000177</td>
<td>0.000157</td>
<td>-0.000020</td>
</tr>
</tbody>
</table>

| Mean        | 0.000239 | 0.000251 | 0.000012 |
| SD          | 0.00004  | 0.00004  | 0.00005  |

| Mean        | 0.000227 | 0.000201 | -0.000026 |
| SD          | 0.00006  | 0.00007  | 0.00004  |

Note: SR = sweat rate, CN = control group, HWI = experimental group, ∆ = delta, SD = standard deviation.
## APPENDIX V

Haematocrit raw data (Study 2)

### Table 13. Raw data for pre and post blood haematocrit (%) as described in Chapter 4 for 10 subjects (Study Two).

<table>
<thead>
<tr>
<th>HWI subjects</th>
<th>Hct Pre</th>
<th>Hct Post</th>
<th>Δ Hct</th>
<th>CN subjects</th>
<th>Hct Pre</th>
<th>Hct Post</th>
<th>Δ Hct</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>46.46</td>
<td>47.32</td>
<td>-0.86</td>
<td>1</td>
<td>49.43</td>
<td>53.03</td>
<td>-3.61</td>
</tr>
<tr>
<td>5</td>
<td>52.59</td>
<td>50.83</td>
<td>1.75</td>
<td>6</td>
<td>53.04</td>
<td>49.57</td>
<td>3.48</td>
</tr>
<tr>
<td>9</td>
<td>52.73</td>
<td>51.72</td>
<td>1.00</td>
<td>7</td>
<td>53.10</td>
<td>54.55</td>
<td>-1.45</td>
</tr>
<tr>
<td>10</td>
<td>50.00</td>
<td>48.36</td>
<td>1.64</td>
<td>8</td>
<td>50.88</td>
<td>50.51</td>
<td>0.37</td>
</tr>
<tr>
<td>12</td>
<td>49.55</td>
<td>49.59</td>
<td>-0.04</td>
<td>11</td>
<td>44.95</td>
<td>50.00</td>
<td>-5.05</td>
</tr>
</tbody>
</table>

| Mean         | 49.74   | 50.43    | 0.70  | Mean        | 49.72   | 48.47    | -1.25 |
| SD           | 2.58    | 1.79     | 1.13  | SD          | 3.36    | 2.16     | 3.35  |

Note: Hct = haematocrit, CN = control group, HWI = experimental group, Δ = delta (post-pre), SD = standard deviation.
### APPENDIX X

**Haemoglobin raw data (Study 2)**

Table 14. *Raw data for pre and post blood haemoglobin (g/dL) as described in Chapter 4 for 10 subjects (Study Two).*

<table>
<thead>
<tr>
<th></th>
<th>HWI subjects</th>
<th>Hb Pre</th>
<th>Hb Post</th>
<th>Δ Hb</th>
<th></th>
<th>CN subjects</th>
<th>Hb Pre</th>
<th>Hb Post</th>
<th>Δ Hb</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>12.6</td>
<td>13.2</td>
<td>6.0</td>
<td></td>
<td></td>
<td>14.2</td>
<td>15.8</td>
<td>1.6</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>15.4</td>
<td>15.0</td>
<td>-4.0</td>
<td></td>
<td></td>
<td>14.9</td>
<td>13.8</td>
<td>-1.1</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>14.7</td>
<td>15.4</td>
<td>7.0</td>
<td></td>
<td></td>
<td>15.4</td>
<td>16.2</td>
<td>0.8</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>15.0</td>
<td>15.6</td>
<td>0.6</td>
<td></td>
<td></td>
<td>14.9</td>
<td>15.0</td>
<td>0.1</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>14.9</td>
<td>15.3</td>
<td>4.0</td>
<td></td>
<td></td>
<td>13.7</td>
<td>13.9</td>
<td>0.2</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Mean</th>
<th>14.5</th>
<th>14.9</th>
<th>2.7</th>
<th></th>
<th>Mean</th>
<th>14.6</th>
<th>14.9</th>
<th>0.3</th>
</tr>
</thead>
<tbody>
<tr>
<td>SD</td>
<td>1.1</td>
<td>1.0</td>
<td>4.5</td>
<td></td>
<td>SD</td>
<td>0.7</td>
<td>1.1</td>
<td>1.0</td>
<td></td>
</tr>
</tbody>
</table>

Note: Hb = haemoglobin, CN = control group, HWI = experimental group, Δ = delta (post-pre), SD = standard deviation.
### APPENDIX Y

Perceptual raw data (Study 2)

Table 15. *Raw data for thermal sensation, thermal comfort and ratings of perceived exertion during exercise as described in Chapter 4 for 10 subjects (Study Two).*

