Rapid Heat Acclimation Strategies for use in the Military

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Abstract

Military units often deploy abroad to provide international aid for peacekeeping, disaster relief and conflict resolution. Therefore, military personnel are required to operate in environments different to that in which they typically train. Recent, current, and anticipated future deployments involved countries primarily with hot climates, environments that impair physical and cognitive performance. Furthermore, within the military paradigm burdensome loads and protective clothing, as well as the possibility of very short notice deployment can exacerbate the impact on performance as well as safety. Therefore, to ensure both operational success as well as the safety of military personnel it is imperative to have strategies that mitigate the effects of heat. In the initial phase of this thesis a literature review highlighted the problems of operating in the heat within a military context and explored methods that could feasibly improve performance in hot environments. Primarily, the literature review highlighted that due to a multitude of uncontrollable factors within military operations, it was more useful to obtain beneficial heat adaptations through heat acclimation prior to deployment. It also noted that different forms of heat (humid and arid) could cause very different responses, largely due to a limited capacity for sweat to evaporate in humid environments.

Operational problems were addressed experimentally by comparing the performance of appropriately dressed military personnel in extreme humid and arid environments. Humid environments elicited a greater thermal strain, likely due to a requirement to carry a heavier load, and reduced sweat evaporation, causing increases in rectal temperature and heart rate, while the arid environment induced a higher skin temperature. Therefore, the first heat acclimation study evaluated the performance of practical, passive, post-exercise heating methods (sauna and hot-water immersion) in a humid environment. Both sauna and hot-water immersion reduced rectal temperature, skin temperature, and heart rate, and increased fluid consumption and sweat rate. However, no differences were observed in cognitive performance. Following passive, post-exercise heat acclimation, it was examined whether thermal tolerance could be maintained using intermittent heat exposure (IHE); additional passive, post-exercise heating every 2-3 d for ~3 wk. IHE further reduced rectal temperature and increased sweat rate but did not affect performance compared to a control condition that underwent decay, thereby indicating that IHE may not only maintain, but enhance thermal tolerance. Cognitive performance was then further evaluated using a

mechanistic study designed to independently elevate rectal temperature to 38.5°C, to determine the influence of core temperature on cognition during exercise in the heat. Elevated rectal temperature did not impair cognitive performance but appeared to increase cerebral oxidative metabolism (assessed using near-infrared spectroscopy).

The results indicated that passive, post-exercise IHE, following an initial heat acclimation programme, is a feasible and efficient method to mitigate negative effects of heat on physical performance and to improve safety in military units. While the benefits do not extend to cognitive performance this is likely due to cerebral adjustments that overcome the disturbance to homeostasis caused by the heat.

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List of Abbreviations

°C	degrees Celsius
AU	arbitrary units
$b.min^{-1}$	beats per minute
CI	confidence interval
d	day(s)
h	hour
HA	heat acclimation
Hz	hertz
IHE	intermittent heat exposure
kg	kilograms
$km.h^{-1}$	kilometres per hour
L	litres
$L.h^{-1}$	litres per hour
min	minutes
mL	millilitres
NC	no change
NZDF	New Zealand Defence Force
RER	respiratory exchange ratio
RH	relative humidity
s	seconds
SD	standard deviation
TTE	time to exhaustion
USG	urine specific gravity
$\dot{V}CO_2$	rate of carbon dioxide production
$\dot{V}E$	minute volume of expiration
$\dot{V}O_2$	rate of oxygen consumption
$\dot{V}O_{2peak}$	peak rate of oxygen consumption
VT1	first ventilatory threshold
WBGT	wet-bulb globe temperature
WT	walking time

Attestation of Authorship

I hereby declare that this submission is my own work and that, to the best of my knowledge and belief, it contains no material previously published or written by another person (except where explicitly defined), nor material which to a substantial extent has been submitted for the award of any other degree or diploma of university or other institution of higher learning.

Edward Ashworth

September 2020

Supervisor Signatures

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September 2020

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September 2020

Co-authored Works

Chapters 2 and 7 of this thesis have been submitted to peer-review journals for publication. Both papers were prepared alongside Professor Andrew Kilding and Professor Jim Cotter. Chapters 3-6 are all being prepared for submission. Each authors contribution is detailed in brackets.

Submitted co-authored works (Chapter 2 and Chapter 7)

Ashworth, E., Cotter. J., Kilding, A., "Strategies for coping in hot environments for military personnel with short deployment notice" (under review – Military Medicine)
(Ashworth 84%, Cotter 8%, Kilding 8%)

Ashworth, E., Cotter. J., Kilding, A., "Cognitive performance is impaired with high core temperature and is unaffected by menthol supplementation" (under review – European Journal of Applied Physiology)
(Ashworth 88%, Cotter 6%, Kilding 6%)

Co-authored works awaiting submission (Chapters 3-6)

Ashworth, E., Cotter. J., Kilding, A., "Differences in physiological responses to a simulated military pack march in hot-dry and hot-wet environments"
(Ashworth 90%, Cotter 3%, Kilding 7%)

Ashworth, E., Cotter. J., Kilding, A., "Passive, post-exercise heat acclimation successfully induces heat adaptations after five days"
(Ashworth 88%, Cotter 5%, Kilding 7%)

Ashworth, E., Kilding, A., “Cognitive performance is unaffected after five days of passive, post-exercise heat acclimation”
(Ashworth 95%, Kilding 5%)

Ashworth, E., Cotter. J., Kilding, A., “Adaptations to a successful passive, post-exercise heat acclimation can be retained with periodical heat exposures”
(Ashworth 88%, Cotter 6%, Kilding 6%)

Conference Presentations

Ashworth, E., Cotter, J., Kilding, A., Comparison of Post-Exercise Heat Acclimation Methods in a Military Context (2019) *Sport and Exercise Science New Zealand 2019, 27th – 29th November*

Ashworth, E., Cotter, J., Kilding, A., Comparison, Passive, Post-Exercise Intermittent Heat Exposure can Maintain and Enhance Thermal Adaptations from Heat Acclimation (2020) *Virtual 8th International Conference on the Physiology and Pharmacology of Temperature Regulation (vPPTR) 2020, 26th – 29th October*

Dedication

This thesis is dedicated to my father, Miles Ashworth, who died proudly the day after the thesis was submitted. Thank you for everything you taught me and for encouraging all my pursuits.

"A ship is safe in harbour, but that's not what ships are built for"

WHO DARES WINS

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Ethical Approval

Ethical approval was obtained for each study. Chapter 3 received ethical approval from both the Auckland University of Technology Ethics Committee (AUTEC) (17/420) and the New Zealand Defence Force (6755/1). Chapters 4, 5 and 6 were all obtained from AUTEC (18/195) as was Chapter 7 (19/368).

Chapter 1 Introduction

1.1 Overview

International emergencies arising from national conflict or natural disasters often require international aid to provide humanitarian assistance (Paquin et al., 2010). Member states of peacekeeping organisations, such as the United Nations (UN), supply military personnel to provide security, disaster relief and conflict resolution (United Nations, 2020). These interventions require military personnel to deploy into environments different to that in which they live and train which can impair performance. Furthermore, in the case of events such as disaster relief the notice period prior to deployment can be very short, exacerbating any environment-induced performance deficits. Recent multi-national military operations have typically required soldiers to deploy into hot environments (Bolton et al., 2006; Buller et al., 2011). Inherent dangers exist when operating in these environments, and as conflicts are expected to rise with climate change (Buhaug, 2016; Stewart, 2002), there is an increased desire to further understand how these environments affect military performance and safety, as well as to develop strategies that can mitigate negative effects.

1.2 Background

1.2.1 Global Military Response

International military operations are often required to help resolve conflict, specifically to protect civilians, and provide humanitarian assistance to those in need (United Nations, 2020). While there are multiple reasons that conflicts exist, many arise due to resource availability; either a shortage of human necessities (e.g. water, food, shelter) (CNA, 2007; Koubi, 2019; Stewart, 2002), or an abundance of natural products that can be sold at a profit (e.g. diamonds, oil, drugs) (Humphreys, 2005; Ross, 2004; Roy, 2018). In both cases an inability of the government to appropriately manage resources can fractionalise the population (CNA, 2007; Roy, 2018; Wegenast et al., 2014), which is often exacerbated by cultural, religious, and socio-economic divides (Abu-Bader et al., 2019; Paquin et al., 2010; Stewart, 2002; Taydas et al., 2010). Frequently, this occurs in developing countries with a low economic capacity that lack the necessary governance to control resource distribution (CNA, 2007; Koubi, 2019), especially when resource availability changes, such as with environmental patterns, or the discovery of natural products. Societal fractionalisation leads to civil unrest (Wegenast et al., 2014), causing factions to emerge (Roy, 2018). When negotiation for the redistribution of resources breaks down, these factions seek to gain control of the resources, often through armed conflict (Basedau et al., 2014; Humphreys, 2005; Roy, 2018). If resources provide substantial financial benefits to the conflicting groups, that overcomes the cost of war, conflicts can escalate into civil war (Ahluwalia et al., 2016). Conflicts typically limit access to human necessities and displace populations, thereby allowing for overspill of the problem into neighbouring regions and states (CNA, 2007; Smith, 2007). When conflicts arise, states look for international support, often with the UN (Paquin et al., 2010). The UN then attempts to protect civilians from violence, as well as facilitating the delivery of humanitarian aid (United Nations, 2020). Armed UN peacekeepers have been shown to both effectively limit the likelihood of civil war re-emerging (Paquin et al., 2010) and ensure the fair distribution of supplies (Sharp et al., 1994). Therefore, it is essential for military units to travel to different parts of the world to actively aid international peace efforts.

While much is currently being done to prevent conflicts from arising it is likely that the environmental impact of climate change will increase civil conflicts in the coming years (Buhaug, 2016; CNA, 2007; Stewart, 2002). Agrarian societies, such as many of the developing nations, rely on their own internal production of food both nutritionally and financially as exports (Humphreys, 2005; Koubi, 2019). Extreme weather patterns brought on by climate change, predominantly drought, cause crop production to be affected (Koubi, 2019), increasing the risk for regions with hot climates, especially those with fragile governance. Indeed, analysis of peasant revolts in China (Jia, 2014) and human crises in Europe (Zhang et al., 2011) from the 1500s onwards has revealed that drought and significant food shortages were related to increased conflict. Without food to live on, many populations will be forced to resettle in less affected, more fertile areas (CNA, 2007; Koubi, 2019; Smith, 2007), which are often already populated, leading to limited agricultural resource availability (CNA, 2007), and creating the conditions for civil conflict, as is already being seen in some African nations (Obioha, 2008). As these events are anticipated to rise it is important to prepare for them. Therefore, from a military personnel perspective, soldiers should prepare physically for peacekeeping roles, as well as for the demands of different environments, in particular hot and/or humid environments, to ensure optimal performance, and therefore achieve the overarching political objectives.

1.2.2 Problem Identification

Due to the rise in frequency of deployment to hot and/or humid environments the New Zealand Defence Force (NZDF) highlighted a desire to further develop practical and efficient strategies to counter performance degradation in the heat. Heat is a major environmental hazard, with elite squadron leaders estimating that 25% of soldiers deployed into hot climates were affected by heat illness, in some instances collapsing after prolonged patrols. While the anecdotal rate of heat illness occurrence in elite NZDF units is much higher than that reported in south-eastern USA (2%) (Gardner et al., 1996), Kuwait (5%) (Bolton et al., 2006) and Afghanistan (0.3%) (Buller et al., 2011), it provides a more personal insight than is provided by hospital records from military campaigns as it also alludes to individuals who may not have required treatment beyond first aid.

Within the military, heat illness primarily presents as exertional heat illness (Stacey et al., 2015), where core temperature is elevated as metabolic heat production is unable to be offset by heat loss mechanisms (Hosokawa et al., 2019). While anecdotal evidence unsurprisingly exceeds that presented in reports, it is possible that the high rate of heat illness reported by elite NZDF personnel may reflect the environmental and physical demands of their operations, as well as motivational factors associated with being in a competitive team environment. Overseas operations typically involve patrolling (Hepler et al., 2017); long duration, burdened walking with occasional high intensity activity. The long duration of the patrols, in addition to the carried packs and webbing, increase endogenous heat production, which is a major determinant in causing exertional heat illness, and is exacerbated by protective clothing that restricts heat loss (Armstrong et al., 2010; Goforth et al., 2015; Johnson et al., 1995; Stacey et al., 2015; Tomes et al., 2017). While recent international conflicts have centred around the arid environments of the Middle East and Afghanistan, the NZDF has major operational duties in southeast Asia and the southwest Pacific, which typically present as high humidity environments.

Both environments limit heat loss avenues, increasing heat gain and predisposing personnel to heat illness (Lee et al., 2010b). Arid environments limit convective heat loss and in high temperature can cause direct heat gain from the environment (Akerman et al., 2016; Cramer et al., 2016b; McLellan et al., 1996), while humid environments reduce the capacity for sweat evaporation, the primary heat loss mechanism (Adams et al., 1975; Maughan et al., 2012). Furthermore, there can be limited time for adjustment to the environment in short notice deployments such as disaster relief or tactical operations. When time for adaptation to the operational environment is limited the prevalence of heat illness rises (Bolton et al., 2006; Bricknell, 1995; Gasparrini et al., 2016; Willcox, 1920) and is therefore of primary concern. For the military, consideration of the operational context is also required as the effects of exertional heat illness impact more than just the affected individual. As work is conducted in small groups, a single member of a group requiring medical attention may incapacitate, or at least compromise, the effectiveness of the whole group, thereby affecting the entire operation.

In addition to temporarily incapacitating individuals, heat illnesses can cause organ dysfunction and death (Goforth et al., 2015). Sustained organ damage can permanently affect quality of life, and prior heat illness is predictive of higher hospitalisation rates (Phinney et al., 2001) and all-cause mortality (Wallace et al., 2007). Therefore, reducing the occurrence of heat illness is important not only for operational success, but also for the health, wellbeing, and longevity of personnel.

1.2.2.1 Deployment notice

At least 90 d notice prior to departure is provided for long-duration deployment, which are typical for the military. These longer operations are typically conducted from a fully equipped base that has a continual food and water supply, as well as air-conditioned barracks and shaded areas that mitigate environmental effects. Furthermore, on arrival, personnel are typically given at least a week to naturally acclimatise before commencing operations. With such support, and relatively low casualty rates, these operations are much more successful and safer than the rapid deployments that occur when military personnel are required to arrive in theatre at very short notice and perform immediately, such as during disaster relief. These short notice deployments pose the biggest challenge due to the lack of time that can be spent planning mission-specific details, such as logistics, gear loadouts and tactical operations. For the NZDF, regional deployments (southeast Asia or southwest Pacific) could be within 12 h, while global deployments could be as little as 24 h. Given that such rapid mobilisation increases the risk of heat illness during the mission (Bolton et al., 2006; Bricknell, 1995), investigations are required into strategies that help mitigate the effects of heat to ensure operational safety and success.

1.2.2.2 What is desired

The NZDF desires that soldiers can operate effectively, both physically and cognitively upon arrival in hot climates. Long duration, self-paced physical activities, such as patrolling, are typically impaired in the heat (Adams et al., 1975; El-Helou et al., 2012; Ely et al., 2007) due to physiological strain reducing the descending motor drive to continue exercising (Nybo et al., 2001a; Racinais et al., 2015). Physiological strain arises because of the need to distribute blood to the cutaneous circulation for cooling in addition to skeletal muscle to facilitate exercise (González-Alonso et al., 2008; Kenney et al., 2014), which is exacerbated by the carried load (Kenefick et al., 2017; Knapik, 1997b) and restrictive clothing in a military context (Aoyagi et al., 1994; Cheung et al., 1998; McLellan et al., 1992).

Additionally, optimising cognitive function is important as impaired cognition accounts for most accidents in training and battles (Vrijkotte et al., 2016), with high ambient air temperature shown to be a determining factor of helicopter pilot error (Froom et al., 1993). NZDF psychologists determined alertness and working memory to be the most vital areas of cognition for military operations, both of which have previously been shown to be impaired by the heat (Faerevik et al., 2003; Grego et al., 2005), and by body armour (Caldwell et al., 2011; Mahoney et al., 2007). Secondary cognitive variables of interest were reaction time, cognitive throughput, and declarative memory, all of which were expected to be impaired during military deployments abroad (Gaoua et al., 2011; Lieberman et al., 2006; Schmit et al., 2017; Vrijkotte et al., 2016).

1.2.2.3 Current Protocol

Protocols and strategies currently recommended are athlete centred, and therefore have restricted use within a military setting, which leads to minimal heat alleviation strategies being used by military units (Fig. 1-1). Individuals are monitored, in line with recommendations, with potentially at risk personnel identified by group leaders prior to, or during, deployment (STO/NATO, 2013). Cooling strategies, consisting primarily of pouring water over symptomatic individuals, are used minimally as water is often limited and required for drinking, hygiene, and cooking. Furthermore, rest prior to deployment is seen as important to mentally prepare and optimise physical performance, especially for short notice deployments.

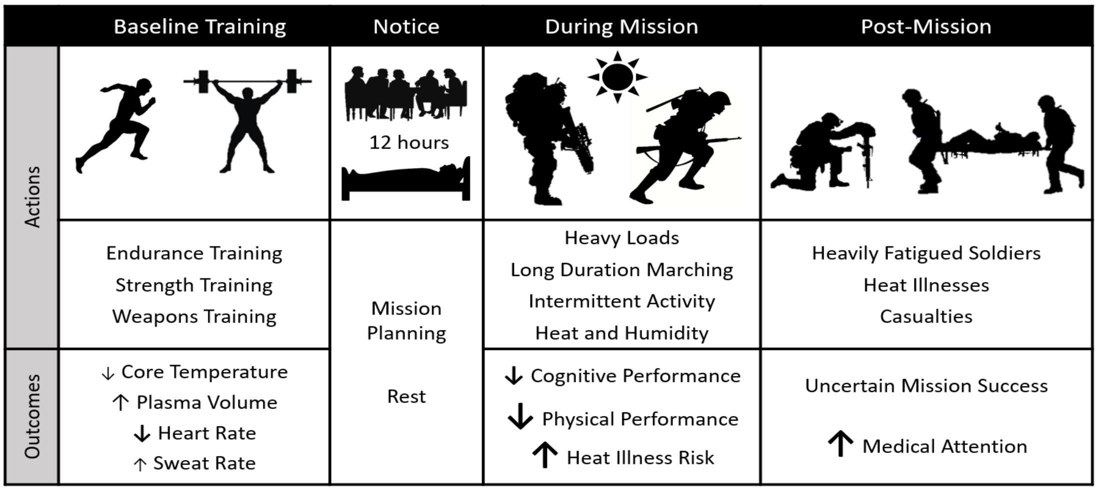

Figure 1-1. Schematic detailing the actions followed by soldiers during rapid deployment and how they affect the performance and health of soldiers during a mission.

The minimal use of heat alleviation strategies described in the literature (Bergeron et al., 2012; Faulkner, 2016; Racinais et al., 2015) is unsurprising given that the literature primarily focusses on athletic populations, or military units that are aware of their deployment in advance. Current recommendations for performance in the heat do not address the unique demands of elite military units that operationally deploy at very short notice. Strategies that minimise workload, and therefore endogenous heat production, such as by having ample rest, before and after exercise, as well as managing work-rest ratios, may not be applicable in certain operational scenarios, and may pre-dispose individuals to heat illness (Rav-Acha et al., 2004). Similar limitations prevent the application of strategies that minimise the environmental effects of heat, such as planning operations or patrols around the weather, actively seeking shade, or the removal of gear following activity to cool down (Radakovic et al., 2007). While a range of cooling options exist for the athlete, such as ice-vests and cold-water immersion exercise (Barr et al., 2009; Bongers et al., 2017; Casa et al., 2007; Ciuha et al., 2016; Gibson et al., 2019; Giesbrecht et al., 2007; McDermott et al., 2009; Teunissen et al., 2014; Watkins et al., 2018), the nature and location of military tasks limits the practicality of such interventions. For example, ice-vests can be uncomfortable and can add to the workload or interfere with body armour function (Carter et al., 2007), making them impractical, while skin cooling methods, including cold-water immersion, require access to specialist facilities that are not always available (Siegel et al., 2012). Ultimately, for military personnel, the unknown components of their operations means that while many of these methods could be used, situations can arise where they could compromise mission objectives and as such they cannot be relied upon. What becomes evident then is that strategies that take place prior to deployment are the most controllable factors to mitigate the effects of heat (Fig. 1-2).

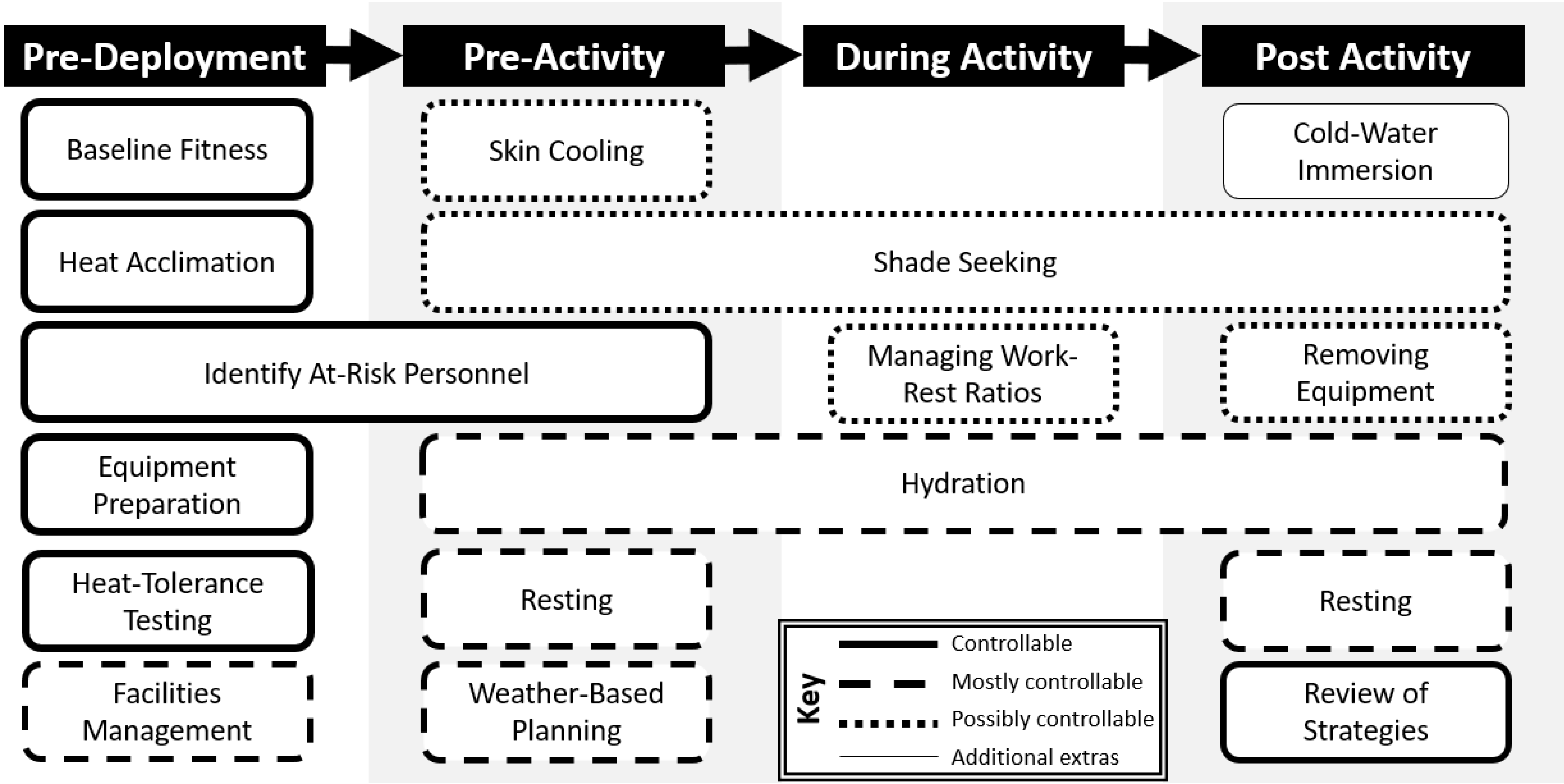

Figure 1-2. Schematic detailing heat strategies that can be used by the military at different time-points in a deployment cycle and how practical they are.

Prior to deployment, both military personnel and the facilities can be prepared to help mitigate the effects of heat on operational performance. Facilities should have cool, shaded areas (Bailey et al., 2008), with equipment that can help cool individuals who have been affected by the heat, such as cold-water access (Casa et al., 2012; Casa et al., 2007). Areas should be well ventilated, with air conditioning available in buildings and vehicles (Countryman et al., 2013; Yaglou et al., 1957), and clothing designed to maximise air flow (Adams et al., 1994; Ueda et al., 2006). Ultimately, preparation of facilities is not always possible as many short-term missions will not be run from major bases and in such circumstances controlling factors that affect the individual will be more important. Due to the large individual variability in physiological responses to physical exertion in the heat, testing should be conducted to determine which individuals are most susceptible to the effects of heat (Buller et al., 2017; Larsen et al., 2015a; Stacey et al., 2014). While the Israeli Defense Force uses a heat tolerance test to screen individuals for heat intolerance (Druyan et al., 2013; Epstein et al., 2017; Moran et al., 2007), and indeed for assessing the ability of those who have previously had heat illness before they return to duty (Ketko et al., 2015), its use elsewhere appears limited. Heat tolerance tests help both accustom individuals to the perceptions of performing in the heat, as well as to identify at risk personnel, who can then either be withheld from deployment, given additional heat training, or be closely monitored (Parsons et al., 2019). Without heat-tolerance testing, at-risk personnel can potentially be identified based on aerobic fitness which confers a partially heat-acclimated status (Cheung et al., 1998; Lisman et al., 2014; Pandolf et al., 1977a; Ravanelli et al., 2019). Although high aerobic fitness is associated with having a lower resting core temperature (Alhadad et al., 2019; Cheung et al., 1998; Pandolf et al., 1977a; Selkirk et al., 2008), increased sweat rate (Ichinose et al., 2009; Lamarche et al., 2018), and a lower exercising heart rate (McLellan, 2001; Sakurada et al., 1998), aerobic fitness alone has also been shown to be unrelated to thermal tolerance (Sawka et al., 1992) and the ability to adapt to hot environments (Corbett et al., 2018; Gibson et al., 2019; Tyler et al., 2016). Military operations are often planned with long notice periods, allowing most military groups to use in-situ heat acclimatisation to prepare for working in the heat prior to operational service (Charlot et al., 2017; Malgoyre et al., 2018; Pichan et al., 1985). An equally effective option is to use artificial heat exposure (e.g., an environmental chamber) prior to deployment to induce physiological adaptations that enhance performance in the heat over several weeks (Hellon et al., 1956), a process known as heat acclimation (HA). The positive effects of HA are well known and include reductions in core temperature, and heart rate and an increase in sweat rate (Périard et al., 2016; Tyler et al., 2016). Using HA to induce physiological adaptations that aid performance in the heat, prior to departure, provides an inherent heat mitigation strategy that overcomes the unknown components of military operations that could render other strategies infeasible or unreliable.

1.3 Rationale and Thesis Aims

Considering the above information, military units deploying into hot climates at short notice require recommendations to guide decision making that mitigates the effects of heat on soldier performance and safety. Therefore, the overarching aim of the thesis was to progress the current literature to provide recommendations specific to the problems faced by elite military units deploying to hot environments at short notice. The main environment in question was the hot-humid environment found in southeast Asia and the Pacific, with temperatures of ~33°C and 75% relative humidity experienced frequently. Additionally, the arid environment experienced in the Middle East and Afghanistan, characterised by temperatures peaking above 45°C, with low humidity, is also of interest. In these environments, interventions that could help optimise performance and improve safety would lead to operational success and reduced casualty rates. To achieve these goals a series of studies were designed to answer questions that specifically related to operations of the NZDF, but which could be applied to other defence forces or occupations. The aims of the studies were as follows:

i. To quantify how physical and cognitive performance is impacted in hot-humid and hot-arid environments and the contrast between the operational environments
ii. To evaluate the use of short-term passive, post-exercise HA as a feasible method of inducing beneficial physical and cognitive heat adaptations
iii. To determine whether intermittent heat exposures provides a means for maintaining HA adaptations for prolonged periods of time, thereby allowing short-notice deployment with an elevated thermal tolerance.

1.4 Thesis Organisation

Figure 1-3. Schematic of the overall thesis structure.

Following this introductory chapter, the thesis consists of eight further chapters (Fig 1-3). Chapter 2 is a literature review that amalgamates heat-related research from military, athletic and occupational populations. Firstly, the physiological effects of physical exertion in hot environments are described within a military context. Secondly, existing strategies that might help mitigate the effects of heat are discussed in relation to their practical application within military units. Finally, recommendations are provided around strategies that could enhance performance, from which the five experimental studies comprising this thesis were developed.

The first study (Chapter 3) investigates the physiological impact of both hot-humid and hot-arid environments within a military context. Then, three investigations evaluate HA protocols that could improve both physical and cognitive performance of military personnel in the heat. The first HA study (Chapter 4) looks at comparing the physical performance and physiological adaptations to short-term passive, post-exercise HA in both sauna and hot-water immersion (HWI). Then the effects of post-exercise sauna and HWI HA is evaluated in relation to cognitive performance (Chapter 5). These are then progressed in Chapter 6 using intermittent heat exposure to maintain adaptations to a prior HA programme, thereby providing a mechanism through which military personnel receiving short notice prior to deployment could deploy with an elevated baseline level of thermal tolerance. Finally, a further look at the mechanisms that dictate cognitive performance in a military environment is reported in Chapter 7.

The final chapter is an overall discussion, in which key findings are highlighted, with the interrelation of studies highlighting the potential of the proposed interventions. These interventions provide practical strategies that can be implemented within the military, and ways in which future studies can build on these outcomes to increase their effectiveness and efficiency. Ultimately, the thesis addresses the problems faced by elite units of military personnel facing short notice deployments by developing strategies to improve performance in hot environments.

The literature review and research studies are presented based on the publication guidelines and word limits for the journals they were submitted to or were targeted for submission to. As such, aspects of each chapter may repeat certain information. Between chapters a brief linking section provides the rationale for the direction of the thesis. All citations are in

American Psychological Association (APA) format, with a single reference list at the end of the thesis.

1.5 Significance of Thesis

The findings presented in this thesis are primarily of value to military personnel, but also pertain to athletes, or indeed any person required to perform physically or cognitively in a hotter environment, e.g., occupational personnel during heat waves, fire-fighting or other disaster relief work. Specifically, the thesis addresses issues directly relating to short-notice deployments of the NZDF into hot environments.

Short notice deployments present a unique problem that remains minimally addressed in the literature. By better understanding the unique factors of military performance and how it integrates with short deployment notice allows strategies to be adapted for the military paradigm. Furthermore, working alongside the NZDF ensures the strategies tested in this thesis were practical and relevant, and therefore could readily be implemented with relevant military groups. Developing these strategies within military personnel could provide a means to mitigate the effects of heat on performance while also improving safety. By improving performance, it increases the chance of mission success by increasing the amount of work that can be done, while improvements in safety minimises casualties.

Chapter 2 Literature Review

2.1 Background

Military units deploying abroad are often exposed to challenging environments. One is heat stress, which presents as high ambient temperature, often augmented by high humidity, resulting in heat strain. Heat strain affects many physiological systems, compromising physical and potentially also cognitive performance (Brotherhood, 2008; Charlot et al., 2017; Hargreaves, 2008; Junge et al., 2016; Sawka et al., 1993; Schmit et al., 2017; Stubblefield et al., 2006). Heat has impaired military performance for thousands of years, with ancient Greek and Roman reports highlighting the dangers of warfare in the heat, largely noting that heavily armoured soldiers were more affected (Bricknell, 1995; Casa et al., 2007; Goldman, 2001). It was not until British colonisation that more detailed reports were compiled outlining the dangers of transitioning into a hotter environment (Lind, 1771). Those most affected by the heat were frequently new arrivals in the summer months, indicating that individuals could acclimatise to the environment within a few months (Lind, 1771). While this was still a problem during World War I campaigns in the Middle East (Bricknell, 1995; Willcox, 1920), by World War II an invested interest in how to prevent or limit these problems scientifically was undertaken in military groups. This interest was brought on by a wave of heat-related injuries sustained both in the field and in training camps (Cook, 1955; Schickele, 1947). Safety regulations were implemented to adjust carried load, clothing worn and to dictate the duration and intensity of activities based on the environmental temperature and humidity (Schickele, 1947; Yaglou et al., 1957). Studies progressed further after World War II, looking to minimise the carried load (Knapik, 1997a) and provide better clothing for such conditions (Gonzalez, 1986; Joy et al., 1968), as well as the first investigations into using heat acclimatisation to prepare soldiers for hotter environments by eliciting chronic adaptations (Adolph, 1969; Fox et al., 1963; Ladell, 1951; Lind et al., 1963). Planned acclimatisation was investigated first, allowing soldiers a period of time in a new climate to adapt to the environment (Fox et al., 1964; Fox et al., 1963; Ladell, 1951; Lind et al., 1963; Piwonka et al., 1967; Strydom et al., 1966; Wyndham et al., 1954), while later developments in heat chambers allowed artificial heat exposure to induce such adaptations (Fein et al., 1975; Gonzalez et al., 1974; Roberts et al., 1977; Shvartz et al., 1979), a process known as heat acclimation (HA). From these investigations cardiovascular strain was determined to be a major limiting factor of performance in the heat (González-Alonso et al., 2003; González-

Alonso et al., 1998; González-Alonso et al., 1999), prompting investigations into hydration status and blood volume regulation mechanisms (Cadarette et al., 1984; Francesconi et al., 1983; González-Alonso et al., 2008; González-Alonso et al., 1995; Nadel et al., 1980; Sawka et al., 1992). With technological advancements reducing the time to deploy soldiers to different climates abroad, it is important that research develops to ensure soldiers are adequately prepared when exposed rapidly to extreme climates. Therefore, the aim of this narrative review is to consider 1) the physiology of exercising or working in ambient heat stress in a military context, and 2) the effectiveness and practicality of strategies for coping in hot environments, with an emphasis on HA. This review will also highlight the challenges of optimising HA within the military, which may identify and guide future directions for military-specific HA research.

2.1.1 Physiological Response During Physical Work in the Heat

In the heat, blood flow is reduced in splanchnic (Chen et al., 2013; Crandall et al., 2008; Nielsen et al., 1993; Selkirk et al., 2008), inactive muscle (Nielsen et al., 1993) and potentially cerebral (Nybo et al., 2001a, 2001b) circulations, to elevate skin blood flow for cooling (Charkoudian, 2016; Cramer et al., 2016a). During exercise, active skeletal muscle blood flow must also increase substantially to deliver oxygen and substrates to exercising tissue (González-Alonso et al., 2003; Lee et al., 2017). Work performed by exercising muscle produces heat, which usually comprises the majority of total heat load, requiring a further increase in skin blood flow to protect thermal homeostasis (González-Alonso et al., 2000; Tucker et al., 2004). Skin blood flow typically increases alongside core temperature, but plateaus when core temperature reaches ~38°C, at ~50% of maximal skin blood flow (González-Alonso et al., 2008; González-Alonso et al., 1999; Racinais et al., 2017a). Exercise is facilitated when cerebral, skin, and skeletal muscle perfusion requirements are met (González-Alonso et al., 2008; Lee et al., 2017; Savard et al., 1988). However, cardiovascular demand is exacerbated by increases in exercise intensity that promote blood flow to skeletal muscle (if it has not plateaued), while increases in core or skin temperature elevate blood flow to the cutaneous vasculature (González-Alonso et al., 1998; González-Alonso et al., 2008; Greaney et al., 2016). As blood flow and volume is redistributed peripherally, central blood volume declines, which can be exacerbated in long-duration exercise by sweat-induced dehydration (Charkoudian, 2016; Taylor, 2000; Tripathi et al., 1990). If central blood volume becomes insufficient to support blood flow requirements, the cutaneous and skeletal muscular circulations compete for the limited blood supply (González-Alonso et al., 1998; González-Alonso et al., 2008; Kenefick, 2017).

During the early stages of exercise, it appears intensity is maintained by restricting skin blood flow to provide adequate blood supply to exercising skeletal muscle at the cost of reduced cooling, accelerating the rise in core temperature (González-Alonso et al., 1998; González-Alonso et al., 2008; González-Alonso et al., 1999; Kenney et al., 2014; Savard et al., 1988). However, prior to termination of exercise in fixed-workload trials, skeletal muscle blood flow is reduced (González-Alonso et al., 2003). In self-paced exercise, a reduction in exercise intensity occurs early as an anticipatory response to limit the strain of the competing circulations and allow task completion (Périard et al., 2016; Schlader et al., 2011; Tatterson et al., 2000; Tucker et al., 2004). Although measures of integrated electromyographic activity indicate that motor unit recruitment reduces (Reilly et al., 2006; Tucker et al., 2004; Tyler et al., 2015; Wingfield et al., 2016), this is not accompanied by a reduction in vascular conductance in the exercising muscle (González-Alonso et al., 2003; González-Alonso et al., 1998). This indicates that the reduction in skeletal muscle blood flow is due to a drop in central blood pressure caused by exacerbated cardiovascular demand (González-Alonso et al., 1998), secondary to high temperature of peripheral tissue (Cotter et al., 2001; González-Alonso et al., 2003; Kenefick et al., 2010). It is unknown whether reduced motor unit recruitment occurs alongside or because of high core temperature, or whether other physiological feedback mechanisms play a more substantial role (Brink-Elfegoun et al., 2007; González-Alonso et al., 1999; Inzlicht et al., 2016; Nybo et al., 2001a).

Much of this research has uncovered physiological processes and mechanisms that have been determined within and applied to athletic situations, thereby under-representing military-specific factors that increase and complicate the challenges of exercising in the heat (Fig. 2-1). For example, protective clothing and equipment reduce skin-to-air contact, impairing convective and evaporative heat loss (Cramer et al., 2016a), while also affecting radiative heat gain depending on both the layers and permeability of clothing (Brode et al., 2010). In this situation skin blood flow increases in an attempt to dissipate heat, further straining the limited blood supply while achieving little additional heat loss (Fogarty et al., 2004). The combined weight of body armour, webbing and a backpack adds to physiological demand by increasing metabolic cost, elevating skeletal muscle blood requirements (Puthoff et al., 2006). Furthermore, soldiers typically have a lower aerobic fitness level than the athletes used in the majority of heat research (Bedno et al., 2014; Campos et al., 2017; Knapik et al., 2017), so would likely have a lower thermal tolerance (Cheung et al., 1998), even before considering carried loads and restrictive clothing. Altogether, these aspects exaggerate cardiovascular demand, diminish work capacity (Johnson et al., 1995; Tomes et al., 2017) and predispose soldiers to exertional heat illnesses (Bricknell, 1995; Carter et al., 2005; Phinney et al., 2001), although these relations remain equivocal (Stacey et al., 2015).

Exertional heat illness occurs in uncompensable heat stress where the metabolic heat production of exercise is unable to be offset by heat exchange with the environment, and exercise intensity is insufficiently downregulated by the individual, leaving them incapacitated (Stacey et al., 2014). While this often is present in the form of heat exhaustion, extreme cases can cause heat stroke, which can impair central nervous system function (Casa et al., 2012; Epstein et al., 2012), cause organ damage (Goforth et al., 2015; Sagui et al., 2017) and lead to death (Cheuvront et al., 2005; Rav-Acha et al., 2004; Schickele, 1947; Willcox, 1920). Investigations at a basic training facility found 2% of recruits suffered exertional heat illness during summer months (Gardner et al., 1996), while others observed a 40% higher all-cause mortality at a 30-year follow-up in those with prior exertional heat illness (Wallace et al., 2007). While this could be associated with chronic organ and tissue damage (Wallace et al., 2007), whether the relationship is, or is not, causal remains to be determined.

Cognitive Tasks	
Minimal	Moderate
Clothing	
Shirt and Shorts	Full Combat Armour and Pack
Carried Load	
Minimal	30-76 kg
Muscle Groups	
Lower Body	Upper and Lower Body
Activity Duration	
Very Specific and Known	Unknown
Notice	
Usually > 1 Year	Potentially < 12 Hours

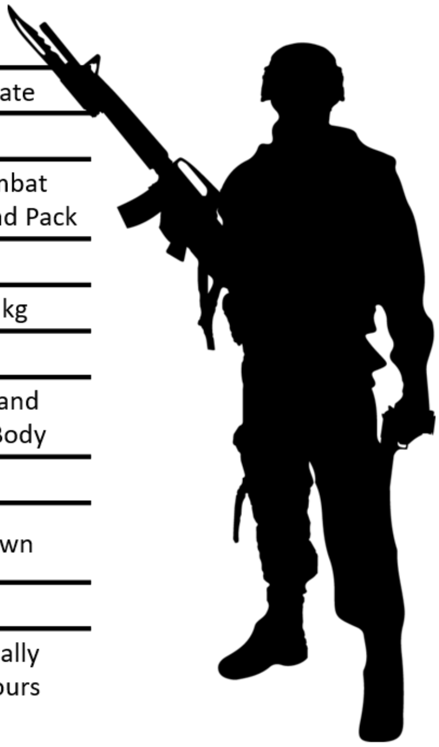

Figure 2-1. Differences in performance expectations between soldiers and athletes.

2.2 Strategies to Combat the Effects of Heat

Acute heat exposure negatively affects both physical and cognitive performance, therefore a strategy to maintain performance and health is desirable (Parsons et al., 2019). Many military operations require relocating to hotter environments for specific missions including disaster relief and unexpected events, before being withdrawn. Deployment notice can sometimes be very short (~12 hours) allowing minimal, if any, time for heat preparation. This scenario highlights the importance of strategies to reduce the effects of the heat. Such strategies can occur at the level of the environment, and the level of the individual. For example, the living environment can often be modified in advance to minimise thermoregulatory requirements (i.e. air-conditioned barracks, shaded areas) (Budd, 2008; Yaglou et al., 1957), and aid thermal recovery following exertion (i.e. ice baths, cold water) (Casa et al., 2012). Similarly, personal protective equipment should be designed to facilitate heat loss and minimise burdened weight (Adams et al., 1994; Knapik, 1997a).

Several acute strategies can be used at the level of the individual to offset heat strain, but the unpredictable nature of military tasks and rapidly changing circumstances mean they cannot always be relied upon (Radakovic et al., 2007). Nonetheless, behavioural modification (i.e. shade-seeking, rest) can prevent excessive elevations in core temperature (Rav-Acha et al., 2004), and are often inherent within military guidelines in the form of heat index charts to minimise casualties (Blanchard, 2008; Buller et al., 2011). This attenuated rise in core temperature can also be achieved with cooling mechanisms, such as ice vests (Barr et al., 2009) or cold-water immersion (Racinais et al., 2015), used before, during or after exercise. However, ice vests can be uncomfortable, impair body armour function, add to carried weight and requires facilities to generate ice (Bongers et al., 2017; Kenny et al., 2011). Similarly, cold-water immersion, shown to drastically lower core temperature (Casa et al., 2012; Casa et al., 2007), requires access to large quantities of cool water. When water supply is limited it should preferentially be used for drinking and hygiene. If facilities are available, consumed water should be chilled (Lee et al., 2013) and supplemented with electrolytes to prevent hyponatraemia (Sawka et al., 2000) and increase palatability (Burdon et al., 2012). Recent research has also looked at perceptual cooling devices, such as cooling collars (Lee et al., 2014; Minniti et al., 2011; Sunderland et al., 2015) and menthol (Best et al., 2018; Mündel et al., 2010; Stevens et al., 2017b), which may reduce thermal strain. Whether such an intervention is appropriate within a military context, where reduced perceptions could potentially lead to individuals pushing beyond their limits, remains to be determined.

These strategies are all viable options, but all are limited by being potentially unavailable. Therefore, strategies such as HA that take place prior to deployment can be more controlled and develop adaptations that would be augmented by the acute strategies outlined above.

2.2.1 Heat Acclimation

HA can prevent decrements in both physical and cognitive performance (Parsons et al., 2019), and likely reduces organ damage (Omassoli et al., 2019), by altering key underlying physiological variables. It is likely that subcellular adaptations to transport, stress, contractile and metabolic proteins (reviewed elsewhere (Horowitz, 2016; Horowitz et al., 2007; Muga et al., 2008)) helps lower resting body temperature, enhance heat dissipation and tolerance (Périard et al., 2015; Périard et al., 2016; Taylor, 2014) and potentially reduce metabolic rate (Horowitz, 2001). Systemic adaptations also occur with plasma volume expansion increasing skin blood flow which facilitates heat loss via convection and through sweat evaporation which help lower core and skin temperatures. These adaptations allow a higher exercise intensity to be maintained at a given core temperature, or for a lower core temperature to be maintained at a given exercise intensity, thereby improving performance, and reducing injury susceptibility (Hargreaves, 2008; Junge et al., 2016; Nielsen et al., 1993).

In-situ heat acclimatisation over several weeks is regarded as the best-practice methodology to adjust personnel to the environment they will operate in (Bergeron et al., 2012; Périard et al., 2016). Even then, arrival in the environment for acclimatisation can pose a challenge as personnel are not adjusted to the heat. Recent research, primarily in athletic contexts, has used HA to induce adaptations comparable to in-situ acclimatisation (Bergeron et al., 2012; Racinais et al., 2015). However, military-specific factors may prevent the direct transferal of athletic findings to military populations (Fig. 2-1).

For an in-depth review on methods to minimise the effects of heat on military personnel, when ample deployment notice is given, the reader is referred to the recent review of Parsons et al. (2019). However, alternatives are required when notice is considerably shorter; less than one week and, on occasion, less than one day (Bergeron et al., 2012; Racinais et al., 2015). Therefore, this section aims to discuss the adaptations that occur because of HA, and how they relate to a military environment.

2.2.1.1 Physiological Adaptations

2.2.1.1.1 Plasma Volume

During acute heat exposure, plasma volume is redistributed and eventually declines as fluid is lost primarily through sweat, but also respiratory losses, urine, and faecal formation (Maughan et al., 2007). As a result, blood availability for skin and skeletal muscle becomes restricted, which can reduce performance in high-intensity or long duration activities by limiting cooling and skeletal muscle blood flow. However, with continuous exercise, low central blood volume, reduced renal blood flow and plasma hyperosmolality stimulate aldosterone and anti-diuretic hormone secretion, upregulating fluid retention mechanisms and stimulating thirst to restore plasma and therefore blood volumes (Fig. 2-2) (Akerman et al., 2016; Périard et al., 2016). When repeatedly exposed to this stimulus the increase in plasma volume exceeds baseline values, aiding resilience against subsequent exposures. HA programmes have seen plasma volume expansion in as little as two days (Senay et al., 1976). Plasma volume increases of more than 20% have been reported (Beaudin et al., 2009; Costa et al., 2013), although ~7% is more common (Buchheit et al., 2011; Fujii et al., 2012; Garrett et al., 2014). The greater blood volume likely facilitates blood supply to active skeletal muscle and cutaneous circulations simultaneously (Périard et al., 2016; Taylor, 2000), reducing the cardiovascular burden, therefore increasing the cardiovascular reserve to support performance at higher intensities or for longer durations.

Because increasing plasma volume effectively increases the amount of blood that can be distributed throughout the body, researchers have explored ways of augmenting the increase seen with HA. For instance, permissive dehydration, to exacerbate the reduction in central blood volume, is hypothesised to increase aldosterone concentration, promote fluid retention and stimulate thirst (Akerman et al., 2017; Garrett et al., 2014; Neal et al., 2016a). Garrett et al. (2014) found 5 days of HA (involving 90 minutes cycling per day with core temperature maintained at 38.5°C in 35°C, 60% relative humidity (RH)) in an experimental group abstaining from fluid intake, (Garrett et al., 2014) to obtain an 8% mean increase in plasma volume, compared to only a 4% mean increase in controls drinking *ad libitum* during sessions. Alternatively, consumption of protein supplements immediately post-exercise has been explored (Goto et al., 2010; Okazaki et al., 2009a; Okazaki et al., 2009b). These supplements increase plasma albumin content, creating an oncotic gradient to draw fluid into the vascular space to elevate blood volume (Goto et al., 2010; Okazaki et al., 2009a; Okazaki et al., 2009b). However, it has not been investigated as to whether supplement-derived plasma volume enhancement leads to improved performance.

2.2.1.1.2 Heart Rate

Elevated blood volume caused by HA enables blood pressure to be maintained in the heat, even with high blood flow demands from skeletal muscle and the cutaneous circulation. While animal studies indicate that over time this could potentially invoke morphological cardiac adaptations that increase ventricular compliance and inotropic state (Heled et al., 2012; Horowitz, 2003), the increased preload helps increase stroke volume (Périard et al., 2016) allowing heart rate to decrease while maintaining cardiac output (Périard et al., 2011; Tyler et al., 2016). Heart rate is also independently elevated by high core and skin temperatures to increase cutaneous blood flow (Chou et al., 2018). During HA, core, and skin temperature decline, therefore heart rate is reduced. While lowered heart rate does not improve thermoregulation *per se*, it indicates a larger cardiac reserve, therefore a reduced cardiovascular strain, making it an optimal outcome for any HA programme. Heart rate can be seen to decline in the first few days of a HA programme, suggesting the changes underlying this occur rapidly, making them relevant to short HA timeframes desired by the military (Faulkner, 2016; Garrett et al., 2009; Pandolf, 1998).

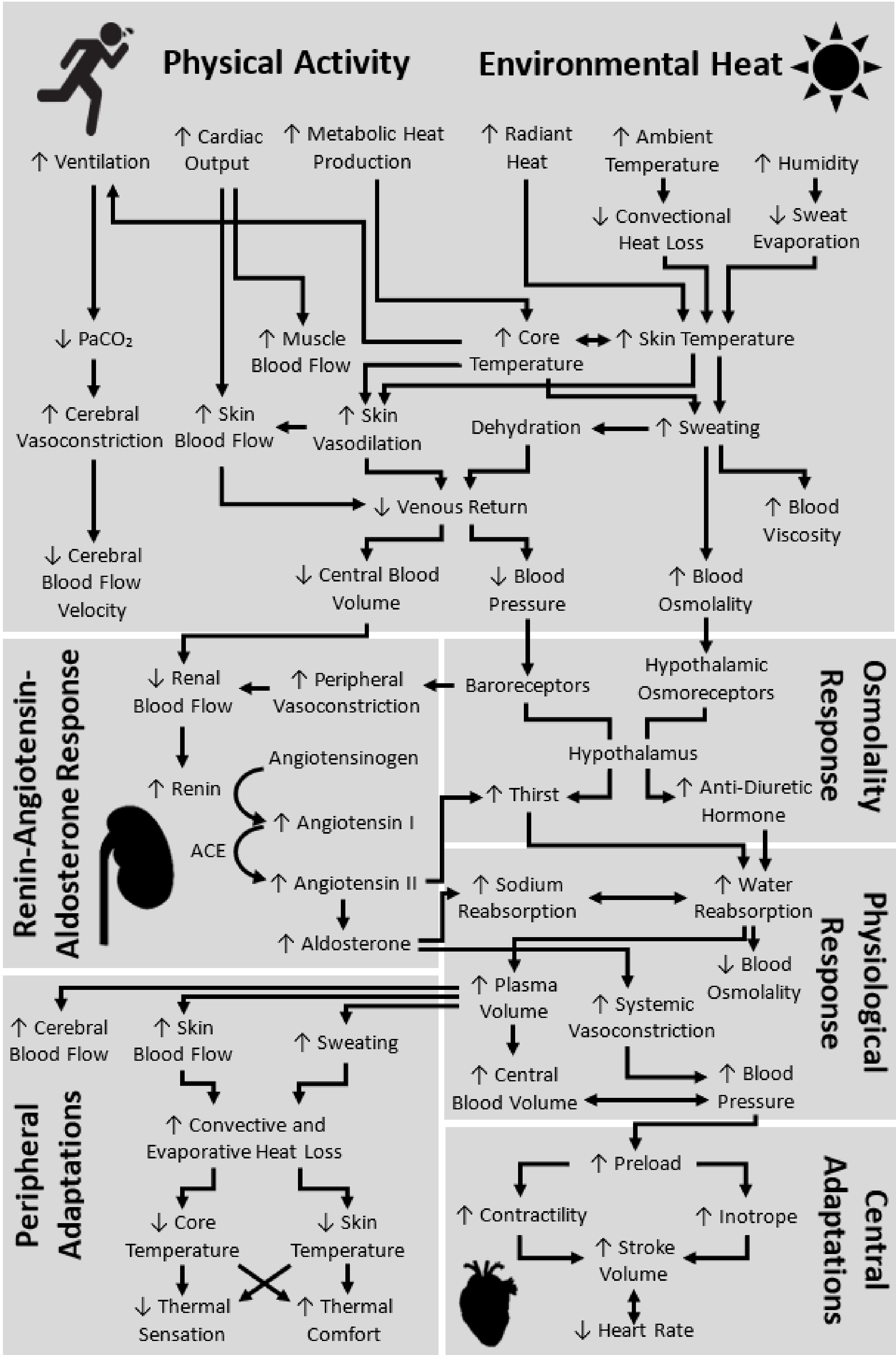

Figure 2-2. Schematic detailing some of the body's major responses to exercise in the heat, from the acute responses to the chronic adaptations that occur with repeated exposures.

2.2.1.1.3 Skin Blood Flow

Skin blood flow translocates thermal energy to the surface, heating the skin to facilitate convective heat loss between the skin and the air, while also facilitating evaporation (and production) of sweat, thereby cooling the blood. With elevated plasma volume, blood flow to cutaneous vasculature increases, facilitating heat dissipation (Fig. 2-2) (Nielsen et al., 1990; Tripathi et al., 1990). However, while many studies report increased skin blood flow after HA (Best et al., 2014; Fujii et al., 2012; Garrett et al., 2014; Goto et al., 2010) some observe decreases (Chen et al., 2013), or even no change (Best et al., 2014; Neal et al., 2016a; Nielsen et al., 1993; Regan et al., 1996). These inconsistencies may be due to differences in acute hydration state brought on by water restrictions in some studies, as well as measurement variability (Jan et al., 2005). Alternatively, the plateauing of skin blood flow during exercise (González-Alonso et al., 2008) may increase blood transit time through cutaneous circulations. Therefore, a more complete heat loss can occur, helping to widen the core-to-skin temperature gradient, facilitating heat transfer away from the core (Kenney et al., 2014).

Despite inconsistencies around changes in skin blood flow, mechanistic studies have found HA to increase skin blood flow at a given core temperature in fixed-intensity trials, helping increase the rate of heat dissipation (Lorenzo et al., 2010; Ravanelli et al., 2019; Roberts et al., 1977; Tyler et al., 2016; Yamazaki et al., 2003). When wearing military clothing any HA-mediated increase in skin blood flow will likely be less effective in promoting heat loss than current research would assume but may still contribute to total heat loss and slow the rise in core temperature. Within this, it is important that soldiers do not compromise the limited skin-air contact that does exist. Certain sunscreens (Aburto-Corona et al., 2016; House et al., 2013) and deodorants (Aburto-Corona et al., 2016; Quatrale et al., 1981) can impair both convective and evaporative heat loss more than others, while similar problems may occur when using eye-black or camouflage paint.

2.2.1.1.4 Sweat Rate

Sweating provides the main avenue of heat loss in hot environments (Adams et al., 1975; Bergeron et al., 2012) and at elevated work-rates, if humidity is low enough to facilitate its evaporation (Gavin, 2003). Hypotonic fluid is secreted from a vast network of eccrine sweat glands located across almost the entire body surface. Sweat output and its distribution show large variability across individuals and body segments, and varies with exercise intensity, posture, local skin pressure and temperature (Kondo et al., 1998; Nishiyama et al., 2001; Taylor et al., 2013), while the cooling (i.e., evaporative) outcome is further governed by overlying clothing and load carriage patterns (Taylor et al., 2013). With HA, the core temperature threshold for sweating reduces (Nielsen et al., 1993), while sweat gland sensitivity heightens, (Roberts et al., 1977) thereby increasing the overall sweat response (Sawka et al., 2011b). Furthermore, primate studies reveal that sweat glands undergo hypertrophy (Sato et al., 1990) and have increased blood supply (Okuda et al., 1980) following HA, likely due to increased skin blood flow, which facilitates sweat production and secretion (Sato et al., 1983). By increasing sweat production more heat is lost (assuming low humidity), reducing the rate of rise in core temperature, and enabling exercise at higher intensities or for longer durations (Fig. 2-2). Additionally, sweat electrolyte content decreases (Schmit et al., 2015; Taylor, 2000), shown by reduced sodium concentration (Kirby et al., 1986; Périard et al., 2016; Stacey et al., 2018) and osmolality (Marshall et al., 2007; Patterson et al., 2014), which help protect against hyponatraemia (O'Brien et al., 2001; Oh et al., 2018; Winger et al., 2011). Sweating adjustments to HA take the longest to occur (Armstrong et al., 1991; Fox et al., 1964; Tyler et al., 2016), but are seen in some short-term protocols (Casadio et al., 2016; Dileo et al., 2016; Karlsen et al., 2015; Mee et al., 2015b; Mee et al., 2017; Neal et al., 2016a; Patterson et al., 2004; Poirier et al., 2015), albeit at lower magnitudes (Tyler et al., 2016). Interestingly, increases in sweat rate may not be beneficial to military personnel operating in high humidity environments where sweat cannot evaporate, or those wearing protective clothing with low moisture permeability, and in extreme cases those required to wear protective suits (Sawka et al., 1993). Such clothing can impede or prevent sweat from evaporating, raising the microclimate humidity (Taylor, 2015; Ueda et al., 2006) and causing sweating to occur without heat loss, resulting in dehydration which is detrimental to performance (Casa et al., 2012; Cotter et al., 2014; Fortney et al., 1984; Racinais et al., 2015; Sawka et al., 1992). As dehydration is highly likely to occur in such situations fluid intake is required to minimise negative effects on cognitive (Adan, 2012; Grandjean et al., 2007; Lieberman, 2007) and physical performance (Cheung et al., 1998; Cheuvront et al., 2010; Sawka et al., 2012), whilst also helping to maintain central blood volume. Advice for hydration has already been well reviewed in current literature (Cotter et al., 2014; Koulmann et al., 2003; McCartney et al., 2017; Shirreffs, 2009), although for some military units access to water may be limited and those guidelines may require modification. Assuming HA is beneficial, personnel wearing restrictive clothing may benefit from shorter

HA protocols that induce a lesser sweat response, but still provide other valuable adaptations (see below).

2.2.1.1.5 Core Temperature

A high core temperature is associated with negative effects on comfort, inflammatory responses (Guy et al., 2016), organ function (Goforth et al., 2015; Sagui et al., 2017), descending corticomotor drive (Garrett et al., 2011; Tucker et al., 2004), as well as performance (Galloway et al., 1997; Marino et al., 2000; Nielsen et al., 1993; Nybo et al., 2001a; Tucker et al., 2004). Typically, HA evokes a lower resting core temperature (Karlsen et al., 2015) and reduces the rate of rise in core temperature due to improved heat dissipation (Daanen et al., 2011). Increases in sweat rate and convectional heat loss from increased skin blood flow usually enables a lower core temperature at the same relative intensity as before HA (Fig. 2-2). In an investigation involving military personnel, Cheung and McLellan (Cheung et al., 1998) found 10 days of HA (10 days of walking at 4.8 km.h^{-1} at a 3-7% gradient for 1 h in combat clothing in 40°C, 30% relative humidity over two weeks), to reduce resting core temperature by ~0.2°C regardless of aerobic fitness, in line with most studies of less than 14 days (Tyler et al., 2016). A lower resting core temperature increases the heat-sink capacity of the body, enabling more work to be achieved before cooling mechanisms are upregulated (Garrett et al., 2014; James et al., 2017c; Shen et al., 2015).

2.2.1.1.6 Skin Temperature

As core temperature decreases with HA, it is important that skin temperature also reduces to ensure the core-to-skin temperature gradient facilitates heat transfer to the periphery (Gisolfi et al., 1969; Smolander et al., 1991). Although rarely seen at rest (James et al., 2017c), during exercise, skin temperature lowers with HA (Gibson et al., 2015; Mee et al., 2017; Racinais et al., 2014). However, in a military context, the influence of clothing minimises skin to air contact, mitigating the rate of cooling. Instead, benefits would likely be seen through the role of skin temperature in the perception of heat. Skin temperature initiates behavioural thermoregulation (Schlader et al., 2013) and has been suggested to majorly contribute to pacing strategies (Kenefick et al., 2010; Schlader et al., 2011). By lowering skin temperature with HA, perceptual and physiological enhancements help to prolong exercise (Cheuvront et al., 2010).

2.2.1.2 Perceptual Changes

Skin temperature (Sawka et al., 2012; Schlader et al., 2011), heart rate and core temperature all play a role in regulating perceptual responses to heat (Flouris et al., 2015; Périard et al., 2014). As these reduce with HA, exercise in the heat feels easier, shown by improved thermal comfort, thermal sensation and rating of perceived exertion (Chalmers et al., 2014; Lee et al., 2016; Saat et al., 2005), especially following active HA (Malgoyre et al., 2018). Some short-term HA studies see changes primarily in perceptual outcomes, with negligible improvements to physiological variables (Kelly et al., 2016). In military settings a combination of peer pressure and adrenaline may overcome perceptual inputs, placing soldiers in physiological danger without being aware of how their body is responding (Malgoyre et al., 2018).

2.2.1.3 Aerobic Performance

Endurance performance is impaired in high ambient temperatures (El-Helou et al., 2012; Ely et al., 2007), by a combination of factors including elevated core and skin temperature (Périard et al., 2014; Sawka et al., 2012), reduced central blood volume (Charkoudian, 2016; Kenefick et al., 2010; MacDougall et al., 1974; Taylor, 2000; Tripathi et al., 1990), systemic low-grade inflammation (Guy et al., 2016; Selkirk et al., 2008) and perceptual responses to heat (Racinais et al., 2015). Physiological changes that improve thermoregulatory mechanisms enable endurance performance in the heat to be improved following HA (Keiser et al., 2015; Tyler et al., 2016). A meta-analysis by Tyler et al. (2016) showed medium (7-14 days) and long term (>14 days) HA protocols improved performance by ~20%, while short-term (<7 days) protocols resulted in improvements of 7%. Improvements are measured either with a time to exhaustion test, or a time-trial test, with time to exhaustion tests showing disproportionally greater improvements than time-trials (Tyler et al., 2016). Time to exhaustion tests have been criticised for being invalid for sporting situations compared to a time-trial which integrates perceptual responses through the self-regulation of pace (Atkinson et al., 2007; Laursen et al., 2007). However, in a military setting they can be just as valid because many military tasks are conducted at fixed intensities.

2.2.1.4 Individual Variation in Heat Tolerance

Physiological differences between people causes individual variation in the heat (Corbett et al., 2018), where some perform better than others despite similar performances in temperate conditions (Kampmann et al., 2008; Karlsen et al., 2015; McDermott et al., 2007; Stacey et al., 2014). Those who struggle with heat exposure, and indeed those who have had prior heat illness, should undergo heat-tolerance testing (Moran et al., 2007; Schermann et al., 2017). These individuals may require extra medical attention after deployment, or be closely supervised during additional HA before deployment, to induce protective physiological adaptations that will help minimise heat injury risk (Casa et al., 2012; Druyan et al., 2013; Taylor et al., 1997). Despite these efforts it is still likely that some soldiers arriving in hot environments will experience adverse effects (Bricknell, 1995; Willcox, 1920).

Certain sub-populations are more prone to heat illness. Sex differences potentially place females at a thermoregulatory disadvantage, largely due to anthropometric differences (Corbett et al., 2020; Kazman et al., 2015). Furthermore, females sweat less than males (Sawka et al., 1983; Shapiro et al., 1980) which, although potentially minimising dehydration, can reduce heat loss (Sawka et al., 1983). Accordingly, it has been suggested that females may require additional HA to obtain the same adaptations as males (Mee et al., 2015a; Mee et al., 2017). Unfortunately, limited information exists regarding the effects of the menstrual cycle on thermal tolerance and adaptations (Armstrong et al., 2005; Carpenter et al., 1988; Inoue et al., 2005; Kolka et al., 1989; Tenaglia et al., 1999) due to the majority of studies in females controlling for this by testing women at the same time-point in their menstrual cycle (Corbett et al., 2020; Mee et al., 2015b).

Aging also influences thermal tolerance, with older people having higher core temperatures and lower sweat rates, increasing their risk of heat illness (Kenney et al., 1987; Wagner et al., 1972) if the opportunity for behavioural thermoregulation (e.g., lower pacing or resting) is constrained. While age does not appear to affect responsiveness to HA (Tyler et al., 2016), the lower baseline for thermal tolerance in older personnel means they would likely benefit from extended HA protocols (Kenney et al., 1987; Wagner et al., 1972). Despite this, studies looking at heat illness incidence rates often find no relationship with age, possibly due to absolute fitness requirements (King et al., 2019; Li et al., 2018).

Aerobic fitness is tightly linked with improved performance in the heat (Cheung et al., 1998; Pandolf et al., 1977a), with those with higher aerobic fitness being more economical (Smoljanić et al., 2014) and having enhanced cardiovascular capacity that helps combat the effects of heat (Périard et al., 2016). However, aerobic fitness is not a substitute for HA (Corbett et al., 2018) and, in HA studies, has not been shown to affect the degree of heat adaptation (Tyler et al., 2016). Finally, there are other important factors impacting on thermal tolerance, and although considered beyond the scope of this review, include medication (Ramphal-Naley, 2012), disease (Armstrong et al., 2007; Nelson et al., 2018), skin coverings such as camouflage paint and tattoos (Luetkemeier et al., 2017), sleep restriction (WRAIR/ARI, 1987), and jet-lag (Monk, 1991). It is important that group leaders are aware of these factors during deployment so they can assess and monitor each individual and adjust activity levels and exposure (if possible). Furthermore, in the event of a heat illness, additional monitoring is required to safely manage symptoms until appropriate medical attention can be administered (Donoghue et al., 2000). Monitoring technology may enhance this (Buller et al., 2017; Pham et al., 2020; Tharion et al., 2013), but may not be useful in extreme scenarios, emphasising the importance of pre-deployment heat adaptation.

2.2.1.5 Cognitive Performance

As acute effects of heat stress on cognitive performance has been reviewed elsewhere, both during exercise (Chang et al., 2012; Lambourne et al., 2010; Tomporowski, 2003), and in passive (non-exercising) heat (Gaoua, 2010; Hancock et al., 2003; Martin et al., 2019; Schmit et al., 2017), this section will focus on areas relevant both to the military and HA.

Military tasks require a diverse cognitive workload rarely seen in athletic situations, which along with the complex nature of cognitive testing (Lieberman et al., 2005b), may be why this area of performance has received comparatively little attention. Retrospective military reports indicate that cognitive errors are more common in higher temperatures (Froom et al., 1993; Martin et al., 2019), but these claims are not supported by experimental studies in the wider literature (Bhattacharyya et al., 2017; Hancock et al., 2007; Hancock et al., 2003; Schmit et al., 2017). The discrepancy likely centres around task-specific responses to low-risk, lab-based, cognitive testing (Gaoua et al., 2011; Patterson et al., 1998), and a lack of standardisation in regard to the heat stimulus (Gaoua, 2010). Furthermore, many studies have a delay between exercise termination and cognitive testing (Cian et al., 2001; Grego et al., 2005; Jimenez-Pavon et al., 2011; Radakovic et al., 2007), and therefore do not capture cognitive performance during exercise. The recovery period likely enables cognitive function to recover and improve compared to performance during exercise (Chang et al., 2012; Lambourne et al., 2010), which may make them invalid and potentially misleading for military applications in which critical decision making can occur during exercise.

The effects of HA on cognitive performance are less clear. Studies have shown improvements in reaction time (Radakovic et al., 2007) and correct responses to rapid visual processing (Radakovic et al., 2007), and no effect on visual inattention (Patterson et al., 1998) and simple motor performance (Patterson et al., 1998; Radakovic et al., 2007), while time perception has improved (Tamm et al., 2015) or worsened (Patterson et al., 1998) in different studies. Certain adaptations to HA may aid cerebral function by way of constraining hyperthermia, maintaining cerebral blood flow, or lessening discomfort and therefore minimising distractions. Although cerebral blood flow increases with exercise intensities up to ~60% $\dot{V}O_2$max, it declines at higher intensities (Hellstrom et al., 1996; Moraine et al., 1993; Ogoh et al., 2009); a relationship likely further influenced by exercise duration and exacerbated by high body temperature (Nybo et al., 2002; Nybo et al., 2001c). Therefore, increased plasma volume may be thought to improve cognitive function through increased cerebral blood flow at these intensities, for reasons mentioned above. However, alterations in cerebral blood flow do not appear to affect cognitive performance (Shoemaker et al., 2020; Shoemaker et al., 2019). Cerebral autoregulation enables cerebral blood flow to be maintained to some extent despite changes in mean arterial blood pressure brought on by both exercise and heat reducing cerebral blood flow (Kenney et al., 2014; Ogoh et al., 2009; Périard et al., 2011). Brain oxygen, glucose and lactate uptake are not related to reduced cerebral blood flow but do decline at very high intensity exercise (Ide et al., 2000; Ogoh et al., 2009). The continued uptake of nutrients may explain why when manipulating cerebral blood flow with hypercapnia there are minimal changes to cognitive performance (Ogoh et al., 2014). Other mechanistic findings indicate that cerebral neural activation (Ogoh et al., 2014) or alterations in cerebral metabolism (Ogoh, 2017) may play a larger role. The lack of understanding as to why cognitive performance appears affected, and may be improved, is an aspect of HA that is yet to be properly investigated. While it is hard to replicate military decision making in the manner it would be encountered in the field, it is important to use tasks of a similar nature to better understand the foundational cognitive processes being undertaken and how they might be affected both by heat and with HA. New insights using brain imaging technology have begun to better understand how cognition is affected in the heat, even showing that head cooling may help overcome the negative impact of hyperthermia (Xue et al., 2018). Future studies should extend this by adding exercise to the paradigm, to develop a greater understanding of what causes impairments to cognitive function in the heat.

2.2.1.6 How to Achieve Heat Acclimation

The efficacy of several different HA protocols has been reported in the literature. Many factors, such as the heat modality, ambient conditions, and sessions' frequency, number and duration can be adjusted to influence the physiological response to heat and exercise. While these factors have often been chosen or adapted to produce the best outcomes in sporting applications, they can be impractical for military contexts. For example, most HA protocols involve exercising in a heat chamber, allowing environmental conditions to replicate that of a desired environment (Garrett et al., 2012; Garrett et al., 2009; James et al., 2017c; Karlsen et al., 2015; Mee et al., 2015b; Neal et al., 2016a). However, these facilities are often hard to access and cannot accommodate large numbers of participants. Within each session, most studies use low or moderate intensity exercise (45-65% $\dot{V}O_2$max) (Casadio et al., 2016; Charlot et al., 2017; Cotter et al., 1997; Dileo et al., 2016; Fujii et al., 2012; Gibson et al., 2015; Weller et al., 2007), with sessions lasting at least one hour (Best et al., 2014; Casadio et al., 2016; Cotter et al., 1997; Garrett et al., 2009; Garrett et al., 2014; James et al., 2017c; Mee et al., 2015b; Neal et al., 2016a; Patterson et al., 2014; Racinais et al., 2014). For the military, this means adding extra exercise sessions, which may impair other training (Casadio et al., 2017; Guy et al., 2016), and could result in overtraining (Walker et al., 2016).

Recent athletic HA studies have made an effort to maintain the thermal strain during exercise across a HA regime using the controlled hyperthermia technique, i.e. intensity is adjusted regularly to ensure core temperature is maintained at ~38.5°C during exercise sessions (Beaudin et al., 2009; Garrett et al., 2012; Garrett et al., 2009; Garrett et al., 2014; Gibson et al., 2015; James et al., 2017c; Magalhaes Fde et al., 2010; Mee et al., 2015b; Mee et al., 2017; Neal et al., 2016a; Patterson et al., 2014; Ruddock et al., 2016; Weller et al., 2007), but this requires additional equipment and vigilant monitoring of participants using intrusive equipment (Fig 2-3). Furthermore, typical HA programmes take two weeks to see meaningful changes in sweat responses (Bergeron et al., 2012; Garrett et al., 2011; Patterson et al., 2004, 2014; Poirier et al., 2015; Voltaire et al., 2002), which does not suit military groups with short deployment notices.

2.2.1.6.1 Short-term Heat Acclimation

Recent literature has focused on optimising short-term (< 7 days) HA (Brade et al., 2013; Casadio et al., 2016; Charlot et al., 2017; Chen et al., 2013; Dileo et al., 2016; Garrett et al., 2012; Garrett et al., 2009; Garrett et al., 2014; Goto et al., 2010; Guy et al., 2016; James et al., 2017c; Karlsen et al., 2015; Kelly et al., 2016; Mee et al., 2015b; Mee et al., 2017; Neal et al., 2016a; Petersen et al., 2010; Sunderland et al., 2008; Walker et al., 2001; Willmott et al., 2016) to minimise the barriers present in HA and prevent potential interference with higher priority training objectives (Casadio et al., 2017; Casadio et al., 2016; Kelly et al., 2016). However, again this requires additional training sessions and access to specialist facilities, such as heat chambers (Gibson et al., 2015; James et al., 2017c). The reduced programme length also limits the magnitude of adaptations (Tyler et al., 2016). While a lack of increase in sweat rate might limit dehydration, this may occur at the cost of other adaptations, and would soon develop upon deployment (Karlsen et al., 2015). While short-term HA may be practical for athletic groups (and some military situations), the reduced magnitude of changes makes it less desirable for groups deploying with ample notice, and the length of the programme is likely incompatible for short-notice deployment units (Fig 2-3). For deployments of slightly longer notice, it might serve as a primer for more chronic adaptations to develop during deployment.

2.2.1.6.2 Passive Heat Acclimation Methods

Passive heat exposure modalities, such as saunas or hot-water immersion facilities, allow groups of people to acclimate at once (Fig 2-3), and can be installed easily. Passive HA may alleviate concerns that essential training may be impaired by additional sessions being conducted in the heat (Fig 2-3), although to what extent normal training can be affected is currently unclear. Passive heat methods have typically been employed post-exercise, allowing exercise to elevate core temperature that can be maintained or further increased by passive heat (Scoon et al., 2007; Zurawlew et al., 2016; Zurawlew, 2018), while there may also be benefits to having exercise metabolites in the circulation during passive heating (Kissling et al., 2019). The following sections consider passive heating methods currently in use and the evidence surrounding their physiological and functional effectiveness.

2.2.1.6.2.1 Sauna

Saunas are a hot-dry (65-110°C, 10-30% relative humidity) room designed to induce cardiovascular strain and a sweat response (Hannuksela et al., 2001). Increases in peripheral blood distribution help invoke cardiovascular and hormonal adaptations that are beneficial for coping in the heat (Fig. 2-2). Scoon et al. (2007) reported four 30-minute post-exercise saunas (90°C) per week for three weeks increased plasma volume by 7%, while improving time to exhaustion by 32%. Supporting this, Stanley et al. (2015) found a plasma volume increase of 18% after four 30-minute post-exercise sauna exposures (87°C, 11% RH). The larger increase could be due to sessions occurring on consecutive days, although further comparison between studies is limited by the lack of a performance test.

2.2.1.6.2.2 Hot-water Immersion

Hot-water immersion works similarly to sauna and has also been used to maintain an elevated core temperature after exercise. Zurawlew et al. (2016) had an experimental group bathe in 40°C water for 40 minutes following training on six consecutive days, allowing for an additional ~1°C rise in rectal temperature, compared to controls bathed in 34°C water. In a heated (33°C, 40% RH) 5-km running time-trial the intervention group improved 4.9%, linked to a lower core temperature, skin temperature and earlier sweat onset. Similar findings were observed in a subsequent study, by the same research group, which also saw reductions in end-exercising heart rate and $\dot{V}O_2$, and no significant change in plasma volume (Zurawlew, 2018). Brazaitis and Skurvydas (2010) produced similar findings using immersion in 44°C water up to the waist for 45 minutes on alternating days over a two-week period, without prior exercise. Although no performance test was conducted, this resulted in lower core temperature (↓ 0.3°C), heart rate (↓ 12 bpm) and psychological strain, and an increased sweat rate (↑ 40%) during hot-water immersion on the final day when compared to day 1 (Brazaitis et al., 2010).

In summary, both sauna and hot-water immersion provide a heat exposure stimulus without requiring additional exercise, which may benefit military groups with heavy training schedules. These two passive heating modalities are yet to be directly compared in a HA context, so it is unclear whether they offer unique adaptations that may help before travelling to stressful environments. Furthermore, no study had compared either method to a more traditional, exercising HA programme, so it is unclear what differences exist in maximal adaptive capacity as well as the rates of adaptation each offer. Further investigations are required to evaluate the performance of both passive heating methods and to optimise their ability to induce heat adaptations.

2.2.1.7 Heat Re-acclimation

One method that could enable rapid HA in military personnel is re-acclimation. This topic has recently been thoroughly reviewed elsewhere (Daanen et al., 2018), and so will be discussed only briefly here. Heat re-acclimation occurs following a period away from heat after completing an initial HA programme. Here, a few HA sessions are used to restore, or maintain, heat adaptations which otherwise begin to decay (Périard et al., 2016). As studies in this area are relatively few, results vary, with some studies finding a day of HA is lost with every two days with one heat exposure a week (Garrett et al., 2011), while a single HA session every 5 days can sustain adaptations (Périard et al., 2016; Pryor et al., 2018). Within a military context, where deployment time can be unknown, re-acclimation could maintain a heat-acclimated state for a long period of time. Despite this area of research still being in its infancy, the potential to regain the adaptations of a previously completed heat-acclimation regime in a very short space of time (Fig 2-3), or to continuously maintain them is promising. Within the military, maintaining these adaptations after acclimatising on deployment or during training in a warmer climate are both convenient and feasible. This would allow heat-acclimated soldiers to deploy to hotter climates at very short notice with minimal heat-related performance impairments.

2.2.1.8 Recommendations

In-situ acclimatisation in the operational environment allows all-day exposure to the environmental conditions that will be worked in, and therefore is often the most desirable way to adjust to the heat. However, this is not always possible, and indeed deployment to this environment must also be considered. In more temperate environments where soldiers typically train, HA is an effective way to induce physiological adaptations to protect the body against thermal disturbances to homeostasis. If possible, the use of heat chambers for HA is well supported (Taylor, 2000; Tyler et al., 2016), although it is less practical for large groups and requires additional training sessions (Casadio et al., 2017). Whether or not supervision (both by person and technical equipment) is available to support these sessions dictates whether controlled hyperthermia or fixed-intensity exercise should be conducted (Fig 2-3).

Controlled hyperthermia is currently considered the best-practice method for HA (Gibson et al., 2015; Patterson et al., 2014). However, it requires intrusive and expensive equipment to provide real-time measures of core temperature, and because of this has often been overlooked in favour of fixed-intensity protocols (Parsons et al., 2019). Fixed-intensity protocols provide a simpler option by conducting sessions at a fixed power output. These sessions require less participant monitoring but over the course of the protocol, as adaptations occur, the thermal strain is reduced, minimising the heat stimuli for adaptation. Instead, by exercising at a fixed heart rate, the cardiovascular strain can be maintained in a similar manner to controlled hyperthermia, while requiring less monitoring equipment. Alternatively, when heated facilities that can be readily exercised in are unavailable, passive HA can provide an effective alternative (Fig 2-3). While further studies are required to determine the best use of this approach, the results from recent studies are promising, demonstrating both performance enhancing and protective adaptations (Scoon et al., 2007; Stanley et al., 2015; Zurawlew et al., 2018b; Zurawlew et al., 2016).

When considering the length of the HA protocol it is important to consider how HA integrates with other training requirements. This may impact the length of the HA protocol as conducting sessions on consecutive days may become impractical (Casadio et al., 2017). Furthermore, the overall load and fatigue state of soldiers during HA phases also requires attention as arriving at the deployed destination in an over-trained state will render adaptations meaningless (Li et al., 2018; Schmit et al., 2018). If operational flexibility is low (i.e., mission objectives are fixed and must be completed within a precise timeframe) it becomes even more desirable than usual for HA adaptations to be as complete as possible as there is limited opportunity for behavioural adjustments to the heat (Schlader et al., 2011). Therefore, the use of a long-term HA protocol to generate these adaptations is ideal, although if notice before deployment is short re-acclimation would be more suitable (Fig 2-3). The re-acclimation would require having already conducted a long-term HA protocol, and then maintaining those adaptations for a prolonged period, to hold an elevated baseline thermal tolerance. Such a strategy would likely only be used in special units that are aware in advance that they could be called upon to deploy at short notice into different climates. If operational flexibility is moderate-high, then HA prior to deployment would likely act as a primer to minimise the effects of heat immediately upon arrival and provide a baseline thermal tolerance that would be enhanced in the coming days (Fig 2-3). Regardless, if ample notice is given prior to deployment, it makes sense to obtain maximally beneficial adaptations, if other training allows it.

2.3 Conclusion

Both physical and cognitive performance are impaired during exercise in the heat. HA induces underlying physiological adaptations which enhance thermoregulatory and cardiovascular function, which are responsible for at least part of the improved performance in the heat. While HA studies to date inform strategies for athletes preparing for competition in the heat, there is minimal consideration of military specific factors such as restrictive clothing, carried loads, large groups being acclimated, or short deployment notice. For military units that might expect to deploy at short notice (< 1 day), the options regarding HA are limited to proactively planning to maintain heat adaptations for a prolonged and unspecified period. However, this approach has received limited attention in the literature due to this unique set of circumstances. Therefore, further investigations are required to optimise HA for military application. Specifically, the identification of effective, practical, and feasible methods of HA, or re-acclimation, which can be undertaken by large groups of military personnel at short notice to prepare for deployment to hot environments.

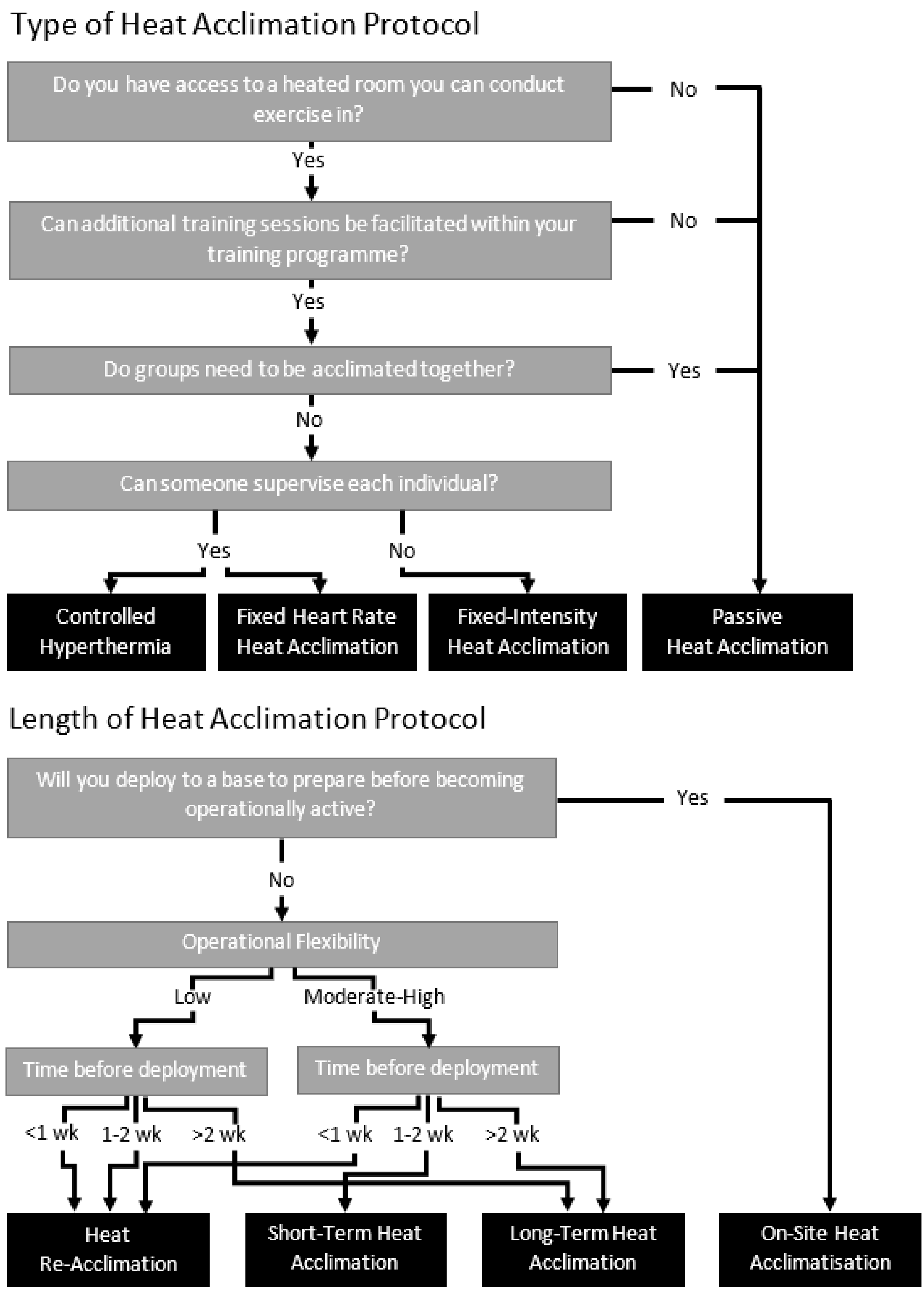

Figure 2-3. Flow diagrams to determine the most appropriate form of heat acclimation, and how long the heat acclimation protocol should be, prior to deployment. Groups are defined as > 5 personnel. Operational flexibility is the ability to change the activities done during the operation (i.e., ability to stop and rest or change the objective).

Chapter 3 Physiological Effects of Hot Environments on Military Performance

3.1 Introduction

Military personnel deployed abroad are often exposed to different environments from that which they typically live and train in (Parsons et al., 2019). Regions with tropical climates are predisposed to conflict as weather patterns that affect food production can lead to civil unrest, which in extreme cases leads to conflict which can then warrant international intervention (Humphreys, 2005; Koubi, 2019). Additionally, with climate change affecting crop growth, mass migration of peoples is reaching a new level, leading to resource competition, which increases the chances of conflict, and therefore means military operations in extreme environments are also likely to rise (Brzoska et al., 2016; CNA, 2007; Reuveny, 2007; Smith, 2007).

Hot environments pose a unique challenge to military operations as military-specific factors, such as carrying heavy loads and wearing protective gear, increases endogenous heat production and restricts heat loss (Taylor, 2015), thereby predisposing military personnel to exertional heat illness (Casa et al., 2012). Exertional heat illness can present as heat syncope, heat exhaustion, and in extreme cases heat stroke, which can cause organ damage, and in some cases death (Carter et al., 2005; Goforth et al., 2015; Howe et al., 2007). Therefore, understanding how to avoid such events is important for safety, as well as military performance in such environments.

Hot environments are typically characterised by either very high ambient temperatures and low humidity (i.e., arid), or high ambient temperatures and high humidity. Arid environments are typical of desert terrain and have been encountered recently by numerous international militaries in Afghanistan and the Middle East (Armed Forces Health Surveillance Branch, 2019). Humid conditions are often found in jungle environments, and have been encountered in tropical regions of Asia (Forster, 1951; Haisman, 1972). Regarding the heat stress differences between the environments, the high ambient temperature in arid environments causes environmental heat gain (Nadel, 1979), while the high vapour pressure in humid environments minimises sweat evaporation (Akerman et al., 2016; Gonzalez et al., 1974). Given that evaporative heat loss is the main avenue for heat loss during physical activity in humans, a greater thermal challenge is likely to occur in humid environments (Bergeron et al., 2012; Maughan et al., 2012).

In military contexts the environmental characteristics and terrain influence the carried loads and protective clothing requirements of each soldier (Eddy et al., 2015; Larsen et al., 2011), which may inadvertently augment the effects of hot environments (Boffey et al., 2018; McLellan, 2001). For example, arid environments consist primarily of open areas where air support is available, and soldiers often move alongside vehicles. Consequently, the carried pack is relatively light, but as open conflict is more likely, more body armour is worn, further restricting heat loss from the torso (Johnson et al., 1995). Conversely, a humid jungle environment often requires self-sufficiency, requiring a larger pack. However, as camouflage and stealth play a greater role, less body armour may be worn.

Given the environmental differences in the presentation of heat and the expected mission objectives dictating a unique gear loadout, it is likely that the environments place different physiological strain on soldiers. Understanding these differences allows training plans prior to deployment to be tailored for each environment. Additionally, identification of physiological variables that influence or predict subsequent performance in the heat is desirable as they may help inform safety outcomes and assist both deployment selection and real-time monitoring of individuals in the field. Therefore, the aims of the current study were two-fold. Firstly, to determine physiological responses to military activity in arid and humid environments. And secondly, to determine factors that may predict performance both prior to and during exercise in arid and humid environments.

3.2 Methods

3.2.1 Experimental Design and Overview

A randomised, repeated measures cross-over design was used, with 9 participants completing two 120-min heat-stress tests (HSTs), with one HST conducted in a humid environment (33°C, 75% relative humidity (RH) (27 g.m^{-3} absolute humidity)) and the other in an arid environment (46°C, 10% RH (7 g.m^{-3} absolute humidity)), based on the worst case-scenarios in South-East Asia, and the Middle East, respectively. Temperatures were matched on wet-bulb globe temperature (~30°C WBGT). During each HST several physiological, perceptual, and cognitive assessments were conducted (Fig. 3-1). Each HST was conducted at least one week apart. University (AUTEC: 17/420) and New Zealand Defence Force (6755/1) ethical approval was acquired and informed consent obtained in writing from all participants as per the *Declaration of Helsinki*.

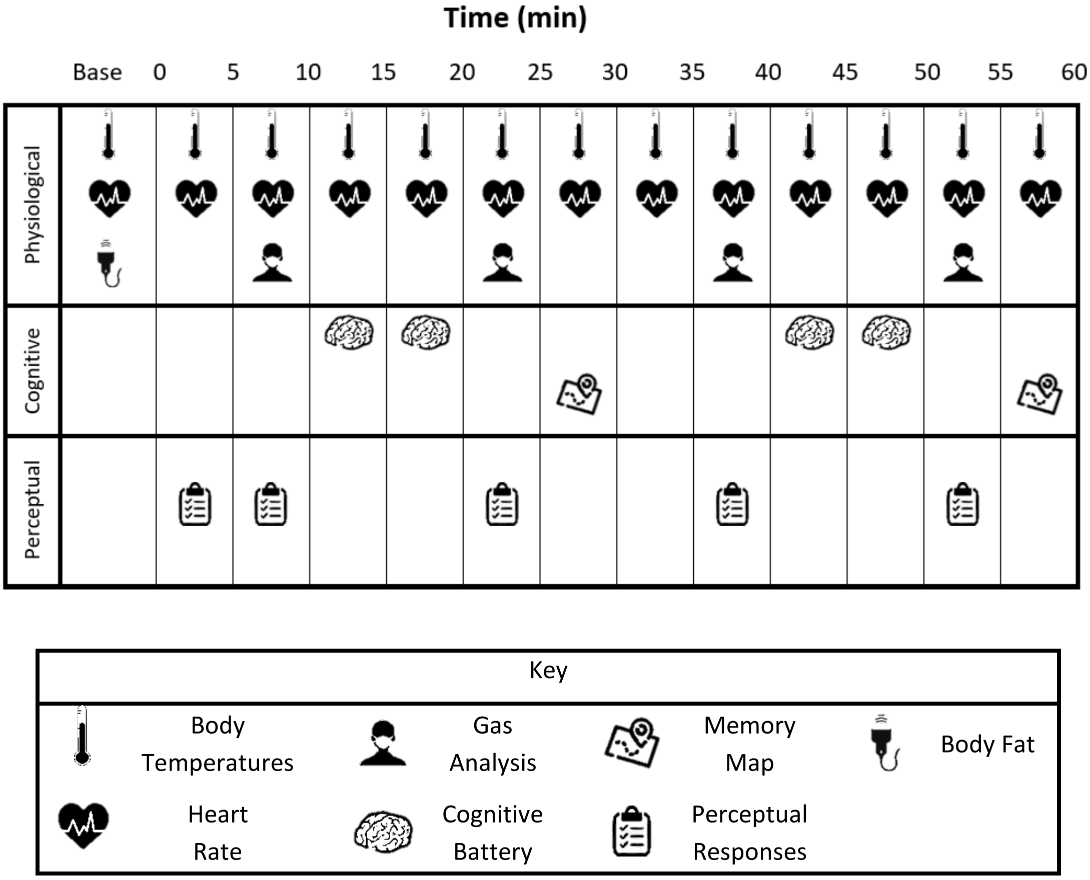

Figure 3-1. Schematic of tests conducted over the first 60 min in each heat-stress test. From 60 to 120 min measures were taken in the same order.

3.2.1.1 Participants

Nine pack-fit military personnel (8 males, 1 female) volunteered to participate in the study (age 32.6 ± 9.4 years, body mass 81.1 ± 10.0 kg, 2.4 km run time 9:40 ± 1:11 min, estimated $\dot{V}O_2$ 54.2 ± 6.1 $mL.kg^{-1}.min^{-1}$). The female participant completed tests 28 days apart to ensure both tests were conducted during the follicular phase of the menstrual cycle, confirmed by self-reported menstruation.

3.2.2 Heat-Stress Tests

HSTs were conducted at the same time of the day for each participant. Participants were asked to avoid strenuous activity for the 24 h preceding each HST and were asked to record their food intake so that it could be replicated for the subsequent trial. Each HST was carried out in an environmental chamber (Design Environmental, Simultech Australia, Australia), beginning with 10 min of seated rest, followed by walking on a treadmill (Platinum Club Series, Life Fitness, Illinois, USA) at a fixed speed of 5 $km.h^{-1}$ for 2 h (Druyan et al., 2013; Epstein et al., 2012; Ketko et al., 2015) or until termination criteria were met. Termination could occur at any time due to either voluntary termination, or key physiological variables exceeding the ethical limits of rectal temperature (> 39.3°C) (Aoyagi et al., 1995) or heart rate (> 95% age-predicted maximum for 1 min) (Tanaka et al., 2001). Walking time was taken as the time at test termination. Participants were dressed according to the environment they would be operating in. For the arid environment participants wore body armour (~10 kg), a small backpack (~15 kg), helmet, and hiking shoes (total ensemble 31.1 ± 2.3 kg) (Fig 3-2). In the humid environment participants wore load carrying webbing (~ 8 kg), a large backpack (25 kg), a jungle hat, and jungle boots (total ensemble 36.4 ± 2.1 kg) (Fig. 3-2). In both environments participants also carried a rifle (~3 kg, included in total ensemble weights) and wore military uniform comprised of long-sleeved shirt and trousers. Fluid intake was allowed *ad libitum* up to a maximum of 2 $L.h^{-1}$, as per military rations, and was recorded.

Figure 3-2. Gear loadouts for the humid (left) and arid (right) environments for each heat-stress test.

3.2.2.1 Baseline measures

Prior to the start of each trial a urine sample was obtained from each participant and analysed for urine specific gravity (USG), a marker of hydration status, using a urine refractometer (Atago, Japan). Body fat was assessed by way of ultrasound (12L, Vivid S5, GE Healthcare, Chicago, IL) of the abdomen, 2 cm lateral to the umbilicus (Leahy et al., 2012; Mike Marfell-Jones et al., 2006). The reading provided a measurement of subcutaneous adipose tissue thickness at the abdomen, which has been shown to have a very strong correlation with body fat measured by DEXA (Leahy et al., 2012; Wagner, 2013). Participants were weighed, post-void, both semi-nude and fully dressed (i.e., all protective equipment on). The same weights at the end of the HSTs were used to calculate whole-body sweat rate (Eq. 3-1) (Buono et al., 2009) and evaporated sweat rate (Eq. 3-2) (Amos et al., 2000). While these equations do not account for sweat dripping from the participant, this value is likely negligible as most sweat was retained in the clothing.

(semi-nude weight change + fluid consumption) ÷ walking time Equation 3-1

(fully dressed weight change + fluid consumption) ÷ walking time) Equation 3-2

3.2.2.2 Continuous measures

Core temperature was recorded rectally, using a flexible thermistor (Hinco Instruments, Australia) self-inserted ~12 cm beyond the anal sphincter. Skin temperature was measured on the right-hand side of the body at the chest, bicep, thigh, and calf using skin temperature probes. Rectal and skin temperatures were logged at 1 Hz (SQ2020, Grant Instruments, Cambridge, UK). In preparation for analysis, rectal and skin temperature readings were filtered due to noise caused by connections with the logger and occasional skin temperature probes losing contact with the skin due to the humid microenvironment. A filter was applied to remove all readings that changed by more than 0.1°C.s^{-1}. Then a low-pass Butterworth filter of 0.02 Hz was applied to the data. Missing data were filled with linear interpolation.

Mean skin temperature was calculated using Eq. 3-3. (Ramanathan, 1964):

$$\mathrm{T_{Sk}} = 0.3\mathrm{T_{Chest}} + 0.3\mathrm{T_{Bicep}} + 0.2\mathrm{T_{Thigh}} + 0.2\mathrm{T_{Calf}} \qquad \text{Equation 3-3}$$

If a thermistor became askew or off the skin, the equation was modified to proportionally compensate the weights of the three remaining sensors to maintain the summation of coefficients to 1.0 (e.g., $\mathrm{T_{Sk}} = 0.375\mathrm{T_{Chest}} + 0.375\mathrm{T_{Bicep}} + 0.25\mathrm{T_{Thigh}}$ if the calf reading was lost). No temperature was calculated if two sensors produced no signal. Averages over 10 min periods were used for analysis, including during the rest period.

Cardiac frequency was measured using a heart rate monitor (Polar RS800CX, Kempele, Finland), with values recorded every 5 min.

The slope of each continuous measure was calculated by the change from walking onset to exercise termination divided by walking time.

3.2.2.3 Periodic measures

Several measures were taken periodically throughout each HST. Perceptual measures were taken every 15 min, involving ratings of perceived exertion (RPE) (15-point scale ranging 6-20), thermal discomfort (1-10), thermal sensation (1-13), feeling (-5 - +5) and sleepiness (1-9). Gas analysis was conducted for 4 min every 15 min with participants breathing through a mouthpiece connected to a calibrated, automated system (Trueone 2400, Parvo Medics, Utah, USA) enabling expired gas concentrations and volumes to be determined. The rate of change in these measures was taken as the difference between that reported at walking onset, and that reported at exercise termination divided by the walking time within each participant within each session. Carbohydrate oxidation was calculated using Equation 3-4 (Jeukendrup et al., 2005).

$$4.21\ \dot{V}CO_2 + 2.962\ \dot{V}O_2 \qquad \text{Equation 3-4}$$

3.2.2.4 Cognitive Testing

A series of cognitive assessments were completed during each HST. Each battery lasted ~10 min and was begun at 10, 40, 70 and 100 min, unless test termination occurred prior. Simple reaction time was assessed using an electronic tablet (Nova 2 Lite, Huawei, Shenzhen) application (Reaction Time Tests for Science, Andrew Novak, 2016) which required participants to respond to a red circle appearing on a screen. Discrimination reaction time was also assessed in this manner, with participants again responding to a red circle, but avoiding responding to blue and black circles that appeared. A serial arithmetic task was used to assess cognitive throughput (Kase, 2009) to determine information processing speed. This required subtracting either 7 or 9 from a 4-digit number as many times as possible within a minute. A digit span task was used to assess working memory (Hocking et al., 2001). Participants were required to memorise a series of numbers read out to them, and repeat them back, in the reverse order. The test began with 3 digits being read out and increased by 1 digit after correctly recalling numbers twice at a given level, with the test ending once two incorrect sequences were given at the same level. The first test for all non-reaction time cognitive tasks represented the familiarisation and was not included in the analysis. Following completion of this cognitive testing battery a NASA task-load index (TLX) was given to participants to indicate how they perceived the tasks to be, specifically in relation to mental, temporal, and physical demands, as well as performance, effort and frustration (21-point scale).