<table>
<thead>
<tr>
<th>HWI Subjects</th>
<th>TS pre</th>
<th>TS post</th>
<th>Δ TS</th>
<th>TC pre</th>
<th>TC post</th>
<th>Δ TC</th>
<th>RPE pre</th>
<th>RPE post</th>
<th>Δ RPE</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>3.75</td>
<td>4.13</td>
<td>0.38</td>
<td>2.00</td>
<td>1.00</td>
<td>-1.00</td>
<td>11.75</td>
<td>11.00</td>
<td>-0.75</td>
</tr>
<tr>
<td>5</td>
<td>5.38</td>
<td>5.13</td>
<td>-0.25</td>
<td>2.25</td>
<td>1.88</td>
<td>-0.38</td>
<td>12.50</td>
<td>11.50</td>
<td>-1.00</td>
</tr>
<tr>
<td>9</td>
<td>4.94</td>
<td>5.44</td>
<td>0.50</td>
<td>1.00</td>
<td>1.00</td>
<td>0.00</td>
<td>9.11</td>
<td>8.00</td>
<td>-1.11</td>
</tr>
<tr>
<td>10</td>
<td>6.13</td>
<td>6.00</td>
<td>-0.13</td>
<td>2.75</td>
<td>2.88</td>
<td>0.13</td>
<td>11.25</td>
<td>12.25</td>
<td>1.00</td>
</tr>
<tr>
<td>12</td>
<td>4.19</td>
<td>4.50</td>
<td>0.31</td>
<td>1.375</td>
<td>1.50</td>
<td>0.13</td>
<td>10.13</td>
<td>11.00</td>
<td>0.88</td>
</tr>
</tbody>
</table>

Mean: 4.88, TS: 5.04, Δ: 0.16, TC: 1.88, Δ: 1.65, RPE: 10.95, Δ: 10.75, RPE: -0.20
SD: 0.94, Δ: 0.33, Δ: 0.70, Δ: 0.78, Δ: 0.48, Δ: 1.34, Δ: 1.62, Δ: 1.05

<table>
<thead>
<tr>
<th>CN Subjects</th>
<th>TS pre</th>
<th>TS post</th>
<th>Δ TS</th>
<th>TC pre</th>
<th>TC post</th>
<th>Δ TC</th>
<th>RPE pre</th>
<th>RPE post</th>
<th>Δ RPE</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5.44</td>
<td>5.67</td>
<td>0.22</td>
<td>2.28</td>
<td>2.11</td>
<td>-0.17</td>
<td>11.67</td>
<td>11.78</td>
<td>0.11</td>
</tr>
<tr>
<td>6</td>
<td>5.50</td>
<td>5.50</td>
<td>0.00</td>
<td>2.00</td>
<td>2.00</td>
<td>0.00</td>
<td>11.13</td>
<td>11.00</td>
<td>-0.13</td>
</tr>
<tr>
<td>7</td>
<td>5.38</td>
<td>5.44</td>
<td>0.06</td>
<td>1.75</td>
<td>2.00</td>
<td>0.25</td>
<td>10.75</td>
<td>10.75</td>
<td>0.00</td>
</tr>
<tr>
<td>8</td>
<td>4.38</td>
<td>5.19</td>
<td>0.81</td>
<td>1.63</td>
<td>2.00</td>
<td>0.38</td>
<td>11.25</td>
<td>11.00</td>
<td>-0.25</td>
</tr>
<tr>
<td>11</td>
<td>4.00</td>
<td>4.00</td>
<td>0.00</td>
<td>1.00</td>
<td>1.00</td>
<td>0.00</td>
<td>7.00</td>
<td>6.63</td>
<td>-0.38</td>
</tr>
</tbody>
</table>

Mean: 4.94, TS: 5.16, Δ: 0.22, TC: 1.73, Δ: 1.82, RPE: 10.36, Δ: 10.23, Δ: -0.13
SD: 0.70, Δ: 0.34, Δ: 0.48, Δ: 0.46, Δ: 0.22, Δ: 1.91, Δ: 2.05, Δ: 0.19

Note: TS = thermal sensation, TC = thermal comfort, RPE = rating of perceived exertion, CN = control group, HWI = experimental group, Δ = delta, SD = standard deviation.
APPENDIX Z

The statements of contribution to the publication located in Chapter 2

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*Candidate contribution:*

The candidate participated in all stages of the development of this paper. The candidate provided an overall contribution greater than that of any co-author. As primary author, the
candidate conducted the literature search and produced the first draft of the manuscript which was revised with feedback from the co-authors.

Co-author contributions:

Dr Christopher Stevens, Professor Peter Hassmén and Professor Shi Zhou were co-authors on this paper and contributed to the concept, editing and provided valuable feedback for the manuscript. Dr Chris Stevens covered the cost of the publishing the manuscript.

We the undersigned agree with the above stated “proportion of work undertaken” for the above published peer-reviewed manuscript contributing of the thesis:

Candidate (Author 1)

Author 2

Author 3

Author 4