Furthermore, a declarative memory task was also conducted using a memory map. The task involved memorising a simplified, fictional urban town plan, regarding a predefined route, the roads travelled along, landmarks and directions. The task was presented to participants at 25 and 85 min for 2 min, alongside a list of predetermined questions they would be required to answer. Following removal of the memory map participants were required to retain the information for ~30 min. At 55 and 115 min the predetermined questions were read aloud, and participants answered orally.

3.2.3 Data Analysis

Data analysis was conducted in two phases: the first compared the change in physiological variables over time between the two environments, while the second involved a linear regression between each variable and physical performance in each environment. All analyses were conducted in R version 3.6.1 (R foundation for Statistical Computing, Vienna, Austria).

To compare variables between environments, linear mixed models were fitted for each variable. For each mixed model, Q-Q plots were used to ensure homoscedasticity. Environment, time (if appropriate), and order (whether the arid or humid HST was conducted first) were used as fixed effects, with participant as the random effect. The model-generated estimated means are reported, with either standard deviation or 95% confidence intervals and *p* values where appropriate. The alpha level was 0.05. For data with multiple time points *post hoc* tests, were conducted using a time by environment interaction, with a Bonferroni correction applied.

For regression analyses, predetermined variables of interest were selected and inputted into a linear regression model along with the performance outcome; walking time. The lm.beta function, from the QuantPsyc package, was used for analysing each regression. Data are reported as both standardised (β) and unstandardised (B) regression coefficients, with a 95% confidence interval shown. The strengths of the standardised regressions were classified by the following correlation guidelines: very weak < 0.2, weak 0.2-0.4, moderate 0.4-0.6, strong 0.6-0.8, and very strong 0.8-1.0 (Evans, 1996).

Due to the differences in pack loads, in addition to collecting oxygen consumption through gas analysis, the estimated oxygen requirements of each condition were calculated using the predictive energy equation of Pandolf et al. (1977b):

$$M = 1.5W + 2(W+L)(L/W)^2 + \eta(W+L)(1.5V^2 + 0.35VG) \qquad \text{Equation 3-5}$$

Where M is metabolic rate, W is weight, L is load, η is the terrain coefficient (1 for treadmill), V is velocity and G is gradient.

The estimated watts were converted into $kcal.kg^{-1}.h^{-1}$ using a conversion factor of 0.86 (Taguchi et al., 2004). Then estimated relative $\dot{V}O_2$ value was calculated using ACSM guidelines (American College of Sports Medicine, 2010) where 1 $kcal.kg^{-1}.h^{-1}$ = 3.5 $mL.kg^{-1}.min^{-1}$. These calculations revealed the humid environment would be expected to induce 6% greater oxygen requirement.

3.3 Results

3.3.1 Environmental Differences

The actual temperature and humidity during the humid trials was 33.4 ± 0.6 °C and 78 ± 2% RH (28 g.m^{-3} absolute humidity), while in the arid trials it was 44.3 ± 0.5°C and 21 ± 2% RH (13 g.m^{-3} absolute humidity), providing WBGTs of 31.1°C and 31.5°C, respectively. Baseline characteristics of body mass, body fat, USG and sleep quality were not different between environments (all p > .262).

No differences were observed in walking time (WT) between the two environments (Humid: 73.1 ± 12.8 min; Arid: 82.3 ± 22.0 min; p = .155) (Fig. 3-3). In the humid environment 56% of sessions (5/9) were terminated due to rectal temperature rising beyond the ethical threshold limit. One session was terminated due to elevated heart rate, while the remaining three were voluntarily terminated. In the arid environment trial, 44% of sessions (4/9) were terminated due to reaching the ethical rectal temperature threshold, one session due to elevated heart rate, and the remaining four sessions were voluntarily terminated.

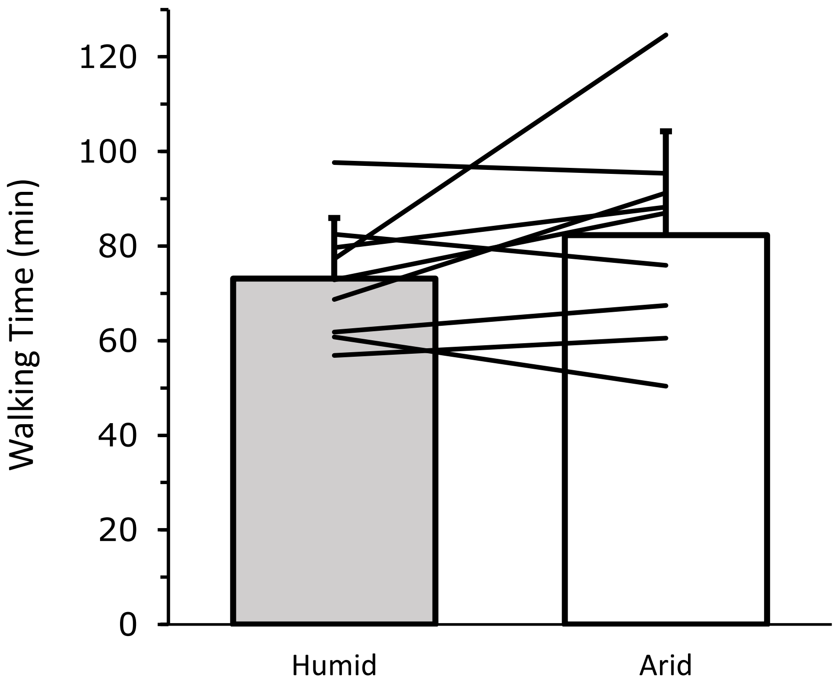

Figure 3-3. Walking time before test termination in a simulated pack march in humid (33°C, 78% RH) and arid (44°C, 21% RH) environments in appropriate military protective equipment. Data displayed as mean ± SD. Individual responses are displayed by individual black lines.

Table 3-1. Physiological and perceptual responses during a simulated pack march in full military protective in humid (33°C, 78% RH) and arid (44°C, 21% RH) environmental conditions. Data are displayed as estimated mean ± SD.

Variable	Humid	Arid	*p* value
Rectal Temperature (°C)			
Resting	36.9 ± 0.4	36.9 ± 0.4	.967
Average	38.1 ± 0.4	37.8 ± 0.4	**<.001***
Maximum	38.9 ± 0.5	39.0 ± 0.7	.676
Slope (°C.h^{-1})	1.7 ± 0.3	1.6 ± 0.3	.462
Skin Temperature (°C)			
Resting	34.1 ± 0.7	34.2 ± 0.8	.423
Average	36.2 ± 0.3	36.6 ± 0.3	**<.001***
Maximum	36.9 ± 0.5	37.6 ± 0.7	**.010**
Slope (°C.h^{-1})	1.9 ± 0.7	2.0 ± 0.7	.642
Heart Rate (b.min^{-1})			
Resting	76 ± 14	76 ± 13	.880
Average	146 ± 21	141 ± 23	**<.001***
Maximum	169 ± 17	168 ± 12	.869
Slope (b.min^{-1}.h^{-1})	39 ± 13	40 ± 14	.893
Sweat Rate (L.h^{-1})	1.2 ± 0.3	1.3 ± 0.3	.187
Evaporated Sweat Rate (L.h^{-1})	0.6 ± 0.6	0.9 ± 0.4	**.045***
Rate of Fluid Consumption (L.h^{-1})	0.6 ± 0.3	0.7 ± 0.5	.577
USG Pre	1.011 ± 0.006	1.016 ± 0.007	.069
Body Mass Loss (%)	2.1 ± 1.0	2.4 ± 1.0	.284

*p value < .05 between conditions

Note: slopes are calculated from exercise onset, and not resting values.

3.3.1.1 Physiological Differences

While no differences were evident at rest, during exercise rectal temperature was higher in the humid environment ($p < .001$; Table 3-1, Fig. 3-4). However, no significant differences were observed in the slope of rectal temperature between environments (Table 3-1). When extrapolated to determine how long it would be before rectal temperature reached 40°C, exercise in the humid environment was projected to last 95 min, compared to 120 min in the arid environment (Fig. 3-4). Conversely, the arid environment had a ~0.5°C higher skin temperature across the trial, despite no baseline differences, or differences in the rate of rise in skin temperature (Table 3-1). Heart rate in the humid environment was elevated by ~5 b.min^{-1} over the trial in comparison to the arid environment, although other differences in heart rate were minimal (Table 3-1). Although overall sweat rate was not significantly different between conditions, evaporated sweat rate was ~40% greater in the arid environment (Table 3-1). No differences were observed in any measure of hydration (Table 3-1).

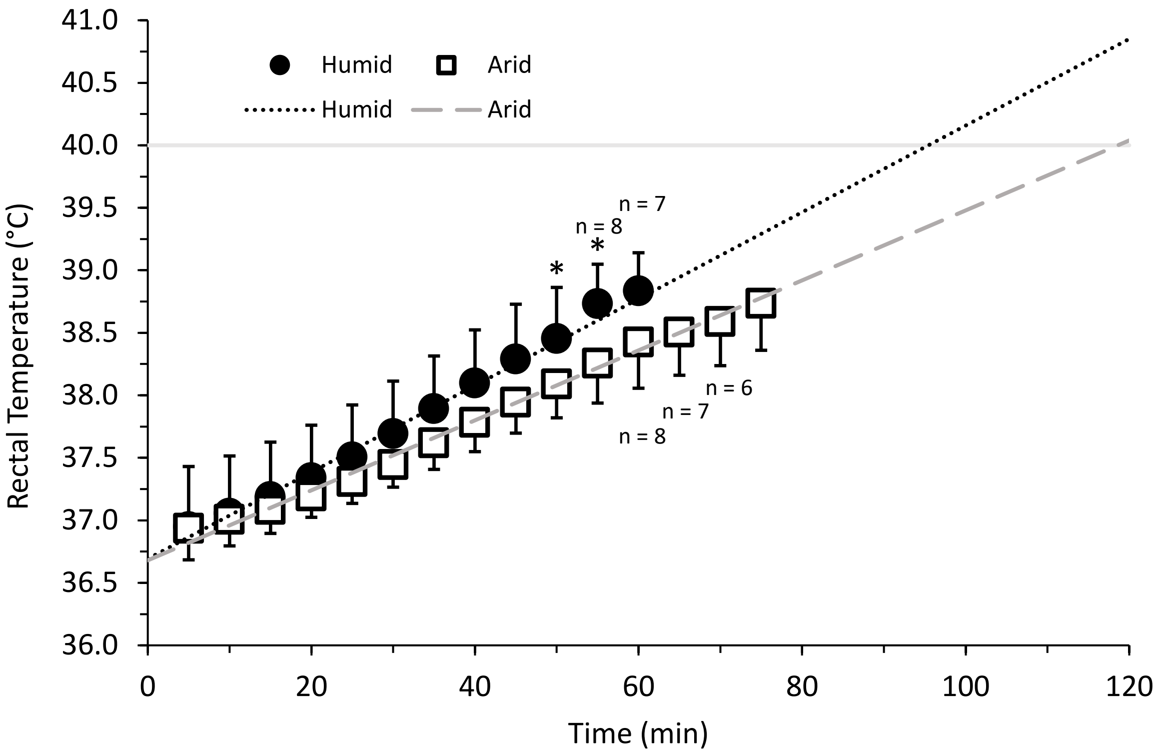

Figure 3-4. Rectal temperature during a simulated pack march in either a humid (33°C, 78% RH) or arid (44°C, 21% RH) environment taken as an average of the prior 5 min. Trendlines display the predicted means based on recorded data, only for when *n* = 9. Data is plotted as mean ± standard deviation for *n* = 9 unless otherwise stated (data is stopped once *n* < 6). **p* <.05 between conditions at an individual time-points.

Metabolic variables of $\dot{V}O_2$, $\dot{V}CO_2$ and $\dot{V}E$ all increased significantly throughout both trials (all $p < .001$). Between conditions, a greater $\dot{V}O_2$ was present in the humid condition (Humid: 19.8 ± 2.5 mL.kg^{-1}.min^{-1}; Arid: 18.0 ± 2.2 mL.kg^{-1}.min^{-1}; $p < .001$), supported by increases in $\dot{V}E$ (Humid: 47.0 ± 12.1 L.min^{-1}; Arid: 42.6 ± 9.8 L.min^{-1}; $p < .001$) and $\dot{V}CO_2$ (Humid: 1.40 ± 0.21 L.min^{-1}; Arid: 1.28 ± 0.18 L.min^{-1}; $p < .001$). Furthermore, the observed 10% greater oxygen requirement in the humid environment, was similar to the calculated *a-priori* estimate which suggested a 6% greater oxygen requirement. Regarding estimated substrate use there was no difference in respiratory exchange ratio (Humid: 0.88 ± 0.04; Arid: 0.88 ± 0.05; p = .848), although the greater carbohydrate oxidation in humid conditions approached significance (Humid: 1.2 ± 0.3 $g.min^{-1}$; Arid: 1.1 ± 0.4 $g.min^{-1}$; p = .063).

3.3.1.2 Perceptual Differences

All perceptions worsened throughout each condition (all $p < .001$). There were no differences between environments for thermal discomfort, thermal sensation, sleepiness or feeling (all $p > .186$). However, RPE was significantly elevated in the humid environment compared to the arid environment (Humid: 12.9 ± 2.6; Arid: 12.4 ± 2.8; p = .040).

3.3.1.3 Cognitive Differences

No differences in cognitive performance existed between environments (all $p > .220$) or over time (all $p > .075$). Similarly, cognitive perception was not different between the environments in the task-load index (all $p > .075$), although increases in mental, physical, and temporal demand, as well as effort and frustration all occurred over time in both environments (all $p < .011$) (Fig. 3-5).

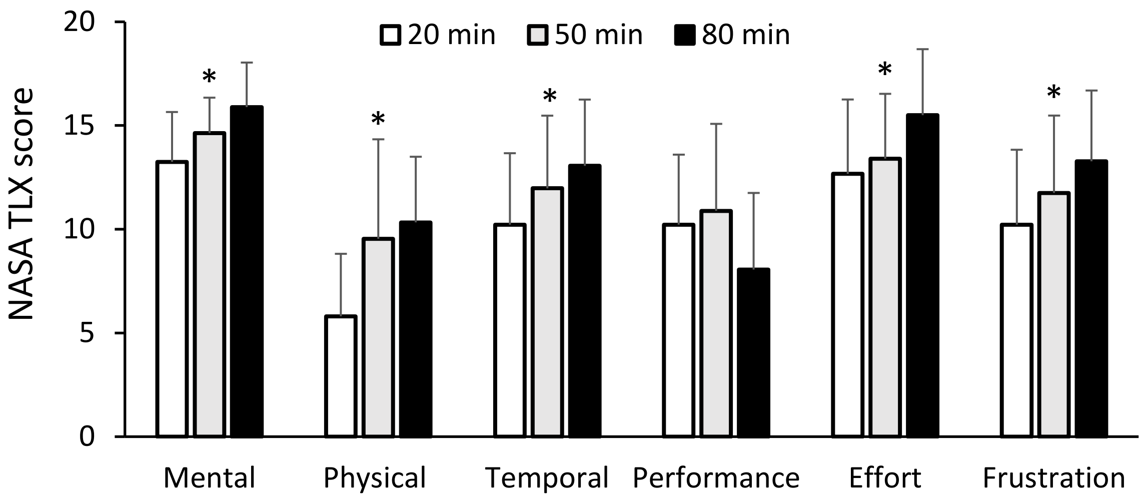

Figure 3-5. Pooled responses to the NASA task-load index (TLX) following completion of a cognitive battery during military-specific heat-stress tests in both humid (33°C, 78%RH) and arid (44°C, 21%RH) environments. *indicates a significant effect of time, regardless of the environment.

3.3.2 Regression

Both standardised and unstandardised regression coefficients between individual measures and WT are presented in Table 3-2. Baseline predictors returned generally weak predictors of WT, although lower body fat in the arid environment and high body mass in the humid environment both provided moderately strong predictions of performance (longer WT; Table 3-2). The slope of skin temperature also had a moderately strong negative relationship with WT in the arid environment but not in the humid environment (Fig. 3-6B). The change in heart rate during exercise was strongly associated with WT in the humid environment (Fig. 3-6E). Sweat rate (Fig. 3-6C) had a moderate relationship with performance in the humid environment, whereas only a trivial association was observed in the arid environment (Table 3-2). The rate of change in perceptual measures of thermal sensation and sleepiness (Fig. 3-6F) were strong or very strong predictors of performance in both conditions, although RPE had a much weaker relationship (Table 3-2).

Table 3-2. Regression analysis predicting walking time (WT) using performance predictors prior to, and during a simulated heat-stress pack march in humid (33°C, 78% RH) and arid (44°C, 21% RH) environments. Data are displayed as standardised (β) or unstandardised (B) coefficients with a 95% confidence interval.

	Humid		Arid	
	β	B	β	B
Baseline Characteristics				
Aerobic Fitness	.18 (-.55, .75)	0.4 (-1.5, 2.2)	.58 (-.13, .90)	2.1 (-0.5, 4.7)
Resting Rectal Temperature (°C)	-.31 (-.80, .44)	-9 (-32, 15)	-.15 (-.74, .57)	-15 (-103, 74)
Resting Skin Temperature (°C)	-.28 (-.80, .47)	-5 (-21, 11)	-.30 (-.80, .46)	-9 (-36, 17)
Resting Heart Rate ($b.min^{-1}$)	-.23 (-.78, .51)	-0.2 (-1.0, 0.6)	.18 (-.55, .75)	0.3 (-1.2, 1.8)
Body Fat (mm)	-.19 (-.79, .59)	-0.1 (-0.5, 0.3)	-.39 (-.86, .43)	-0.4 (-1.3, 0.5)
Body Mass (BM; kg)	.39 (-.37, .84)	0.5 (-0.5, 1.5)	.15 (-.57, .74)	0.3 (-1.7, 2.3)
Surface Area (SA; m^3)	.58 (-.13, .90)	38 (-9, 84)	.29 (-.46, .80)	32 (-62, 126)
SA : BM ($cm^3.kg^{-1}$)	.15 (-.57, .74)	0.2 (-0.8, 1.1)	.22 (-.52, .77)	0.4 (-1.2, 2.1)
Exercising Characteristics				
Rectal Temperature Slope ($°C.h^{-1}$)	-.73 (-.94, -.12)	-32 (-59, -5)	-.54 (-.89, .19)	-36 (-86, 14)
Skin Temperature Slope ($°C.h^{-1}$)	-.24 (-.78, .51)	-4 (-20, 12)	-.56 (-.89, .16)	-19 (-43, 6)
Heart Rate Slope ($b.min^{-1}.h^{-1}$)	-.61 (-.91, .08)	-0.6 (-1.3, 0.1)	-.23 (-.78, .51)	-0.4 (-1.8, 1.0)
Sweat Rate ($L.h^{-1}$)	.74 (.07, .95)	22 (-4, 49)	.48 (-.26, .87)	31 (-19, 80)
Fluid Consumption Rate ($L.h^{-1}$)	.40 (-.36, .84)	16 (-17, 49)	-.35 (-.82, .41)	-14 (-49, 21)
Thermal Sensation Change ($AU.h^{-1}$)	-.65 (-.92, .02)	-5 (-11, 0)	-.80 (-.96, -.30)	-13 (-21, -4)
Sleepiness Change ($AU.h^{-1}$)	-.79 (-.95, -.26)	-5 (-9, -2)	-.87 (-.97, -.48)	-10 (-15, -5)
RPE Change ($AU.h^{-1}$)	.17 (-.56, .75)	1 (-6, 9)	-.37 (-.83, .39)	-4 (-13, 5)

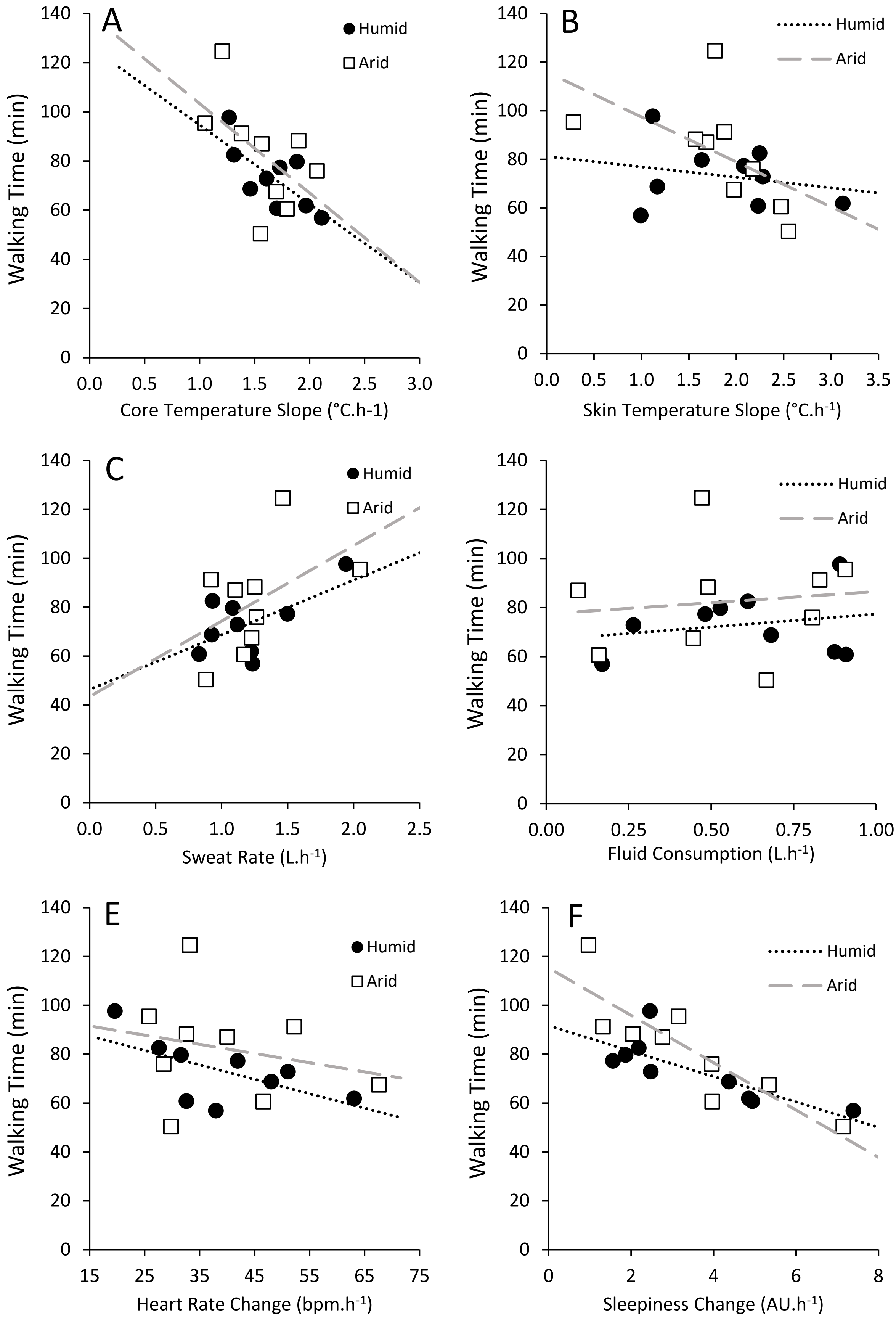

Figure 3-6. Regression analysis between physiological variables and performance (walking time) during a simulated pack march in humid (33°C, 78% RH) and arid (44°C, 21% RH) environments. Individual data points are plotted, with linear trendlines for each condition. AU – arbitrary units. Regression coefficients can be found in Table 3-2.

3.4 Discussion

The first aim of this study was to compare the physiology of each environment, which showed the humid environment to be marginally more stressful, with higher rectal temperature, higher heart rate and a greater oxygen requirement. The understanding of these differences allows for specific preparation ahead of deployment, including heat acclimation, equipment design and mission planning. The second aim was to assess the strength of physiological variables at predicting performance in hot environments. To this end several factors were found in each environment that predicted performance, including factors unique to each environment.

3.4.1 Performance

Despite differences in environmental conditions, gear loadouts and physiological responses, there was no difference seen in pack march performance between arid and humid environments (Fig. 3-3), on average, with minimal differences in the reasons for test termination. Together these similarities indicate the overall thermal strain in both environments was similar, likely due to the comparable WBGT, originally developed to quantify heat stress (Yaglou et al., 1957). However, the WBGT does not account for the difference in clothing and protective equipment worn by soldiers. It was expected that the larger and heavier pack carried in the humid environment would exacerbate endogenous heat production while also impairing evaporative heat loss and thereby cause earlier test termination (Dorman et al., 2009). However, it is possible that the combination of body armour and backpack in the arid environment may have comparatively restricted heat loss from the chest (Johnson et al., 1995), helping to nullify the effects of a heavier pack in the humid condition.

3.4.2 Body Temperatures

Higher rectal temperature was observed in the humid environment than the arid environment (Table 3-1, Fig. 3-4). While this is likely partially accounted for by the additional metabolic heat production caused by the heavier carried load (Dorman et al., 2009), there was also a lower evaporated sweat rate, with the same absolute sweat rate, suggesting reduced evaporative heat loss. Despite no statistical difference in the rate of rise in rectal temperature, extrapolation of the data revealed that rectal temperature would reach 40°C 25 min faster in the humid environment (Fig. 3-4). While in likelihood participants can still perform beyond this threshold safely (Ely et al., 2009; Lee et al., 2010a; Veltmeijer et al., 2015), it represents a limit at which heat stroke is known to occur, and therefore where exercise should be restrained (Goforth et al., 2015; Smith et al., 2016). Indeed, reducing core temperature below 40°C rapidly after exercise drastically reduces the mortality risk (Casa et al., 2012). However, in the field the heat remains present and rectal temperature will continue to rise even after the cessation of exercise, placing soldiers in danger, even if exercise is stopped (Giesbrecht et al., 2007; Smith et al., 2017). In the humid environment a 40°C rectal temperature would have been seen only 20 min after the average termination time, highlighting the imminent danger of exercise in hot environments. However, it should be noted that although 95 min is where rectal temperature is calculated to reach 40°C in the humid condition (Figure 3-4), this value falls outside of the standard deviation (Figure 3-3), suggesting internal cues can help reduce risk by terminating exercise in both environmental conditions. When operating in these environments, particularly humid environments, continuous physiological monitoring of individuals may be valuable to ensure activities are conducted safely (Buller et al., 2017; Parsons et al., 2019; Tharion et al., 2013), as is understanding methods for rapidly cooling individuals (Carter et al., 2007; Casa et al., 2012; Epstein et al., 2012).

The strength of the relationships between rectal temperature and performance is strengthened by the ethical termination of trials when rectal temperature exceeded 39.3°C, although internal cues leading to test termination, such as central fatigue likely also played a role (Hargreaves, 2008; Nybo et al., 2001a; Tucker et al., 2004). The termination of the test based on rectal temperature may also explain the stronger relationship between rectal temperature slope and performance in the humid environment, where 56% of HSTs were terminated due to high rectal temperature, compared to only 44% in the arid environment. Nonetheless, this ethical limit was put in place as it was deemed unsafe for rectal temperature to rise any further and is the point where physical activity should be restrained in the field, if possible (Goforth et al., 2015; Taylor et al., 1997). Therefore, to prioritise safety, core temperature should be monitored. Although less practical, the ability to monitor core temperature during exercise, either through the use of a heat tolerance test prior to departure or real-time monitoring of soldiers in the field (Buller et al., 2017; Epstein et al., 2017), provides a much stronger predictor of performance (Table 3-2). High rates of rise in core temperature have previously been identified to increase hyperthermia risk and heat-illness symptoms (Armstrong et al., 2010; Maughan et al., 2012), highlighting the desire for a reduced rate of rise in core temperature (Hunt et al., 2016).

The arid environment induced a higher skin temperature (Table 3-1), likely through heat gain from the environment that occurs when temperatures exceed 35°C (Nadel, 1979). Elevated skin temperature impairs heat loss as it minimises the core-to-skin temperature gradient (Chou et al., 2018). However, as the humidity is lower in the arid environment, evaporative heat loss is facilitated (Akerman et al., 2016), explaining the lower rectal temperature despite a higher skin temperature. The higher skin temperature in the arid environment likely explains the stronger relationship with performance, which was of moderate strength, compared to only a weak relationship in the humid environment (Fig. 3-6B). Furthermore, skin temperature may directly influence the perceptual relationships with performance, which were among the strongest predictors of performance in both environments (Table 3-2), consistent with previous findings (Flouris et al., 2015; Schlader et al., 2013). Whether the higher skin temperature in the arid environment partially explains the stronger relationships between perceptual changes and performance in the arid environment, however, is uncertain as a lack of perceptual differences existed between environments (Table 3-1). Perceptions are produced by the brain integrating numerous physiological signals to generate behavioural responses to help cope with environmental stress (Fleming et al., 2014; Morante et al., 2008; Périard et al., 2014; Schlader et al., 2011). Therefore, as a response to exercise becoming uncompensable, thermoregulatory behaviour leads to the termination of the test (Cheung et al., 1998; González-Alonso et al., 1999; Pimental et al., 1987). Thereby having a lower skin temperature could delay the rate at which perceptual feelings worsen, allowing prolonged performance before voluntary termination, although there were only marginally more voluntary terminations in the arid environment. The absence of relationship between rating of perceived exertion and performance may highlight military ‘mental toughness’, hypothesised to place individuals in danger as they disregard internal cues to cease exercise (Buller et al., 2017; Epstein et al., 2012; Howe et al., 2007; Parsons et al., 2019). If valid, overcoming these internal cues exacerbates the danger of these environments as continuing to exercise further elevates core temperature which can ultimately be fatal (Parsons et al., 2019). Understanding that in these environments the accumulated heat gain from both endogenous and exogenous sources, and not simply exercise intensity alone, is the primarily cause of fatigue and casualties, may help develop monitoring strategies (Macpherson, 1962). The data in the current study found that directly addressing heat in monitoring questions, by enquiring of others how hot or sleepy they are feeling, will likely given a better indication of how much longer they can safely exercise for.

3.4.3 Cardiovascular

Cardiovascular differences were apparent between the two environments, with a higher heart rate during the HST in the humid environment (Table 3-1). Furthermore, cardiovascular variables were better predictors of performance in the humid environment, whereas aerobic fitness, which is often cardiovascular dependent, was a better predictor in the arid environment (Table 3-2). While aerobic fitness and heart rate were expected to have a similar relationship with performance, it is possible that in the humid environment the heavier carried load, and subsequent increase in cardiovascular demand, accounts for part of this discrepancy. Furthermore, fitter individuals can tolerate higher core temperatures (Cheung et al., 1998), therefore the withdrawal of participants due to having a high rectal temperature, which occurred more frequently in the humid environment, limits aerobic fitness influencing the walking time.

During exercise, elevations in cardiac output, facilitated by an increase in heart rate, are required to ensure both cutaneous and skeletal muscle circulations receive adequate blood supply (Cramer et al., 2016b; González-Alonso et al., 2003). A larger underlying blood volume facilitates higher stroke volume and a more widespread distribution of blood, allowing heat loss while maintaining performance (González-Alonso et al., 1998; Taylor, 2000). A greater blood volume may be more important in humid environments as sweat evaporation is restricted by high humidity (Maughan et al., 2012), thereby causing insensible sweat loss, where dehydration occurs without beneficial heat loss (Eichna, 1943; King et al., 2016; Taylor, 2017). As central blood volume declines a greater stress is placed on the cardiovascular system (Charkoudian, 2016; González-Alonso et al., 1998), limiting peripheral blood flow. As the perfusion of cutaneous circulations is reduced, heat transfer becomes limited, thereby causing increases in core temperature (Casa et al., 2012; González-Alonso et al., 1998; Kenefick et al., 2010; Nadel et al., 1980). Alternatively, a greater reliance may be placed on convective heat loss mechanisms, thereby requiring an increased cardiac output to elevate cutaneous blood flow (Chou et al., 2018; Kenney et al., 2014; Tebeck et al., 2019), shown by an elevated heart rate in the humid environment (Table 3-1). The importance of limiting cardiovascular demand is further illustrated by the strong ability of the change in heart rate to predict performance (Fig. 3-6E). When the cardiovascular system can no longer increase cardiac output to support perfusion of both skeletal muscle and cutaneous circulations blood flow is reduced, first to cutaneous, and then to skeletal muscle circulations (González-Alonso et al., 2003; González-Alonso et al., 2008; Kenney et al., 2014). Without the muscular blood flow to sustain oxygen requirements for exercising muscle intensity is reduced, which in this experiment meant test termination (Tucker et al., 2004). Heart rate monitoring is one of the simplest real-time monitoring methods available (Eggenberger et al., 2018), and by assessing the rate of rise in heart rate it allows evasive steps to be taken to prevent exhaustive limits being reached by the individual.

3.4.4 Sweat Rate

No differences in sweat rate were seen between the environments (Table 3-1). However, evaporated sweat was significantly lower in the humid environment (Table 3-1), likely due to the vapour pressure gradient being reduced by the humidity, preventing sweat evaporation (Maughan et al., 2012). As sweat is unable to evaporate, core temperature rises (McLellan et al., 1996; Sawka et al., 1993), underlying the elevated rectal temperature in the humid condition (Fig. 3-4), whereas the evaporation of sweat in the arid environment would have helped maintain a lower rectal temperature (Fig. 3-4) (McLellan et al., 1992). Sweat rate changes were closely linked to performance in both environments (Table 3-2). In the humid environment sweat rate strongly predicted performance, while sweat rate had a weak negative relationship (Fig. 3-6C). This suggests sweating facilitates performance, but only if the sweat evaporates. If sweat does not evaporate then heat is not lost from the body and water loss merely adds to dehydration (Cheung et al., 1998; Taylor, 2017). Conversely, despite conditions favouring the evaporation of sweat the arid environment only had a moderately strong relationship between sweat rate and performance, (Table 3-2). As sweat could more readily evaporate, it is likely that this was not a limiting factor, and therefore other variables were more directly linked to performance.

3.4.5 Metabolic

The metabolic strain during the HST was greater in the humid environment, illustrated by larger $\dot{V}O_2$ and $\dot{V}CO_2$. The greater pack weight in the humid environment likely accounts for some of this difference as more muscular work is required to carry the pack (Knapik, 1997a). Indeed, the relatively greater $\dot{V}O_2$ in the humid environments occurred close to the expected relative value based on load carrying energy expenditure predictions (Pandolf et al., 1977b).

Furthermore, lighter individuals are known to have a greater relative metabolic demand when carrying heavy absolute loads (Bilzon et al., 2001). Therefore, the increased oxygen requirement from the additional relative workload likely creates a strong relationship between body mass and performance, as this would also add to metabolic heat production (Table 3-2).

3.4.6 Cognitive

Minimal changes in cognitive performance existed both within and between environments. Many of the tasks used in the cognitive assessments were relatively simple, which have been shown to be largely unaffected by heat (Hancock et al., 2003; Mazloumi et al., 2014). However, research has shown load carriage (Caldwell et al., 2011; Eddy et al., 2015) and physical fatigue (Vrijkotte et al., 2016) to impair simple cognitive processes. Despite no differences in cognitive performance, self-reported cognitive demand of tasks increased across trials in both conditions (Fig. 3-5). It is possible participants felt more strained when doing the tasks, but could still allocate sufficient cognitive resources to the task to complete them accurately (Lambourne et al., 2010). If this is the case, greater thermal stress, physical fatigue, or more complex tasks could impair cognition.

3.5 Conclusion

While physiological and cognitive responses to military specific physical activity in humid and arid environments share many similar traits, significant differences do exist and should be accounted for. Specifically, the expected environmental parameters and gear loadout of the humid environment likely increases heat production while also impairing cooling due to limited sweat evaporation resulting in increased rectal temperature and heart rate, which would likely impair pack marching performance. While many physiological variables provided a strong prediction of performance, perceptual variables provided the strongest relationships. The lack of relationship between the difficulty of exercise and performance suggests monitoring questions should focus on the heat, not the exercise, to ensure wellbeing. Understanding the dangers of heat and improving monitoring strategies and preparation ahead of deployment will help minimise soldier casualties.

Link

The first experimental chapter helped set the foundation to build heat acclimation (HA) strategies upon. By understanding the physiological parameters that are associated with safe performance: core temperature, heart rate, sweat rate and perceptions, it provides targets for heat mitigation strategies to improve. One key variable that was highlighted in the literature review as being a potential difference between athletes and military personnel was whether high sweat rates would improve performance, likely by increasing heat loss, or simply add to dehydration. It was shown to be a beneficial response, with an elevated sweat rate improving thermal tolerance.

The next step was to trial HA techniques that were deemed feasible within a military setting by the literature review, namely passive, post-exercise HA. A similarly designed heat-stress test was used either side of the intervention period to allow comparisons between studies. However, as military personnel were unavailable for this study, members of the general population were used and as a result the pack load was reduced for safety reasons. Passive, post-exercise HA was conducted following aerobic exercise in either a sauna, or in HWI, as these facilities are both available to NZDF military units, and indeed are both widely available and easily installable in-situ. The following chapter, Chapter 4, details the physiological and physical performance response to passive, post-exercise HA, while Chapter 5 looks at how cognitive performance is affected over the same intervention. Due to the high inter-individual variability of cognitive performance, only those who had completed both HA protocols were included in the analysis, thereby effectively reducing the number of participants from 25 to 15. As such, there are slight discrepancies between physiological parameters between the studies.

Chapter 4 Heat Acclimation Effects on Physical Performance

4.1 Introduction

International military operations involve travelling to different climates, often with higher temperature and humidity. In these climates, heat stress from the environment and endogenous heat production from working muscle combine to elevate body temperature, which limits physical capacity (Garrett et al., 2009; Keiser et al., 2015; Racinais, 2010). In military personnel the ability to lose heat is compromised by restrictive clothing while heat production is exacerbated by carried loads (Countryman et al., 2013). Such factors increase the risk of heat-related illnesses in military populations, ranging from heat syncope through to death as elevated core temperatures (> 40°C) can cause permanent organ damage (Boffey et al., 2018; Goforth et al., 2015). Therefore, strategies that can reduce the incidence of heat illnesses, without compromising performance are highly sought after.

The scientific literature on heat mitigation strategies favours athletic populations; a group that typically has a more predictable and broader array of options to help regulate body temperature. Conversely, military operations can be dynamic and unpredictable, making it hard to apply such options to this population (Hosokawa et al., 2019). As strategies that take place in the hot environment (i.e., cooling, shade-seeking, resting) may not necessarily be relied upon, there is a need to optimise strategies that take place prior to deployment, such as heat acclimation (HA).

HA is frequently used by athletes preparing for competition in hotter climates. However, current best-practice approaches, which often involve exercising in a heat chamber while continuously monitoring core temperature (Gibson et al., 2019), are often infeasible, especially when surplus to other training requirements (Casadio et al., 2017) such as physical and mission-specific tactical training expected of military personnel right up to deployment.

One method that requires fewer resources is passive, post-exercise heating (Heathcote et al., 2018), whereby physical exertion in temperate conditions elevates core temperature and releases exercising metabolites into the bloodstream, before participants are passively exposed to heat, commonly saunas or hot-water immersion (HWI), to maintain elevations in core and skin temperature. As a result of repeated heat exposure the body adapts to minimise homeostatic disturbance by elevating plasma volume to lower cardiovascular stress (Convertino et al., 1980; Kissling et al., 2019) and by lowering resting core temperature (Zurawlew et al., 2016). While both saunas (Scoon et al., 2007) and HWI (Brazaitis et al., 2010; Zurawlew et al., 2016) have been shown to cause physiological adaptations that mitigate the effects of heat and improve performance relative to control groups, research in this area is limited. However, the thermal uncompensability of both modalities limits the volume of thermal strain and requires further research to determine optimal temperatures and dosages (Kissling et al., 2019).

While both methods are promising, they have not yet been directly compared, nor applied to military scenarios, where additional challenges of reduced skin-to-air surface area and carried weight may nullify the obtained adaptations. Therefore, the aim of this study was to determine and compare the effects of post-exercise sauna and HWI on thermoregulation and physical performance in a military context.

4.2 Methods

4.2.1 Experimental Design and Overview

With institutional ethical approval (18/195), a randomised, repeated measures, cross-over design study was conducted. Twenty-five participants completed two short-term, passive HA regimes involving temperate exercise, sauna and HWI. Performance was assessed before and after each HA regime using a heat-stress test (HST) that simulated a 1 h pack march in hot-humid conditions. During each HST several physiological variables were assessed. After completing a HA regime, a 6 wk washout period was employed to allow heat adaptations to decay before beginning the second phase (Fig. 4-1). In line with the *Declaration of Helsinki*, informed consent was provided in writing by all participants prior to participation.

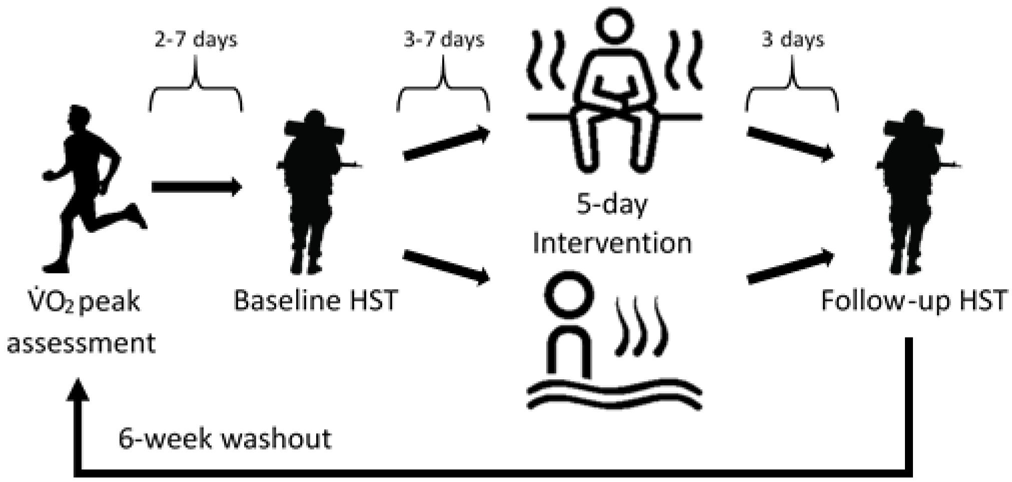

Figure 4-1. Schematic of the experimental design. Participants were randomised into either 5 days of sauna or hot-water immersion intervention before and after completing a heat-stress test (HST). After completing the intervention in one condition participants went through a "wash-out" period of > 6 wk before completing the regime in the opposite condition.

4.2.1.1 Participants

Twenty-five recreationally active males volunteered to participate in the study (age 32.9 ± 9.6 years, body mass 82.3 ± 14.1 kg, $\dot{V}O_{2peak}$ 51.5 ± 6.4 mL.kg^{-1}.min^{-1}). Participants averaged ~300 min of physical activity per week, ~5 min of HWI or sauna exposure per week and had been overseas in hotter climates for an average of 2 days in the past 6 months.

4.2.2 $\dot{V}O_{2peak}$ Assessment

All participants completed a preliminary $\dot{V}O_{2peak}$ aerobic assessment on a motorised treadmill (Pulsar® 3p, h/p/cosmos, Germany). An incremental step-test was conducted with 3 min stages, beginning at 7 km.h^{-1} and increasing by 1 km.h^{-1} to a maximum of 15 km.h^{-1} after which the gradient was increased in 1% increments. When the respiratory exchange ratio (RER) exceeded 1.00 stages were shortened to 1 min and continued until voluntary termination. A minimum value of 40 mL.kg^{-1}.min^{-1} was required for entry into the study to represent the fitness requirements of military personnel (Bedno et al., 2014; Campos et al., 2017).

4.2.3 Heat-Stress Tests

HSTs were completed before and after each HA regime, and at the same time of day within each participant. Participants were asked to avoid strenuous activity for the 24 h preceding each HST. Each HST was carried out in an environmental chamber (Design Environmental, Simultech Australia, Australia), heated to 33°C and 75% relative humidity (RH), and began with 10 min of seated rest in the chamber. Participants then walked on a motorised treadmill (Platinum Club Series, Life Fitness, Illinois, USA) at 5 $km.h^{-1}$ at 1% incline for 1 h, while wearing standard military-issue long-sleeved shirt, trousers, helmet, body armour and a backpack, along with their own shoes (full ensemble = 20.6 ± 0.7 kg). After 1 h, treadmill gradient was increased by 1% every minute (up to a maximum of 15%) until voluntary termination, 20 min passed, or ethical limits of rectal temperature exceeding 39.5°C or heart rate exceeding 95% age-predicted max for 10 s (Tanaka et al., 2001) were reached. Fluid intake was allowed *ad libitum* up to a maximum of 2 L, as per military rations.

4.2.3.1 Temperature Measures

Core temperature was recorded using a flexible thermistor (Hinco Instruments, Australia) inserted 12 cm beyond the anal sphincter. The rate of rise in rectal temperature was later calculated from the overall elevation in rectal temperature divided by exercise time. Skin temperature was measured on the right-hand side of the body at the chest, bicep, thigh, and calf using skin temperature probes. Both rectal and skin temperatures were logged at 1 Hz (SQ2020, Grant Instruments, Cambridge, UK). In preparation for analysis, rectal and skin temperature readings were filtered due to noise caused by connections with the logger and occasional skin temperature probes losing contact with the skin due to the humid microenvironment. A filter was applied to remove all readings that changed by more than 0.1°C.s^{-1}. Then a low-pass Butterworth filter of 0.02 Hz was applied to the data. Missing data were filled with linear interpolation.

Mean skin temperature was calculated using the following formula (Ramanathan, 1964):

$$\mathrm{T_{Sk}} = 0.3\mathrm{T_{Chest}} + 0.3\mathrm{T_{Bicep}} + 0.2\mathrm{T_{Thigh}} + 0.2\mathrm{T_{Calf}} \qquad \text{Equation 4-1}$$

If a thermistor became askew or off the skin, the equation was modified to compensate the weights of the three remaining sensors proportionally to maintain the summation of coefficients to 1.0 (i.e., $\mathrm{T_{Sk}} = 0.375\mathrm{T_{Chest}} + 0.375\mathrm{T_{Bicep}} + 0.25\mathrm{T_{Thigh}}$ if the calf reading was lost). If two sensors produced no signal, no temperature was calculated. Averages over 10 min periods were used for analysis, while additionally 1 min averages while sitting and at the end of the walk were used for resting and end-exercise values, respectively.

4.2.3.2 Cardiovascular Measures

Cardiac frequency was measured using a 3-lead electrocardiogram (Tango+, SunTech Medical, North Carolina), with values recorded at 15 min intervals after a baseline measure taken after 5 min of seated rest in the chamber. Resting and end-exercise heart rate values were obtained from the resting and 55-min time points, respectively. Blood pressure was measured every 15 min as the average of two measurements using an automated pressure cuff (Tango+, SunTech Medical, North Carolina).

4.2.3.3 Metabolic Measures

Expired gas analysis was conducted for 4 min, every 15 min, while participants breathed through a mouthpiece connected to a calibrated metabolic system (Trueone 2400, Parvo Medics, Utah, USA). Data were then analysed as an average of the final 2 min to provide measures of $\dot{V}O_2$, $\dot{V}CO_2$, minute volume ($\dot{V}E$), and RER. Carbohydrate oxidation ($g.min^{-1}$) was calculated using Equation 4-2 (Jeukendrup et al., 2005).

$$4.21\ \dot{V}CO_2 + 2.962\ \dot{V}O_2 \qquad \text{Equation 4-2}$$

4.2.3.4 Perceptual Measures

Perceptual measures were taken at rest outside the chamber, at rest inside the chamber, at exercise onset and then every 15 min during each HST, using both standardised and adapted scales: rating of perceived exertion (RPE: 15-point scale ranging 6-20) (Borg, 1982), thermal discomfort (1-10) (Bedford, 1936), thermal sensation (1-13) (ISO, 1994), feeling (-5 - +5) (Hardy et al., 1989) and sleepiness (1-9) (Hoddes, 1972).

4.2.3.5 Sweat Rate

Whole-body sweat rate was estimated using pre and post-exercise semi-nude body mass, corrected for fluid consumption (Eq. 4-3) (Buono et al., 2009), with the pre-weight taken post-void and no urine excreted during the trials. A fully dressed weight was also taken immediately prior to, and immediately after exiting the heat chamber to calculate evaporated sweat rate (Eq. 4-4) (Amos et al., 2000).

$$\textit{(semi-nude weight change + fluid consumption)} \div \textit{walking time} \qquad \text{Equation 4-3}$$

(fully dressed weight change + fluid consumption) ÷ walking time) Equation 4-4

4.2.3.6 Hydration Measures

Prior to, and immediately following each trial, participants provided a urine sample. Urine was analysed for urine specific gravity (USG) using a refractometer (Atago, Japan).

4.2.4 Heat Acclimation

Participants completed post-exercise HA sessions on five consecutive days. Each session comprised of 40 min continuous aerobic exercise, followed by up to 40 min of either sauna or HWI.

4.2.4.1 Exercise

Upon arrival at the laboratory (19.2 ± 0.5 °C, 63 ± 2% RH) participants were weighed and had their auditory canal temperature measured. Auditory canal temperature was used as a surrogate for core temperature, due to practical advantages of being able to use it throughout each HA session. Exercise was conducted either on a stationary cycling ergometer or a graded treadmill, according to participant preference, and kept constant within participants. Exercise was performed for 40 min at an individually prescribed intensity equivalent to their first ventilation threshold (V-slope method, (Shimizu et al., 1991)), calculated from the initial $\dot{V}O_{2peak}$ assessment. Throughout the exercise 1 L of water was available for consumption *ad libitum*, while heart rate and RPE were recorded every 10 min. Upon cessation of exercise, mass and auditory canal temperature were taken again before participants were transferred to the sauna or hot-water facility.

4.2.4.2 Post-Exercise Heating

Post-exercise heating was conducted either by sitting in a sauna (~70°C, 19% RH) or mid-sternum immersion in flowing hot-water (~40°C). Prior to HWI, participants were required to rinse off in warm water (<5 s). Auditory canal temperature was taken immediately preceding heat exposure. At 1 min into heat exposure, perceptual measures of thermal discomfort, thermal sensation, feeling, and sleepiness were recorded, along with pulse taken at the wrist. During each heat exposure participants could drink up to 1 L of water *ad libitum.* Participants could terminate the session at any time but were instructed to remain in the sauna or HWI for as long as they felt comfortable, up to a maximum of 40 min. Measures were repeated every 10 min during the post-exercise heating. Auditory canal temperature was also taken every 10 min in the HWI, but this was not possible in the sauna where it was taken immediately upon exiting. A final set of measures were also taken if participants terminated the session early, if >2 min had passed since the last measurement. Participants and drink bottles were then weighed to indicate sweat rate and fluid consumption.

4.2.5 Statistical Analysis

Data analysis was organised into two phases: the first examined thermoregulatory adaptations within the HA period, while the second examined the effects of the HA period on subsequent performance in the heat compared to baseline, and the differences in change of variables between the two conditions. All analyses were conducted in R version 3.6.1 (R foundation for Statistical Computing, Vienna, Austria). For each variable a mixed model ANOVA was used through the lme4 package (Bates et al., 2014), with pairwise comparisons conducted through the emmeans package. Q-Q plots were used to ensure homoscedasticity for each mixed model.

To examine adaptations within the HA period, variables were compared across the five HA sessions. For each outcome, a linear mixed model was fit, where condition or session was included as a fixed effect, and participant was added as a random effect to account for the repeated measures. When evaluating conditions independently, session was used as the fixed effect. Whereas when comparing between conditions, both session and condition were used as fixed effects.

For the second phase of the analysis, linear mixed models were used, with pre-post, condition, a pre-post by condition interaction, time (if appropriate) and order (whether HWI or sauna treatment was used first) used as fixed effects, with participant as the random effect. The interaction effect was used to determine differences in change between the two conditions. Planned contrasts were then used to generate estimated means from the mixed model ANOVA for pre- and post-values within each condition, as well as providing 95% confidence intervals and *p* values. *p* values were adjusted using the Holm correction (Holm, 1979).

4.3 Results

Of the 25 participants, 15 completed both interventions, while 10 completed only one (5 sauna, 5 HWI). All participants completed all 5 HA sessions, except for 1 who completed only 4 in the sauna.

4.3.1 Heat Acclimation Sessions

During the exercise sessions heart rate was not different between the sauna (142 ± 3 b.min^{-1}) and HWI (142 ± 7 b.min^{-1}) conditions (p = .801). Auditory canal temperature increased 0.3°C during exercise and reduced ~0.2°C between sessions (Fig. 4-2; p < .001), regardless of condition (p = .551). Transition time between the exercise and the sauna (4.3 ± 0.3 min) and the HWI (4.6 ± 0.3 min) was not different (p = .350). Actual sauna temperature was 68.9 ± 1.7°C with 21 ± 2% RH, and the hot water temperature was 39.8 ± 0.2°C. Exposure time in the sauna (28.3 ± 8.1 min), was significantly less than during HWI (31.4 ± 9.7 min) with both groups increasing exposure time each session (Fig. 4-2). Auditory canal temperature increased 3.9°C over the heat exposure (p < .001), despite progressively reducing ~0.1°C between sessions (p = .007). Average auditory canal temperature was ~0.7°C greater in the sauna condition (SAU: 37.0°C; HWI: 36.4°C; SAU vs HWI: p < .001), with peak auditory canal temperature being ~1.0°C greater in the sauna condition (SAU: 38.5°C; HWI: 37.5°C; SAU vs HWI: p < .001). Furthermore, heart rate was significantly reduced between sessions in both conditions (Fig. 4-2). Perceptually, only thermal sensation changed between sessions in both sauna and HWI (SAU: ↓ 0.1 arbitrary units.session^{-1} (AU.session^{-1}), p = .002; HWI: ↓ 0.1 AU.session^{-1}, p < .001). Comparatively, perceptions of thermal discomfort (SAU vs HWI: ↑ 0.6; p < .001), and thermal sensation (SAU vs HWI: ↑ 0.4; p < .001) were higher in the sauna, while feeling (SAU vs HWI: ↓ 0.3; p = .039) reduced compared to that seen in HWI, matching the greater auditory canal temperature seen at the end of sauna (SAU vs HWI: ↑ 1.2 AU; p < .001).

Between sessions, fluid consumption increased in both conditions (SAU: ↑ 55 ml.session^{-1}; p = .004; HWI: ↑ 33 ml.session^{-1}; p = .072). However, sweat rate was unchanged between sessions in each condition (p > .196).

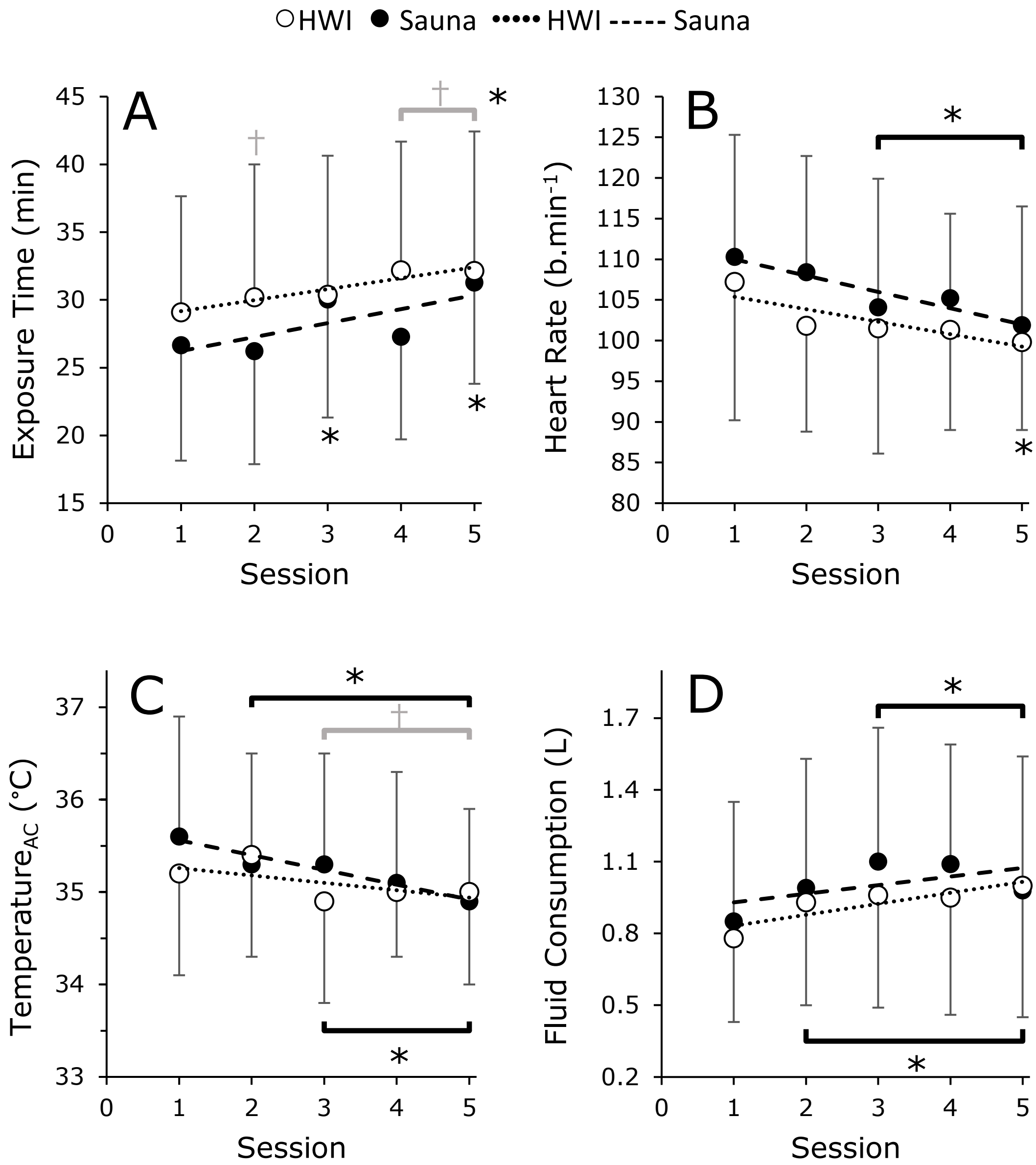

Figure 4-2. Time course of physiological adaptations across five heat acclimation sessions in sauna or hot-water immersion (HWI). Data are reported as mean ± standard deviation. Exposure time (A) is the time spent in the heat modality. Heart rate (B) is the average heart rate during heat exposure. Auditory canal temperature (Temperature$_{AC}$) (C) is the baseline temperature recording before entering the heating modality. Fluid consumption (D) is the total fluid consumed in the entire HA session. **p* < 0.05 vs session 1, † *p* < 0.05 between conditions over time.

4.3.2 Heat-Stress Tests

4.3.2.1 Performance

Participants reached the end of the performance test (20 min cut off) on 14 occasions (17.5%). This was achieved by 3 participants consistently in both pre- and post-tests of each condition and by another participant in both post-tests. Hence, the % change for these individuals was recorded as zero. Even including these values, walking performance time was significantly increased following sauna but not HWI HA, despite tending to do so (SAU: ↑ 13.7%, p = 0.013; HWI: ↑ 12.8%, p = .079; SAU vs HWI: p = .447) (Fig. 4-3). Only one participant had the test terminated involuntarily, after reaching the ethical limit for heart rate in the pre-HWI condition.

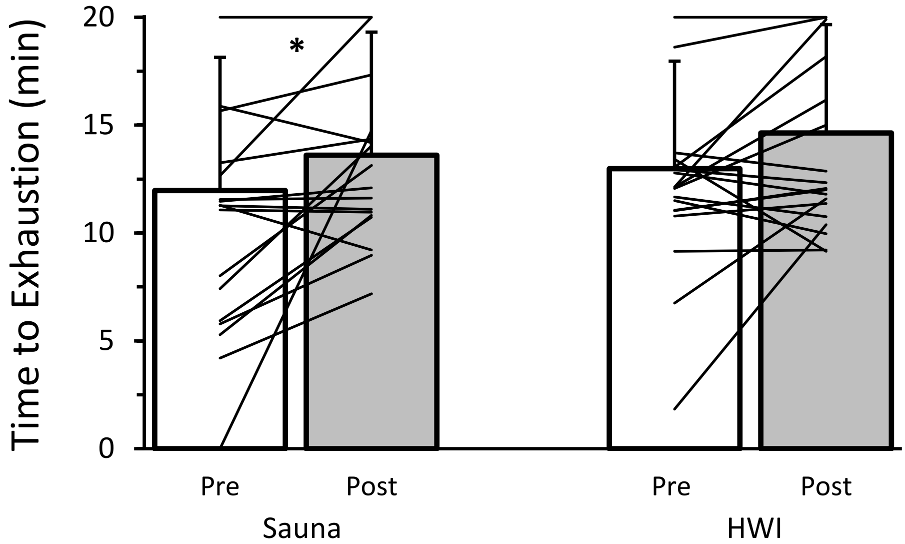

Figure 4-3. Heat-stress test results for time to exhaustion during the ramp protocol that immediately followed 1 h of steady-state walking at 5 km.h^{-1} in heat (33°C, 75% RH) before and after either a sauna or hot-water immersion (HWI) heat acclimation programme. Individual data are represented by black lines. Data are displayed as mean ± standard deviation. *p < .05 within condition between the pre- and post-tests.

4.3.2.2 Physiological Variables

Both rectal and skin temperatures were lower during the second HST in both conditions (Table 4-1), with no between condition differences (all p > .122). However, post-hoc analyses revealed no significant differences within sauna (all p > .092), and only significant from 40 min onwards in the HWI condition (0 to 30 min all p > .064) (Fig. 4-4). Similarly, no significant differences were found in skin temperature for the sauna condition (all p > .189), while the

HWI condition was significant only at 50 min (p = .045, all other p > .104). Heart rate also reduced in both conditions and at each time-point following both sauna and HWI HA (all p < .039), with a slight, but insignificant tendency to be reduced in the sauna (p = .067).

Elevated sweat rate was evident following sauna (p = .028), but not HWI HA (p = .053), although no significant differences were detected between the groups (p = .722) which had similar magnitudes of change (Table 4-1). Furthermore, both conditions showed no change in evaporated sweat rate (SAU: p = .560; HWI: p = .560; SAU vs HWI: p = .804) (Table 4-1). Fluid consumption was increased (SAU: p = .019; HWI: p = .004), with no differences between conditions (SAU vs HWI: p = .551), thereby preventing the increased sweat loss from reducing hydration status (Table 4-1).

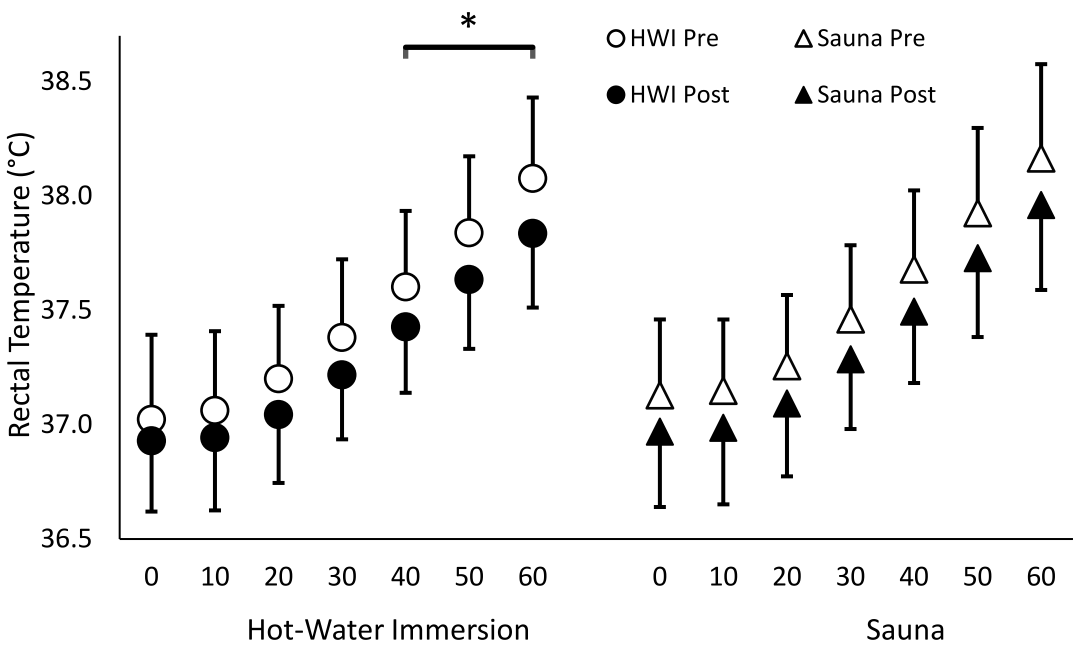

Figure 4-4. Rectal temperature responses both pre and post sauna (triangles) and hot-water immersion (HWI; circles) heat acclimation expressed as 10 min averages ± standard deviation. Displayed comparisons detail the post-hoc tests as there were significant overall effects of both conditions on rectal temperature (both p < .001). *p < .05 within condition between pre- and post-test

4.3.2.3 Metabolic Variables

The $\dot{V}O_2$ over the session reduced significantly following sauna, but not HWI HA (SAU: ↓ 0.81 $mL.kg^{-1}.min^{-1}$, p < .001; HWI: ↓ .21 $mL.kg^{-1}.min^{-1}$, p = .210; SAU vs HWI: p = .010), without a reduction in minute ventilation, (SAU: ↓ 0.71 $L.min^{-1}$, p = .117; HWI: ↑ 0.89 $L.min^{-1}$, p = .097;

SAU vs HWI: p = .013) although both were significantly lower following sauna HA. Increased carbohydrate oxidation was observed following HWI HA but not sauna (SAU: ↓ 0.03 $g.min^{-1}$, p = .372; HWI: ↑ .08 $g.min^{-1}$, p = .021; SAU vs HWI: p = .015) while a decline in $\dot{V}CO_2$ was seen only in the sauna condition (SAU: ↓ 0.05, p < .001; HWI: ↑ .01, p = .293; SAU vs HWI: p < .001).

4.3.2.4 Perceptual Variables

Both conditions lowered RPE similarly (SAU: ↓ 0.5 AU, p = .002; HWI: ↓ 0.4 AU, p < .009; SAU vs HWI: p = .604). While the sauna improved thermal sensation (SAU: ↓ 0.4 AU, p < .001; HWI: ↓ 0.1 AU, p = .474; SAU vs HWI: p = .006), HWI reduced sleepiness (SAU: ↓ 0.1 AU, p = .568; HWI: ↓ 0.7 AU, p < .001; SAU vs HWI: p < .001) and thermal discomfort (SAU: ↓ 0.2 AU, p = .081; HWI: ↓ 0.4 AU, p = .002), although the change in thermal discomfort was not different between conditions (SAU vs HWI: p = .272). Feeling was unchanged in either condition (SAU: ↓ 0.2 AU, p = .401; HWI: ↑ 0.1 AU, p = .401; SAU vs HWI: p = .118).

4.3.2.5 Qualitative Data

While 67% of participants reported a preference towards HWI as a heat acclimation method, 67% of participants felt they improved more in the sauna intervention, with no inverse relationship observed between the two. HWI was largely described as “enjoyable”, although light-headedness and dizziness symptoms were reported by 50% of participants during the acclimation period. The sauna was instead described frequently as “instant heat” that “directly affected the head” but was “easy to get used to”.

Table 4-1. Changes in physiological variables during a heat-stress test, following 5 d of passive, post-exercise heat acclimation in either sauna (n = 20) or hot-water immersion (HWI) (n = 20). Pre-HA data are displayed as estimated means ± SD, while the change is displayed as estimated change with a 95% confidence interval.

	HWI			Sauna		
Variable	Pre	Change	*p* value	Pre	Change	*p* value
Rectal Temperature (°C)						
Resting	37.1 ± 0.3	↓ 0.1 (-0.3, 0.0)	.057	37.1 ± 0.3	↓ 0.2 (-0.3, 0.0)	**.021***
Average	37.6 ± 0.5	↓ 0.2 (-0.2, - 0.1)	**<.001***	37.5 ± 0.5	↓ 0.2 (-0.2, -0.1)	**<.001***
End-Exercise	38.1 ± 0.4	↓ 0.2 (-0.4, -0.1)	**.002***	38.1 ± 0.4	↓ 0.2 (-0.4, -0.1)	**.004***
Rate of Rise ($°C.h^{-1}$)	1.3 ± 0.3	↓ 0.1 (-0.3, 0.0)	**.028***	1.3 ± 0.3	↓ 0.1 (-0.3, 0.0)	**.028***
Skin Temperature (°C)						
Resting	34.4 ± 0.4	NC (-0.3, 0.3)	.758	34.5 ± 0.6	↓ 0.2 (-0.5, 0.1)	.164
Average	35.8 ± 0.7	↓ 0.1 (-0.2, 0.0)	**.035***	35.8 ± 0.8	↓ 0.2 (-0.3, -0.1)	**<.001***
End-Exercise	36.4 ± 0.4	↓ 0.2 (-0.4, 0.0)	**.028***	36.5 ± 0.5	↓ 0.2 (-0.4, 0.0)	**.013***
Heart Rate ($b.min^{-1}$)						
Resting	72 ± 10	↓ 3 (-8, 1)	.085	75 ± 10	↓ 8 (-12, -3)	**.001***
Average	120 ± 7	↓ 6 (-9, -3)	**<.001***	123 ± 7	↓ 10 (-13, -6)	**<.001***
End-Exercise	135 ± 11	↓ 9 (-14, -4)	**<.001***	140 ± 11	↓ 13 (-18, -8)	**<.001***
Sweat Rate ($L.h^{-1}$)	1.1 ± 0.3	↑ 0.1 (0.0, 0.3)	.053	1.0 ± 0.3	↑ 0.1 (0.1, 0.3)	**.028***
Evaporated Sweat Rate ($L.h^{-1}$)	0.4 ± 0.4	↓ 0.1 (-0.3, 0.1)	.389	0.5 ± 0.4	↓ 0.1 (-0.3, 0.1)	.435
Fluid Consumption (L)	0.7 ± 0.4	↑ 0.2 (0.1, 0.4)	**.004***	0.8 ± 0.4	↑ 0.2 (0.0, 0.4)	**.019***
USG Pre	1.017 ± 0.009	NC (-0.004, 0.004)	1.000	1.014 ± 0.009	NC (-0.004, 0.005)	1.000
Systolic Blood Pressure (mm Hg)	150 ± 16	↑ 3 (-4, 11)	.623	150 ± 15	↑ 1 (-6, 8)	.788
Diastolic Blood Pressure (mm Hg)	70 ± 13	NC (-6, 6)	.989	71 ± 12	↓ 2 (-8, 3)	.670

**p* value < .05, calculated within each condition. No significant differences were observed in the change between conditions. NC = No change.

4.4 Discussion

The primary aim of this study was to determine whether passive, post-exercise HA using sauna or HWI invoked beneficial heat adaptations for enhancing performance in military personnel. Using either a sauna or HWI following exercise sessions was found to successfully induced heat-protective adaptations in a short amount of time. In a military setting, such rapidly obtained improvements in performance and safety could be invaluable.

4.4.1 Effects of Passive, Post-Exercise Heat Acclimation

Time to exhaustion improved following sauna, but not HWI HA during a simulated pack march, although both post-tests returned a similar average time to exhaustion (Fig. 4-3). A recent meta-analysis found the median improvement in exercise capacity following HA to be ~8% (Tyler et al., 2016), suggesting the current study was effective at improving military performance. In studies looking at military personnel, comparable improvements were observed by McLellan and Aoyagi (1996) in a similarly designed military march in protective clothing following fixed-intensity HA (45-55% $\dot{V}O_{2peak}$ for 1 h.d^{-1} for 12 days in 40°C, 30% relative humidity), although the effects of heat were enhanced by completing the HA in restrictive nuclear, biological and chemical (NBC) protective suits. That same group also found tolerance time to improve by ~15% in an identical HST following an abbreviated 6 d version of the same HA regime (Aoyagi et al., 1994). Furthermore, improvements have also been seen in both time to exhaustion and performance trials by others using similar passive, post-exercise heating in athletic situations. Zurawlew et al. (2016) used HWI (40 min in 40°C, post-exercise for 6 days) to produce a ~5% improvement in time-trial performance, while Scoon et al. (2007) improved time to exhaustion by 27% following sauna HA (13 sessions following training in 89.9°C). In both studies athletic HSTs were used, limiting the comparisons that can be made. However, the improvements in these studies were attributed to underlying thermoregulatory adaptations, which is likely the reason for the increased work output in the current study.

A reduced core temperature, both at rest and during exercise, increases the capacity for heat gain, helping both performance and safety (Aoyagi et al., 1994; Shen et al., 2015). In the current study, both sauna and HWI resulted in similar reductions in resting rectal temperature (SAU ↓ 0.2°C, HWI ↓ 0.2°C; Table 4-1) and rate of rise in rectal temperature (SAU ↓ 0.1°C.h^{-1}, HWI ↓ 0.1°C.h^{-1}; Table 4-1). This resulted in an additional 10 min of walking (or a 17% longer duration) before reaching the rectal temperature observed at 60 min in the pre-test (Fig. 4-4). Similar improvements in the time taken for rectal temperature to reach pre-test values (~15 min) were seen in the aforementioned study of McLellan and Aoyagi (McLellan et al., 1996), despite the protocol involving twice the number of sessions. Moreover, Cheung and McLellan (Cheung et al., 1998) found 10 days of fixed intensity HA (1 $h.d^{-1}$ walking in 40°C, 30% relative humidity, at 4.8 $km.h^{-1}$ at 3-7% gradient in combat clothing) in military personnel being heat acclimated over 10 days produced a similar ~0.2°C reduction in rectal temperature. Conversely, Charlot et al. (2017) found 5 days of aerobic training (32-56 $min.d^{-1}$) conducted upon arrival at a military base (~40°C, 12% RH) caused rectal temperature to drop ~0.4°C when measured post-exercise using an electronic thermometer. The larger magnitude obtained could be due to additional activities done in the heat, increasing the volume of heat exposure, as would be expected of a military deployment. Typically, the magnitudes of change in resting rectal temperature are larger following longer HA protocols, however the findings of the current study are consistent with similar, and slightly longer studies (Tyler et al., 2016). Studies using similar mixed-modality heating have also found comparable (Zurawlew et al., 2018b), and greater (Zurawlew et al., 2016), changes in rectal temperature following 6 day HWI HA, with auditory canal temperature also shown to decrease after 13 days HWI HA (Bonner et al., 1976). While few studies have looked at core temperature in relation to sauna, Racinais et al. (2017b) found no change in core temperature when passively acclimating using humid heat (~48°C, 50% RH) for 1 $h.d^{-1}$ for 11 days. Conversely, Leppaluoto et al. (1986) observed a resting decrease of 1.1°C and an end-exercise decrease of 1.4°C using a clinical mercury thermometer over 7 days of sauna bathing (~80°C, 30% RH). While the sauna used in this study was cooler than those used in previous studies (Leppaluoto et al., 1986; Scoon et al., 2007; Stanley et al., 2015) this likely does not limit the adaptations as participants perceived it to be more stressful than HWI and averaged only ~30 min per session.

If core temperature decreases, it is important for skin temperature to also decrease to maintain a core to periphery temperature gradient to facilitate heat loss (Kenney et al., 2014; Sawka et al., 2012). In the current study, both HA regimes reduced skin temperature minimally (0.1-0.2°C), with no difference between conditions (Table 4-1). Zurawlew et al. (2018b) found a larger reduction of 0.7°C in a similar HWI experimental paradigm, while Ruddock et al. (2016) saw a reduction of 1°C in a mixed-mode HA programme involving HWI. No sauna study to date has evaluated skin temperature, but Racinais et al. (2017c), using passive HA in a heat chamber, did not observe any difference. How skin temperature is affected between each HA exposure remains to be tested but may provide insights into the greater magnitude observed in the sauna.

In the present study, the rate of rise in rectal temperature during exercise reduced following both HA regimes (Table 4-1). Cardiovascular and sweat rate changes with HA suggest upregulation of evaporative, and to a lesser degree convective, heat loss avenues. Specifically, heart rate was reduced by 10-15 $b.min^{-1}$ in the current study, similar to other studies investigating sauna and HWI exposure (Brazaitis et al., 2010; Racinais et al., 2017b; Zurawlew et al., 2018a; Zurawlew et al., 2016). Furthermore, these magnitudes were comparable to similar length studies when using pooled data from a range of HA protocols produced by a meta-analysis (Tyler et al., 2016). Typically, heart rate reductions are associated with elevated plasma volumes, which while unassessed in the current study, usually increase across HA (Tyler et al., 2016). Having a greater blood volume facilitates blood distribution to both the muscle and cutaneous circulation (MacDougall et al., 1974), while also increasing preload, raising cardiac contractility thereby increasing stroke volume, which lowers heart rate (Schlader et al., 2016; Warburton et al., 2000). It is likely that gradually increasing plasma volume accounted for the reduced heart rate between sessions (Fig. 4-2) as any intrinsic cardiac effect would likely not be evident with low volume heating stimulus. Elevated plasma volume enables blood flow to the cutaneous circulation to be maintained during exercise, thereby promoting convective heat loss and supplying fluid to sweat glands for heat to be lost as sweat (Okuda et al., 1980).

Increased sweat rate was statistically supported following sauna, but not HWI HA, although both produced a similar magnitude (~130 $mL.h^{-1}$) of change (Table 4-1). While no additional measures were taken to support this, increases in sweat rate were likely due to increased blood supply to sweat glands accompanied by functional gland adaptations (Sato et al., 1990) and reduced sudomotor threshold (Shvartz et al., 1979). Increased sweat rate in other post-exercise protocols has not previously been observed although Zurawlew et al. (2018b) had similar magnitudes of change following HWI HA that did not reach significance. Increases in sweat rate have been noted using mixed-mode HA involving HWI (Ruddock et al., 2016) or a climate chamber (Racinais et al., 2017b), although both involved ~90% more HA time, with a 4.5-fold greater duration of exogenous heat exposure as the current study. Methodologically other studies often restrict fluid intake, whereas within the current study fluid intake was allowed *ad libitum* both during HA and in the HSTs. By allowing fluid intake during heating, behavioural adaptations were enabled, shown by fluid intake increasing between sessions that manifested into an increase during the HST. Increasing sweat rate is only beneficial if the sweat can evaporate, which is obstructed by additional clothing used by the military. While both conditions saw no change in evaporated sweat rate the magnitude of change in evaporated sweat rate following HWI was similar to the magnitude of change in fluid consumption. While insensible water loss directly causes dehydration, no difference in hydration was observed in either group. Following sauna HA, the increase in sweat rate was mostly composed of an increase in evaporated sweat rate suggesting enhanced evaporative heat loss. As the current study used only whole-body sweat rate to measure sweat, further studies are required to validate this finding.

Although metabolic differences were seen between the two groups, the magnitudes of these changes were minimal and could be due to several uncontrolled factors, including diet. Differences in $\dot{V}O_2$ following sauna HA suggest improved economy which has previously been seen following active HA (James et al., 2017c). Increased carbohydrate oxidation following HWI HA suggested an additional 6 g of carbohydrates used over the course of the trial, which is neither meaningful nor beyond experimental error. While alterations in metabolism have been seen in animal models, (e.g., Hafen et al. (2019)) and following active HA (King et al., 1985; Kirwan et al., 1987; Young et al., 1985), there remains limited evidence that this occurs under the heating modalities of the current study in humans.

4.4.2 Comparing modes of heating

Overall, differences between the two conditions were minimal, with both providing beneficial adaptations. Minor statistical differences that show only sauna to be capable of increasing sweat rate, and lowering resting heart rate and resting rectal temperature, are likely not meaningfully different when the magnitudes of change are examined (Table 4-1). Given the similarity of adaptations between conditions, it is possible that the exercise stimulus prior to post-exercise heating alone dictates the degree of adaptation. Exercise alone can improve thermal tolerance in tasks < 2 hours, but exogenous heat exposure provides further enhancements (Cohen et al., 1982). Within the context of the current study, it has previously been shown that both post-exercise sauna (Scoon et al., 2007) and HWI (Zurawlew et al., 2016) cause adaptations that are beneficial to performance and safety beyond the effects of exercise, shown by comparisons to control groups not receiving heat exposure. Furthermore, while the heating modality mediums differ, participants remained in both the sauna and HWI until they were unable to tolerate it further, suggesting both exerted a similar relative thermal stress that induced thermoregulatory adaptations. However, the exercising component remains important and it is yet to be determined whether changes to the exercise duration or intensity would have altered adaptations. Using traditional HA strategies, where exercise is conducted in the heat, intensity and duration assessments suggest sessions of ~60 min (Racinais et al., 2015) administered at the same intensity of the desired performance (Schmit et al., 2018; Wingfield et al., 2016). Whether similar recommendations apply to post-exercise heating remains to be explored.

4.4.3 Military Relevance

Regarding military operations, reductions in core and skin temperature allow more work to be completed before heat tolerance limits work capacity (Shen et al., 2015), while simultaneously promoting safety (Faulkner, 2016). In a group of highly motivated individuals, both internal and external cues to keep moving can override self-preservation signals to limit activity, thereby placing the individual in danger (Epstein et al., 2012). By lowering core temperature there is a reduced likelihood of reaching critical limits where organs are damaged, thereby minimising casualties (Armstrong et al., 2010; Casa et al., 2007). Similarly, lowering heart rate increases the cardiac reserve, allowing work output to increase by facilitating muscular blood flow whilst maintaining blood flow to cutaneous circulations for cooling (Horowitz, 2003). Therefore, the observed cardiovascular adaptations help to directly improve performance and safety by increasing the capacity for heat loss. However, caution should be advised when interpreting the improved safety of soldiers following HA programmes. Adaptations that provide a safer working environment may only do so when matched for exercise intensity. Therefore, if soldiers are asked to move as quickly as possible to a new location, they may achieve the task faster, but in doing so the extra demand consumes the HA-induced increase in thermoregulatory capacity, thereby exposing soldiers to heat illness.

Although adaptations in the current study were not as complete as those seen in longer protocols, it is important to note that as military operations are not conducted at a single time-point the magnitude is of lesser importance than in athletic scenarios. Instead, by starting the adaptive process prior to deployment, it minimises adjustment time in the environment, enabling work to be conducted on arrival at a rate that would otherwise take over a week to achieve.

4.4.4 Influence of Fitness

The finding that passive, post-exercise heating improves heat tolerance may be of limited value as physical exercise alone has been shown to improve thermal tolerance (Cohen et al., 1982), calling into question the true effects of post-exercise, passive heating. Both these heating modalities have previously been compared to control groups or conditions, in similar HA protocols, which showed the benefits of the heat exposure (Scoon et al., 2007; Zurawlew et al., 2016). Furthermore, the 200 min of exercise conducted by participants in the current study is below their 300 $min.wk^{-1}$ average, which, although does not discern aerobic exercise, suggests a training effect would be minimal. Furthermore, *a-posteriori* statistics, that included aerobic fitness in the mixed model ANOVA, showed that while aerobic fitness improved heat tolerance at baseline (~4 min), it had no influence on changes in performance (p = .816) or rectal temperature (p = .521).

4.5 Conclusion

In summary, the use of both sauna and HWI following exercise sessions induced modest performance enhancing and thermoregulatory protective adaptations after only 5 days. Furthermore, these changes were tracked daily, allowing on-going assessment of adaptation. Passive, post-exercise heating provides an accessible method of acclimating military personnel to the heat ahead of deployment with minimal impact on other training objectives. As minimal differences existed between the two HA modalities the heating modality can potentially be chosen based on preference and availability.

Chapter 5 Heat Acclimation Effects on Cognitive Performance

5.1 Introduction

Military operations frequently require the deployment of personnel abroad, often to countries with hot climates. In hotter environments cognitive and physical function can be impaired (Parsons et al., 2019), increasing the risk of military casualties (Vrijkotte et al., 2016). Despite being associated with most accidents in training and battle (Vrijkotte et al., 2016), cognitive performance is often unaddressed and overlooked (Lovalekar et al., 2018) and as a result few strategies exist to minimise the effects of heat on cognition.

Cognition is affected by both the absolute temperature and the duration of exposure (Martin et al., 2019). Furthermore, soldiers' cognition is frequently affected by various additional factors including sleep, load carriage, mood, fatigue, and motivation (Eddy et al., 2015; WRAIR/ARI, 1987). Cognitive performance in such extreme environments can be explained by the maximal adaptability model (Hancock et al., 2003). The model proposes that peak cognitive performance occurs at an optimal level of stress that facilitates the use of attentional resources on the task. Attentional resources are utilised by environmental stressors, thereby detracting from the task at hand (Vasmatzidis et al., 2002). By routinely practicing scenarios they expect to encounter, military units familiarise themselves with the task so it requires fewer attentional resources and therefore is less susceptible to error (Hancock et al., 2003). Similarly, physical training helps minimise negative effects exercise may have on cognition. However, few studies have considered strategies to minimise the negative effects of heat on cognition.

Within the military paradigm an inability to behaviourally adjust to the environment, such as shade seeking or reducing workload (Radakovic et al., 2007), means there is less ability to mitigate the effects of heat, thereby allowing heat to become a major stressor that affects cognitive performance. Therefore, strategies are required that can alleviate heat strain for situations where minimal behavioural modification is possible. One strategy used by military personnel and athletes is heat acclimation (HA); repeated exposure to artificial heat in an attempt to promote favourable physiological adaptations that minimise thermal strain (Taylor, 2000). HA traditionally involves exercising in the heat on consecutive days for several weeks. However, recent research has focussed on methods to achieve the same physiological benefit with minimal disruption to training objectives (Casadio et al., 2017). One such method is passive, post-exercise HA that uses passive heating, commonly sauna or hot-water immersion (HWI), following an exercise session conducted in a temperate environment. HA induces physiological adaptations that culminate in the reduction of core temperature at rest and during exercise (Heathcote et al., 2018; Rahimi et al., 2019; Tyler et al., 2016) as well as reducing the perception of heat (Rahimi et al., 2019; Tyler et al., 2016; Zurawlew et al., 2016). By reducing core temperature, exercise in a heated environment would cause less of a perturbance to homeostasis, therefore more attentional resources could be allocated to cognitive tasks, thereby minimising cognitive impairment typically associated with acute heat exposure. Previous studies have shown HA to both improve rapid visual processing and reaction (Radakovic et al., 2007) while others have observed no effect on cognition (Curley et al., 1983; Patterson et al., 1998). In studies where no effects were reported it was identified that the tasks were too easy (Patterson et al., 1998), and therefore subsequent tests should use more complex tasks.

In consideration of the desire for strategies that mitigate the effects of heat on cognition the aim was to determine and compare the effects of two practical post-exercise, passive HA strategies on military-relevant cognitive tasks. The current paper presents the variables relating to cognitive performance, while a more in-depth analysis of physiological variables is presented elsewhere (Chapter 4).

5.2 Methods

5.2.1 Experimental Design and Overview

A randomised, repeated-measures cross-over designed study was conducted with 15 participants (age 31.9 ± 10.4 years; body mass 81.4 ± 12.4 kg; $\dot{V}O_{2peak}$ 51.9 ± 4.9 mL.kg^{-1}.min^{-1}). Each participant completed two short-term passive, post-exercise HA regimes: one in sauna and one in HWI, with 6 weeks separating each regime. A heat-stress test (HST), simulating a pack-march in hot conditions, was completed before and after each HA regime. During each HST a range of cognitive, physiological, and perceptual variables were assessed. Ethical approval was obtained from the Auckland University of Technology ethics committee

(18/195) and informed consent was provided in writing by all participants prior to participation in accordance with the *Declaration of Helsinki*.

5.2.2 $\dot{V}O_{2peak}$ Assessment

All participants completed a preliminary $\dot{V}O_{2peak}$ assessment on a motorised treadmill. The test began at 7 km.h^{-1} and was increased 1 km.h^{-1} every 2 min. At 15 km.h^{-1} the treadmill speed was maintained, and gradient was increased in 1% increments. When the respiratory exchange ratio exceed 1.0 stages were shortened to 1 min and continued until voluntary termination. A minimum standard of 40 mL.kg^{-1}.min^{-1} was required for entry into the study.

5.2.3 Heat-Stress Tests

Both HSTs performed by a participant in a regime were performed at the same time of day in a well-lit environmental chamber (Design Environmental, Simultech Australia, Australia) set to 33°C and 75% relative humidity (RH). Each pre-HA HST was performed at least three days prior to beginning a HA regime, while the post-test was performed three days after completion of the HA regime. Each HST began with 10 min of rest inside the environmental chamber prior to 1 h of simulated pack marching on a motorised treadmill (Platinum Club Series, Life Fitness, Illinois, USA) at 5 km.h^{-1} and 1% incline. Participants wore military dress including a long-sleeved shirt, trousers, helmet, body armour and a backpack, along with their own shoes (ensemble mass = 20.62 ± 0.68 kg). Participants were permitted to drink up to 2 L of water *ad libitum* during the HST.

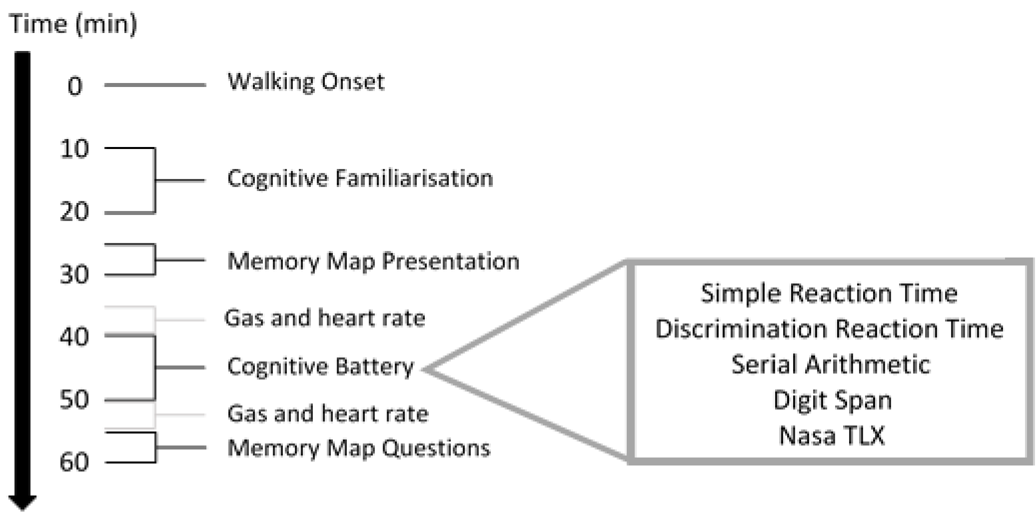

Figure 5-1. Schematic detailing the timing of the cognitive and physiological assessments during heat-stress tests conducted at 5 km.h^{-1} for 60 minutes in 33°C, 75% RH. Rectal and skin temperature as well as heart rate were measured throughout the trial.

5.2.3.1 Physiological measures

Several physiological measures were recorded throughout each HST. Rectal temperature was measured with a flexible thermometer (Hinco Instruments, Australia) inserted ~12 cm beyond the anal sphincter. Skin temperature was measured using probes placed on the chest, bicep, thigh, and calf. Both skin and rectal temperatures were recorded at 1 Hz (SQ2020, Grant Instruments, Cambridge, UK). Heart rate was measured continuously using a 3-lead echocardiogram (Tango+, SunTech Medical, North Carolina). Gas analysis was conducted every 15 min for 4 min, with participants' expired air analysed using an automated gas analysis system (Trueone 2400, Parvo Medics, Utah, USA) to calculate rates of oxygen consumption ($\dot{V}O_2$), minute volume ($\dot{V}E$) and carbon dioxide production ($\dot{V}CO_2$).

5.2.3.2 Perceptual measures

Perceptual measures of thermal sensation (13 point-scale ranging from 1-13), feeling (-5 - +5), sleepiness (1-9) and rate of perceived exertion (RPE) (6-20) were recorded at 15 min intervals.

5.2.3.3 Cognitive Assessments

A cognitive test battery involving tests of reaction time, cognitive throughput, working memory and declarative memory was conducted during each HST (Fig. 5-1), as recommended by military psychologists (New Zealand Defence Force). At 10 min, familiarisation of the tasks was performed, before the main cognitive battery began at 40 min. During this main cognitive battery there was a break between each task of approximately 30 s. Additionally, at 25 min, a memory task was presented to participants to be recalled at 55 min (Fig. 5-1). Where appropriate a balanced Latin-square was used to counterbalance cognitive tasks.

5.2.3.3.1 Reaction Time

Both simple and discrimination reaction time were assessed using a reaction time application (Reaction Time Tests for Science, Andrew Novak, 2016) on an electronic tablet (Nova 2 Lite, Huawei, Shenzhen). Participants either held the device or placed it on the treadmill screen in front of them during the task based on preference, and this was held constant between HSTs within a participant. Simple reaction time required participants to respond by tapping when a red circle appeared on the screen. In the discrimination reaction time task, participants again responded by tapping when a red circle appeared but had to avoid responding to blue and black circles. Processing speed was calculated as the difference in reaction time between the two tasks.

5.2.3.3.2 Cognitive Throughput

A serial arithmetic task was used to assess cognitive throughput (Kase, 2009). This required continually subtracting either 7 or 9 from a 4-digit number as many times as possible within a minute. This test was also done verbally, with the researcher reading the initial numbers aloud and the participant calling out each response.

5.2.3.3.3 Working Memory

A digit span task was used to assess working memory (Conklin et al., 2018; Hocking et al., 2001). A series of numbers were read aloud, and participants were asked to repeat them back, but in the reverse order (i.e., 1 2 3 becomes 3 2 1). The span started at three digits and increased after two correct responses until participants failed twice at one span.

5.2.3.3.4 NASA Task-Load Index

Perceptual responses were also measured in relation to the cognitive battery. Upon completion of the cognitive battery a NASA task-load index (TLX) sheet was presented to participants where they marked their perceived mental demand, physical demand, temporal demand, performance, effort and frustration (Hart et al., 1988).

5.2.3.3.5 Declarative Memory

The memory task involved presenting participants with a fictional map of a basic urban environment. Participants memorised a prescribed route, paying attention to landmarks and road names. All the questions they were to be asked were presented alongside the map to minimise learning effects. The map was placed on the treadmill screen ~40 cm from the participants who were allocated 2 min to study the map before the map and question sheet were removed. 30 min later the questions were read aloud, and participants asked to recall what they could.

5.2.4 Heat Acclimation

Each HA regime was conducted on five consecutive days comprised of continuous aerobic exercise immediately followed by passive heat exposure in either a sauna or HWI facility.

5.2.4.1 Exercise

Participants either ran on a motorised treadmill or cycled on a stationary cycling ergometer, according to participant preference, and kept constant within participants across HA days and HA regimes. Exercise was conducted for 40 min at an intensity equivalent to their first ventilatory threshold, as calculated using the V-slope method (Shimizu et al., 1991) from their $\dot{V}O_{2peak}$ assessment. Participants were permitted to drink water *ad libitum*, up to a maximum of 1 L during exercise.

5.2.4.2 Post-Exercise Heating

After exercise participants were immediately transferred to either the sauna (~70°C, 20% RH) or HWI (~40°C) facility. Participants were instructed to sit for as long as possible, up to a maximum of 40 min, but for safety could terminate the session at any point. Participants were permitted to drink water *ad libitum*, up to a maximum of 1 L during sauna or HWI.

5.2.5 Data Analysis

All analyses were conducted in R version 3.6.1 (R foundation for Statistical Computing, Vienna, Austria). All continuous physiological variables were analysed at the time point closest to the experimental cognitive battery. For heart rate, metabolic and perceptual measures, this was taken as the average from measures taken at 35 and 50 min. For rectal and skin temperature an average of the cognitive battery period (40-50 min) was used for analysis. Skin temperature was calculated using the following equation (Ramanathan, 1964)

$$T_{Skin} = 0.3T_{Chest} + 0.3T_{Bicep} + 0.2T_{Thigh} + 0.2T_{Calf} \quad \text{Equation 5-1}$$

For each outcome variable a mixed model ANOVA was used from the lme4 package (Bates et al., 2014). The model included fixed variables of order (whether sauna or HWI was completed first), condition (sauna or HWI), pre-post (whether the test was the pre- or post-test), with a specified condition by pre-post interaction and with participants added as the random effect. The order output was used to determine if there was a learning effect carried over between conditions. The condition output was used to determine if there was a difference between conditions. The pre-post output was used to determine whether an overall HA effect was present. The interaction term was used to determine whether the change in variables was different between conditions.

Planned post-hoc analyses were performed using pairwise comparisons, with the emmeans package, on the previously generated mixed model ANOVA to differentiate the effects of sauna and HWI. All comparisons had p values adjusted using the Tukey method for comparing a family of four estimates. Data are reported as mean ± standard deviation (SD) for absolute values, while changes are reported as mean with a 95% confidence interval (CI).

5.3 Results

5.3.1 Heat Acclimation

All participants completed all HA sessions in both conditions. During exercise, average heart rate did not differ between conditions (SAU: 143 ± 12 b.min^{-1}; HWI: 141 ± 14 b.min^{-1}; SAU vs HWI: p = .426). Time spent in each heating modality increased significantly in both conditions (SAU: ↑ 1.3 min.session^{-1}, p = .017; HWI: ↑ 1.0 min.session^{-1}, p = .048, SAU vs HWI: p = .737), but the mean exposure time was greater in the HWI condition (SAU: 27.8 ± 7.7 min; HWI: 30.9 ± 8.9 min; SAU vs HWI: p = .007). The sauna induced significantly higher thermal discomfort, thermal sensation, auditory canal temperature and worse feeling than HWI across the HA period (all p < .043), while there were no differences between the conditions in heart rate, or sleepiness (all p > .149). Regardless of condition, reductions were seen between sessions in heart rate, thermal discomfort, thermal sensation, and auditory canal temperature (all p < .046), but not sleepiness or feeling (all p > .368).

5.3.2 Heat Stress Tests

5.3.2.1 Physiological

Rectal temperature was reduced following HA regardless of condition (p = .007) (Table 5-1). Post-hoc tests showed that only HWI HA induced a statistically significant reduction, although no differences were evident between conditions (SAU: p = .059; HWI: p = .007; SAU vs HWI: p = .522) (Fig. 5-2, Table 5-1). However, skin temperature was not significantly affected by HA, with no differences between conditions (HA: p = .065; SAU: p = .159; HWI: p = .065; SAU vs HWI: p = .745) (Table 5-1). While heart rate decreased over HA and in both conditions, there was again no difference between conditions (HA: p = <.001; SAU: p < .001; HWI p < .001; SAU vs HWI: p = .235) (Table 5-1). Metabolic variables of $\dot{V}O_2$, $\dot{V}E$ and $\dot{V}CO_2$ did not change in either condition (all p > .282) (Table 5-1).

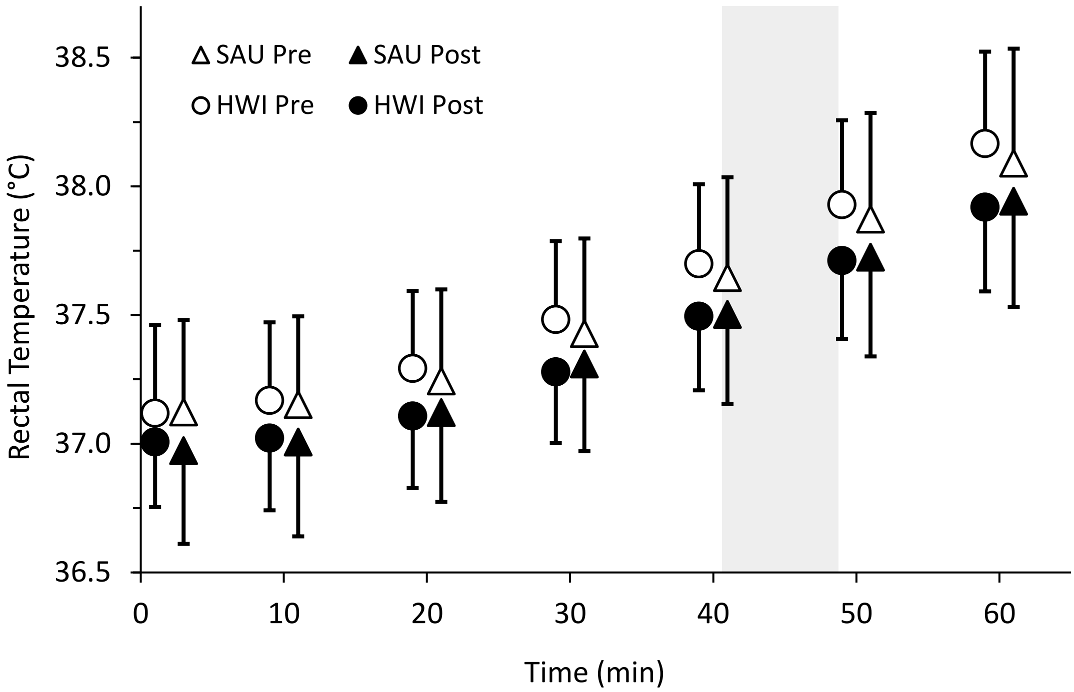

Figure 5-2. Rectal temperature during either the pre- or post-heat-stress test in both sauna and hot-water immersion (HWI) conditions. The time of the cognitive battery is shaded in light grey. Data are recorded as 10 min averages, off-set for clarity. Data are presented as mean ± SD.

5.3.2.2 Perceptions

No differences were seen in any NASA TLX variables following HA in either condition (all $p > .064$) (Table 5-1). Both conditions saw a reduction in RPE (SAU: $p = .014$; HWI: $p = .004$; SAU vs HWI: $p = .710$), with a reduction in thermal sensation observed only in the sauna condition (SAU: $p = .038$; HWI: $p = .336$; SAU vs HWI: $p = .408$), and sleepiness reduced only in the HWI condition (SAU: $p = .367$; HWI: $p < .001$; SAU vs HWI: $p = .051$), although no between-condition differences were statistically significant (Table 5-1). Neither HA protocol influenced feeling (all $p > .116$), or any of the NASA TLX variables (all $p > .064$).

Table 5-1. Summary of physiological and perceptual responses during the cognitive battery pre- and post- heat acclimation (HA). Pre-HA results are displayed as absolute values, while the post-HA results are displayed as a change from baseline. Data are displayed as mean ± SD for baseline values, while the change is displayed as mean change with a 95% CI.

	Sauna		Hot-Water Immersion	
Variable	Pre	Change	Pre	Change
Physiological				
Rectal Temperature (°C)	37.9 ± 0.4	↓ 0.1 (-0.3, 0.0)	37.9 ± 0.3	↓ 0.2 (-0.4 -0.1)*
Skin Temperature (°C)	35.8 ± 0.5	↓ 0.1 (-0.3, 0.1)	36.3 ± 0.4	↓ 0.2 (-0.4, 0.0)
Heart Rate ($b.min^{-1}$)	133 ± 27	↓ 12 (-16, -8)*	130 ± 26	↓ 8 (-13, -4)*
$\dot{V}O_2$ ($mL.kg^{-1}.min^{-1}$)	16.2 ± 1.6	↓ 0.4 (-0.9, 0.1)	16.4 ± 1.3	↓ 0.1 (-0.6, 0.4)
$\dot{V}E$ ($L.min^{-1}$)	36.3 ± 4.1	NC (-1.5, 1.6)	36.4 ± 5.1	↑ 0.9 (-0.7, 2.5)
$\dot{V}CO_2$ ($L.min^{-1}$)	1.14 ± 0.16	↓ 0.03 (-0.06, 0.01)	1.12 ± 0.18	↑ 0.02 (-0.02, 0.05)†
Perceptions				
Thermal Sensation	10.3 ± 2.0	↓ 0.4 (-0.9, 0.0)*	10.3 ± 2.0	↓ 0.2 (-0.6, 0.2)
Feeling	0.8 ± 2.5	NC (-0.7, 0.6)	0.5 ± 2.4	↑ 0.5 (-0.1, 1.1)
Sleepiness	4.6 ± 2.1	↓ 0.1 (-0.8, 0.3)	4.9 ± 2.2	↓ 1.0 (-1.5, -0.5)*
RPE	13.1 ± 2.9	↓ 0.9 (-1.6, -0.3)*	12.6 ± 2.9	↓ 0.8 (-1.4, -0.2)*
NASA TLX				
Mental Demand	16.6 ± 3.3	↓ 0.3 (-1.5, 0.8)	15.4 ± 3.3	↑ 1.1 (-0.1, 2.3)
Physical Demand	7.2 ± 4.3	↓ 0.2 (-1.9, 1.4)	6.7 ± 3.8	↓ 0.7 (-2.4, 1.0)
Temporal Demand	12.0 ± 3.8	↑ 0.7 (-1.0, 2.5)	11.0 ± 4.0	↑ 1.0 (-0.8, 2.7)
Performance	11.0 ± 3.7	↑ 0.1 (-1.4, 1.6)	11.1 ± 3.6	↑ 0.2 (-1.3, 1.7)
Effort	16.4 ± 3.1	↓ 0.4 (-2.0, 1.1)	16.4 ± 2.7	↓ 0.2 (-1.7, 1.4)
Frustration	10.3 ± 4.9	↑ 0.7 (-1.8, 3.2)	10.2 ± 4.7	↑ 0.4 (-2.1, 2.8)

*indicates significant difference between pre and post within a condition, $p < .05$. † indicates significant difference in change between conditions, $p < 0.05$

5.3.2.3 Cognitive

5.3.2.3.1 Reaction Time

Neither simple (↓ 0.01 ms, 95% CI [-0.03, 0.02], *p* = .701) nor discrimination reaction time (↓ 0.01 ms, [-0.03, 0.02], *p* = .517) was affected following HA. Similarly, no differences were observed in processing speed (NC, [-0.03, 0.02], *p* = .756) (Fig. 5-3A).

5.3.2.3.2 Cognitive Throughput

Serial arithmetic was improved ~10% across HA, independently of condition (HA: ↑ 1.6 arbitrary units (AU), [0.1, 3.1], *p* = .043), with no difference in error rate (*p* = .253). Post-hoc analyses revealed a 15% improvement following HWI HA but no change following sauna HA, although there was no statistical difference between the two conditions (SAU: ↑ 0.7 AU, [-1.4, 2.8], *p* = .514; HWI: ↑ 2.4 AU, [0.3, 4.5], *p* = .028; SAU vs HWI: *p* = .255) (Fig. 5-3B).

5.3.2.3.3 Working Memory

There were no differences in digit recall (↑ 0.2 AU, [-0.4, 0.8], *p* = .500), or the error rates during digit recall (↓ 0.5 AU, [-1.8, 0.9], *p* = .504) following HA (Fig. 5-3C).

5.3.2.3.4 Declarative Memory

Three participants were removed from memory analysis after revealing they had acquired memory techniques throughout the course of the study. No difference was found in declarative memory over HA (↑ 0.8 AU, [-1.0, 2.6], *p* = .375), but post-hoc tests showed a 20% improvement following sauna HA, but no change following HWI HA, although there were no statistical differences between the two conditions (SAU: ↑ 3.1 AU, [1.3, 4.9], *p* = .002; HWI: ↑ 0.8 AU, [-1.0, 2.6], *p* = .375; SAU vs HWI: *p* = .437) (Fig. 5-3D).

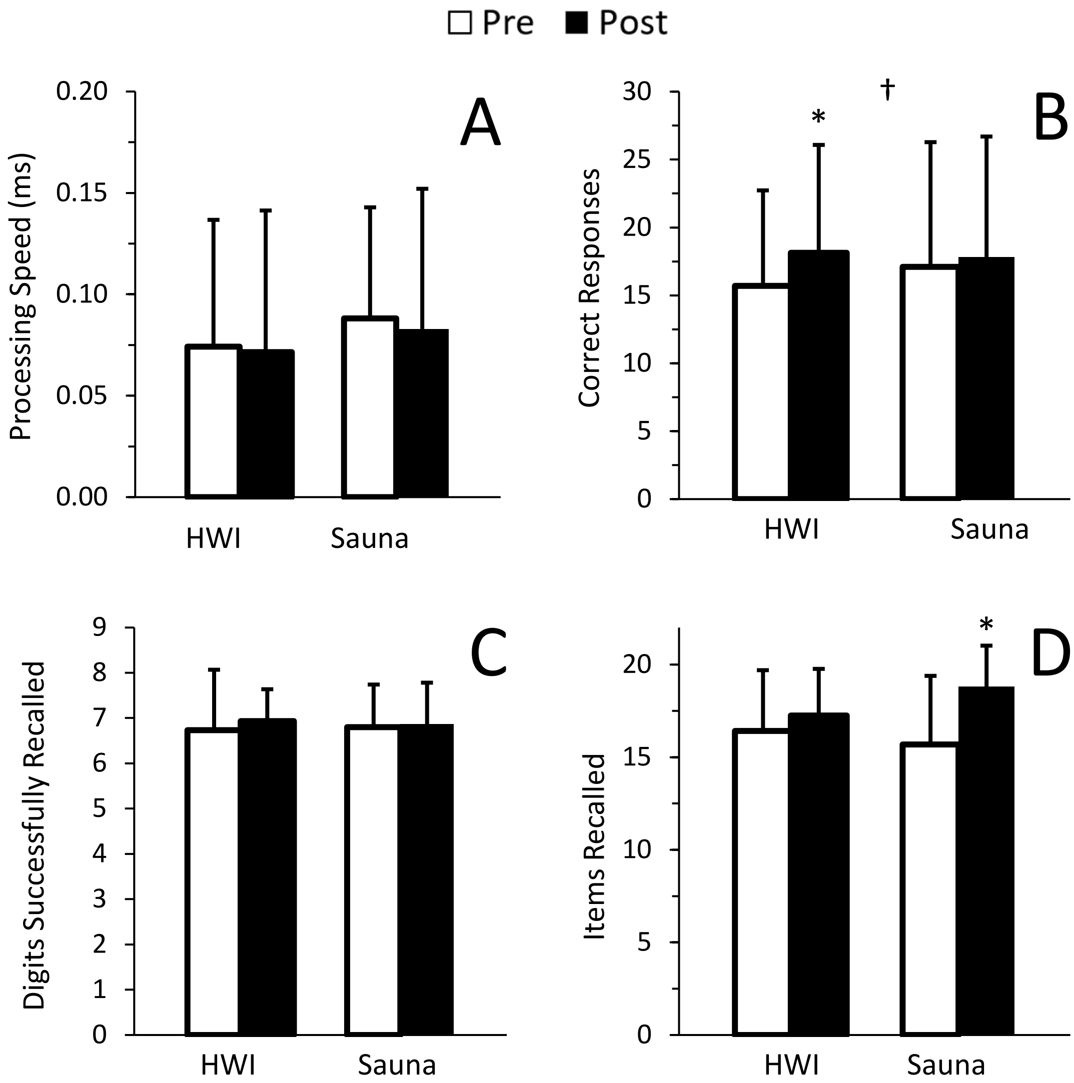

Figure 5-3. Performance scores (estimated mean ± standard deviation) in cognitive tasks during a heat-stress test, before and after 5 d of post-exercise passive heat acclimation in either sauna or hot-water immersion (HWI). A: Processing Speed – calculated as the difference in reaction time between a simple and a discrimination reaction time task. B: Cognitive Throughput – number of correct responses during one minute of serial arithmetic. C: Working Memory – maximum number of digits successfully recalled in reverse order. D: Declarative Memory – number of items successfully recalled. *indicates significant difference between pre and post-test results within a condition, $p < .05$. †indicates a significant overall effect between pre and post-test results, independent of condition.

5.4 Discussion

The main aim of the current study was to evaluate the effects of short-term, passive, post-exercise HA on cognitive performance during a simulated military pack-march. While HA modestly reduced physiological and perceived strain, minimal changes were observed in cognitive function.

Both HA regimes induced beneficial physiological adaptations to the heat (Table 5-1). Although during the post-HA HSTs only HWI HA induced a statistically significant change in rectal temperature, the magnitude of reduction in rectal temperature in both conditions (~0.2°C) is comparable to that seen in other HA regimes, especially that of short-term (< 7 days) HA (James et al., 2017c; Neal et al., 2016a; Tyler et al., 2016). The reduced rectal temperature allows for greater heat storage (Aoyagi et al., 1994; Shen et al., 2015), increasing the work that can be done before body temperature impairs physiological function (Casa et al., 2007; Goforth et al., 2015; Selkirk et al., 2008). Furthermore, the significant reductions in heart rate in both conditions were comparable to similar length HA regimes (Garrett et al., 2009; Poirier et al., 2015; Tyler et al., 2016). The lower heart rate implies a reduced cardiovascular strain (Périard et al., 2011), facilitating simultaneous blood flow to skeletal muscle to support exercise, to the skin for cooling, and to vital organs (González-Alonso et al., 1998). Taken together, these adaptations improve safety (Aoyagi et al., 1997), and physical performance (James et al., 2017a) and would therefore be predicted to mitigate any effects of heat on cognitive function.

Despite the physiological changes, cognitive changes were minimal. Cognition is likely affected by heat through a combination of perceptual and physiological factors that reduce attentional resources available for a task (Hancock et al., 2007; Schmit et al., 2017). It is possible that the perceptual and physiological strain was not sufficient to alter attentional resource allocation, with mean rectal temperature during cognitive testing not exceeding 38°C (Table 5-1). For example, while working memory has previously been shown to be affected by the heat (Racinais et al., 2017b; Schmit et al., 2017), but this performance decrement has been shown to be dependent on core temperature (Hocking et al., 2001). The subtle elevation of rectal temperature during each HST in the current study, likely induced insufficient thermal strain to impair working memory, and therefore the modest reduction in rectal temperature over the course of HA had minimal effect. Furthermore, simple tasks, such as reaction time tasks, are more robust to environmental disturbance as they require fewer cognitive resources (Gaoua, 2010; Hancock et al., 2003), which likely accounts for the lack of change in reaction and processing speed following HA (Fig. 5-3A).

However, an improvement was seen in cognitive throughput, although post-hoc tests showed this occurred only in the HWI condition. The simple nature of the task is overcome by the time limit, requiring response speed to be faster, thereby adding to the cognitive demand (Kase, 2009). Theoretically, improved cognitive throughput would allow a soldier to process information faster following HA. Although the absence of an order effect suggests no long-term learning effect between conditions it remains possible that learning effects occurred within conditions despite attempting to minimise these effects by conducting a full familiarisation during the early stages of each HST (Tao et al., 2019). Further studies are likely needed that examine cognitive throughput in a more field-related setting before further assumptions can be made. While declarative memory was found to improve following sauna HA, the lack of change when both conditions were evaluated together suggests that a minimal effect exists.

Previous studies have also found HA to have minimal effect on cognitive performance (Patterson et al., 1998; Piil et al., 2019; Radakovic et al., 2007). In the current study cognitive performance may have been unaffected as rectal temperature did not exceed the suggested threshold of 38.5°C required to cause a heat-induced impairment in cognition (Schmit et al., 2017). Indeed, other studies have also failed to induce significant physiological strain to affect cognitive performance (Caldwell et al., 2011). In a study with elevated core temperature Piil et al. (2019) saw no effects on complex motor performance, although this could be due to testing being conducted at the same rectal temperature (~40°C), thereby maintaining the degree of thermal strain despite the HA inducing a lower resting rectal temperature. Conversely, Patterson et al. (1998) induced a large reduction in rectal temperature of 0.7°C, compared to only ~0.2°C in the current study. Despite rectal temperature in the post-HA HST being decreased to below the proposed 38.5°C threshold where cognitive performance is suggested to become impaired, no changes were found in visual inattention, vigilance or spatial and temporal orientation (Patterson et al., 1998). However, the tasks selected were unaffected between familiarisation and acute heat exposure, suggesting that the tasks were not affected by the heat to begin with, therefore any improvement would likely have been due to learning effects (Patterson et al., 1998). As the independent effects of heat on the cognitive tasks were not assessed in the current study it is unclear whether the same limitation existed. Therefore as well as ensuring there is adequate thermal stress, it is also important to assess the direct effects of heat on cognitive tasks prior to implementing an intervention (Gaoua, 2010).

5.4.1 Limitations

The current study was limited in several ways. The lack of a control condition, where cognitive tasks were performed in thermoneutral conditions, meant the direct effect of heat on cognition was not assessed. Therefore, the lack of changes seen in the current study may reflect the thermal strain being insufficient to cause cognitive impairment. Furthermore, in the areas where a change was seen, it is unclear whether this is simply due to a learning effect. Therefore, future studies should look to firstly establish the direct effects of heat on each cognitive variable prior to HA, and secondly to ensure adequate thermal strain is present in HSTs.

5.5 Conclusion

In conclusion, a passive post-exercise HA programme induced beneficial physiological and perceptual changes that reduced thermal strain but did not manifest into beneficial changes in cognitive performance beyond what could be expected of learning effects. It is possible that the heat strain during cognitive testing was insufficient to induce cognitive impairment and that at higher core temperatures the HA-induced reduction in core temperature could maintain or improve cognition.

Link

The success of both sauna and HWI HA protocols showed that in less than a week military units could see improvements to thermal tolerance, that would improve performance and safety in a hot environment. Furthermore, while the magnitudes are lower than those seen in long-term HA studies, the upregulation of heat loss mechanisms throughout the body likely minimises the time it will take to acclimate once deployed to the environment, as operations can take place over long durations, unlike athletic events that are more frequently reported in the literature. However, the 5 d HA period still exceeds the worst-case scenario of potentially less than 12 h notice prior to deployment. As alluded to in Chapter 2, one method to overcome this might be intermittent heat exposure (IHE), which theoretically could allow thermal tolerance to be maintained. Therefore, with foresight, upon completion of one HA protocol participants from Chapters 4 and 5 completed either 18 d of IHE or decay. Five participants did not complete the IHE and decay period, and the experimental design did not involve a cross-over, so again the reported results of the HA period differ from those reported in Chapter 4. While cognitive testing was conducted as in Chapter 5, the lack of findings from Chapter 5, and experimental limitations, meant that it was omitted from the manuscript.

Chapter 6 Intermittent Heat Exposure Following Heat Acclimation

6.1 Introduction

Hot or humid environments negatively impact endurance exercise performance (Keiser et al., 2015; Maughan et al., 2012; Nybo et al., 2014). High ambient temperatures reduce the temperature gradient between the skin and the air, limiting convective heat loss (Cramer et al., 2016b; Wendt et al., 2007), while high humidity reduces the water vapour gradient, thereby limiting the evaporation of sweat (Berglund et al., 1977; Cramer et al., 2016a). When these factors are combined with elevated endogenous heat production from skeletal muscle activity body temperature rises quickly, which acts physiologically and perceptually to limit performance (González-Alonso et al., 2008; Stevens et al., 2017a; Tucker et al., 2004). To offset the thermoregulatory challenge and decrement in performance, athletes often undergo pre-competition heat acclimation (HA) to obtain specific physiological adaptations to the heat (Bergeron et al., 2012; Racinais et al., 2015). Effective HA is usually achieved by training in artificial heat on consecutive days for ~1-2 weeks, while ensuring core temperature is sufficiently elevated to perturb homeostasis, thereby invoking adaptive pathways (Bergeron et al., 2012; Garrett et al., 2011). However, the requirement to monitor individuals and have access to specialist equipment, such as environmental chambers, means that more feasible strategies are sought that can be structured more easily around training objectives (Casadio et al., 2017). For example, routine military activities include physical conditioning, weapons training, and tactical training, therefore adding a traditional HA programme is both impractical and disruptive to training objectives. To overcome this, passive, post-exercise heating, in either a sauna or with hot-water immersion (HWI) has been investigated (Heathcote et al., 2018; Zurawlew et al., 2016) and shows potential as a method that minimally interrupts other training objectives.

Within the military, the use of HA strategies is important to improve performance and safety (Armed Forces Health Surveillance Branch, 2019; Parsons et al., 2019) as high casualty rates result from an increased susceptibility to heat illnesses (Goforth et al., 2015; Hosokawa et al., 2019), caused by restrictive clothing and equipment minimising heat loss (Adams et al., 1994; Gavin, 2003; Havenith, 1999), and carried loads adding to heat production (Knapik, 1997a). Furthermore, the use of cooling strategies can be hard to implement as cooling facilities are less readily available and exposures are more sustained. Therefore, the use of HA prior to deployment is clearly justified. However, deployment notice to military units can be as short as 12 h and therefore the implementation of a multi-week HA strategy is challenging, and alternative strategies are required. One technique used to obtain complete heat adaptations in a shortened timeframe is the concept of heat re-acclimation. Here, an initial HA programme is conducted in full, and sometime later a second, shorter HA programme is conducted to rapidly reobtain beneficial physiological adaptations. Re-acclimation studies to date indicate adaptations are regained at a faster rate than they are obtained during the initial HA (Racinais et al., 2015; Weller et al., 2007), likely due to underlying thermal memory or plasticity (Horowitz, 2001). Thermal plasticity occurs following repeated environmental exposure when gene expression is altered to express proteins that preserve homeostasis in the exposed environment (Horowitz, 2001). Thereafter a relatively small stimulus is required to invoke molecular changes that produce a certain HA phenotype (Horowitz, 2002).

However, re-acclimation has a similar problem for short-notice military deployments, as the re-acclimation period is also longer than the notice period. An alternative method of intermittent heat exposure (IHE), whereby periodical exposure to heat could provide sufficient stimuli to prevent the decay of adaptations (Pryor et al., 2018; Taylor, 2000), could overcome such problems. However, relatively little research has considered how IHE can be used to sustain adaptations following HA. Alone, IHE every 3 d has been shown to induce minimal benefits after 3 weeks, and to be much less effective than daily HA (Gill et al., 2001). However, when used after a HA programme a single IHE session every 5 d can sustain beneficial adaptations in heart rate and core temperature (Pryor et al., 2018), likely as a result of stimulating prepared underlying molecular processes to sustain their phenotypical expression (Horowitz, 2002). If adaptations can be sustained by periodic exposure to heat, then it may be possible to establish and maintain an elevated baseline thermal tolerance within an individual for a prolonged period. By raising the thermal tolerance of a military unit, it is conceivable that if rapid deployment was required military personnel could depart upon request with minimal effects on performance and safety. To investigate this concept, the aim of the current study was to determine the effects of passive, post-exercise IHE as a method to retain beneficial physiological adaptations and performance to the heat in a military context.

6.2 Methods

6.2.1 Experimental Design and Overview

Each participant completed an initial short-term HA programme using post-exercise, passive HA using either sauna (SAU) or hot-water immersion HWI. Following HA, participants from each of these conditions were further split into decay (DEC) or IHE groups, thereby creating four groups: sauna decay (DEC_{SAU}), sauna IHE (IHE_{SAU}), HWI decay (DEC_{HWI}) and HWI IHE (IHE_{HWI}). Those in the IHE groups completed additional HA sessions every 2-3 d over an 18 d period involving exercise and passive, post-exercise heat exposure, while DEC groups completed the exercise component only. Heat-stress tests (HSTs) that simulated a 1 h pack march were conducted in hot-humid conditions (33°C, 75% relative humidity) to assess performance before (pre-HA HST) and after initial HA (post-HA HST), as well as following the 18 d DEC and IHE period (post-IHE HST). During the HSTs physiological, and perceptual variables were assessed.

6.2.1.1 Participants

Nineteen participants took part in the experiment (age 31.7 ± 9.8 years, body mass 82.7 ± 14.4 kg, $\dot{V}O_{2peak}$ 52.6 ± 6.1 mL.kg^{-1}.min^{-1}), split into three groups of five and one group of four (DEC_{HWI}). Fifteen participants had previously completed a structured HA programme as part of another study (Chapter 4) which had concluded at least 6 wk prior, allowing for adequate decay of beneficial adaptations (Ashley et al., 2015), while four were new participants. All participants provided informed consent prior to participation in line with the *Declaration of Helsinki* and institutional ethics approval (18/195).

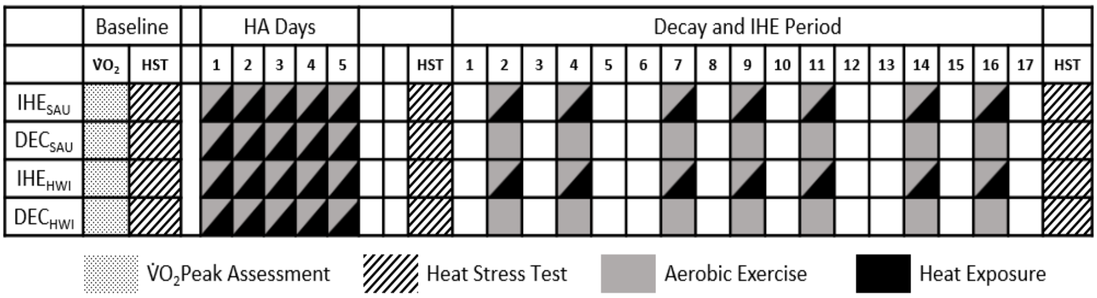

Figure 6-1. Schematical illustration of the experimental time scale. Each group completed baseline $\dot{V}O_2$ and heat-stress tests (HSTs). Within 2-7 d participants began a 5 d heat acclimation (HA) programme using passive, post-exercise heating in either sauna (SAU) or HWI. A second HST was completed 3 d after completion of the HA programme, followed immediately by either a DEC or IHE period. During this time the IHE group completed heat

exposures as per the initial HA every 2-3 d, while the DEC group completed the exercise component only. After ~18 d all participants completed a final HST.

6.2.2 $\dot{V}O_{2Peak}$ Assessment

Each participant completed a preliminary $\dot{V}O_{2peak}$ aerobic assessment in temperate conditions on a motorised treadmill (Pulsar® 3p, h/p/cosmos, Germany). Starting at 7 km.h^{-1} intensity was increased by 1 km.h^{-1} every 3 min, to a maximum of 15 km.h^{-1} after which the gradient was increased in 1% increments. When the respiratory exchange ratio (RER) exceeded 1.00 stages were shortened to 1 min and continued until voluntary termination. All participants exceeded the minimum $\dot{V}O_{2peak}$ of 40 ml.kg^{-1}.min^{-1} required for entry into the study.

6.2.3 Heat-Stress Tests

Three HSTs were completed as per Fig. 6-1. Each HST was completed at the same time of day by each participant, who were asked to avoid strenuous activity and limit alcohol and caffeine consumption for the 24 h preceding each HST. HSTs were carried out in an environmental chamber (Design Environmental, Simultech Australia, Australia), set to 33°C and 75% relative humidity (RH) (absolute humidity = 14 g.m^3). Following 10 min of seated rest in the chamber participants walked on a motorised treadmill (Platinum Club Series, Life Fitness, Illinois, USA) at 5 km.h^{-1} at 1% incline for 1 h, while wearing standard military-issue long-sleeved shirt, trousers, helmet, body armour, a backpack, and their own shoes (full ensemble = 20.6 ± 0.7 kg). After 1 h treadmill gradient was increased 1% every minute (up to a maximum of 15%) until voluntary termination, 20 min elapsed, or upon reaching ethical limits of rectal temperature (> 39.5°C) or heart rate (> 95% age-predicted max for 10 s) (Tanaka et al., 2001). Fluid consumption was permitted *ad libitum* up to a maximum of 2 L, as per military rations.

6.2.3.1 Temperature Measures

Core temperature was recorded rectally, using a flexible thermistor (Hinco Instruments, Australia) inserted 12 cm beyond the anal sphincter. Skin temperature was measured using thermistors placed on the chest, bicep, thigh, and calf on the right-hand side of the body and secured with surgical tape (3M Micropore Tape, 3M, New Zealand). Rectal and skin temperatures were logged at 1 Hz (SQ2020, Grant Instruments, Cambridge, UK). In preparation for analysis, rectal and skin temperature readings were filtered involving removal of all readings that changed by more than 0.1°C.s^{-1} and applying a low-pass Butterworth filter of 0.02 Hz to the data. Missing data were filled with linear interpolation.

Mean skin temperature was calculated using the following formula (Ramanathan, 1964):

$$T_{Skin} = 0.3T_{Chest} + 0.3T_{Bicep} + 0.2T_{Thigh} + 0.2T_{Calf} \qquad \text{Equation 6-1}$$

Sensors occasionally lost contact with the skin due to the high moisture content within the clothing. If this happened the equation was modified to estimate mean skin temperature when one sensor was missing. This modification involved compensating the weights of the three remaining sensors proportionally to maintain the summation of coefficients to 1 (i.e., $T_{Sk} = 0.375T_{Chest} + 0.375T_{Bicep} + 0.25T_{Thigh}$ if there was no calf reading). If two sensors produced no signal, skin temperature was not calculated. Averages over 10 min periods were used for analysis, while 1 min averages of sitting and at the end of steady-state walking were used for resting and end-exercise values, respectively.

6.2.3.2 Cardiovascular Measures

Cardiac frequency was measured using a 3-lead electrocardiogram (Tango+, SunTech Medical, North Carolina), with values recorded at 15 min intervals after a baseline measure was taken while seated inside the chamber. Resting and end-exercise heart rate values were obtained after 5 min of seated rest and after 55 min of walking, respectively.

6.2.3.3 Metabolic Measures

Expired gas analysis was conducted every 15 min, for 4 min, while participants breathed through a mouthpiece connected to a calibrated metabolic cart (Trueone 2400, Parvo Medics, Utah, USA). Data were then analysed as an average of the final 2 min to provide measures of $\dot{V}O_2$, $\dot{V}CO_2$, minute volume ($\dot{V}E$), and RER at each time-point during the HST. Carbohydrate oxidation (g.min^{-1}) was calculated using Equation 6-2 (Jeukendrup et al., 2005).

$$4.21\,\dot{V}CO_2 + 2.962\,\dot{V}O_2 \qquad \text{Equation 6-2}$$

6.2.3.4 Perceptual Measures

Perceptual measures were taken at rest outside the chamber, at rest inside the chamber, at exercise onset and then every 15 min during each HST using both standardised and adapted scales: Rating of perceived exertion (RPE) (15-point scale ranging 6-20) (Borg, 1982), thermal discomfort (1-10) (Bedford, 1936), thermal sensation (1-13) (ISO, 1994), feeling (-5 - +5) (Hardy et al., 1989) and sleepiness (1-9) (Hoddes, 1972).

6.2.3.5 Sweat Rate

Whole-body sweat rate was estimated using pre and post-exercise semi-nude body mass, corrected for fluid consumption (Eq. 6-3) (Buono et al., 2009), with the pre-weight taken post-void and no urine excreted during the trials. To calculate evaporated sweat rate weight was measured immediately prior to entering and immediately after exiting the heat chamber in full dress (Eq. 6-4) (Amos et al., 2000).

(semi-nude weight change + fluid consumption) ÷ walking time Equation 6-3

(fully dressed weight change + fluid consumption) ÷ walking time) Equation 6-4

6.2.3.6 Hydration Measures

Prior to, and immediately following each trial, participants provided a urine sample that was analysed for urine specific gravity (USG) using a refractometer (Atago, Japan).

6.2.4 Initial Heat Acclimation Protocol

Participants completed post-exercise, passive HA sessions on five consecutive days. Each session comprised of 40 min continuous aerobic exercise, followed by up to 40 min of either sauna or HWI.

6.2.4.1 Exercise

Upon arrival at the laboratory (19.2 ± 0.5 °C, 63 ± 2% RH) participants were weighed and had their auditory canal temperature measured. Exercise was conducted either on a graded treadmill or a stationary cycling ergometer, according to participant preference. Exercise was performed for 40 min at an individually prescribed intensity equivalent to their first ventilation threshold (V-slope method, (Shimizu et al., 1991)), calculated from the initial $\dot{V}O_{2peak}$ assessment. Heart rate and RPE were recorded every 10 min throughout the exercise and 1 L of water was available for *ad libitum* consumption. Upon cessation of exercise, weight and auditory canal temperature were measured before participants were transferred to the sauna or HWI facility.

6.2.4.2 Post-Exercise Heating

Post-exercise, passive heating was conducted either by sitting in a sauna (~70°C, 20% RH) or mid-sternum immersion in hot-water (~40°C). Prior to HWI participants were required to rinse off in warm water (<5 s). Auditory canal temperature was taken immediately preceding heat exposure. On exposure to the heat perceptual measures of thermal discomfort, thermal sensation, feeling, and sleepiness were recorded, along with pulse taken at the wrist. During each heat exposure participants could drink up to 1 L of water *ad libitum.* Participants could terminate the session at any time but were requested to remain in the sauna or HWI for as long as they felt comfortable, up to 40 min. Measures were repeated every 10 min during the post-exercise heating. Auditory canal temperature was also taken every 10 min in the HWI, but this was not possible in the sauna where it was taken immediately upon exiting. A final set of measures were also taken if participants terminated the session early, if meaningful time (>2 min) had passed since the last measurement. Participants and drink bottles were then weighed to indicate fluid consumption and for calculation of sweat rate.

6.2.5 Intermittent Heat Exposure

Participants in either IHE group continued to complete HA sessions every 2-3 d for 18 d. Sessions were conducted identically to those during the initial HA protocol.

6.2.6 Decay

Participants in either DEC group continued to complete the exercise component of each HA session every 2-3 d for 18 d but received no heat exposure.

6.2.7 Statistical Analysis

All analyses were conducted in R version 3.6.1 (R foundation for Statistical Computing, Vienna, Austria) using the lme4 and emmeans packages (Bates et al., 2014). All models were tested for normality using histograms and homoscedasticity using Q-Q plots. Analyses produced estimated means, standard deviations, confidence intervals and *p* values, which were adjusted using the Holm correction for multiple comparisons where appropriate. Absolute data are reported as estimated mean ± standard deviation (SD), while changes are reported as estimated mean change with a 95% confidence interval. Statistical analysis was split into four phases: 1) analyses of the change in variables during heat exposure across the HA and IHE period were conducted, irrespective of heating modality. Each variable was entered into a mixed model ANOVA with session and time (if appropriate) entered as fixed effects and participant entered as the random effect. ANOVAs were run for each condition, as well as compared between conditions by entering condition as an additional fixed effect; 2) differences between pre- and post-HA HSTs for the initial HA phase were examined for each condition (SAU and HWI). A mixed model ANOVA was run for each variable with fixed effects of pre-post and condition as well as an interaction between the two was conducted. Estimated means were then calculated to obtain pre-post differences for sauna and HWI. The interaction between pre-post and condition was used to determine if any differences were present between conditions over the HA period; 3) differences between pre-HA or post-HA and post-IHE HSTs were analysed for each group (DEC and IHE), irrespective of heating modality. A mixed model ANVOA was run for each variable within the specified comparison with fixed effects of pre-post and group, along with the interaction between the two, and a random effect of participant. Estimated means were calculated and used to obtain post-HA to post-IHE differences in each group: DEC or IHE. A significant interaction between group and pre-post was used to determine a difference between the groups, and 4) to evaluate differences between conditions within a group (i.e., SAU vs HWI within IHE), a mixed model ANOVA was run within that group, with fixed effects of condition and pre-post as well as their interaction. If the interaction was significant it was deemed that a difference in the change between the conditions existed. Estimated means were calculated and used to obtain differences between conditions in each group (i.e., DEC_{SAU} vs DEC_{HWI}).

6.3 Results

Of the 19 participants all participants completed all sessions in the HA programme, apart from one participant in the DEC_{SAU} group who completed 4. Post-IHE HSTs were conducted an average of 19 ± 3 d following the post-HA HST, with all participants completing all sessions at 2-3 d intervals. Therefore, participants in both IHE groups averaged 7 IHE sessions, while those in the DEC_{SAU} and DEC_{HWI} groups averaged 7.6 and 7.5 sessions, respectively.

6.3.1 Heat Acclimation Sessions

During the HA period the exercise component caused a 0.3°C rise in auditory canal temperature, with no differences between conditions (p = .525). The heating exposure time was not statistically different between conditions, despite a tendency to be longer in HWI (SAU: 27.8 ± 7.6 min; HWI: 30.9 ± 8.9 min; SAU vs HWI: p = .052). Exposure duration was found to increase in the HWI condition only, although the change was not different to that seen in the sauna (SAU: ↑ 0.5 min, 95% CI [-0.5, 1.5], p = .360; HWI: ↑ 0.7 min, [0.0, 0.1], p = .032; HWI vs SAU: p = .684). While heart rate reduced significantly in the sauna condition, there was a tendency to increase during HWI (SAU: ↓ 2 $b.min^{-1}$, [-3, -1], p < .001; HWI: ↑ 1 $b.min^{-1}$, [0, 3], p = .074; SAU vs HWI: p = .001). No changes in sweat rate were seen in either group (both p > .262), while fluid consumption increased in the HWI condition only (SAU: no change (NC), [0.00, 0.01], p = .782; HWI: ↑ 0.05 L, [0.00, 0.10], p = .013; SAU vs HWI: p = .074). Although thermal sensation tended to be less pronounced in HWI (HWI: ↓ 0.1 arbitrary units (AU), [-0.2, 0.0], p = .088), no differences in perceptions were observed in either group (all other p > .106). Mean auditory canal temperature across sessions was found to reduce in sauna, but not HWI, although no difference existed between conditions (SAU: ↓ 0.2 $AU.session^{-1}$, [-0.3, -0.1], p = .001; HWI: NC, [-0.2, 0.2], p = .636; SAU vs HWI: p = .323).

6.3.2 Intermittent Heat Exposure Sessions

Exercise caused a rise in auditory canal temperature of ~0.3°C in both DEC and IHE groups, with no differences between groups (p = .404). During the IHE sessions, exposure time was significantly longer in the HWI than the sauna (SAU: 29.9 ± 7.3 min; HWI: 36.6 ± 5.7 min; SAU vs HWI: p < .001), although exposure time in the sauna increased across the IHE period (SAU: ↑ 0.8 min, [0.1, 1.6], p =.029; HWI: NC, [-0.02, 0.03], p =.867). Mean auditory canal temperature was ~0.4°C higher in the sauna (SAU: 36.4°C; HWI: 36.0°C; SAU vs HWI: p = .039), as was peak auditory canal temperature (SAU: 38.0°C; HWI: 37.1°C; $p < .001$). No changes were observed across IHE in either condition for sweat rate (both $p > .223$), heart rate (both $p > .244$) or auditory canal temperature (both $p > .245$), although fluid consumption increased significantly more in the sauna condition (SAU: ↑ 0.04 L, [0.01, 0.07], $p = .028$; HWI: ↑ 0.02 L, [-0.03, 0.07], $p = .36$; SAU vs HWI: $p = .039$). HWI sessions saw an improvement in feeling and a decline in sleepiness across the IHE period, which both differed significantly from that seen in the sauna (Feeling: SAU: ↓ 0.1 AU, [-0.2, 0.0], $p = .079$; HWI: ↑ 0.1 AU, [0.0, 0.2], $p < .001$; SAU vs HWI: $p < .001$; Sleepiness: SAU: NC, [-0.1, 0.1], $p = .587$; HWI: ↓ 0.1 AU, [-0.2, 0.0], $p = .042$; SAU vs HWI: $p = .028$). No other perceptual changes were seen in either condition (all $p > .173$).

6.3.3 Heat-Stress Tests

6.3.3.1 Performance

Three participants (1 DEC_{HWI}, 1 IHE_{HWI} and 1 DEC_{SAU}) reached the 20-min ethical limit in each HST they completed and therefore were excluded from analyses of performance.

There was a tendency for improved time to exhaustion in SAU though differences between conditions were not statistically significant across the initial HA period (SAU: ↑ 3.9 min, 95% CI [-0.1, 7.5], $p = .071$; HWI: ↑ 3.3 min, [-0.8, 7.4], $p = .105$) (Table 6-1). Following the DEC and IHE period a significant reduction was seen in DEC compared to the post-HA HST (DEC: ↓ 2.6 min, [-5.1, -0.1], $p = .038$; IHE: ↑ 0.1, [-2.2, 2.5], $p = .898$), although there was no difference between conditions (DEC_{SAU} vs DEC_{HWI}: $p = .620$) (Fig. 6-2). When compared to the pre-HA HST both DEC and IHE groups tended to increase, but again this did not reach statistical significance (DEC: ↑ 2.2 min, [-0.4, 4.8], $p = .056$; IHE: ↑ 2.3 min, [-0.1, 4.6], $p = .056$). While no differences were found within the DEC group ($p = .769$), the IHE_{HWI} saw a larger improvement than the IHE_{SAU} group (IHE_{SAU}: ↑ 1.0 min, [-2.5, 4.6], $p = .607$, IHE_{HWI}: ↑ 3.8 min, [-0.1, 7.8], $p = .064$; IHE_{SAU} vs IHE_{HWI}: $p = .043$).

6.3.3.2 Physiological Variables

Across the trial, rectal temperature was significantly lowered following both SAU and HWI HA (SAU: ↓ 0.3°C, [-0.4, -0.2], $p < .001$; HWI: ↓ 0.2°C, [-0.3, 0.1], $p < .001$) (Fig. 6-2). During the DEC and IHE period a significant difference was observed between groups ($p < .001$) as the DEC group increased rectal temperature, while the IHE group which continued to reduce (DEC: ↑ 0.1°C, [0.1, 0.2], $p < .001$; IHE: ↓ 0.1°C, [-0.1, 0.0], $p = .001$) (Table 6-1). No differences were observed between conditions within either the DEC or IHE groups (both $p > .101$). However, when compared to the pre-HA HST, both groups had significantly lower rectal temperature (DEC: ↓ 0.1°C, [-0.2, -0.1], $p < .001$; IHE: ↓ 0.2°C, [-0.3, -0.2], $p < .001$), which was reduced significantly more in the IHE group (DEC vs HWI: $p = .048$) (Table 6-1). Although no difference was found between conditions within the IHE group (IHE_{SAU} vs IHE_{HWI}: $p = .587$), there was a significant difference between conditions within the DEC group, with DEC_{HWI} providing a larger reduction in rectal temperature (DEC_{SAU}: ↓ 0.1°C, [-0.2, 0.0], $p < .001$; DEC_{HWI}: ↓ 0.3 °C, [-0.5, -0.2], $p < .001$; DEC_{SAU} vs DEC_{HWI}: $p = .005$). No differences were observed in the rate of rise in rectal temperature after HA (both $p > .327$), or between either the pre- or post-HA and the post-IHE HSTs for DEC and IHE groups (all $p > .127$) (Table 6-1).

Skin temperature was only reduced following HA in SAU (SAU: ↓ 0.3°C, [-0.5, -0.2], $p < .001$; HWI: NC, [-0.2, 0.3], $p = .667$) (Table 6-1). No significant differences were detected between the post-HA and post-IHE HSTs in either DEC or IHE groups (DEC: NC, [-0.1, 0.2], $p = .841$; IHE: ↓ 0.1°C, [-0.3, 0.0], $p = .079$) (Table 6-1). Compared to the pre-HA HST, both DEC and IHE groups tended towards a reduction in skin temperature although this was significant only in the IHE group, with no difference between groups (DEC: ↓ 0.1°C, [-0.3, 0.0], $p = .072$; IHE: ↓ 0.3°C, [-0.4, -0.1], $p < .001$; DEC vs IHE: $p = .182$). While the pre-HA to post-IHE HST comparison showed no difference between conditions in the DEC group ($p = .536$), within the IHE group there was a significant reduction in skin temperature in the IHE_{SAU} group, although this did not differ from the IHE_{HWI} group (IHE_{SAU}: ↓ 0.4 °C, [-0.6, -0.1], $p < .001$; IHE_{HWI}: ↓ 0.2°C, [-0.4, 0.1], $p = .112$; IHE_{SAU} vs IHE_{HWI}: $p = .211$).

Heart rate significantly reduced in both conditions following the initial HA period, with a greater decline following sauna HA (SAU: ↓ 11 $b.min^{-1}$, [-15, -7], $p < .001$; HWI: ↓ 5 $b.min^{-1}$, [-10, -1], $p = .008$; SAU vs HWI: $p = .033$) (Table 6-1). Over the DEC and IHE period no changes were observed in either group (both $p > .172$), with both groups remaining significantly lower than the pre-HA HST (DEC: ↓ 6, [-11, -2], $p = .005$; IHE: ↓ 5, [-9, -1], $p = .010$; DEC vs IHE: $p = .653$) (Table 6-1).

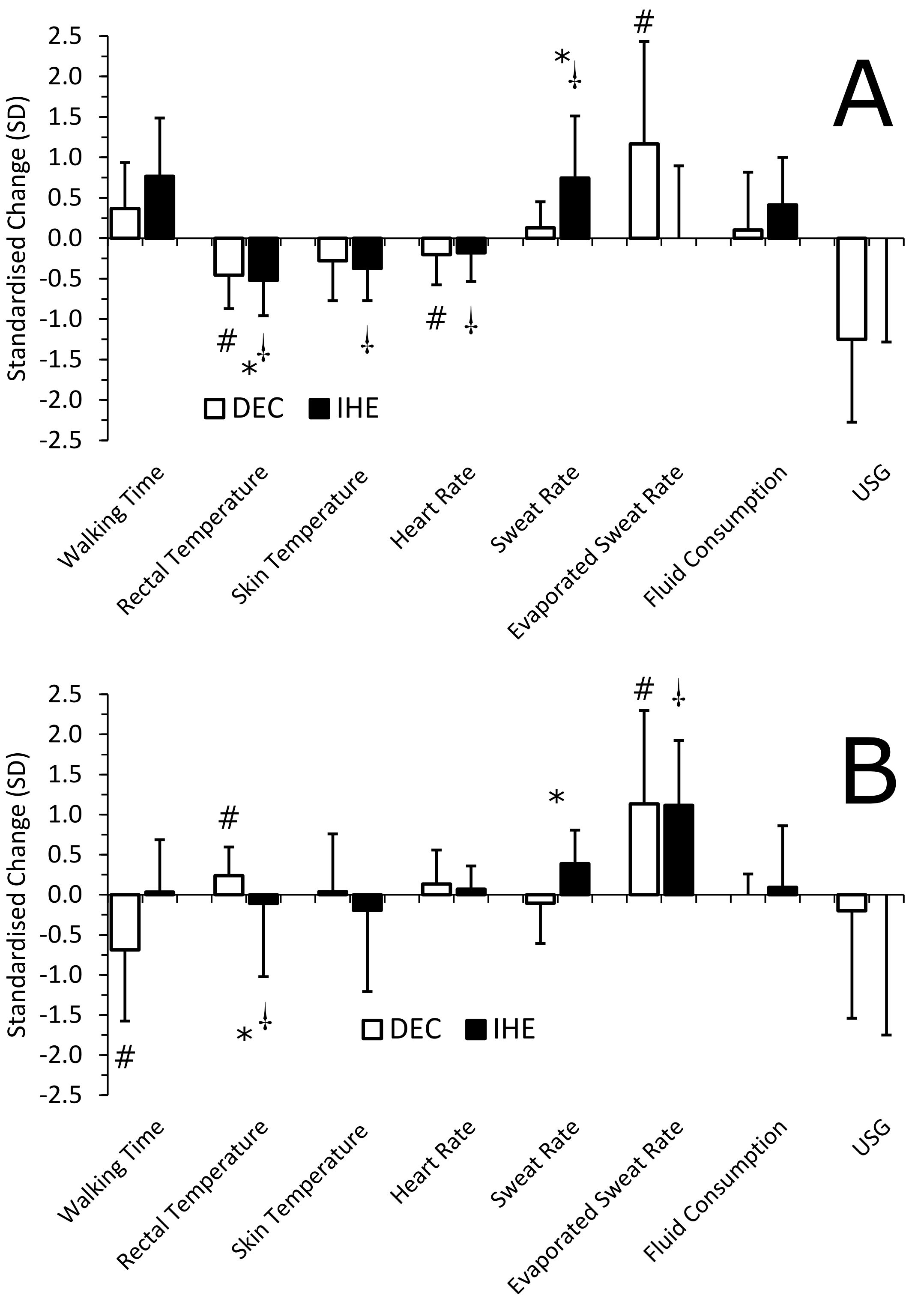

Figure 6-2. Changes in physiological variables following 19 d of decay (DEC) or passive, post-exercise intermittent heat exposure (IHE) following an initial 5 d passive, post-exercise heat acclimation (HA) programme. Data are displayed as change from pre-HA values (A) and change from post-HA values (B). Variables are plotted as a function of the standard deviation (SD) of the baseline measures. (i.e. (post-IHE – pre-HA) / $SD_{pre\text{-}HA}$) All data are displayed as mean ± SD. # $p < .05$ between baseline and decay value, ⸸ $p < .05$ between baseline and IHE value, * $p < .05$ between change in groups.

Table 6-1. Changes in physiological variables during heat-stress tests (33°C, 75% RH) at baseline (pre-HA), following a 5 d heat acclimation (HA) programme (post-HA) and following subsequent decay (DEC) or intermittent heat exposure (IHE). Data from sauna and hot-water immersion interventions are pooled for each analysis. Pre- and post-HA values are displayed as mean ± SD, while the pre-post differences are displayed as mean change, with 95% confidence intervals.

			Change from Post-Test	
Variable	Pre-HA	Post-HA	DEC	IHE
Time to Exhaustion (min)	8.8 ± 4.7	12.42 ± 4.6	↓ 3.4 (-6.4, 0.4) $^{\beta}$	↑ 0.1 (-2.5, 2.8) †
Rectal Temperature (°C)				
Resting	37.1 ± 0.4	36.9 ± 0.4*	↑ 0.2 (0.0, 0.3) $^{\alpha}$	↓ 0.1 (-0.2, 0.0) $^{\alpha, \beta, \dagger}$
Average	37.6 ± 0.3	37.3 ± 0.3*	↑ 0.1 (0.1, 0.2) $^{\alpha, \beta}$	↓ 0.1 (-0.1, 0.0) $^{\alpha, \beta, \dagger}$
End-Exercise	38.1 ± 0.4	37.8 ± 0.4*	↑ 0.1 (-0.1, 0.3) $^{\beta}$	↓ 0.1 (-0.2, 0.0) $^{\beta, \dagger}$
Slope (°C.h^{-1})	1.3 ± 0.3	1.3 0.3	NC (-0.2, 0.2)	NC (-0.2, 0.2)
Skin Temperature (°C)				
Resting	34.4 ± 0.6	34.3 ± 0.6	↑ 0.2 (-0.2, 0.6)	↓ 0.1 (-0.4, 0.3)
Average	35.8 ± 0.4	35.6 ± 0.3*	NC (-0.1, 0.2)	↓ 0.1 (0.3, 0.0) $^{\alpha}$
End-Exercise	36.4 ± 0.4	36.3 ± 0.4*	↓ 0.1 (-0.3, 0.1)	↓ 0.2 (-0.4, 0.0) $^{\alpha}$
Heart Rate (b.min^{-1})				
Resting	71 ± 9	65 ± 9*	↑ 4 (-3, 10)	↑ 3 (-3, 9)
Average	107 ± 13	99 ± 13*	↑ 3 (-1, 7) $^{\alpha}$	↑ 3 (0, 7) $^{\alpha}$
End-Exercise	132 ± 17	120 ± 17*	↑ 3 (-4, 9) $^{\alpha}$	↑ 3 (-4, 9) $^{\alpha}$
Sweat Rate (L.h^{-1})	1.1 ± 0.2	1.2 ± 0.2	NC (-0.2, 0.1)	↑ 0.1 (0.0, 0.3) $^{\alpha, \dagger}$
Evaporated Sweat Rate (L.h^{-1})	0.5 ± 0.4	0.4 ± 0.4	↑ 0.3 (-0.6, -0.1) $^{\alpha, \beta}$	↑ 0.3 (-0.5, -0.1) $^{\beta}$
Fluid Consumption (L)	0.9 ± 0.5	1.0 ± 0.5	NC (-0.2, 0.2)	NC (-0.2, 0.2)
USG Pre	1.017 ± 0.007	1.014 ± 0.007	↑ 0.002 (-0.004, 0.009)	↑ 0.004 (-0.002, 0.010)

*indicates $p < .05$ between pre- and post-HA HSTs, $^{\alpha}$ indicates $p < .05$ between pre-HA and post-IHE HST, $^{\beta}$ indicates $p < .05$ between post-HA and post-IHE HST, † indicates $p < .05$ between the change in Decay and IHE.

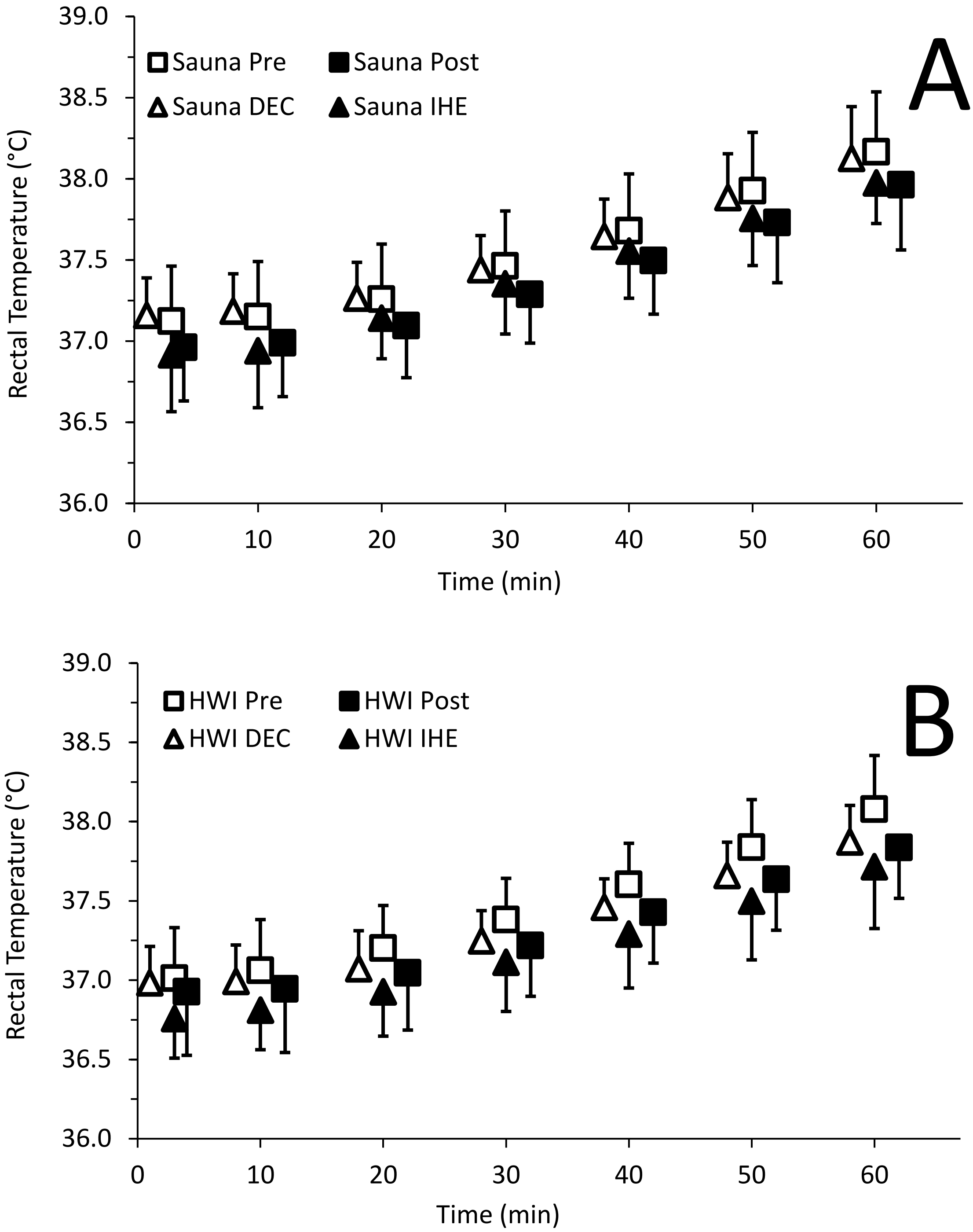

Figure 6-3. Mean rectal temperature across a heat-stress test conducted pre- and post-heat acclimation as well as following a period of decay or intermittent heat exposure (IHE) using heat exposures of either sauna (A) or hot-water immersion (B; HWI). Data are displayed as mean ± SD. Data are offset from 10-min time points for clarity.

Sweat rate was unchanged following HA in either condition (both $p > .206$) (Table 6-1, Fig. 6-4). Furthermore, sweat rate was not significantly changed following the DEC and IHE period despite a tendency to increase in the IHE group that was significantly different to the change in the DEC group (DEC: NC, [-0.2, 0.1], $p = .507$; IHE: ↑ 0.1 $L.h^{-1}$, [0.0, 0.3], $p = .053$; DEC vs IHE: $p = .045$) (Table 6-1). Although there was no difference between conditions in the IHE group ($p = .622$), within the DEC group DEC_{SAU} increased sweat rate significantly more than DEC_{HWI} group (DEC_{SAU}: ↑ 0.1 $L.h^{-1}$, [0.0, 0.2], $p = .191$; DEC_{HWI}: ↓ 0.2, [-0.3, -0.1], $p = .031$; DEC_{SAU} vs DEC_{HWI}: $p = .011$). When compared to the pre-test, the IHE group had a significantly elevated sweat rate (Fig. 6-4) that had increased significantly more than in the DEC group (DEC: NC, [-0.2, 0.2], $p = .620$; IHE: ↑ 0.3 $L.h^{-1}$, [0.1, 0.5], $p = .002$; DEC vs IHE: $p = .026$), with no differences between conditions within the DEC or IHE groups (both $p > .327$) (Table 6-1).

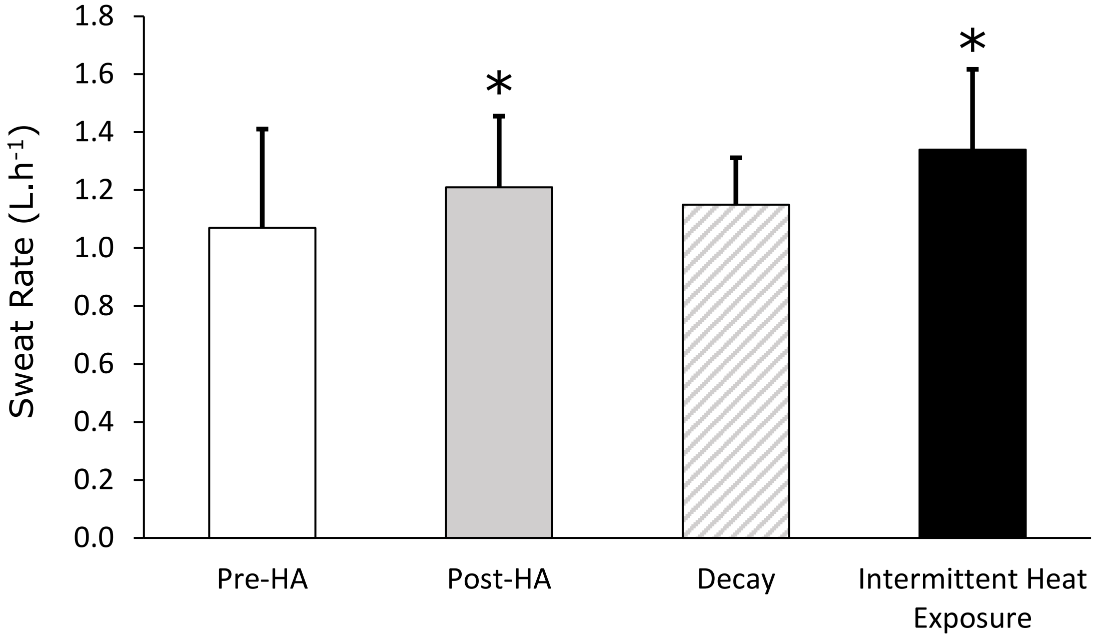

Figure 6-4. Changes in sweat rate over the course of both sauna and hot-water immersion (HWI) heat acclimation (HA) and the subsequent decay (DEC) and intermittent heat exposure (IHE) period. Aggregated means of both groups (DEC and IHE) are used for pre-HA and post-HA values, with the DEC and IHE results shown as projected changed based on the within group changes from post-HA to post-IHE HSTs. *$p < .05$ compared to pre-HA HST.

No changes in evaporated sweat rate were seen over HA (both $p > .476$). Following the decay and IHE period, significant increases in evaporated sweat rate were seen in both groups, with no difference between groups (DEC: ↑ 0.3, [0.1, 0.6], $p = .005$; IHE: ↑ 0.3, [0.1, 0.5], $p = .006$; DEC vs IHE: $p = .675$) (Table 6-1), or between conditions within those groups (both $p > .070$). When compared to the pre-HA HST, only the DEC group had a significant reduction, although this did not reach statistical significance compared to the IHE group (DEC: ↓ 0.4, [-0.7, 0.0], $p = .040$; IHE: NC, [-0.3, 0.3], $p = .982$; DEC vs IHE: $p = .077$).

Fluid consumption did not change following HA (both $p > .469$) or following the decay and IHE period in either group compared to both the post-HA HST (both $p = 1.000$), and the pre-HA HST (both $p > .126$) (Table 6-1). Similarly, no differences were seen in hydration as assessed by USG either before or after the HST over the course of HA ($p > .266$), between post-HA and post-IHE HSTs (all $p > .205$) or between pre-HA and post-IHE HSTs (all $p > .152$) (Table 6-1).

6.3.3.3 Metabolic Variables

Following initial HA, reductions in $\dot{V}O_2$ and $\dot{V}CO_2$ were seen in the sauna condition, but not the HWI condition ($\dot{V}O_2$: SAU: ↓ 0.6 $mL.kg^{-1}.min^{-1}$, [-1.1, -0.2], $p = .005$; HWI: ↓ 0.3 $mL.kg^{-1}.min^{-1}$, [-0.8, 0.2], $p = .134$; $\dot{V}CO_2$: SAU: ↓ 0.04 $L.min^{-1}$, [-0.08, -0.01], $p = .006$; HWI: ↑ 0.02 $L.min^{-1}$, [-0.02, 0.06], $p = .207$). While no difference was seen following the decay and IHE period in $\dot{V}O_2$ or $\dot{V}CO_2$ ($\dot{V}O_2$: both $p > .228$; $\dot{V}CO_2$: both $p > .338$), a reduction was seen compared to the pre-HA HST for both variables in the DEC group, with the change in $\dot{V}O_2$ significantly different to that seen in the IHE group ($\dot{V}O_2$: DEC: ↓ 0.7 $mL.kg^{-1}.min^{-1}$, [-1.0, -0.3], $p < .001$; IHE: ↓ 0.1 $mL.kg^{-1}.min^{-1}$, [-0.4, 0.3], $p = .576$; DEC vs IHE: $p = .010$; $\dot{V}CO_2$: DEC: ↓ 0.04 $L.min^{-1}$, [-0.07, -0.01], $p = .011$; IHE: ↓ 0.02 $L.min^{-1}$, [-0.05, 0.02], $p = .263$; DEC vs IHE: $p = .227$). $\dot{V}E$ was unchanged following HA (both $p > .104$) or following either decay or IHE compared to either the post-HA HST (both $p = 1.000$), or the pre-HA HSTs (both $p > .877$).

Conversely, following the HA period, reductions in carbohydrate oxidation and RER were only seen in the HWI condition (Carbohydrate oxidation: SAU: ↓ 0.06 $g.min^{-1}$, [-0.15, 0.03], $p = .130$; HWI: ↑ 0.12 $g.min^{-1}$, [0.02, 0.21], $p = .012$; RER: SAU: NC, [-0.02, 0.02], $p = .774$; HWI: ↑ 0.03, [0.01, 0.05], $p = .002$). Although both groups tended to lower RER following the decay and IHE period, this did not reach statistical significance (DEC: ↓ 0.01, [-0.03, 0.00], $p = .076$; IHE: ↓ 0.02, [-0.04, 0.00], $p = .057$), while no differences were seen in carbohydrate oxidation (both $p > .144$). Compared to the pre-HA HST, neither DEC or IHE groups showed any changes in RER (both $p > .442$) or carbohydrate oxidation (both $p > .444$).

6.3.3.4 Perceptual Variables

RPE was only significantly reduced following HA in SAU, although it tended to reduce following HWI (SAU: ↓ 0.7, [-1.3, -0.1], $p = .027$, HWI: ↓ 0.5, [-1.1, 0.1], $p = .069$). While no differences were found in either the DEC or IHE group between the post-HA and post-IHE HSTs (both $p > .770$), an overall reduction from pre-HA was observed in both groups (DEC: ↓ 0.7, [-1.3, 0.0], $p = .036$; IHE: ↓ 0.7, [-1.3, 0.0], $p = .036$).

Sleepiness was shown to reduce following the initial HA in both conditions (SAU: ↓ 0.6, [-1.0, -0.2], *p* = .001; HWI: ↓ 0.7, [-1.1, -0.2], *p* = .001). While no differences were detected across the DEC and IHE period (both p > .204), compared to pre-HA values there was a significant reduction in both groups (DEC: ↓ 0.4, [-0.9, 0.0], *p* = .036; IHE: ↓ 0.4, [-0.9, 0.0], *p* = .036).

No differences in thermal comfort, thermal sensation or feeling were seen across HA (all *p* > .305), following the decay and IHE period (all *p* = 1.000), or in either DEC or IHE groups compared to pre-HA (all *p* > .235).

6.4 Discussion

The primary aim of this study was to determine the effectiveness of passive, post-exercise IHE to maintain beneficial heat adaptations obtained from a prior short-term HA programme. The present results indicate that IHE can maintain several important physiological parameters that aid physical performance and safety when operating in hot environments.

Physical performance typically improves by 7% following short-term (< 7 d) HA (Tyler et al., 2016), with time to exhaustion or capacity tests typically inducing greater improvements (Scoon et al., 2007; Tyler et al., 2016) although the reported range in the literature extends from 0 (Aoyagi et al., 1998) to 33% (Sunderland et al., 2008). In the present study no statistically significant improvement in time to exhaustion followed the initial 5 d HA, likely due to the small sample size as improvements have previously been seen in identical, and near identical protocols (Zurawlew et al., 2016). During the decay period following the initial HA, performance is expected to decline as underlying physiological adaptations diminish (Daanen et al., 2018). Employing a similar study design to the present study, Garrett et al. (2009) conducted a 5 d HA programme (90 min.d^{-1} in 40°C, 60% RH at a clamped core temperature of 38.5°C) which induced a ~15% performance improvement over the HA period. However, weekly HSTs revealed that 2 and 3 wk of decay caused performance to return to pre-HA levels (Garrett et al., 2009). Similarly, the current study saw performance significantly reduce following 18 d of decay to levels resembling pre-HA values (Table 6-1; Fig. 6-2). However, following IHE performance was maintained (Table 6-1; Fig. 6-2), suggesting that the continued heat stimulus retained thermoregulatory adaptations. Furthermore, while the IHE_{SAU} group continued to increase sauna exposure time throughout the IHE period highlighting an improved heat tolerance, the IHE_{HWI} group saw no increase, likely as most participants completed the maximal exposure duration from the start of the IHE period. To our knowledge no other study has investigated the effects of IHE on performance. For military units with short deployment notice and concerns with heat-induced performance impairments upon destination arrival, IHE provides a promising strategy that could maintain beneficial physiological adaptations and physical performance to assist upon arrival in a hot climate.

Reductions in core temperature are typically observed across HA (Faulkner, 2016; Heathcote et al., 2018; Tyler et al., 2016), consistent with the reduced rectal temperature at rest, at end-exercise, and on average following short-term HA in both conditions during the present study (Fig. 6-3). While the DEC group saw rectal temperature return to pre-HA values, the IHE group saw a further reduction (Table 6-1; Fig. 6-2; Fig. 6-3). Specifically, end-exercise core temperature adaptations typically decay at ~2.6%.d^{-1} (Daanen et al., 2018), whereas in the current study a rate of ~1.7%.d^{-1} was observed in the decay group between the post-HA and post-IHE HSTs. Indeed, following initial HA programmes that initiated similar reduction in rectal temperature, both Poirier et al. (2015) (15 d cycling 90 min.d^{-1} at 50% $\dot{V}O_2$max in 40°C, 20% RH) and Garrett et al. (2009) (5 d cycling at clamped core temperature of 38.5°C in 40°C, 60% RH) found that after 2 wk of decay, rectal temperature had returned to pre-HA values. However, in the current study after 18 d of decay rectal temperature was still reduced relative to pre-HA (Fig. 6-2A). The maintenance of a low rectal temperature in the current study could be due to frequent aerobic exercise that can maintain heat adaptations (Aoyagi et al., 1998; Cohen et al., 1982).

Despite rectal temperature still being reduced after 18 d, the augmented reduction obtained with IHE further increased the capacity for heat gain to improve performance and safety (Aoyagi et al., 1994; Shen et al., 2015). Previous attempts to reobtain core temperature adaptations from a prior HA programme have returned differing results. Following 26 d of decay Weller et al. (2007) found a single day of RA (100 min walking at ~5.5 km.h^{-1} in 32°C, 18% RH) returned rectal temperature to post-HA values, while Ashley et al. (2015) suggested 4 d of RA after 2 wk of decay, and 5 d following 4 wk of decay, was required to restore rectal temperature. However, both these studies returned core temperature to the value seen post-HA, whereas in the current study (with heat exposure each 2-3 d) rectal temperature reduced further than during the initial HA programme (Fig. 6-2B). IHE has previously been used every 5 d for 25 d by Pryor et al. (2018) following ~10 d of mixed-mode HA (90-240 min in 40°C, 40% RH). Although, rectal temperature remained significantly lower than at pre-HA, no further decreases were observed. The greater volume of heat exposure used by Pryor et al. (2018) during HA may have induced stronger physiological adaptations (Moss et al., 2019) that, although untested, may require smaller or less frequent stimuli to maintain. Indeed, over the HA period the change in end-exercise rectal temperature seen by Pryor et al. (2018) was ~3 times greater than that seen in the current study. The minimal heat exposure (~2.5 h) used in the current study during the initial short-term HA may have limited the upregulation of adaptive mechanisms (Guy et al., 2015; Moss et al., 2019; Taylor et al., 1997). However, during the IHE period the additional exposure likely continued to progress these adaptations, causing changes typically associated with longer HA programmes. For groups planning to use IHE to maintain heat adaptations for a prolonged period, the use of shorter HA programmes could ultimately induce more complete adaptations.

Differences in skin temperature were seen primarily in the sauna condition, both following HA and following IHE_{SAU} compared to pre-HA. The high ambient temperature of the sauna likely accelerates the heating of skin temperature more rapidly than HWI (Hannuksela et al., 2001), thus provoking adaptations that minimise the rate at which the skin heats up. However, no differences in skin temperature between IHE and DEC groups were observed (Table 6-1, Fig. 6-2B), supporting the results of a previous IHE study (Pryor et al., 2018). Other data regarding the effects of additional heat exposure on skin temperature are scarce, while the effects of decay return inconsistent results. Studies evaluating the decay of skin temperature over periods < 1 wk, report both rapid rates of decay (Daanen et al., 2011; Stephens et al., 1981) and minimal changes (Neal et al., 2016b). During a longer decay period Weller et al. (2007) found skin temperature to be maintained following 12 d of decay, but to have risen 0.8°C after 26 d of decay, similar to the findings of the current study, which saw no change in skin temperature following 18 d of decay (Table 6-1, Fig. 6-2B). Although skin temperature was not different between DEC and IHE in the current study, for arid environments, where skin temperature is elevated to a greater degree, it may be more beneficial to use sauna HA and IHE to reduce skin temperature. Having a lower skin temperature reduces thermal discomfort (Bulcao et al., 2000) and facilitates heat loss by increasing the temperature gradient between the core and periphery (Cramer et al., 2016b; Gisolfi et al., 1969).

Central adaptations, such as heart rate, are among the fastest heat adaptations to occur (Faulkner, 2016). Across HA heart rate was reduced at rest, during and at end-exercise time points, at magnitudes comparable to the literature (Tyler et al., 2016). However, following the DEC and IHE period both groups significantly increased heart rate, with no differences between the groups (Table 6-1, Fig. 6-2B). While end-exercise heart rate decayed at a slightly lower rate ($1.3\%.d^{-1}$) compared to that seen in the literature ($\sim 2.3\%.d^{-1}$) (Daanen et al., 2018), this could be explained by the exercise component alone being able to maintain cardiovascular adaptations

(Aoyagi et al., 1998). However, the similar rate of decay, in the IHE group was unexpected. The lack of change observed here is in contrast to that shown by Pryor et al. (2018) where IHE enabled post-exercise heart rate to be ~14% lower than that seen in the decay group. As no changes were seen across the IHE sessions it is possible that the stimuli warranted no further cardiovascular adaptions, which are amongst the fastest adaptations to occur (Faulkner, 2016; Mitchell et al., 1976; Stanley et al., 2015). As most participants were able to reach the time-limit placed on IHE sessions, the adaptive stimuli were likely lessened (Gibson et al., 2019). Finding a method of ensuring the constant progression of heat strain in passive heating protocols would therefore be valuable both for the implementation of IHE, as well as longer passive, post-exercise HA programmes available in the current literature (Heathcote et al., 2018).

Despite a lack of change in sweat rate over the course of HA, following IHE sweat rate was significantly elevated compared to pre-HA whereas no change was observed in the DEC group (Fig. 6-4). Following decay from HA, sweat rate typically declines, with reductions of up to 247% seen over a 26 d decay period (Weller et al., 2007). However, other studies have observed no significant change following a 2 wk decay, despite a tendency to reduce (Poirier et al., 2015). Conversely, investigations in re-acclimation studies have shown sweat rate to increase (Pichan et al., 1985; Weller et al., 2007), although the short exposure volume during re-acclimation is insufficient to induce further increases in sweat rate beyond that of the initial HA. Furthermore, IHE has previously been unable to maintain sweat rate adaptations, despite increasing over the initial HA period (Pryor et al., 2018). Sweat rate adaptations typically take over two weeks to occur (Kirby et al., 2019; Poirier et al., 2015; Sawka et al., 2011a), so it is likely that the emergence of this finding is a result of the accumulated volume of heat exposure (Fox et al., 1964). The increased sweat rate following IHE helps regulate body temperature by facilitating the loss of heat through evaporative means (Amos et al., 2000; Sawka et al., 1993). Being able to achieve an increase in sweat rate over time, without the need for a long, concentrated block of HA provides a much more efficient and practical means to obtaining crucial heat adaptations in military personnel.

6.5 Conclusion

In summary, application of IHE to maintain adaptations from a previously conducted HA programme appears a beneficial approach, and in some cases may even enhance desirable physiological adaptations for performing in the heat. For military groups that may receive minimal notice before being deployed to a hot environment, a short passive, post-exercise HA programme, that is minimally disruptive to training and other commitments, may provide a basis for maintenance of elevated thermal tolerance, thereby improving operational performance and safety upon arrival in hot environments.

Link

The success of IHE in maintaining thermal tolerance provided a successful means by which an elevated baseline thermal tolerance could be maintained for prolonged periods. Therefore, the physical aim of the thesis; to provide a feasible means to minimise the effects of heat in military units who could deploy with as little as 12 h notice, was achieved. However, cognitive performance remained unaffected. Preliminary results from the military study in Chapter 3 had shown cognitive performance to decline after ~1 h, but it was unclear if this was due to fatigue or the heat. While ultimately, the end results showed no effects on cognition in both Chapter 3 and Chapter 5, anecdotally participants were cognitively impaired and losing focus towards the end of heat-stress tests. Therefore, a more mechanistic consideration of how cognition might be affected by the heat was warranted. In addition to raising the complexity of cognitive tasks by using computer-based tasks that were previously unavailable, physiological measures of brain function were recorded using near-infrared spectroscopy. By independently manipulating core temperature it was hoped that a deeper understanding of how cognition is affected within a military setting would be achieved.

Chapter 7 Isolated Effects of Core Temperature on Cognition

7.1 Introduction

Military operations require not only physical performance (Birrell et al., 2010; Hunt et al., 2016), often with heavy loads (Kenefick et al., 2017; Knapik, 1997b), but also cognitive performance (Martin et al., 2019; Martin et al., 2020; Vrijkotte et al., 2016). Indeed, cognitive impairment accounts for most accidents in both training and battle (Vrijkotte et al., 2016), and declines faster than physical function during sustained operations (Lieberman et al., 2006). Extreme environments further restrict the availability of cognitive resources thereby impairing cognitive function (Hancock et al., 2003; Vasmatzidis et al., 2002).

One such environment is the hot or humid environment where a multitude of physiological, psychological, and perceptual factors can detract from cognitive processes and thereby impair cognition. Poor decision making is more frequent in hot environments (Froom et al., 1993; Martin et al., 2019), likely increasing the risk of casualties (Bhattacharyya et al., 2017), which has been assumed to be as a function of elevated core temperature (Martin et al., 2019). Some suggest that when core temperature exceeds ~38.5°C cognitive performance begins to decline (Schmit et al., 2017), whereas others suggest it is the direction of change in core temperature that has a greater influence on cognition (Allan et al., 1979a; Allan et al., 1979b; Hancock et al., 2003). Furthermore, during passive hyperthermia brain activity has been shown to alter as a method of preserving performance (Jiang et al., 2013; Liu et al., 2013; Qian et al., 2013; Xue et al., 2018), suggesting an inherent ability to mitigate environmental disturbances to cognition.

Within military operations, several factors can impair cognition including core temperature (Hocking et al., 2001; Schmit et al., 2017), skin temperature, perceptions (Gaoua, 2010; Gaoua et al., 2017), dehydration (Cian et al., 2001; Cvirn et al., 2019; Ganio et al., 2011; Nolte et al., 2013), nutritional status (Bandelow et al., 2010; Owen et al., 2004; van Dokkum et al., 1996), experience (Hancock et al., 2003), environmental conditions (Saini et al., 2017), solar radiation (Piil et al., 2020), physical (Bhattacharyya et al., 2017; Eddy et al., 2015; Grego et al., 2005; Yanovich et al., 2015) and cognitive fatigue (Head et al., 2017; Lieberman et al., 2006), carried loads (Williams et al., 1997) and sleep deprivation (Lieberman et al., 2005a), among others. Therefore, the aim of this study was to isolate the effects of elevated core temperature and determine its influence on cognitive performance within a military context.

If core temperature plays a major role in impairing cognition, then the effects of heat could be minimised by cooling garments or heat acclimation strategies (Hemmatjo et al., 2017; Patterson et al., 1998). Indeed, head cooling and cooling collars have been successful in overcoming the negative effects of heat on cognition (Gaoua et al., 2011; Lee et al., 2014). Recently, the use of a menthol mouth-rinse, which provides perceptual cooling, has been shown to improve physical performance (Flood et al., 2017; Mündel et al., 2010; Stevens et al., 2016). Therefore, a secondary aim was to determine whether menthol mouth-rinse could preserve cognitive function within a military context in the heat.

7.2 Methods

7.2.1 Experimental Design and Overview

A randomised, repeated measures, cross-over design was employed, during which each participant completed three experimental sessions assessing cognitive function during military-specific exercise in the heat (Fig. 7-1), after familiarisation. The sessions were comprised of a normothermic session (CON) and two hyperthermic sessions. One of the hyperthermic sessions included repeated mouth-rinse using a menthol solution (MENT), which was controlled for in the other hyperthermic trial using an identical volume water mouth-rinse (HOT), which also occurred in CON. During each session, cognitive, physiological, and perceptual and cognitive measures were recorded. Each experimental session was completed at the same time of day for each participant, with at least 1 wk, but no more than 3 wk, between each trial. With institutional ethical approval (AUTEC 19/368), and in accordance with the *Declaration of Helsinki*, participants provided written, informed consent.

7.2.1.1 Participants

Eight participants (3 males, 5 females) took part in the study. Participants were habitually active, averaging 289 ± 148 min of structured exercise per week. Female participants completed each condition during the follicular phase of the menstrual cycle, as confirmed by self-reported menstruation. No female participants were using oral contraceptives.

7.2.2 Familiarisation

Prior to any experimental session, participants were required to undergo a familiarisation session lasting 30 min. During this time, the tasks were explained in full, and participants practiced all cognitive tasks until both the participant and experimenters were satisfied that any further learning effects were minimal.

7.2.3 Experimental Session

7.2.3.1 Pre-heating

Upon arrival in the laboratory participants provided a urine sample and privately inserted a rectal thermometer (Hinco Instruments, Australia) ~12 cm beyond the anal sphincter. Participants were then immersed in 40°C water until their rectal temperature reached 38.5°C (in HOT and MENT) or, in 36°C in CON for a similar length of time. At the onset of heating participants completed a simple reaction time task (Reaction Time Tests for Science, Andrew Novak, 2016) requiring a response when a red circle appeared but avoiding responding to blue and black circles. The test was used to provide a baseline of cognition to be compared between sessions. During the pre-heating, perceptual measures of thermal discomfort (1-10) (Bedford, 1936), thermal sensation (1-13) (ISO, 1994), feeling (-5 - +5) (Hardy et al., 1989) and sleepiness (1-9) (Hoddes, 1972) were recorded alongside heart rate at 37.5°C, 38.0°C and 38.5°C, or at corresponding times during the control phase. The length of the CON session was determined by the time each individual’s rectal temperature took to reach 38.5°C in preceding trials, or in the event of the CON session occurring first, based on a rate of increase of 0.4°C per 10 min established *a-priori* during pilot trials.

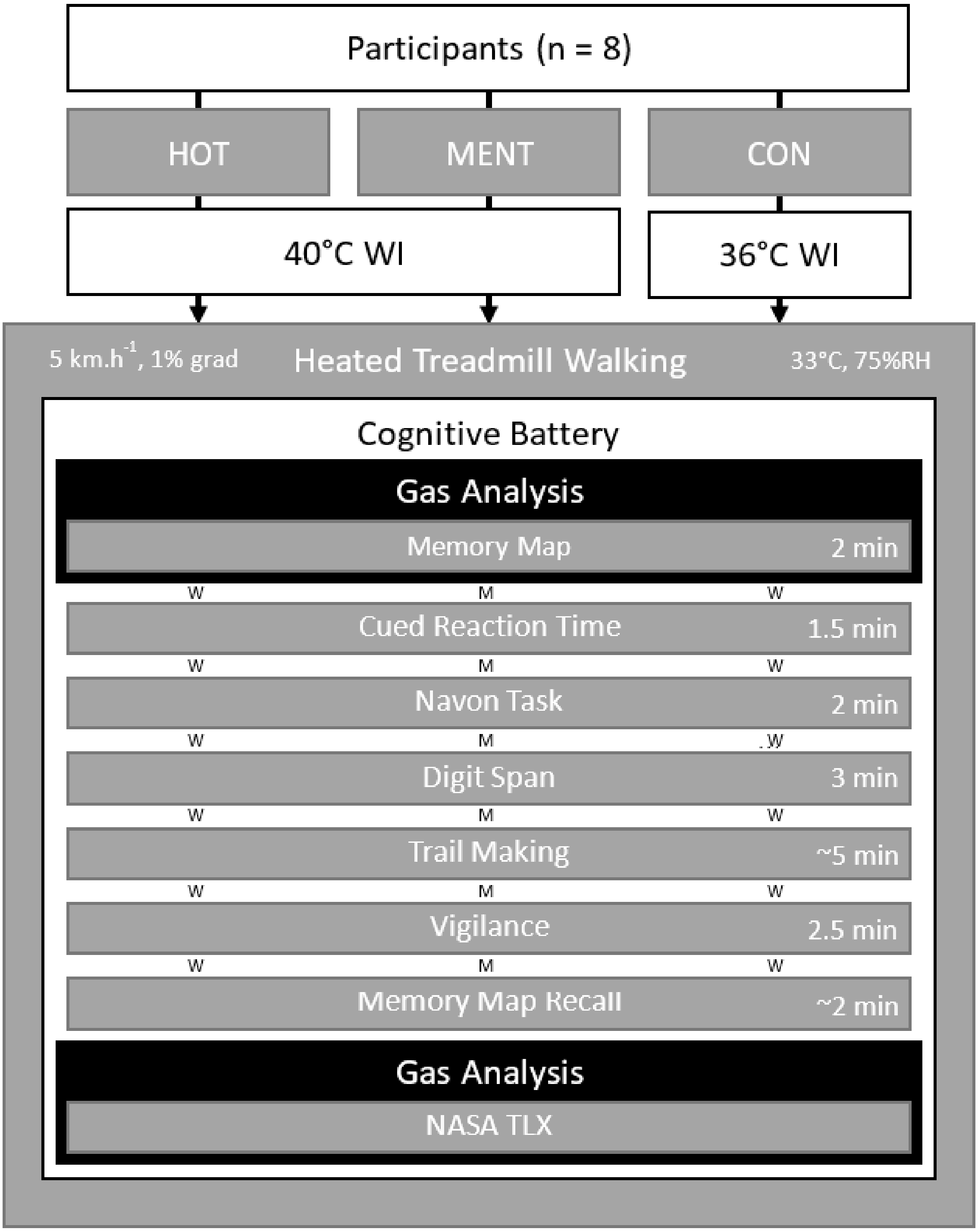

Figure 7-1. Schematic representation of the experimental design. In each experimental condition participants were initially immersed in water (WI), either heated to 40°C or 36°C. Following this they walked in the heat while completing a cognitive testing battery. Following each task participants were prescribed a mouth-rinse of either water (W) or menthol (M) during a ~1 min interlude.

7.2.3.2 Transition to exercise in heat

When rectal temperature reached 38.5°C, or a similar time had passed in CON, participants exited the water and immediately dried off. This 38.5°C temperature was used as the onset for walking because it has been shown to impair cognitive function (Schmit et al., 2017), and it allowed core temperature to continue rising but not exceeding the ethical limit of 39.5°C before completing the protocol. Skin temperature sensors were then attached to the participant's chest, bicep, thigh, and calf before they donned military clothing (long-sleeved shirt and trousers) and their own shoes. Participants were then escorted to the laboratory and weighed before entering the heat chamber (Design Environmental, Simultech Australia, Australia) set to 33°C and 75% relative humidity. A weighted body armour vest (20 kg) was worn over the military clothing and a near-infrared spectroscopy (NIRS) sensor was placed onto the forehead (see below). Participants were then instructed to walk on a motorised treadmill (Platinum Club Series, Life Fitness, Illinois, USA) for 30 min at 5 km.h^{-1} and 1% gradient. Expired gas was collected during the first 4 min and final 3 min of the walk using a calibrated metabolic system (TrueOne 2400, Parvo Medics, Utah, USA).

7.2.3.3 Menthol Supplementation

Prior to each task participants were given a 25 mL mouth-rinse with either water (in CON and HOT) or 0.1% concentration (Best et al., 2018) menthol (Pure Nature, Auckland, NZ) in MENT. Total fluid volume was 150 mL in each condition (Fig. 7-1). Participants were instructed to swill the solution for 5 s, before spitting it into a bowl. The menthol solution was prepared by mixing menthol with distilled water at a 1:999 ratio, heating it to 50°C and stirring for 2 h before storing at room temperature.

7.2.3.4 Cognitive Testing

Cognitive tasks were randomised for each participant using either in-built randomisation for computer tasks, or Latin squares for paper-based tasks.

7.2.3.4.1 Declarative Memory

The memory task involved participants being asked to memorise a fictional map of an urban environment. The map detailed a prescribed route through several streets to reach a target house. The list of questions that would later be asked was provided alongside the map to minimise learning effects. Participants were given 2 min to study the map before it was removed. Then, 25 min later, the questions were read aloud, and participants asked to correctly answer as many as possible, up to a maximal score of 22.

7.2.3.4.2 Reaction Time (go/no-go)

A cued reaction time task was presented to assess go/no-go reaction time (Posner et al., 1984). A box was presented on each side of the screen with a focal point in the middle. Participants were asked to focus on the focal point and respond to a 'GO' signal presented in one of the boxes, by tapping the left, or right, key. Immediately prior to the 'GO' signal appearing a cross appeared in one of the boxes, cueing the response. The cue was in the same box as the 'GO' signal 75% of the time. Forty trials were run, allowing calculation of reaction times for both cued, and uncued stimuli, as well as accuracy rates.

7.2.3.4.3 Perceptual Processing

The Navon task was used to evaluate perceptual processing (Navon, 1977). Large letters, constructed from repeated smaller letters, were presented one at a time on the screen in front of participants. Participants then had to determine whether the letter 'H' or 'O' was present in the image by responding yes or no on a keyboard. Forty images were presented, from which reaction times and correct response rates were calculated when the stimuli were global, local, and when none was present.

7.2.3.4.4 Working Memory

Digit span was used to assess working memory (Conklin et al., 2018). A series of numbers was read out and participants asked to recall them in the reverse order to that in which they were read (i.e., 123 becomes 321). Spans started at 3 digits long and progressed after a correct response. After three incorrect responses at a single level the test was stopped. The last successful span, and the first span on which an error was made were recorded.

7.2.3.4.5 Executive Function and Cognitive Flexibility

A trail making task was used to assess executive function (Arbuthnott et al., 2000). For task A, participants were given a sheet with numbers 1-25 inside their own circles randomly scattered across the page. The numbers then had to be connected using a pencil, in order and as quickly as possible without passing through other circles. Following this task, participants were presented a similar task (task B) with numbers 1-13 and letters A-L. In this task, participants had to switch sets, alternating between numerical and alphabetical (i.e., 1A2B3C). For both tasks, time to completion was recorded, as well as errors of the numbering order, and errors going through other circles.

7.2.3.4.6 Vigilance

The Mackworth clock task was used to assess vigilance (Giambra et al., 2013; Mackworth, 1948). Participants monitored a clock hand ticking around the screen. When the clock hand skipped a second participants responded by pressing a button on the keyboard. Correct and incorrect reaction times, as well as percentage of correct responses were recorded.

7.2.3.4.7 NASA Task-Load Index

Following the recall of the memory items participants were connected to the gas analysis for a further 3 min. During this time, they were presented with a NASA task-load index (TLX) to complete, giving information on the mental, temporal, physical demands and well as performance, effort, and frustration.

7.2.3.5 Physiological and Perceptual Measures

Heart rate (Platinum Club Series, Life Fitness, Illinois, USA) and perceptual measures of thermal discomfort, thermal sensation, feeling, sleepiness and rating of perceived exertion (RPE: 15-point scale ranging 6-20) (Borg, 1982) were recorded at 5, 15 and 30 min into the walk. Following the walk a second urine sample was taken and both pre- and post-test samples were analysed for urine specific gravity (USG) using a urine refractometer (Atago, Japan) to provide hydration measures.

Rectal and skin temperatures were recorded at 1 Hz (SQ2020, Grant Instruments, Cambridge, UK). In preparation for analysis, rectal and skin temperature readings were filtered due to noise caused by connections with the logger and occasional skin temperature probes losing contact with the skin due to the humid microenvironment. A filter was applied to remove all readings that changed by more than 0.1°C.s^{-1}. Then a low-pass Butterworth filter of 0.02 Hz was applied to the data. Missing data were filled with linear interpolation. Mean skin temperature was calculated using the following formula (Ramanathan, 1964):

$$T_{Skin} = 0.3T_{Chest} + 0.3T_{Bicep} + 0.2T_{Thigh} + 0.2T_{Calf} \qquad \text{Equation 7-1}$$

If a thermistor became askew or off the skin, the equation was modified to compensate the weights of the three remaining sensors proportionally to maintain the summation of coefficients to 1.0 (i.e., $\mathrm{T_{Sk}} = 0.375\mathrm{T_{Chest}} + 0.375\mathrm{T_{Bicep}} + 0.25\mathrm{T_{Thigh}}$ if the calf reading was lost). If two sensors produced no signal, no temperature was calculated. Averages over 5-min periods were used for analysis, with the relative difference between each analysis point and the prior analysis point used to determine the direction and magnitude of change in rectal temperature.

7.2.3.5.1 Near-infrared Spectroscopy Analysis

NIRS was used as a practical method of collecting cerebral adjustments within an ambulatory setting (Boone et al., 2015). NIRS allows measurement of oxygenated and deoxygenated haemoglobin within the cerebral tissue of the frontal lobe. A NIRS sensor was placed ~1 cm above the eyebrow and held in place by an opaque headband that prevented light interference throughout the walk in the heat chamber. Data were logged by an oximeter at 2 Hz (OxiplexTS, ISS, Champaign, IL). A Butterworth filter of 0.01 Hz was applied to all data to remove noise, mostly from movement artefact. Data were then standardised to the initial 5 min of cognitive testing to provide a baseline, allowing subsequent calculation of baseline-adjusted data points every 5 min, using the accumulative average of the prior 5 min. The estimated oxygenation difference was calculated as the baseline-adjusted difference between oxygenated haemoglobin and deoxygenated haemoglobin.

7.2.4 Statistical Analysis

All analyses were conducted in R version 3.6.1 (R foundation for Statistical Computing, Vienna, Austria). For all variables a mixed model was used from the lmer package (Bates et al., 2014), with session (chronological session number) and condition as fixed effects, with participant as the random effect. Planned pairwise comparisons were then carried out on the mixed model using the emmeans package with condition as the defining variable. Each mixed model was checked for homoscedasticity using Q-Q plots. All values are reported as the model's estimated mean ± standard deviation.

It has been suggested that the direction of core temperature movement has a greater role than the absolute core temperature during cognitive tasks (Allan et al., 1979a; Allan et al., 1979b). Therefore, *a-posteriori* analyses were carried out to investigate the relationship between the direction of change in rectal temperature and cognitive performance. This involved re-running the analysis, for only the observations when rectal temperature was higher than it had been at the previous time point. A second *a-posteriori* analysis used the same method but only if the rate of rise in rectal temperature was >0.5°C.h^{-1}.

7.3 Results

7.3.1 Pre-Heating

Duration immersed at the start of each session averaged 36.6 ± 5.7 min and was not different between conditions (all p > .523). Rectal temperature was not different at baseline between conditions (all p > .481) and increased in HOT and MENT (both p < .001) but not in CON (p = .911). Perceptions of thermal sensation, thermal discomfort and feeling deteriorated in HOT and MENT compared to CON (all p < .001). There were no differences between MENT and HOT (all p > .264) other than sleepiness being 1.0 ± 0.8 AU higher in MENT (p = .002), which was also elevated 1.3 ± 0.8 AU compared to CON (p < .001). Heart rate was 31 ± 13 bpm higher in HOT and MENT (p < .001), than CON, with no differences between HOT and MENT (p = .776). Fluid consumption was 0.3 ± 0.1 L higher in HOT and MENT (HOT: 0.5 ± 0.3 L; MENT: 0.5 ± 0.2 L; HOT vs MENT: p = .969) than in CON (CON: 0.2 ± 0.3 L, both p < .001) but this did not affect hydration status (all p > .552). Baseline cognition was similar between conditions (all p > .827).

7.3.2 Cognitive Results

No differences were detected in cognitive performance between conditions for any task (Table 7-1). Towards the end of the trial there was a tendency towards a difference in cognitive performance between HOT and CON conditions (Table 7-1) in vigilance false starts (p = .056), vigilance percent correct (p = .087), and declarative memory (p = .116).

Table 7-1. Cognitive performance while walking on a treadmill whilst wearing military dress in the heat (33°C, 75% RH) while either normothermic (CON), hyperthermic (HOT) or hyperthermic with the aid of a menthol mouth-rinse (MENT). *p* values display the results when comparing between all conditions from pairwise comparisons. Results displayed as estimated mean ± SD.

Task	CON	HOT	MENT	*p* value
Reaction Time (go/no-go)				
Cued RT (ms)	321 ± 52	311 ± 32	305 ± 43	>.486
Uncued RT (ms)	374 ± 61	361 ± 51	369 ± 62	>.999
Correct (%)	96 ± 4	95 ± 6	96 ± 4	>.999
Perceptual Processing				
Global RT (ms)	731 ± 129	688 ± 116	721 ± 144	>.482
Local RT (ms)	716 ± 156	714 ± 171	692 ± 126	>.999
None RT (ms)	802 ± 224	724 ± 113	778 ± 186	>.399
Correct (%)	96 ± 4	92 ± 5	93 ± 7	>.716
Working Memory				
Digit Span 1st Error (level)	7.3 ± 1.2	6.9 ± 1.2	6.8 ± 1.0	>.999
Maximum Span (level)	7.3 ± 1.0	6.8 ± 0.7	7.3 ± 0.7	>.316
Executive Function				
Trail-Making A (min)	1.1 ± 0.3	1.1 ± 0.5	1.1 ± 0.2	>.999
Trail-Making B (min)	1.2 ± 0.5	1.2 ± 0.7	1.2 ± 0.4	>.999
Trail-Making Errors	2.6 ± 3.5	5.4 ± 7.3	2.1 ± 2.6	>.445
Vigilance				
False Starts	1.5 ± 1.2	4.2 ± 3.0	2.6 ± 2.6	>.056
Correct RT (ms)	491 ± 43	521 ± 59	496 ± 50	>.672
Correct (%)	79 ± 8	68 ± 16	78 ± 14	>.087
Memory				
Correct Responses	14.4 ± 1.9	8.3 ± 4.9	12.6 ± 3.7	>.116

7.3.3 Physiological Responses during exercise in the heat

In relation to cognitive task performance, rectal temperature was increasing in 50% of trials during the memory task presentation (12/24), 63% during the cued reaction time task (15/24), 79% during the Navon task (19/24), and > 95% in the tasks that followed (>23/24). The slope of rectal temperature was ~1°C.h^{-1} steeper during CON (CON: 1.3 ± 0.4°C.h^{-1}) compared to HOT or MENT (HOT: 0.3 ± 0.7°C.h^{-1}; MENT: 0.3 ± 0.4°C.h^{-1}; CON vs HOT: $p < .001$; CON vs MENT: $p < .001$; MENT vs HOT: $p = .946$), but attained only 37.9°C by completion of exercise.

There were no differences between conditions in $\dot{V}O_2$ (CON: 16.3 ± 1.1 mL.kg^{-1}.min^{-1}; HOT: 16.2 ± 1.4 mL.kg^{-1}.min^{-1}; MENT: 16.1 ± 1.7 mL.kg^{-1}.min^{-1}; all $p = 1.000$), $\dot{V}CO_2$ (CON: 1.01 ± 0.16 L.min^{-}

[1]; HOT: 0.98 ± 0.25 L.min^{-1}; MENT: 0.97 ± 0.23 L.min^{-1}; all p > .517) and RER (CON: 0.88 ± 0.05; HOT: 0.85 ± 0.06; MENT: 0.85 ± 0.07; all p > .214).

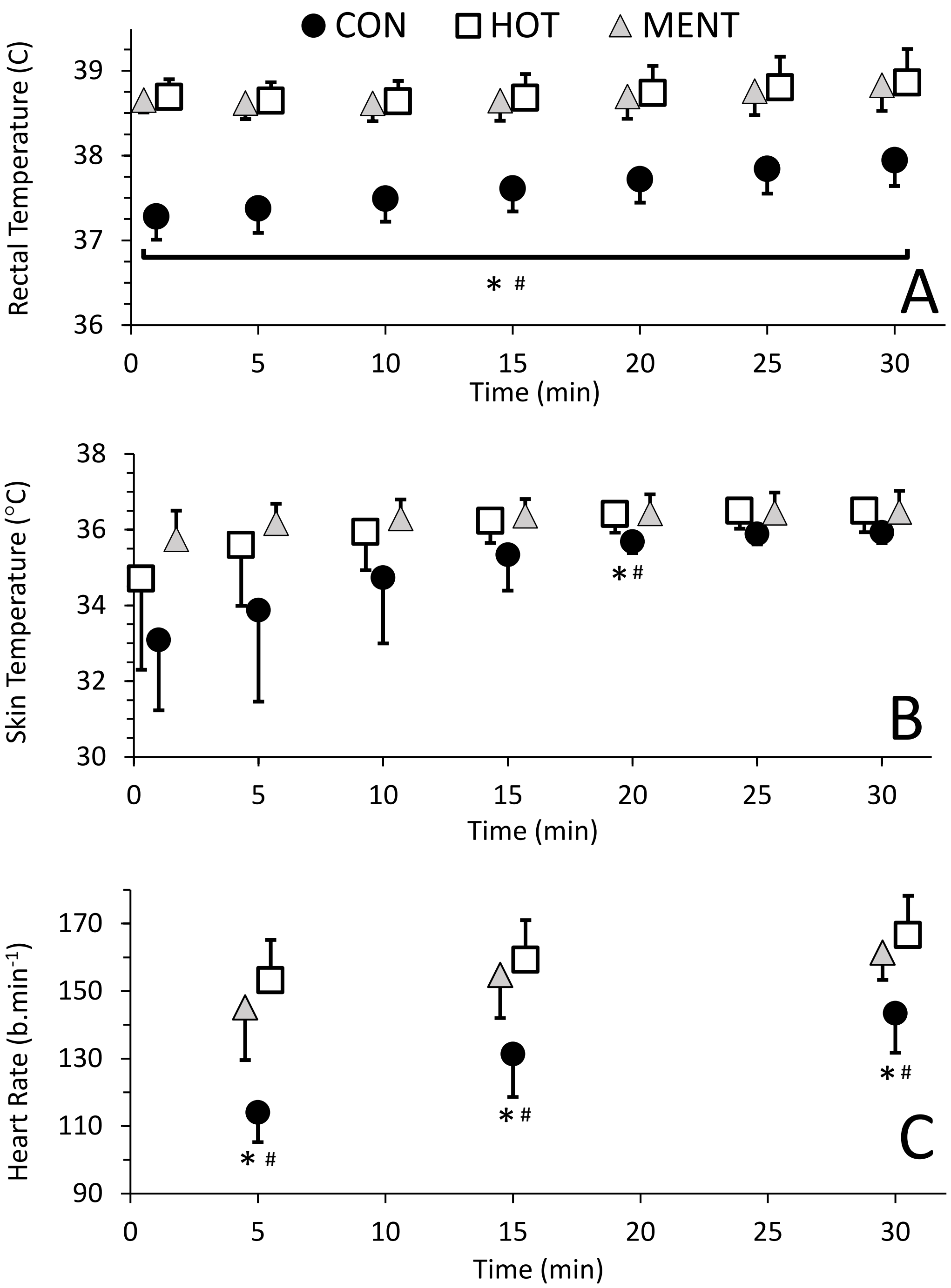

Figure 7-2. Physiological measures during cognitive testing while walking in military dress in the heat (33°C, 75% RH) while either normothermic (CON), hyperthermic (HOT) or hyperthermic with the aid of a menthol mouth-rinse (MENT). Measures of rectal temperature (A), skin temperature (B), and heart rate (C) were all obtained throughout the trial. Data are reported as mean ± SD. MENT and HOT results are offset along the time axis for clarity. * indicates p < .05 between CON and HOT. #indicates p <.05 between CON and MENT.

7.3.4 Perceptual Responses

Thermal discomfort, feeling, sleepiness and rating of perceived exertion all deteriorated in HOT and MENT compared to CON (all p > .001), with no differences between MENT and HOT (all p > .174) (Fig. 7-3). Thermal sensation, however, was 2 ± 1 AU greater in the HOT than the CON condition (CON: 8.8 ± 1.4; HOT: 10.8 ± 1.3; MENT: 9.8 ± 1.8; CON vs HOT: p = .001; CON vs MENT: p = .111; MENT vs HOT: p = .111). No differences were seen between conditions in any aspect of the NASA task-load index (all p > .191).

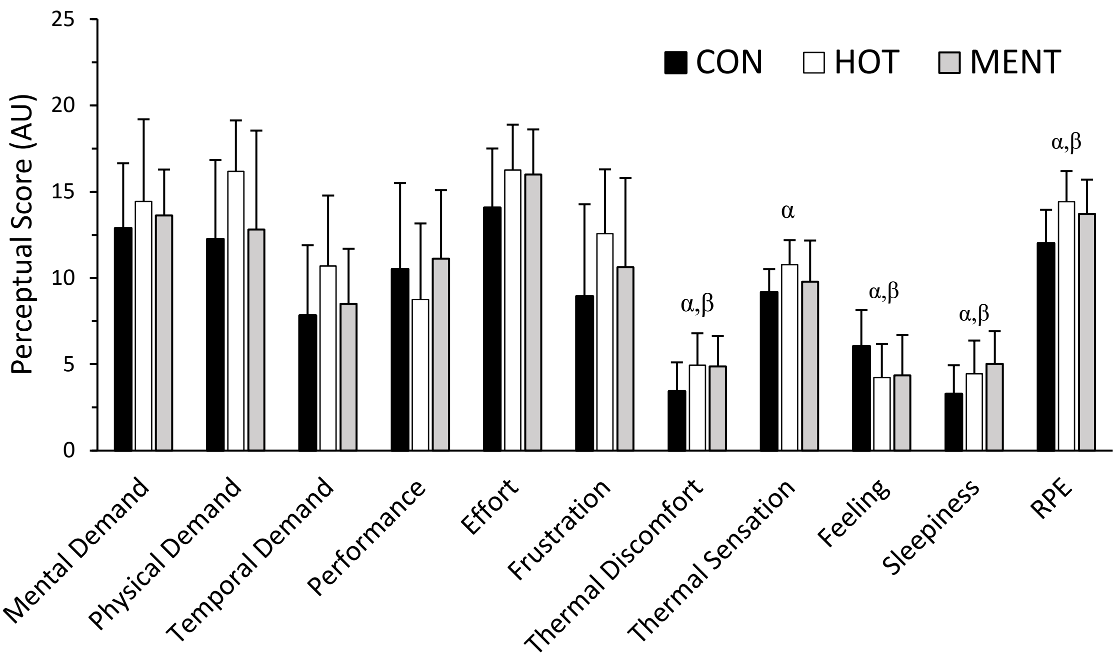

Figure 7-3. Perceptual responses to cognitive tasks during a 30-min military-dressed heated treadmill walk in humid heat (33°C, 75% RH) while either normothermic (CON), hyperthermic (HOT) or hyperthermic with the aid of a menthol mouth-rinse (MENT). Perceptions consist of the NASA Task-Load Index for cognitive tasks, as well as common heat-related perceptions. Feeling is normalised to a positive scale. $^{\alpha}$indicates p < .05 between CON and HOT, $^{\beta}$indicates p < .05 between CON and MENT, no differences were observed between MENT and HOT.

7.3.5 Near-Infrared Spectroscopy

There was a greater increase in oxygenated haemoglobin of 2.0 ± 4.2 µM in HOT and 2.5 ± 4.3 µM in MENT compared to the CON trial (CON: 0.3 ± 3.7 µM; HOT: 2.3 ± 4.8 µM; MENT: 2.8 ± 5.0 µM; CON vs HOT: p = .024; CON vs MENT: p = .009; HOT vs MENT: p = .510). Deoxygenated haemoglobin was 0.7 ± 1.1 µM lower in the MENT trial than CON and 0.6 ± 1.3 lower than HOT (CON: 0.4 ± 1.2 µM; HOT: 0.3 ± 1.5 µM; MENT: -0.3 ± 1.1 µM; CON vs HOT: p = .823; CON vs

MENT: p = .017, HOT vs MENT: p = .017). However, estimated oxygenation difference (oxygenated – deoxygenated haemoglobin) increased 2.1 ± 3.7 µM and 2.6 ± 4.1 µM over the HOT and MENT trials compared to the CON trial (CON: -0.1 ± 3.3 µM; HOT: 2.0 ± 4.1 µM; MENT: 2.5 ± 4.9 µM; CON vs HOT: p = .025; CON vs MENT: p = .006; HOT vs MENT: p = .481) (Fig. 7-4), although no differences were evident for any individual time point (all p > .104).

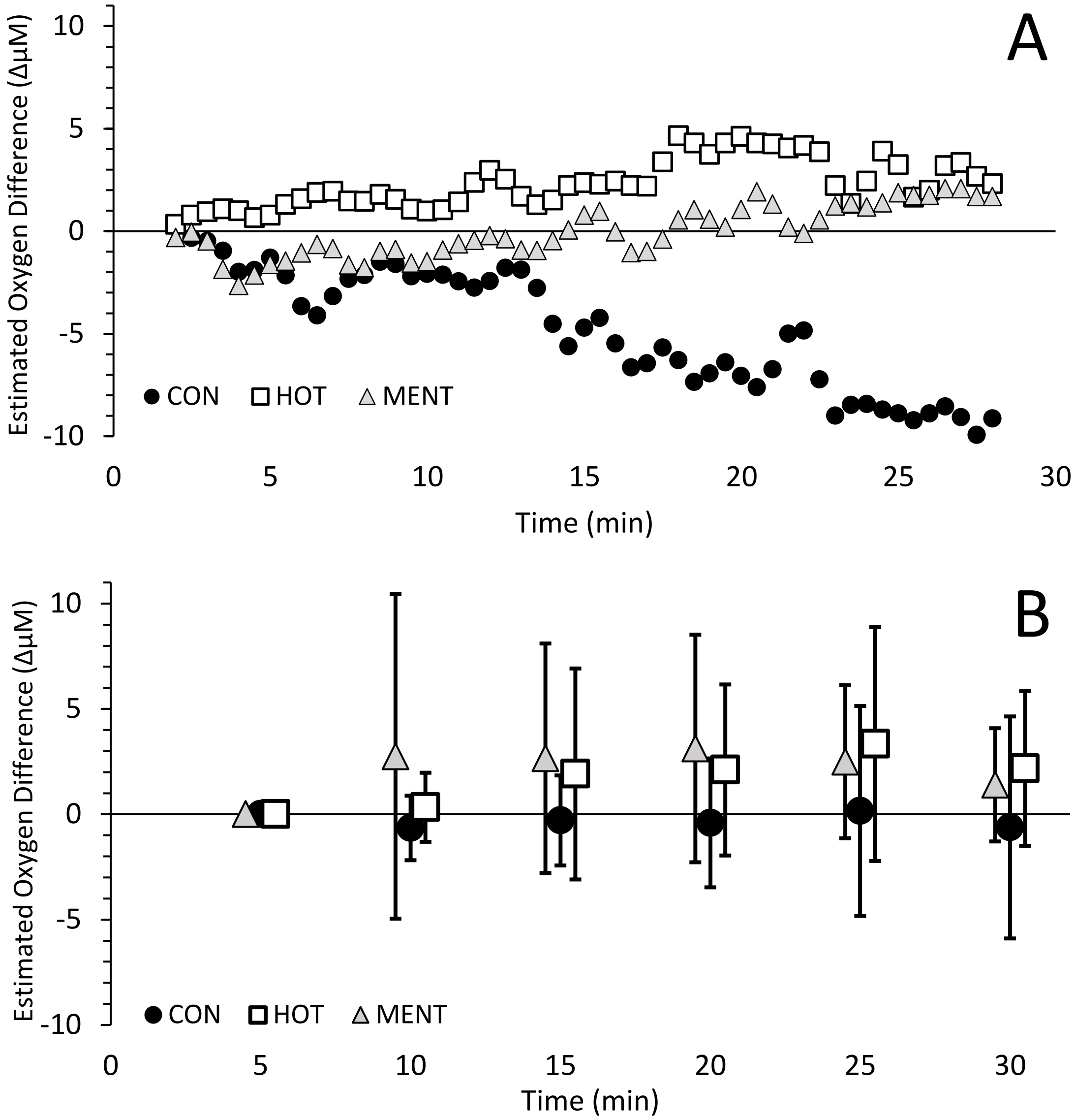

Figure 7-4. Estimated oxygen difference in cerebral tissue, calculated using baseline-adjusted cerebral tissue oxygenated and deoxygenated haemoglobin measured from the forehead using near-infrared spectroscopy. Both an individual subjects data (A) and the group means (B) are displayed over the course of the trial. Readings were obtained while completing a battery of cognitive tasks during a 30-min heated (33°C, 75% RH) walk (5 km.h^{-1}) while either normothermic (CON), hyperthermic (HOT) or hyperthermic with the aid of a menthol mouth-rinse (MENT). *indicates p < .05 between CON and both HOT and MENT.

7.3.6 Theory of rising core temperature

Due to methodological limitations providing the potential for participants to cool down during transition between the pre-heating facility and the heat chamber, there were occasions during the test where rectal temperature was declining. When tasks were re-analysed, excluding tasks completed while rectal temperature was declining, there remained no significance differences between conditions for any cognitive test. Furthermore, when re-analysed using only participants whose rectal temperature was rising at a rate of 0.5°C.h^{-1} or more, again no changes in significance were observed between conditions in the cognitive performance.

7.4 Discussion

The primary aim of this study was to determine whether heat-related impairments in cognitive function were a product of core temperature, and secondly to determine whether a menthol mouth-rinse could mitigate any potential performance decline. The main findings indicate no measurable effect of moderately elevated core temperature on cognitive performance in a range of cognitive demands during exercise in the heat, therefore there was also no demonstrable beneficial effect of menthol mouth-rinse as a cooling strategy.

To our knowledge, this is the first study to report the independent effects of core temperature on cognitive performance during exercise in a heated environment. Despite ensuring tests were conducted at a core temperature previously shown to impair elements of cognition, which induced greater physiological and heat-related perceptual strain in HOT and MENT compared to CON, no differences in cognitive performance were observed (Table 7-1, Fig. 7-3). The lack of relationship between core temperature and cognitive performance has previously been suggested (Taylor et al., 2016), but not tested. Therefore, it is likely that in field settings, other factors play a greater role in impairing cognition. Indeed, Hocking et al. (2001) used a similar experimental design, and found that preheating participants by having them walk in the heat (40 min at 5 km.h^{-1} in 35°C, 65% RH) led to minimal changes in cognition. However, unlike the present study, Hocking et al. (2001) observed differences in working memory using the same digit span task. While the impaired cognition was linked to higher core temperature in their study, the lack of such a finding in the current study (Table 7-1) indicates that fatigue or thermal discomfort from the exercise pre-heating method used by Hocking et al. (2001) may have played a larger role. Minimal changes were also observed by Caldwell et al. (2011) during walking in the heat between a group wearing military uniform compared to a control group. The relatively low core temperatures reached (max ~38.3°C) may have limited the effects of heat on cognition, with it hypothesised that more stressful conditions might impair cognitive performance (Caldwell et al., 2011). However, in the current study, mean maximal rectal temperatures of 38.9°C also resulted in no effects on cognitive performance (Table 7-1), in line with another study that induced a similarly elevated core temperature using exercise in a hot environment (Caldwell et al., 2012). The core temperature at testing onset was based on when cognitive performance begins to decline (Schmit et al., 2017), with an expectation that core temperature would rise throughout the military march. Furthermore, the temperature at the start of exercise was chosen to prevent rectal temperature exceeding an ethical limit of 39.5°C, as temperatures exceeding 40°C can risk heat stroke (Goforth et al., 2015).

While the selected threshold of 38.5°C may have been too low to compromise cognitive performance, it appears to have influenced cerebral function. In both hyperthermic conditions the estimated oxygenation difference increased. The increased cerebral oxygen requirement suggests the brain required additional resources to preserve cognitive performance, consistent with increases in cerebral oxygen extraction fraction previously seen during hyperthermic exercise (Rasmussen et al., 2010) alongside increased cerebral metabolic rate for oxygen (González-Alonso et al., 2004; Rasmussen et al., 2010). Hocking et al. (2001) also showed alterations at the level of the brain to occur as a function of core temperature rather than ambient temperature. Using electroencephalography, it was shown for several tasks that there were transient increases in amplitude and decreases in latency when measuring steady state visual evoked potentials in relevant areas of the brain (Hocking et al., 2001). Furthermore, studies using functional magnetic resonance imaging have shown executive function to be impaired under passive hyperthermia, and that brain activity is altered to support task performance, despite no changes occurring in the performance itself (Liu et al., 2013). Functional magnetic resonance imaging has also shown head cooling to mitigate negative effects of hyperthermia in some brain regions, including changes to entire functional networks (Xue et al., 2018). In the current study the perceptual cooling used in MENT caused a reduction in deoxygenated haemoglobin, but this did not cause a difference in estimated oxygenation difference compared to that seen in HOT (Fig. 7-4). Although this implies menthol may alter the mechanisms by which cognitive activity is affected in the heat, no perceptual differences were seen between MENT and HOT. Therefore, it remains unclear whether menthol may have any effect on cognitive performance, and cognitive activity, in a more stressful paradigm.

Although heat strain may have been insufficient to impair cognitive performance in the present study, an alternative theory suggests that the direction of change in core temperature is a more important factor in determining cognitive strain (Allan et al., 1979a; Allan et al., 1979b). Acknowledging this theory, we analysed only tasks completed while rectal temperature was rising and found no cognitive differences. One confounding factor that may have influenced this was that although rectal temperature was increasing in each condition, the rate of increase was far greater in CON. However, when only tasks that had a rate of rise in rectal temperature of 0.5°C.h^{-1} or more were analysed, no differences were observed. Whether the rate of rise in CON had the same effect as a higher absolute temperature in HOT and MENT cannot be discerned from the current data. To gain mechanistic insights as to how core temperature influences cognitive, and indeed physiological function, future studies should investigate the influence of the rate of rise in core temperature on cognition at different absolute temperatures.

7.5 Conclusion

In summary, no relationship was evident between core temperature and cognitive performance, which indicates that cognitive impairments reported during operations in such climates may be independent of moderately elevated core temperatures. Therefore, the use of heat mitigation strategies and devices are unlikely to improve cognition in hot environments. However, heat is known to accelerate the onset of fatigue and therefore how these factors interact with cognition likely requires further exploration. In the presence of thermal and exertional stresses, increases in the estimated oxygenation difference across the frontal lobe suggest an increased cerebral oxygen metabolism, which may be the underlying mechanism by which the brain adjusts to preserve cognitive performance.

Chapter 8 Discussion and Practical Application

8.1 Summary of Findings

This experimental thesis attempted to develop practical solutions to the unique military paradigm of rapid deployment into hot environments. At the beginning of this thesis, it was noted that current advice and recommendations for performing in hot environments provided minimal options for military units deploying at short notice. Thereafter the experimental body of work attempted to provide solutions to this unique military paradigm, which was achieved in Chapter 6, with intermittent heat exposure (IHE) following an initial HA period providing a means by which baseline thermal tolerance could be elevated and then maintained, with minimal disruptions to other training objectives, thereby helping to mitigate the effects of heat on physical performance upon arrival in theatre. Therefore, the following sections will discuss firstly how strategies outlined in this thesis impact physical performance and the physiological parameters that facilitate these changes, and secondly how these strategies influence cognitive performance and the mechanistical underpinnings of cognition in these environments.

8.2 Physical Performance

The key findings from this thesis in relation to physical performance were:

- Given the uncontrollable nature of military operations, having strategies that induce thermal adaptations prior to deployment are likely more practical and beneficial than strategies that need to be relied upon in the environment (Chapter 2)
- Military operations in a humid environment place greater physiological strain on soldiers (Chapter 3)
- Change in perceptions of heat provide a strong predictor of physical performance termination (Chapter 3)
- Sauna and HWI provide comparable modes of passive, post-exercise HA (Chapter 4)
- Sauna and HWI can provide beneficial adaptations in 5 d that lead to improved thermal tolerance and safety when operating in the heat in a military context (Chapter 4)
- IHE using sauna and HWI can maintain thermal tolerance for at least 18 d in a military context (Chapter 6)
- IHE following short-term, passive, post-exercise HA may enhance adaptations to levels typically seen following longer HA protocols (Chapter 6)

While studies and reviews have assessed the determinants of endurance performance in the heat in athletes (James et al., 2017b; Tyler et al., 2016), military specific factors, particularly load carriage and protective equipment, make it hard to directly extrapolate these findings to a military cohort (Parsons et al., 2019). Although military studies that have investigated heated pack marches exist, they are largely used as HSTs to evaluate an intervention (Aoyagi et al., 1995; DeMaio, 2009; Selkirk et al., 2008), or to assess heat tolerance ahead of returning to duty (Druyan et al., 2013; Epstein et al., 2017; Moran et al., 2007). Hence, the purpose of the first study of this thesis was to gain a better understanding of the physiological variables that relate to fixed-intensity pack march performance in both humid and arid environments (Chapter 3). Military volunteers for the study were equipped according to NZDF recommendations for each environment, allowing assessment of the operational scenarios, rather than simply the ambient conditions. While performance was similar in both conditions, the underlying physiology differed between environments. Rectal temperature and heart rate were both higher in the humid environment (Table 3-1, Fig. 3-4), likely due to additional endogenous heat production, but also impaired sweat evaporation impairing cooling mechanisms (Table 3-1). Indeed, each of these factors had moderate to strong negative relationship with performance in each environment (Table 3-2, Fig. 3-6). In the arid environment perceptions were more tightly related to performance than in the humid environment, despite not being statistically different, perhaps due to the higher relative skin temperature (Flouris et al., 2015; Schlader et al., 2011) which had a moderately strong relationship with performance (Fig. 3-6). By uncovering this information, it provided a platform to develop coping strategies in subsequent chapters by targeting areas that limit performance, specifically, the benefits of an elevated sweat rate, which in more restrictive clothing may have minimally facilitated cooling, and simply added to dehydration. Furthermore, while verbal monitoring of individuals during operations is commonplace (Parsons et al., 2019), the results found a lack of relationship between RPE and performance (Table 3-2). Instead, thermal sensation and sleepiness proved a much better predictor of exercise termination, suggesting that questions regarding these aspects should be used when monitoring individuals. As the humid environment posed the greatest threat to safety, with rectal temperature predicted to reach critical values after only 95 min of walking (Fig. 3-4), as well as being more frequently experienced by NZDF personnel, it was chosen to be targeted in subsequent studies.

In designing subsequent studies, facilities were considered that could either be accessed or installed on military bases, to invoke heat adaptations that would improve safety and performance in a military context. Most HA studies to date have used long-duration acclimation sessions in artificially heated environments (i.e., a climate chamber) that replace other training sessions. However, military units are unlikely to sacrifice other training sessions as aerobic fitness, strength, weapons, and tactical training are all equally critical to mission success. Recent research in post-exercise, has highlighted passive HA as an efficient method as it enables training sessions to be integrated with heat exposure, without requiring access to climate chambers (Casadio et al., 2017; Casadio et al., 2016; Heathcote et al., 2018; Zurawlew et al., 2016). Indeed, the use of both sauna and HWI after exercise have previously yielded reductions in rectal temperature and heart rate, showing potential to improve safety, as well as improving performance (Brazaitis et al., 2010; Scoon et al., 2007; Zurawlew et al., 2016). Whether these benefits would translate to the military paradigm was uncertain, as was whether different heat adaptations could be invoked by the different heating modalities. Accordingly, a short-term 5 d HA intervention was chosen due to its minimal hindrance to other training objectives. It was anticipated that this timeframe would be sufficient to initiate adaptive pathways (Tyler et al., 2016), thereby minimising the time to adjust to the new climate by providing an elevated baseline from which to adapt from. Beneficial adaptations were induced by both sauna and HWI, with a reduced rectal temperature and heart rate observed alongside improved perceptual responses (Fig. 4-4, Table 4-1). The reduction in rectal temperature was likely aided by a heightened sweat rate that increased evaporative heat loss, resulting in a lower slope of the rise in rectal temperature (Table 4-1). While normally interpreted in relation to performance (Hargreaves, 2008), when core temperature is treated as a safety measure to prevent heat illness it amplifies the importance and relevance of these findings. Indeed, when the results of the sauna and HWI HA protocols are amalgamated the reduction in rectal temperature, alongside the reduced rate of rise in rectal temperature, is calculated to result in an additional 21 min of exercise at this fixed intensity before reaching a critical threshold of 40°C; a 16% increase in time to exhaustion (Fig. 4-4).

Comparing the rate of rise in rectal temperature between the studies in this thesis is difficult due to the higher workload caused by the heavier pack in Chapter 3. However, it was estimated that the benefits of a 0.2°C reduction in rectal temperature observed in Chapter 4 would translate into a 6% increase in time to exhaustion when using the graph-predicted rectal temperature slope (Fig. 8-1). If, in addition to the reduction in resting rectal temperature seen in Chapter 4, the rate of rise in rectal temperature were to change as in Chapter 4 then the time to exhaustion would increase by 15% (Fig. 8-1). While studies make limited reference to core temperature safety limits, likely due to investigations primarily occurring in athletes where performance is the major outcome, they have previously been looked at in military studies. McLellan and Aoyagi (McLellan et al., 1996) conducted a 12 d HA period of controlled hyperthermia, set to induce an increase in core temperature of 1.3°C while walking for 60 min at 45-55% $\dot{V}O_2$max in 40°C, 30% RH, while wearing either nuclear, biological, and chemical protective (NBC) suits or a shirt and shorts. Participants were assessed for thermal tolerance by intermittently walking (15 min exercise, 15 min rest) to exhaustion in 40°C 30%RH at 4.8 km.h^{-1} while wearing NBC suits. Following HA, the time for core temperature to elevate by 1.5°C increased 23% in the NBC suit protocol, and 12% in the shirt and shorts protocol. To this end passive, post-exercise heating was able to induce a similar protective effect on core temperature, helping mitigate the risk of heat illnesses, to 12 d of walking in the heat. The protocol used in Chapter 4 achieves comparable results while requiring ~50% less training time, and ~20% less direct heat exposure, highlighting its practicality and efficiency for use in this population.

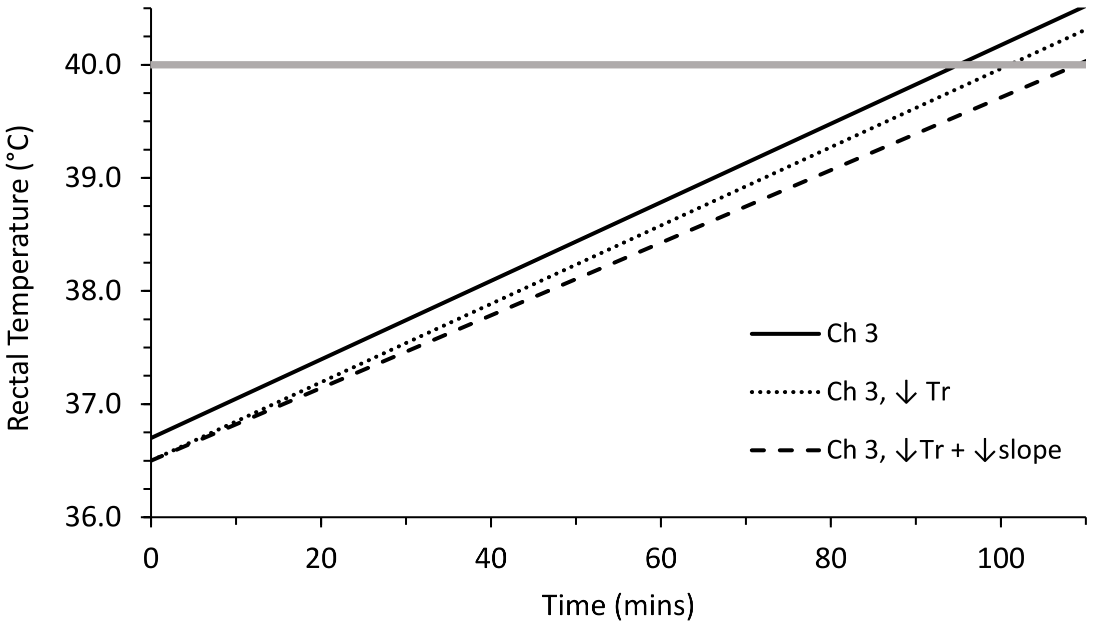

Figure 8-1. Rectal temperature response in military personnel operating in a humid environment, and how the heat acclimation strategies in Chapter 4 may affect the rectal temperature response. Both the reduction in rectal temperature (Tr), and the reduction in rectal temperature and slope of rectal temperature gain (Tr + slope), from Chapter 4 are fitted to the original results from Chapter 3, providing estimated increases of 6% and 15% in predicted time to reach 40°C.

Safety was also improved through the reduction of heart rate over the course of both HA protocols (Table 4-1). While having a lower heart rate *per se* does not improve safety, the changes underlying a reduced heart rate can. Specifically, heart rate reduces in HA programmes primarily due to increased plasma volume (Kissling et al., 2019; Tyler et al., 2016). By increasing blood volume through plasma volume, it simultaneously facilitates blood distribution to the skin for cooling, to the muscles to maintain exercise intensity, and to vital organs to sustain life (Fogarty et al., 2004; González-Alonso et al., 1998; González-Alonso et al., 2008). For example, if blood supply to the gastrointestinal system is reduced endotoxins can leak from the gut, resulting in endotoxemia, commonly found in heat stroke victims (Amorim et al., 2015; Sakurada et al., 1998; Selkirk et al., 2008; Wendt et al., 2007). As well as promoting safety, the increased blood volume can also enable skeletal muscle or cutaneous blood flow to facilitate performance (Savard et al., 1988; Tebeck et al., 2019). In the heat blood volume can be diminished through dehydration (Casa et al., 2012; Stöhr et al., 2011), especially when sweat rates are high (Nielsen et al., 1997; Patterson et al., 2014). While sweat rate increased following HA, a concomitant increase in fluid consumption likely helped limit the reduction in blood volume, thereby aiding performance and recovery (Brake et al., 2003; Larsen et al., 2015b).

Perceptions were shown to be among the best predictors of performance (Table 3-2), therefore their improvement following HA likely accounted for some of the improvements in performance (Fig. 4-3). However, the primary perceptual improvement following HA was a reduction in RPE, whereas Chapter 3 revealed RPE to have minimal associations with performance (Table 3-2). It is possible that this discrepancy is due to a combination of the lower absolute rectal temperatures reached in Chapter 4 minimally influencing thermal perceptions, and the "mental toughness" of military personnel in Chapter 3 causing a reluctance to admit when exercise is hard (Buller et al., 2017; Epstein et al., 2012; Howe et al., 2007).

The adaptations induced in Chapter 4 were beneficial but were not rapidly obtained as would be required for elite units deploying abroad with less than 12 hours' notice. With foresight an additional experiment followed upon conclusion of HA to evaluate the decay, and the possibility of sustaining adaptations using IHE (Chapter 6). Several studies had previously investigated the decay of adaptations from traditional HA programmes (Daanen et al., 2018; Pandolf, 1998), while decay from passive, post-exercise HA was only published during the course of this thesis (Zurawlew et al., 2019). IHE was a potential method that might sustain heat adaptations, with a single HA session every 5 days being recommended (Périard et al., 2016; Taylor, 2000). During the production of this thesis it was reported that a single HA session every 5 days could retain heart rate and core temperature adaptations (Pryor et al., 2018). In Chapter 6 IHE was conducted every 2-3 days, with performance outcomes evaluated after a 3 wk period. The decay group retained a significant reduction in rectal temperature compared to baseline, despite elevated rectal temperature and heart rate (Table 6-1, Fig. 6-2, Fig. 6-3). Although performance declined, maintaining a lower core temperature may improve safety even after 3 wk by increasing the margin for heat gain before organ damage can occur (Aoyagi et al., 1994; Shen et al., 2015). However, the use of IHE proved additionally effective. Performance was preserved to a greater degree than in the decay group, with further decreases in rectal temperature and increases in sweat rate that were significantly different from those seen in the decay group (Table 6-1, Fig.

6-2, Fig. 6-3, Fig. 6-4). The preservation of performance and improved thermal tolerance in the IHE group showed that IHE may provide a means to enhance or preserve passive, post-exercise HA adaptations for a prolonged period. For military units that may receive short deployment notice of <12 h it is possible that IHE could maintain an elevated baseline of thermal tolerance, enabling enhanced performance, and improved safety upon deployment.

8.3 Cognitive Performance

Key findings:

- Cognitive performance appears equally affected between arid and humid environments (Chapter 3)
- Although cognitive performance may be preserved in the heat, cognitive tasks feel harder and more challenging (Chapter 3 and Chapter 5)
- Heat acclimation does not improve cognitive performance during exercise of ~1 hour in humid heat (Chapter 5)
- A moderately elevated core temperature does not alter cognitive performance (Chapter 7)
- A moderately elevated core temperature alters cerebral oxygenation, suggesting cognitive performance is preserved due to cerebral autoregulation overcoming the effects of hyperthermia (Chapter 7)

A secondary aim of this thesis was to evaluate the benefits HA might have on cognitive performance given the limited attention cognition has received in the literature. Although improvements were observed over the HA period that would likely minimise the effects of heat as a stressor on cognition as per the maximal adaptability model, there was limited evidence that cognitive performance improved. It was likely that no effects were observed in Chapter 5 due to core temperature not being high enough to cause sufficient stress to impair cognition (Schmit et al., 2017). Therefore, to gain further insight into the mechanistic underpinnings of cognitive performance in a military context, cognition was revisited in Chapter 7 which aimed to address the limitations of Chapter 5 by being designed to elevate rectal temperature through means that did not cause physically induced fatigue. As elevated rectal temperature was hypothesised to impair cognitive performance a control group, completing the same tests without an elevated rectal temperature, was used, as was another hyperthermic group that had access to a cooling method to offset the negative effects of heat. The cooling method chosen was menthol mouth-rinse due to its practicality in field settings and ability to improve endurance performance (Flood et al., 2017), likely by improving perceptual responses that otherwise downregulate central processes relating to motor recruitment (Tucker et al., 2004). Furthermore, the use of a cooling collar had previously been shown to mitigate the effects of heat on cognition (Lee et al., 2014), suggesting the effects of core temperature on cognition were able to be overcome. To encapsulate the military paradigm cognitive tests were administered during exercise, whereas many studies only assess cognition following exercise, which is known to allow cognitive function to recover (Chang et al., 2012). While minimal changes were seen in cognition between groups (Table 7-1), cerebral adjustments were observed (Fig. 7-4). Both hyperthermic groups demonstrated an increase in the estimated oxygenation difference, suggesting greater cerebral oxygen consumption. Previous investigations had also observed increases in oxygen consumption as well as alterations in functional networks underlying cognitive behaviour (González-Alonso et al., 2004; Hocking et al., 2001; Liu et al., 2013; Rasmussen et al., 2010; Xue et al., 2018). Therefore, although performance on cognitive tasks was not impaired as a function of core temperature, cognitive function appears to be altered, which could lead to negative task performance in more complex tasks, or when additional stressors are present.

8.4 Practical Applications

Based on the research conducted herein, several recommendations can be made for military units expecting to deploy on short notice. Primarily, military units expecting to perform in hot environments should aim to elevate their baseline thermal tolerance. This thesis showed the use of IHE following completion of a HA programme successfully sustained beneficial adaptations that mitigated the effects of heat for a prolonged period. Therefore, adaptations could be obtained at convenience and then sustained until required, where the notice period would otherwise not provide sufficient time for acclimation (Fig 8-2). Additionally, using passive, post-exercise HA has minimal impact on other training objectives, thereby allowing planned training to continue. Physiological adaptations obtained from HA and maintained with IHE will help preserve performance and minimise the chance of heat illnesses when operating in hot environments (Fig. 8-2). Although HA cannot be timed for those with short-notice deployment, military units receiving more notice may benefit from a HA programme conducted prior to departure.

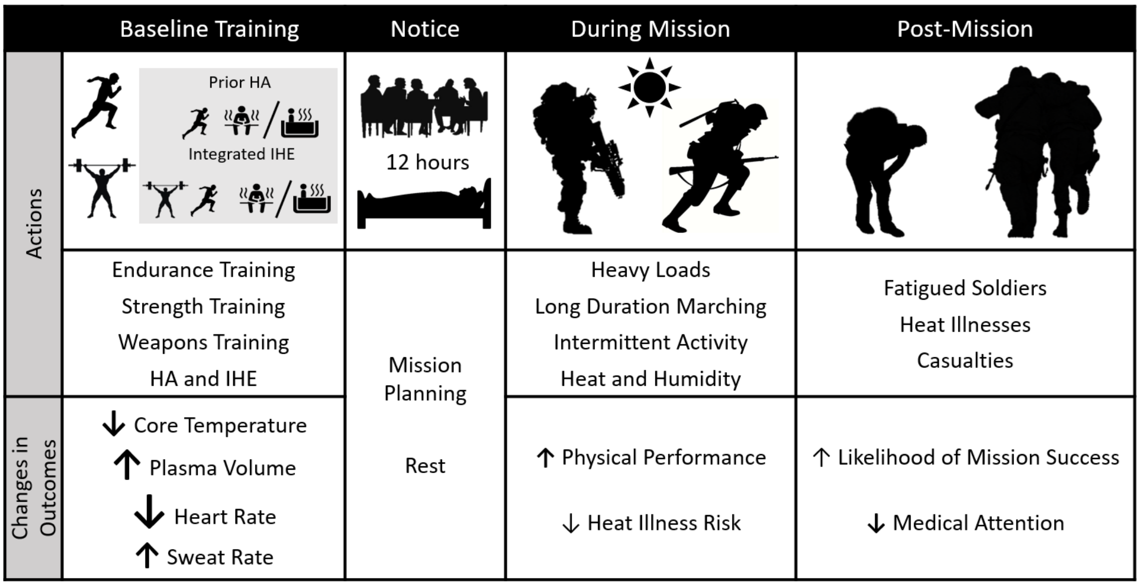

Figure 8-2. Schematic detailing proposed the effects of heat acclimation (HA) and intermittent heat exposure (IHE) for military units expecting to be rapidly deployed into hot environments. Changes in outcomes indicate the expected changes that would be obtained from HA and IHE compared to standard training of endurance, strength, and weapons (Figure 1-1).

Another aspect worth consideration is that although Chapter 3 highlighted that humid and arid environments have similar effects on performance, the differences in physiological responses suggest that heat strain is felt in different ways. While not investigated in this thesis, the higher skin temperatures observed in the arid environment may respond well to skin cooling interventions if available and appropriate, while humid environments may require more frequent breaks to prevent excessive heat production contributing to hyperthermia. Therefore, operational planning should consider factors of operational objectives, gear loadouts, required facilities and individual monitoring to minimise the risk of operating in these environments.

8.5 Limitations

Despite the studies in this thesis providing novel outcomes and refining HA approaches, they are not perfect and therefore require the attention and consideration of the following limitations:

a. The thesis aimed to provide information on, and solutions to the problems encountered in the heat by military personnel. However, only in one study (Chapter 3) did military personnel participate. The reasons for this largely lie within ethical applications for the first study taking over a year to be processed, with ethical approval required from the university, and the NZDF, which itself required approval from the NZ government and the Crown. During this time further delays occurred due to a training death within the military, again pushing back the start date for testing. Furthermore, additional participants recruited in the latter stages of the thesis testing was interrupted by the COVID-19 outbreak. These delays as well as a slow recruitment process led to future studies being adjusted to use civilian populations. To ensure the external validity of collected results participants for the remaining studies (Chapters 4-6) were required to meet a minimum entry requirement regarding their fitness, placing individuals in line with that seen in military groups. However, certain alterations such as reducing the pack weight had to be made for ethical reasons surrounding minimising injury risk. To achieve this while maintaining practical applicability the backpack load was reduced while the volume of the pack remained the same, thereby maintaining the same coverage over the skin and clothing so that restrictions to heat loss might be similar. It is unlikely that these limitations will have a substantial impact on the changes observed in any of the studies herein, but should be considered, nonetheless.

b. The sample sizes in this thesis were potentially sub-optimal for several chapters (Chapters 3, 6 and 7). Chapter 3 was first impacted by delayed ethical processing that led to the original cohort being suspended for over a year, and largely disappearing once ethics had been obtained. As recruitment continued into 2020 the testing was then affected by the COVID-19 pandemic, which also limited the sample size for Chapter 7. Chapter 6 saw small sample sizes due to the splitting of a reasonably sized cohort into 4 groups, with no more than 5 in a group. Combining sauna and HWI groups together within either the decay group or IHE group, due to the similarities between the two found in Chapter 4, helped to overcome this problem, and improve the statistical power of the test. The statistical power of the tests was also improved through the experimental design of studies allowing for repeated measures to be collected within subjects, thereby minimising the variability of the responses, with the use of a mixed model ANOVA accounting for participant drop out. This was particularly beneficial in Chapter 7, where the sample size was much smaller than anticipated but as the repeated measures increased the correlation among repeated measures, it allowed for reasonable power.

c. The lack of a true control group in Chapters 4 and 5 can detract from their findings as it is unclear whether the observed changes were due to the exercise or heating component of the HA protocol. The decision to exclude control groups was made primarily on the basis that prior research had compared these passive, post-exercise HA techniques against control groups, and found significantly better outcomes in the intervention groups (Scoon et al., 2007; Zurawlew et al., 2016). Furthermore, as participants were already required to complete two HA programmes, followed by a decay or IHE programme (~40 hours contact time per participant), it was deemed excessive to have them partake in a further control condition, which would then lead to sample size issues. Therefore, the conclusions of these studies relate to the adaptations following passive, post-exercise HA, and not passive HA per se, with the exercise component having an untold input onto the final outcomes. However, the positive results of Chapter 6, which had an exercising control group (decay group), suggest that the independent effects of the heat likely elicited a large proportion of the overall adaptations.

d. Throughout the HSTs deployed in the studies relating to HA (Chapters 4-6) rectal temperature remained relatively low compared to those seen in Chapter 3 when evaluating the limits of military performance in these environments, perhaps due to the lower endogenous heat production caused by having to reduce the carried load. In relation to physical performance, the HSTs in Chapters 4-6 had a ramp protocol following an hour-long walk in the heat to provide TTE whereas Chapter 3 used absolute TTE. While the TTE in Chapter 3 largely relies on thermal tolerance, a greater degree of muscular strength and endurance is factored into the TTE of Chapters 4-6 due to the inclined walking, which may mask the effects of heat adaptation on performance behind muscular fatigue that triggers voluntary exercise termination. However, all physiological, perceptual, and cognitive measures were obtained during the fixed-intensity part of the HSTs in Chapters 4-6, albeit with less thermal stress and fatigue than experienced by military participants in Chapter 3.

e. Extrapolation of the findings of this thesis into field settings can be challenging. While as many aspects as possible were controlled, the military environment provides many unique and unpredictable stressors that simply cannot be recreated in the laboratory environment (i.e., fear, lack of cooling facilities, unknown exertional requirements). Such factors therefore need to be considered alongside these findings and interpreted accordingly.

f. While the ethical rectal temperature cut-off of 39.3°C for studies involving military personnel (Chapter 3) and 39.5°C for recreationally active participants is in line with other research in this area, it is much lower than what has been reported in the literature, especially amongst elite athletes (Seto et al., 2005). Because the cut-off value limited performance by causing involuntary withdrawal, it impacted the time to exhaustion in Chapter 3, and prevented the exploration of cognition at higher rectal temperatures in Chapter 7. In Chapter 3 50% of trials were terminated due to high rectal temperature. While this is an important finding, as the cut-off is placed where it would be advised for exercise to stop, it removes the ability of the individual to be able to tolerate a higher rectal temperature, which would affect TTE. Furthermore, it provided potentially confusing results in the regression analysis, as because a high rectal temperature alone was the reason for test termination, it created an auto-collinearity, and therefore created uncertainty as to how predictive of performance the rate of rise in rectal temperature is. In Chapter 7, while it is possible that the rectal temperature was insufficient to cause a hyperthermia-induced cognitive impairment, the 38.5°C starting rectal temperature used was at the limit of what could be achieved during a 30 min walk. Indeed, two participants had rectal temperatures exceeding 39.4°C at the end of hyperthermic trials, suggesting that given the experimental paradigm, the rectal temperature chosen was as high as it could be within the ethical boundaries.

8.6 Future Research

The main aim of this thesis was to develop strategies to minimise the effects of heat in military units facing short notice deployment. Initially this was achieved in Chapter 4 using sauna and HWI as part of a short-term, passive, post-exercise HA protocol that successfully induced adaptations to mitigate the effects of the heat. HA in this area has received relatively little research, but due to its practicality will likely become more commonplace, and therefore require more information as to the timing of heat exposure in relation to exercise, the temperatures of the heating modalities, the time spent in the heating modalities and the duration of the programme. Indeed, the findings that adaptations continued to progress in the IHE phase in Chapter 6 was indicative that a plateau in heat adaptation was yet to be reached. While short-term HA strategies may be more applicable to athletic groups who are inherently aware of their travel to such climates with ample notice, it also applies to large military groups deploying to hotter climates as part of larger operations, especially if limited medical facilities are available in the environment.

The crux of this thesis centred around the use of IHE to sustain beneficial HA adaptations for a prolonged period, an area which has received relatively little research. While IHE sustained, and even improved, certain HA adaptations it is unknown how long IHE can sustain adaptations. If IHE can retain desirable adaptations for ~8 months then it could be possible to naturally acclimate over the hotter summer months and retain those adaptations year-round, thereby removing the need for HA. Likewise, for groups being repeatedly deployed to the same hotter climate it may allow adaptations from natural acclimatisation to be sustained until the next deployment cycle. While IHE has been shown to be effective, both in this thesis (Chapter 6), and in the published literature (Pryor et al., 2018), the most efficient way to sustain these adaptations is yet to be investigated. Such investigations could then consider individual variations in thermal tolerance, allowing IHE to be tailored to individuals.

Regarding cognition, it is clear further studies are required to investigate the interaction between cognitive performance and exercise in the heat. Complex tasks that appear in real-world military scenarios should be evaluated, rather than assessing individual elements of cognition, to give more directly applicable outcomes. From a mechanistic point of view, the qualitative psychological models used to explain cognitive performance are vague and have limited predictive power. By conducting more mechanistic studies it would allow development of quantitative models that provide a better understanding of how cognitive performance is impacted in the heat.

8.7 Conclusion

This thesis aimed to improve the understanding of how military personnel operate in the heat, and how to rapidly prepare military units for deployment to hot environments. Building off previous research, heat acclimation strategies were conceptualised and tested that improved performance and safety when operating in these environments. These strategies were proven to sustain beneficial adaptations, theoretically allowing them to be maintained until deployment, thereby mitigating the effects of heat on operational success. It is hoped that the main strategic recommendations of this thesis will be adopted by military organisations around the world to improve the performance and safety of their soldiers.

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Chapter 10 Appendices

10.1 Appendix A – Ethical Approvals

10.1.1 Chapter 3

Auckland University of Technology Ethics Committee (AUTEC)

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TE WĀNANGA ARONUI O TĀMAKI MAKAU RAU

23 July 2018

Andrew Kilding
Faculty of Health and Environmental Sciences

Dear Andrew

Ethics Application: 17/420 Determinants of endurance performance in heat in the military

Thank you for submitting your application for an amendment to your ethics application above. I am pleased to advise the amendment to the data collection protocol is approved subject to the following conditions:

1. Provision of an updated Information Sheet detailing the amended data collection protocols in the 'What will happen' section.

Please provide me with a response to the points raised in these conditions, indicating either how you have satisfied these points or proposing an alternative approach. AUTEC also requires copies of any altered documents, such as Information Sheets, surveys etc. You are not required to resubmit the application form again. Any changes to responses in the form required by the committee in their conditions may be included in a supporting memorandum.

Please note that the Committee is always willing to discuss with applicants the points that have been made. There may be information that has not been made available to the Committee, or aspects of the research may not have been fully understood.

Once your response is received and confirmed as satisfying the Committee's points, you will be notified of the full approval of your ethics application. Full approval is not effective until all the conditions have been met. Data collection may not commence until full approval has been confirmed. If these conditions are not met within six months, your application may be closed and a new application will be required if you wish to continue with this research.

To enable us to provide you with efficient service, we ask that you use the application number and study title in all correspondence with us. If you have any enquiries about this application, or anything else, please do contact us at ethics@aut.ac.nz.

I look forward to hearing from you,

Yours sincerely

Kate O'Connor
Executive Manager
Auckland University of Technology Ethics Committee

Cc: edeashworth@hotmail.co.uk

AUT

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25 July 2018

Andrew Kilding
Faculty of Health and Environmental Sciences

Dear Andrew

Re Ethics Application: **17/420 Determinants of endurance performance in heat in the military**

Thank you for providing evidence as requested for the amendment to your ethics application, which now satisfies the points raised.

The amendment to the data collection protocols is approved.

Standard Conditions of Approval

1. A progress report is due annually on the anniversary of the approval date, using form EA2, which is available online through http://www.aut.ac.nz/research/researchethics.
2. A final report is due at the expiration of the approval period, or, upon completion of project, using form EA3, which is available online through http://www.aut.ac.nz/research/researchethics.
3. Any amendments to the project must be approved by AUTEC prior to being implemented. Amendments can be requested using the EA2 form: http://www.aut.ac.nz/research/researchethics.
4. Any serious or unexpected adverse events must be reported to AUTEC Secretariat as a matter of priority.
5. Any unforeseen events that might affect continued ethical acceptability of the project should also be reported to the AUTEC Secretariat as a matter of priority.

Please quote the application number and title on all future correspondence related to this project.

AUTEC grants ethical approval only. If you require management approval for access for your research from another institution or organisation then you are responsible for obtaining it. If the research is undertaken outside New Zealand, you need to meet all locality legal and ethical obligations and requirements. You are reminded that it is your responsibility to ensure that the spelling and grammar of documents being provided to participants or external organisations is of a high standard.

For any enquiries, please contact ethics@aut.ac.nz

Yours sincerely,

K O'Connor

Kate O'Connor
Executive Manager
Auckland University of Technology Ethics Committee

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NEW ZEALAND DEFENCE FORCE
Defence Health Directorate
MINUTE

6755/1

Jun 18

DDH

For Information:
PAOR

APPLICATION TO CONDUCT RESEARCH 2018/15: DETERMINANTS OF ENDURANCE PERFORMANCE IN HEAT IN THE MILITARY.

References:
A. DFO 3, Chap 5, Part 14: Authority to Conduct Personnel Research
B. Health Research SOP: Health Research Application Process

Background

1. In accordance with Ref A, Messer's A. Kilding and E. Ashworth, seek to conduct research that uncovers the physiological variables that make people perform better or worse in the heat.

2. The research sought by this application will form part of a wider series of studies looking to explore the optimal methods of rapid heat acclimation. In particular they will look to address problems encountered by the New Zealand Defence Force when they are on deployment overseas.

3. The research looks to involve SOF and is sponsored by COL R. Gillard.

Decision

4. The DDH is charged with the review of all Human related research, primarily with the view to ensuring that it meets the exacting standards for good human health research and also which contributes to the objectives of the Defence Health Strategy.

5. The Health Strategy Reference Group (HSRG) - Health Research, considers all applications for Human related health research on behalf of DDH in accordance with Ref B.

6. The HSRG-Health Research Group recommended the endorsement of this application subject to:

a. It is noted that the research sponsor will soon vacate his current position. The researchers will need to confirm a new research sponsor.

b. The use and mention of the SOF as cohort members in any research document presents a potential security issue for Defence and there may be issues around the publishing of any information in which they (SOF) are referred to as participants. Any reference to the SOF will require NZDF security approval.

2

c. The HSRG maintain concerns regarding the presence of a medical professional during the physical conduct of the research. The HSRG accept that testing protocols ensure a low risk to the test cohort however considered that a medical professional should be available and on call to provide medical assistance if needed during the testing phase. The researchers are to confirm that arrangements are in place to ensure that a medical professional is on standby and readily available if needed.

d. The researchers are to confirm that re-hydration fluids are freely available during and after the physical study, for the participants.

e. The researchers will need to ensure that SOF Health and Safety personnel have been made aware of the research.

f. The researchers are to ensure that participants are able to call a stop at any time during their participation in the study.

Summary

7. The HSRG supports this application subject to the matters above.

Recommendations

8. It is recommended that DHD:

a. Endorse the application.

J. JOSEPHS
MAJ
Secretary- HSRG (Health Research)

Email: james.josephs@nzdf.mil.nz

This application for health related human research **is / is not** endorsed.

A. GRAY
BRIG
DDH

10.1.2 Chapters 4, 5 and 6

Auckland University of Technology Ethics Committee (AUTEC)

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23 July 2018

Andrew Kilding
Faculty of Health and Environmental Sciences

Dear Andrew

Ethics Application: 18/195 Comparison of sauna and hot-water immersion heat acclimation methods in a military context in males.

Thank you for submitting your responses to the points raised by the committee. I am pleased to advise that your application will be approved subject to the following conditions:

1. Amendment of the recruitment poster to include only males;
2. Change the title of the Information Sheet;
3. Insert the overall cost of time on the recruitment flyer;
4. On the Consent Form remove the statement concerning destruction of data since this is incoherent with the statement about indefinite storage.

Please provide me with a response to the points raised in these conditions, indicating either how you have satisfied these points or proposing an alternative approach. AUTEC also requires copies of any altered documents, such as Information Sheets, surveys etc. You are not required to resubmit the application form again. Any changes to responses in the form required by the committee in their conditions may be included in a supporting memorandum.

Please note that the Committee is always willing to discuss with applicants the points that have been made. There may be information that has not been made available to the Committee, or aspects of the research may not have been fully understood.

Once your response is received and confirmed as satisfying the Committee's points, you will be notified of the full approval of your ethics application. Full approval is not effective until all the conditions have been met. Data collection may not commence until full approval has been confirmed. If these conditions are not met within six months, your application may be closed and a new application will be required if you wish to continue with this research.

To enable us to provide you with efficient service, we ask that you use the application number and study title in all correspondence with us. If you have any enquiries about this application, or anything else, please do contact us at ethics@aut.ac.nz.

I look forward to hearing from you,

Yours sincerely

K O'Connor

Kate O'Connor
Executive Manager
Auckland University of Technology Ethics Committee

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24 July 2018

Andrew Kilding
Faculty of Health and Environmental Sciences

Dear Andrew

Re Ethics Application: **18/195 Comparison of sauna and hot-water immersion heat acclimation methods in a military context in males**

Thank you for providing evidence as requested, which satisfies the points raised by the Auckland University of Technology Ethics Committee (AUTEC).

Your ethics application has been approved for three years until 23 July 2021.

Standard Conditions of Approval

1. A progress report is due annually on the anniversary of the approval date, using form EA2, which is available online through http://www.aut.ac.nz/research/researchethics.
2. A final report is due at the expiration of the approval period, or, upon completion of project, using form EA3, which is available online through http://www.aut.ac.nz/research/researchethics.
3. Any amendments to the project must be approved by AUTEC prior to being implemented. Amendments can be requested using the EA2 form: http://www.aut.ac.nz/research/researchethics.
4. Any serious or unexpected adverse events must be reported to AUTEC Secretariat as a matter of priority.
5. Any unforeseen events that might affect continued ethical acceptability of the project should also be reported to the AUTEC Secretariat as a matter of priority.

Please quote the application number and title on all future correspondence related to this project.

AUTEC grants ethical approval only. If you require management approval for access for your research from another institution or organisation then you are responsible for obtaining it. If the research is undertaken outside New Zealand, you need to meet all locality legal and ethical obligations and requirements. You are reminded that it is your responsibility to ensure that the spelling and grammar of documents being provided to participants or external organisations is of a high standard.

For any enquiries, please contact ethics@aut.ac.nz

Yours sincerely,

K O'Connor

Kate O'Connor
Executive Manager
Auckland University of Technology Ethics Committee

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8 October 2018

Andrew Kilding
Faculty of Health and Environmental Sciences

Dear Andrew

Re: Ethics Application: **18/195 Comparison of sauna and hot-water immersion heat acclimation methods in a military context in males**

Thank you for your request for approval of amendments to your ethics application.

The amendment to recruitment protocols (for relevant organisations such as tramping groups) to distribute advert to their members via monthly newsletter) is approved.
I remind you of the **Standard Conditions of Approval.**

1. A progress report is due annually on the anniversary of the approval date, using form EA2, which is available online through http://www.aut.ac.nz/research/researchethics.
2. A final report is due at the expiration of the approval period, or, upon completion of project, using form EA3, which is available online through http://www.aut.ac.nz/research/researchethics.
3. Any amendments to the project must be approved by AUTEC prior to being implemented. Amendments can be requested using the EA2 form: http://www.aut.ac.nz/research/researchethics.
4. Any serious or unexpected adverse events must be reported to AUTEC Secretariat as a matter of priority.
5. Any unforeseen events that might affect continued ethical acceptability of the project should also be reported to the AUTEC Secretariat as a matter of priority.

Please quote the application number and title on all future correspondence related to this project.

AUTEC grants ethical approval only. If you require management approval for access for your research from another institution or organisation then you are responsible for obtaining it. If the research is undertaken outside New Zealand, you need to meet all locality legal and ethical obligations and requirements.

For any enquiries please contact ethics@aut.ac.nz

Yours sincerely,

K O'Connor

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10.1.3 Chapter 7

Auckland University of Technology Ethics Committee (AUTEC)

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18 October 2019

Andrew Kilding
Faculty of Health and Environmental Sciences

Dear Andrew

Ethics Application: 19/368 Cognitive performance in the heat, during exercise

Thank you for submitting your application for ethical review. I am pleased to advise that the Auckland University of Technology Ethics Committee (AUTEC) approved your ethics application at their meeting on 14 October 2019, subject to the following conditions:

1. Clarification about the involvement of the military and their personnel in this research. As this study is not recruiting military personnel, AUTEC wishes the advertisement photographs to be altered to better reflect the participants being recruited and what they will be doing;
2. Provision of independent peer review for the science of this study;
3. Provision of justification for the limitations on the participation of women in this study. AUTEC is of the view that either the scope and potential benefits of this research are limited by the exclusion of women, or the study is redesigned to take into account the physiology of women and that women are fully included. AUTEC advises that the proposed limited inclusion of women breaches privacy principles in requiring unnecessary information to be divulged;
4. Provision of an assurance that a copy of the Consent Form will be provided to the participant with the Information Sheet;
5. Clarification about when consent is being obtained in relation to the use of the screening questionnaire. The researcher and applicant are reminded that identifiable personal data may not be collected and stored prior to consent being obtained;
6. Provision of a safety protocol or plan for the study, including procedures for responding to heat stroke should it occur;
7. Amendment of the Information Sheet as follows:
   a. Inclusion of pictures showing the use of the skin and spectroscopy sensors;
   b. Inclusion of clear advice about the cognitive tests being used;
   c. Inclusion of advice about the collection and use of urine samples;
   d. Break down the information about the testing sessions into 3 parts so that participants understand exactly what will occur in each. The committee suggests that a flow chart of the testing protocols may assist participant understanding.
8. Revision of the advertisement to ensure that it accurately reflects what is going to happen in the study.

Please provide me with a response to the points raised in these conditions, indicating either how you have satisfied these points or proposing an alternative approach. AUTEC also requires copies of any altered documents, such as

Information Sheets, surveys etc. You are not required to resubmit the application form again. Any changes to responses in the form required by the committee in their conditions may be included in a supporting memorandum.

Please note that the Committee is always willing to discuss with applicants the points that have been made. There may be information that has not been made available to the Committee, or aspects of the research may not have been fully understood.

Once your response is received and confirmed as satisfying the Committee's points, you will be notified of the full approval of your ethics application. Full approval is not effective until all the conditions have been met. Data collection may not commence until full approval has been confirmed. If these conditions are not met within six months, your application may be closed and a new application will be required if you wish to continue with this research.

To enable us to provide you with efficient service, we ask that you use the application number and study title in all correspondence with us. If you have any enquiries about this application, or anything else, please do contact us at ethics@aut.ac.nz.

I look forward to hearing from you,

Yours sincerely

Kate O'Connor
Executive Manager
Auckland University of Technology Ethics Committee

Cc: edeashworth@hotmail.co.uk

TE WĀNANGA ARONUI O TĀMAKI MAKAU RAU

Auckland University of Technology Ethics Committee (AUTEC)

Auckland University of Technology
D-88, Private Bag 92006, Auckland 1142, NZ
T: +64 9 921 9999 ext. 8316
E: ethics@aut.ac.nz
www.aut.ac.nz/researchethics

12 November 2019

Andrew Kilding
Faculty of Health and Environmental Sciences

Dear Andrew

Re Ethics Application: **19/368 Cognitive performance in the heat, during exercise**

Thank you for providing evidence as requested, which satisfies the points raised by the Auckland University of Technology Ethics Committee (AUTEC).

Your ethics application has been approved for three years until 11 November 2022.

1. The research is to be undertaken in accordance with the Auckland University of Technology Code of Conduct for Research and as approved by AUTEC in this application.
2. A progress report is due annually on the anniversary of the approval date, using the EA2 form.
3. A final report is due at the expiration of the approval period, or, upon completion of project, using the EA3 form.
4. Any amendments to the project must be approved by AUTEC prior to being implemented. Amendments can be requested using the EA2 form.
5. Any serious or unexpected adverse events must be reported to AUTEC Secretariat as a matter of priority.
6. Any unforeseen events that might affect continued ethical acceptability of the project should also be reported to the AUTEC Secretariat as a matter of priority.
7. It is your responsibility to ensure that the spelling and grammar of documents being provided to participants or external organisations is of a high standard.

AUTEC grants ethical approval only. You are responsible for obtaining management approval for access for your research from any institution or organisation at which your research is being conducted. When the research is undertaken outside New Zealand, you need to meet all ethical, legal, and locality obligations or requirements for those jurisdictions.

Please quote the application number and title on all future correspondence related to this project.

For any enquiries please contact ethics@aut.ac.nz. The forms mentioned above are available online through http://www.aut.ac.nz/research/researchethics

Yours sincerely,

K O'Connor

Kate O'Connor
Executive Manager
Auckland University of Technology Ethics Committee

Cc: edeashworth@hotmail.co.uk

10.2 Appendix B – Tools

10.2.1 Participant Information Sheets

10.2.1.1 Chapter 3

AUT Millennium
17 Antares Place, Rosedale
Auckland, New Zealand

PARTICIPANT INFORMATION SHEET FOR VOLUNTEERS

Determinants of Endurance Performance in Heat in the Military

Researchers: Edward Ashworth BSc, Associate Professor Andrew Kilding PhD

We would like to invite you to take part in a research study. Before deciding whether you would like to take part it is important for you to understand why the research is being done and what it could involve for you, so take the time to read the following information carefully. Feel free to discuss it with others, and to ask us if there is anything that is unclear, or you would like more information on. Take your time to decide whether or not you wish to take part.

What is the purpose of the study?
Heat is a major problem for soldiers deployed overseas who have to undertake hard work in restrictive clothing in hot conditions. To help understand why physical and mental performance is compromised we are aiming to look at how the body responds to the heat in a military specific task. We intend on using the findings to guide a programme that will enhance the factors that respond poorly in heat so that they are improved, which allows overall performance to be improved.

Eligibility:
You will be eligible for the study if:

- You are currently part of the New Zealand Defence Force
- You are capable of carrying a pack of 35kg for long duration

However, you will be ineligible if:

- You have had a prior heat illness
- You have been ill in the past month
- You are currently injured
- You are taking a medication that interferes with exercise or thermoregulatory function
- You have a cardiovascular condition, or have a family history of heart conditions
- You are pregnant
- You are a female who is not currently taking a contraceptive pill

Why have I been invited?
You have been invited to take part as military reports show that a lot of soldiers struggle in the heat upon deployment. You have been invited as you are representative of the soldiers that will be deployed overseas. As you have had similar training the results that you provide can be directly indicative of what others will experience in the heat.

What will I have to do?

You will be required to attend two sessions, at least a week apart, at AUT Millennium, Rosedale, North Shore City Auckland. We will be unable to compensate you for travel costs to and from the facility. During each session you will be required to complete a 2-hour walk in a heat chamber, set to conditions representative of either Middle-Eastern or South-East Asian climates. You will be randomly assigned to a condition. You will be asked to produce a military fitness record on arrival to provide a fitness baseline value. Prior to the session a urine sample will be required in a container that will be given to you. A small, 4ml, blood sample will then be taken to get measures of blood volume and blood cell counts. After this an ultrasound measurement of the abdomen will be taken to give an indication of body fat. You will then be asked to sit in the chamber for 10 minutes, during which time a thermal imaging camera will be set up to record the heat of your body, before you begin the exercise session. The exercise session consists of walking for 2 hours at low intensity. Following this the treadmill gradient will be increased by 1% every minute until voluntary exhaustion, core temperature reaches 39.3°C, heart rate exceeds 95% of maximum or the researcher ends the session based on observed symptoms. During the session several key physiological measures will be taken. Core temperature, skin temperature, and heart rate will all be constantly recorded using a rectal probe, skin temperature sensors and electrocardiogram leads respectively. Sweat rate will be periodically measured with a sweat patch. Gas analysis will also occur using a mouthpiece at times during the test. Cognitive testing will occur during the test to determine your vigilance, memory recall and decision making. You will also be asked about how you are feeling throughout the test. Once the test is done you will provide a second urine sample and then be rehydrated.

What if there is a problem?

Problems could arise from having a high core temperature, but to avoid this your core temperature will be constantly monitored, and if it exceeds a temperature of 39.3°C you will be immediately withdrawn from the chamber to end the test. This is done to ensure core temperature does not rise above 40°C, a temperature where there is a minor risk of medical problems. If there is a problem the participant has the right to remove themselves from the trial at any point, without any questions being asked. If there is a minor problem the researcher should be notified immediately so they can judge how to respond to the problem, including removing the participant from the chamber.

To minimize risks a questionnaire will be filled out which will screen you for any potential variables that could cause an adverse effect in the chamber to prevent you from participating in the first place. This includes medical conditions, illnesses, and medication/drug use. It is important that you are honest on these forms to help ensure your safety.

What are my rights as a participant?

- Your participation is entirely voluntary
- You have the right to withdraw at any time without reason
- You may request your data be withdrawn from the study within 3 months of participation
- Your identity is strictly confidential and no identification of your or your data will be made during the data collection or in publications that arise from the research findings
- You are encouraged to consult with your family/whanau, iwi or hapu regarding participation in this study.

Confidentiality

Data storage/retention/destruction/future use

All personal details obtained from you in the study will be stored in a locked cupboard in the SPRINZ ethics data storage facility, that only the researchers and the SPRINZ ethics offical have access to. It will be stored here for 10 years in accordance with ethical guidelines. You may request your personal details to be destroyed at any time.

Furthermore, any reports presented to the New Zealand Defence Force will contain no identifiable information belonging to you.

Compensation
In the unlikely event that a physical injury occurs as a result of participation you may be covered by the Accident Compensation Corporation (ACC) under the Injury Prevention, Rehabilitation, and Compensation Act 2001. This is not automatic and your case will need to assessed by ACC according to their guidelines.

Further Information and Contact Details
For any further information about the study please contact Edward Ashworth.

Email: Edward.Ashworth@aut.ac.nz
Phone: 0211532216

Approved by the Auckland University of Technology Ethics Committee on *25 July 2018*, AUTEC Reference number *17/420*.

10.2.1.2 Chapters 4-6

AUT Millennium
17 Antares Place, Rosedale
Auckland, New Zealand

Date Information Sheet Produced: 15th May 2018

PARTICIPANT INFORMATION SHEET FOR VOLUNTEERS

Comparison of Sauna and Hot-Water Immersion Heat Acclimation Methods in a Military Context in Males

Researchers: Edward Ashworth BSc (Hons), Associate Professor Andrew Kilding PhD

We would like to invite you to take part in a research study. Before deciding whether you would like to take part it is important for you to understand why the research is being done and what it could involve for you, so take the time to read the following information carefully. Feel free to discuss it with others, and to ask us if anything is unclear or you would like more information. Take your time to decide whether or not you wish to take part.

What is the purpose of the study?
Soldiers often struggle to perform in the heat when they are deployed overseas so we wish to investigate strategies to overcome this decline in performance. Heat acclimation is beneficial for the performance of athletes and military personnel who are travelling to hot environments. We want to test different methods of heat acclimation to determine which is best in a military setting. We hope to use the findings from this study to inform heat acclimation strategies for use within the military. Furthermore the results of this study will be used in academic publications and presentations.

Eligibility:
You will be eligible for the study if:

- You are currently taking part in exercise several times a week
- You are male
- You are between the ages of 18 and 50

However, you will be ineligible if:

- You have had a prior heat illness
- You have been ill in the past month
- You are currently injured
- You are taking a medication that interferes with exercise or thermoregulatory function
- You have a cardiovascular condition, or have a family history of heart conditions
- You have a BMI over 30
- You have a VO_2max of less than 40ml/kg/min (this will be tested in session 1)

Why have I been invited?

You have been invited as you responded to an advert looking for active, healthy individuals, with characteristics representative of military personnel. This means that you will likely respond to the heat in a similar manner which allows the research findings to be implemented within the military.

What will I have to do?

Overview

You will be required to complete two heat-acclimation protocols and one re-acclimation protocol, at AUT Millennium, Rosedale, North Shore City, Auckland as illustrated in table 1. The heat-acclimation protocols will be split into two 8-session blocks which will be separated by 5-7 weeks to allow any adaptations to decay, with each 8-session block taking place within two weeks. Each block consists of a VO_2max test, 5 days of heat acclimation and a pre and a post heat acclimation heat-stress test. Following completion of the 2nd heat-acclimation protocol a re-acclimation period will be used to try to sustain those adaptations for 3 weeks.

VO_2max Testing

Each block will begin with a VO_2maximum test which will require you to run until exhaustion on a treadmill as the speed and gradient are steadily increased. This will take around 20 minutes. During this time your exhaled air will be collected using a tube connected to a mouthpiece (like a snorkel) to allow a computer to measure your body's use of oxygen. You will also wear a heart rate strap around your chest. This test will provide us with an indication of your baseline fitness and allow us to give you appropriate intensity exercise in the sessions that follow. If at this point your fitness level is less than the 40ml/kg/min highlighted in the exclusion criteria then you will be notified of this and will not be able to progress further in the study.

Heat-Stress Tests

The second and eighth session of each block will require you to complete an hour long walk, on a treadmill, in a heat chamber, set to replicate the temperatures found in south-east Asia (33°C, 75% relative humidity). When you arrive for the heat-stress test you will be asked to provide a urine sample in a container given to you. Then a blood sample will then be taken from your forearm vein to measure your red and white blood cells. You will then prepare for the trial by privately inserting a rectal thermometer to monitor your core body temperature, attaching electrocardiogram (ECG) leads to your chest to record your heart rate, being connected to a series of skin temperature sensors to measure skin temperature, having a blood pressure cuff placed around your arm to record blood pressure, and putting on military clothing provided (including a 10 kg backpack) to replicate the conditions of military operations.

Figure 1. Experimental set-up for Heat-Stress Tests

You will then be asked to sit in the chamber for 5 minutes, during which time a thermal imaging camera will record the heat of your body. You will then be moved to the treadmill to begin walking for 60 minutes at 5 km/h. After 60 minutes the treadmill incline will increase 1% every minute. This will continue until volitional exhaustion, or core temperature reaches 39.5°C. During the session core temperature, skin temperature, and heart rate will all be constantly recorded using the rectal probe, skin temperature sensors and ECG leads fitted to you prior to the start of the trial. Gas analysis will occur in the same manner as during the VO_2max testing periodically during the trial. Blood pressure will be taken at certain time points during the test using the blood pressure cuff. Cognitive testing will occur during the test to determine cognitive function, memory recall and decision making. Perceptual measures will also be taken throughout the test.

Heat Acclimation

Each heat-acclimation block involves five consecutive days of post-exercise heat acclimation (sessions 3-7 and 11-15). Each day involves a 40 minute exercise session followed by 40 minutes of passive exposure to heat in either a sauna or a spa. The exercise session will be fixed intensity running at roughly 60% of your maximal capacity based on the results of the VO_2max assessment. Immediately following the exercise session you will be moved to the passive heat exposure modality you have randomly been assigned to. This will involve sitting in either a sauna or a spa for 40 minutes. During this time the researcher will take continuous measures from you, with perceptual measures taken every 10 minutes, along with tympanic temperature.

Table 1. Session schedule for the heat acclimation period. Each of the two 8-session blocks will be completed within 2 weeks, with sessions 2-8 and 10-16 occurring in the space of 9 days.

Heat Acclimation Period	
Session	Activity
1	VO_2max Test
2	Heat-Stress Test (pre)
3	Post-Exercise Heating
4	Post-Exercise Heating
5	Post-Exercise Heating
6	Post-Exercise Heating
7	Post-Exercise Heating
8	Heat-Stress Test (post)
5-7 Week Break	
9	VO_2max Test
10	Heat-Stress Test (pre)
11	Post-Exercise Heating
12	Post-Exercise Heating
13	Post-Exercise Heating
14	Post-Exercise Heating
15	Post-Exercise Heating
16	Heat-Stress Test (post)

Sessions 9-16

The next 8 sessions will take place at least 5 weeks after session 8 to ensure the heat acclimation adaptations have decayed. These 8 sessions will replicate sessions 1-8, with session 9 being the VO_2max test, sessions 10 and 16 being the heat-stress tests while sessions 11-15 will be the post-exercise heat exposure (table 1). This heat exposure will be in the modality not completed in sessions 3-7 so that you will complete one programme with a sauna and one with hot-water immersion.

Re-Acclimation

A re-acclimation period will be conducted immediately following the 2nd block of heat acclimation. This involves attending seven further sessions within 3 weeks and then completing one final heat-stress test. In this re-acclimation period you will be randomly assigned to either exercise only or exercise and heat. If only doing exercise you will complete the 40 minute exercise session seven times in 3 weeks. If doing exercise and heat you will complete 7 sessions identical to that done in the heat acclimation period, but on non-consecutive days. Each session will be separated by one or two days. After the 3 week period is up both groups will complete one final heat-stress test.

Table 2. Session schedule for the re- acclimation period. The seven session of either post-exercise heating or exercise only will take place every 2 or 3 days over a 3-week period, finishing with a final heat-stress test.

Re-Acclimation Period	
Session	Activity
17	Post-Exercise Heating or Exercise Only
18	Post-Exercise Heating or Exercise Only
19	Post-Exercise Heating or Exercise Only
20	Post-Exercise Heating or Exercise Only
21	Post-Exercise Heating or Exercise Only
22	Post-Exercise Heating or Exercise Only
23	Post-Exercise Heating or Exercise Only
24	Heat-Stress Test (final)

What are the costs of participating in this research?

The main cost of your participation will be time, although hopefully much of this will be seen as beneficial to you. Each VO_2max protocol takes approximately 30 minutes. Each Heat-stress test takes approximately 2.5 hours. Each post-exercising heating session takes approximately 90 minutes. Therefore the heat acclimation period will require roughly 26 hours of time, while the re-acclimation period requires a further 13. Together the whole study will take 39 hours.

What are the benefits?

As someone partaking in the research you will gain the benefits of a heat acclimation programme, and will obtained a detailed report of how your body adapts to the two tested methods of heat acclimation. A number of health benefits can results from heat acclimation, including cardiovascular improvements and well as performance enhancement. For the researchers the study will be used as part of a PhD qualification and for academic publications. The military will benefit from this study as it will help inform heat acclimation strategies to be implemented within the defence force.

What if there is a problem?

Problems could arise from having a high core temperature, but to avoid this your core temperature will be constantly monitored, and should core temperature exceed 39.5°C you will be removed from the heat chamber. You have has the right to remove yourself from the trial at any point, without any questions being asked. If you experience a problem at any point during the test or trial, you are encouraged to notify the researcher immediately so they can evaluate the problem, which may include removing you from the chamber.

To minimize risks a questionnaire will be filled out which will screen you for any potential variables that could cause an adverse effect in the chamber to prevent you from participating in the first place. This includes medical conditions, illnesses, and medication/drug use. It is important that you are honest on these forms to help ensure your safety.

How do I agree to participate in this research?

A consent form must first be signed which will be presented to you immediately prior to your first session, before any testing has commenced, to give you time to ask questions after being shown what will happen in the lab. Your participation in this research is voluntary (it is your choice) and whether or not you choose to participate will neither advantage nor disadvantage you. You are able to withdraw from the study at any time. If you choose to withdraw from the study, then you will be offered the choice between having any data that is identifiable as belonging to you removed or allowing it to continue to be used. However, once the findings have been produced, removal of your data may not be possible.

What are my rights as a participant?

- Your participation is entirely voluntary
- You have the right to withdraw at any time without reason
- You may request your data be withdrawn from the study within 3 months of participation
- Your identity is strictly confidential and no identification of your or your data will be made during the data collection or in publications that arise from the research findings
- You are encouraged to consult with your family/whanau, iwi or hapu regarding participation in this study.

What do I do if I have concerns about this research?

Any concerns regarding the nature of this project should be notified in the first instance to the Project Supervisor, Andrew Kilding, andrew.kilding@aut.ac.nz, 09 921 9999 ext 7056

Concerns regarding the conduct of the research should be notified to the Executive Secretary of AUTEC, Kate O'Connor, *ethics@aut.ac.nz* , 921 9999 ext 6038.

Confidentiality
All information you provide and information obtained from you will be managed confidentially by de-identifying all data pertaining to you. All personal details obtained from you in the study will be stored in a locked cupboard in the SPRINZ ethics data storage facility, that only the researchers and the SPRINZ ethics offical have access to. It will be stored indefinitely as it may be required to assist with future military or sport related heat questions. You may request your personal details to be destroyed at any time.

Compensation
In the unlikely event of a physical injury as a result of your participation in this study, rehabilitation and compensation for injury by accident may be available from the Accident Compensation Corporation, providing the incident details satisfy the requirements of the law and the Corporation's regulations.

Further Information and Contact Details
For any further information about the study please contact either Edward Ashworth or Andre Kilding

Edward Ashworth
Email: Edward.ashworth@aut.ac.nz
Phone: 0211532216

Associate Professor Andrew Kilding
Email: andrew.kilding@aut.ac.nz
Phone: 09 921 9999 ext 7056

Approved by the Auckland University of Technology Ethics Committee on *24th July 2018*, AUTEC Reference number *18/195*

10.2.1.3 Chapter 7

AUT Millennium
17 Antares Place, Rosedale
Auckland, New Zealand

Date Information Sheet Produced: 27th September 2019

PARTICIPANT INFORMATION SHEET FOR VOLUNTEERS

Cognitive Performance in the Heat, During Exercise

Researchers: Edward Ashworth BSc (Hons), Professor Andrew Kilding PhD

We would like to invite you to take part in a research study. Before deciding whether you would like to take part it is important for you to understand why the research is being done and what it could involve for you, so take the time to read the following information carefully. Feel free to discuss it with others, and to ask us if anything is unclear or you would like more information. Take your time to decide whether or not you wish to take part.

What is the purpose of the study?
Soldiers often struggle to perform in the heat when they are deployed overseas so in this study, we are investigating strategies to overcome this decline in performance. Cognitive performance is an area that is incredibly important but is under-investigated in these environments. We want to test cognitive performance in simulated extreme environments (heat and humidity) soldiers are often exposed to, and then to find ways that we can overcome these effects. We hope to use the findings from this study to inform heat acclimation strategies for use within the military. Furthermore, the results of this study will be used in academic publications and presentations.

Eligibility:
You will be eligible for the study if:

- You are currently taking part in exercise several times a week

However, you will be ineligible if:

- You have had a prior heat illness
- You have been ill in the past month
- You are currently injured
- You are taking a medication that interferes with exercise or thermoregulatory function
- You have a cardiovascular condition, or have a family history of heart conditions

Why have I been invited?
You have been invited as you responded to an advert looking for active, healthy individuals. This means that you will likely respond to the heat in a similar manner to military personnel which allows the research findings to be implemented within the military.

What will I have to do?

Overview

You will be required to complete three cognitive testing sessions, at AUT Millennium, Rosedale, North Shore City, Auckland. Each test will take ~2 hours, depending on how long it takes your body to heat up, and the tests will be separated by at least 1 week, but no more than 3 weeks.

There will be a familiarisation session, then three experimental sessions that involve being tested under three different conditions as follows:

- Neutral body temperature
- Elevated body temperature
- Elevated body temperature with cooling

The order in which you complete these sessions will be allocated randomly.

Familiarisation

A familiarisation session will take place prior to the experimental sessions to get you familiar with the cognitive tests that will be administered. This will help ensure that you are used to the tests at the time of the first session. This session will take ~30 minutes.

Experimental Sessions

Pre-heating

Prior to each session you will be pre-heated in a spa pool to raise your core temperature to 38.5°C. So we can accurately measure your core temperature, you will be required to privately self-insert a rectal thermometer so we can continuously monitor you during the spa and subsequent cognitive testing. You will then sit in the spa pool submerged up to the armpit until your core temperature reaches this desired temperature. Every 10 minutes you will be sat up near the side of the pool to allow a bit of cooling for 2 minutes before going back into the spa. During this time, you will have your perceptual measures take, including measures of thermal comfort and sleepiness so we can carefully monitor you throughout. Furthermore, you will have unrestricted access to water during this phase. When the target core temperature is reached you will exit the spa pool. Depending on what trial you are completing the next step differs.

Figure 1. Experimental set-up for Heat-Stress Tests

In both the elevated body temperature sessions you will wrap up in a jumper and trackpants (provided) and immediately be escorted to the heat chamber (~1 min) to change into the military clothing. You may be required to lightly cycle if your body temperature is dropping too fast, but once stable we will begin exercise and cognitive testing.

In the neutral body temperature trial, you will instead cool down around the spa pool, and after a few minutes be allowed to dip your legs into a cold-water pool to accelerate the cooling process. Once this reaches the core temperature you started at you will be taken to the heat chamber for exercise and cognitive testing.

Cognitive Testing

You will put on a sun hat, long trousers and a long-sleeved shirt provided by the military as well as a 20 kg body-armour vest. Skin temperature sensors will also be place on your bicep, chest, thigh and calf, with a heart-rate monitor placed around your chest. In addition to this a near-infrared spectroscopy device will be place on your forehead, above one of your eyebrows. You will then begin to walk on a treadmill at 5km/h. During the first 5 minutes you will get used to the speed of the treadmill and during this gas analysis will also be taken which involves breathing into a tube using a snorkel-like mouthpiece for ~4 minutes. Following this the cognitive battery will begin. The whole battery will take ~30 minutes with 1 minute breaks between each task. During the breaks perceptual measures of thermal comfort and rate of perceived exertion will be asked. The tasks used will be as detailed below:

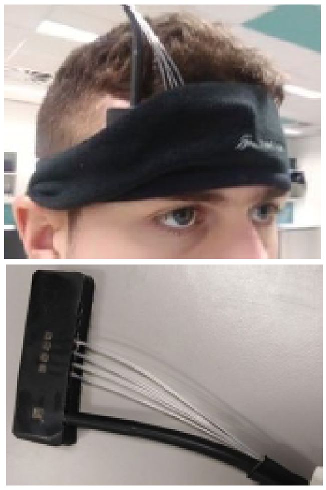


Figure 2. NIRS unit that will be placed on the forehead, and secured in place using a headband.

Digit Span Task

This assesses working memory and requires listening to a series of digits and then repeating them back, but in the reverse order to what they were presented in (i.e. 123 becomes 321). This task will progressively get harder.

Trail-making Test

This task assesses executive function and cognitive flexibility. The task requires connecting circles in numerical order (1, 2 ,3…), and then connecting circles in alternating alpho-numerical order (1, A, 2, B, 3…). This is similar to connect the dots for children.

Cued Reaction Time

This reaction time task assesses your ability to respond to a stimulus when prompted to react, but at times you will be prompted and then asked not to react. This allows us to assess your ability to prevent a pre-planned action.

Vigilance Task

This task involves watching a clock hand tick around. Occasionally the hand will jump a second, and when this happens you are asked to respond.

Where's Wally

This task involves searching images to find Wally, a children's book character.

Navon Task

This task asks you to identify certain letters when they are presented within an image, allowing assessment of your perceptual processing.

Memory Map

A map will be presented to you to memorise. 20-30 minutes later you will be asked to recall the map with a series of pre-set questions.

After completing cognitive testing finishes then a further 3-4 minutes of gas analysis will take place after which testing is finished and you will be escorted out of the chamber and allowed to recover, before privately providing a urine sample so we can assess your hydration. This can then be used to ensure you are adequately hydrated before leaving the lab, as well as being a potential marker of cognitive ability.

The cognitive testing component is identical in each of the trials except for in the cooling condition where you will either be able to use a menthol (mint) mouth-rinse or menthol chewing gum throughout the testing period.

Information for Female Participants
Female participants should be aware that their menstrual cycle will alter their core body temperature. Because core body temperature is a major variable that the experiment depends upon, female participants will need to complete all their tests while in the follicular phase of their cycle. To ensure this, females will be asked to provide and record their menstrual cycle. This will help us to judge when you are in the follicular phase and advise you around the timing of your sessions.
Because the session is very sensitive to resting core temperature, we may have to turn you away from a session if your core temperature is higher than it would be anticipated to be if you were in the follicular phase.

The effects of oral contraceptive pills often maintain a stable core temperature due to their physiological effects and therefore participants taking an oral contraceptive may not have to worry about the above.

What are the costs of participating in this research?
The main cost of your participation will be time. We expect each session to last ~2 hours, but this may be longer or shorter depending on how quickly your body heats up which is a very individually specific thing. Therefore, the whole study will take ~6.5 hours.

What are the benefits?
As someone partaking in the research you will receive a detailed report of how your cognitive ability is affected by the heat and how that compares to other people. For the researchers the study will be used as part of a PhD qualification and for academic publications. The military will benefit from this study as it will help inform heat strategies to be implemented within the defence force.

What if there is a problem?
Problems inherently exist with exercise and with the heat. You have the right to remove yourself from the trial at any point, without any questions being asked. If you experience a problem at any point during the test or trial, you are encouraged to notify the researcher immediately so they can evaluate the problem, which may include removing you from the chamber.

To minimize risks a questionnaire will be filled out which will screen you for any potential variables that could cause an adverse effect in the chamber to prevent you from participating in the first place. This includes medical conditions, illnesses, and medication/drug use. It is important that you are honest on these forms to help ensure your safety.

How do I agree to participate in this research?
A consent form must first be signed which will be presented to you immediately prior to your first session, before any testing has commenced, to give you time to ask questions after being shown what will happen in the lab. Your participation in this research is voluntary (it is your choice) and whether or not you choose to participate will neither advantage nor disadvantage you. You are able to

withdraw from the study at any time. If you choose to withdraw from the study, then you will be offered the choice between having any data that is identifiable as belonging to you removed or allowing it to continue to be used. However, once the findings have been produced, removal of your data may not be possible.

What are my rights as a participant?

- Your participation is entirely voluntary
- You have the right to withdraw at any time without reason
- You may request your data be withdrawn from the study within 3 months of participation
- Your identity is strictly confidential and no identification of your or your data will be made during the data collection or in publications that arise from the research findings
- You are encouraged to consult with your family/whanau, iwi or hapu regarding participation in this study.

What do I do if I have concerns about this research?

Any concerns regarding the nature of this project should be notified in the first instance to the Project Supervisor, Andrew Kilding, andrew.kilding@aut.ac.nz, 09 921 9999 ext 7056

Concerns regarding the conduct of the research should be notified to the Executive Secretary of AUTEC, Kate O'Connor, *ethics@aut.ac.nz* , 921 9999 ext 6038.

Confidentiality

All information you provide and information obtained from you will be managed confidentially by de-identifying all data pertaining to you. All personal details obtained from you in the study will be stored in a locked cupboard in the SPRINZ ethics data storage facility, that only the researchers and the SPRINZ ethics offical have access to. It will be stored indefinitely as it may be required to assist with future military or sport related heat questions. You may request your personal details to be destroyed at any time.

Compensation

In the unlikely event of a physical injury as a result of your participation in this study, rehabilitation and compensation for injury by accident may be available from the Accident Compensation Corporation, providing the incident details satisfy the requirements of the law and the Corporation's regulations.

Further Information and Contact Details

For any further information about the study please contact either Edward Ashworth or Andre Kilding

Edward Ashworth
Email: Edward.ashworth@aut.ac.nz
Phone: 0211532216

Professor Andrew Kilding
Email: andrew.kilding@aut.ac.nz
Phone: 09 921 9999 ext 7056

Approved by the Auckland University of Technology Ethics Committee on *11/12/2019*, AUTEC Reference number *19/368*

10.2.2 Consent Forms

10.2.2.1 Chapter 3

Consent Form

I, ____, hereby agree to voluntarily participate in the study "Determinants of Endurance Performance in Heat in the Military".

I recognize, and have been made aware of the risks and dangers that are involved with the protocol employed in this study. I recognize that this could cause injury of severity up to and including death.

I have been made aware of my rights, and know that I have the right to withdraw from the study at any time without any questions being asked.

I give permission for my prior fitness data to be accessed and used as part of this study.

I have answered questionnaires honestly to allow the researchers to understand my current state of health.

I acknowledge that my commanding officer is aware of my participation in this study but that I have no obligation to share my results with them and this will not influence my career.

I am fully aware of what is going to happen in the research, have had the opportunity to ask questions and questions that I have asked have been answered to my satisfaction.

I wish to receive a full copy of my results by email on completion of the study ☐Yes ☐No
Email: ____

I wish to have my blood samples returned or specially disposed of on completion of the study ☐Yes ☐No
If so, please describe ____

Signed ____

Date: / /

10.2.2.2 Chapters 4-6

Consent Form

Project title: ***Comparison of sauna and hot-water immersion methods for heat acclimation in a military context***
Project Supervisor: ***Andrew Kilding***
Researcher: ***Edward Ashworth***

○ I have read and understood the information provided about this research project in the Information Sheet dated 15th May 2018.

○ I have had an opportunity to ask questions and to have them answered.

○ I understand that taking part in this study is voluntary (my choice) and that I may withdraw from the study at any time without being disadvantaged in any way.

○ I have not been coerced into participating in any way.

○ I understand that if I withdraw from the study then I will be offered the choice between having any data or tissue that is identifiable as belonging to me removed or allowing it to continue to be used. However, once the findings have been produced, removal of my data may not be possible.

○ I am not suffering from heart disease, high blood pressure, any respiratory condition (mild asthma excluded), any illness or injury that impairs my physical performance, or any infection, and have answered the participant screening questionnaire honesty and to the best of my ability.

○ I understand that the thermal imaging will be unable to identify me and will be used for academic purposes only and will not be published in any form outside of this project without my written permission.

○ I agree that my data will be stored confidentially and securely indefinitely, to assist with other heat acclimation studies

○ I agree to provide blood samples.

○ I agree to take part in this research.

○ I wish to receive a summary of the research findings (please tick one): Yes○ No○

○ I wish to have my blood samples returned to me in accordance with right 7 (9) of the *Code of Health and Disability Services Consumers' Rights* (please tick one): Yes○ No○

○ I wish to have my urine samples returned to me in accordance with right 7 (9) of the *Code of Health and Disability Services Consumers' Rights* (please tick one): Yes○ No○

Participant's signature: ....

Participant's name: ....

Participant's Contact Details:

....

....

....

....

Date: |

Approved by the Auckland University of Technology Ethics Committee on type the date on which the final approval was granted AUTEC Reference number type the AUTEC reference number

Note: The Participant should retain a copy of this form.

10.2.2.3 Chapter 7

Consent Form

Project title: ***Cognitive Performance in the Heat, During Exercise***
Project Supervisor: ***Andrew Kilding***
Researcher: ***Edward Ashworth***

(Please tick circles as appropriate)

○ I have read and understood the information provided about this research project in the Information Sheet dated 27th September 2019.

○ I have had an opportunity to ask questions and to have them answered.

○ I understand that taking part in this study is voluntary (my choice) and that I may withdraw from the study at any time without being disadvantaged in any way.

○ I have not been coerced into participating in any way.

○ I understand that if I withdraw from the study then I will be offered the choice between having any data or tissue that is identifiable as belonging to me removed or allowing it to continue to be used. However, once the findings have been produced, removal of my data may not be possible.

○ I am not suffering from heart disease, high blood pressure, any respiratory condition (mild asthma excluded), any illness or injury that impairs my physical performance, or any infection, and have answered the participant screening questionnaire honesty and to the best of my ability.

○ I agree that my data will be stored confidentially and securely indefinitely, to assist with other heat acclimation studies

○ I agree to take part in this research.

○ I wish to receive a summary of the research findings (please tick one): Yes○ No○

○ I wish to have my urine samples returned to me in accordance with right 7 (9) of the *Code of Health and Disability Services Consumers' Rights* (please tick one): Yes○ No○

Participant's signature: ....

Participant's name: ....

Participant's Contact Details:

....

....

....

....

Date:

Approved by the Auckland University of Technology Ethics Committee on 11/12/2019 AUTEC Reference number 19/368

Note: The Participant should retain a copy of this form.

10.3 Appendix C – Statistical Coding Exemplars

10.3.1 Linear Mixed Model ANOVA

```
ct <- lmer(core_temperature ~ condition + time + (1|participant_number), data = cog)
summary(ct)
```

10.3.2 Post Hoc Pairwise Comparisons

As above (9.3.1) then:

```
emmeans(ct, ~ condition, contr = mat2, adjust = "holm")
```

Where:

```
mat2 <- data.frame(c.1 = c(1, -1, 0),
            c.2 = c(1, 0, -1),
            c.3 = c(0, 1, -1))
```

10.3.3 Linear Regression

```
reg <- lm(formula = walking_time ~ sleepch, data = study1)
summary(reg)
```

10.4 Appendix D – Cognitive Task Exemplars

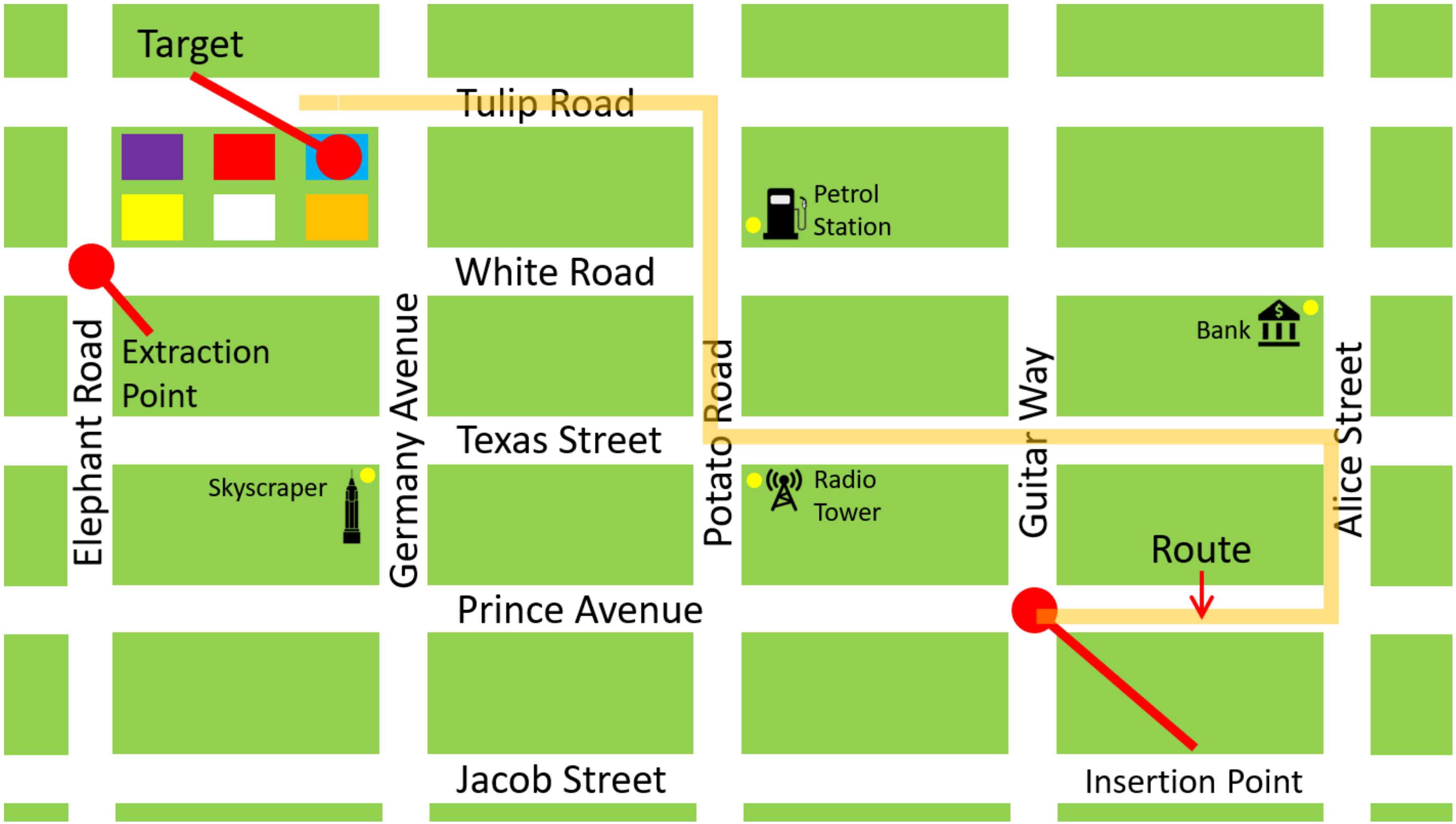
10.4.1 Serial Arithmetic

	Start #	Instruction	Start #	Instruction	Start #	Instruction	Start #	Instruction
	9427	-7	3851	-13	6214	-7	5219	-13
	Target #	Actual #	Target #	Actual #	Target #	Actual #	Target #	Actual #
1	9420		3838		6207		5206	
2	9413		3825		6200		5193	
3	9406		3812		6193		5180	
4	9399		3799		6186		5167	
5	9392		3786		6179		5154	
6	9385		3773		6172		5141	
7	9378		3760		6165		5128	
8	9371		3747		6158		5115	
9	9364		3734		6151		5102	
10	9357		3721		6144		5089	
11	9350		3708		6137		5076	
12	9343		3695		6130		5063	
13	9336		3682		6123		5050	
14	9329		3669		6116		5037	
15	9322		3656		6109		5024	
16	9315		3643		6102		5011	
17	9308		3630		6095		4998	
18	9301		3617		6088		4985	
19	9294		3604		6081		4972	
20	9287		3591		6074		4959	
21	9280		3578		6067		4946	
22	9273		3565		6060		4933	
23	9266		3552		6053		4920	
24	9259		3539		6046		4907	
25	9252		3526		6039		4894	
26	9245		3513		6032		4881	
27	9238		3500		6025		4868	
28	9231		3487		6018		4855	
29	9224		3474		6011		4842	
30	9217		3461		6004		4829	

10.4.2 Digit Span

Participant						Date						Trial Number							
Score						Test Start						Test End							
2		7		8															
9		4		6															
3		7		1															
8		4		9		2													
5		7		4		2													
4		0		1		2													
1		3		0		4		8											
7		9		8		2		4											
3		7		5		0		8											
1		2		6		7		3		0									
2		4		5		1		3		9									
7		9		2		6		4		1									
5		1		3		9		7		5		2							
2		6		4		1		5		3		8							
9		8		1		4		0		2		3							
6		2		9		3		2		4		3		1					
8		3		0		8		1		8		7		4					
0		4		5		2		8		9		1		6					
2		7		2		8		6		7		5		2		6			
9		5		2		1		7		0		2		9		3			
4		2		8		6		4		2		3		5		1			
7		4		2		0		3		8		9		6		2		1	
6		5		9		1		4		8		0		7		3		9	
4		0		2		7		1		3		2		8		6		7	

10.4.3 Memory Maps



Map 1 Questions

Which 5 roads are on your route? (5)

In what order do you make left/right turns on your route? (4)

On the intersection of which 2 roads is your insertion point? (2)

On the intersection of which 2 roads is your extraction point? (2)

What two landmarks do you pass on your route? (2)

What roads are surrounding the compound where the target house is located? (4)

What colour is the target house? (1)

Do you turn left or right from the road to reach the target house? (1)

Which road marks the areas southern boundary? (1)