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MASTER OF SCIENCE BY RESEARCH

Physiological, perceptual and cognitive responses to head compared to torso cooling during explosive ordnance disposal (EOD) related activity in moderate and hot conditions

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Award date:
2012

Awarding institution:
Coventry University

Link to publication

Physiological, Perceptual and Cognitive Responses to Head compared to Torso Cooling during Explosive Ordnance Disposal (EOD) Related Activity in Moderate and Hot Conditions

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A thesis submitted in partial fulfilment of the University's requirements for the degree of Master of Science (by Research) in Applied Physiology

2012

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University

ACKNOWLEDGEMENTS

Firstly, I would like to express my indebtedness to my supervisor, Dr Doug Thake, for his time and what appeared to be an unlimited level of knowledge and expertise, combined with his enthusiastic and insightful approach to research that was both inspiring and encouraging throughout all aspects of my Masters course.

I am extremely grateful to the company NP Aerospace Ltd, particularly Mr Mark Oldroyd, for providing the financial support, materials and equipment required to conduct this study.

Furthermore, thanks goes to the laboratory technicians Mr Roy Petticrew and Mrs Susan Wilson and the work experience students Mark Smith and Vikki Groves for their time, effort and assistance throughout the practical elements of the project.

Fellow masters students, Nick Saxton, Kate Simmons, and Nicky Talbot offered much needed support and for that I am extremely grateful and appreciative.

I owe an unlimited thanks to the participants of this study; for the time they gave up, combined with their efforts and support throughout the data collection period.

Lastly, I am incredibly grateful to all my family and friends for their patience and encouraging nature throughout the practical and written aspects and I know that without that this course would have been much harder to complete.

Many Thanks to All

ABSTRACT

AIM: This study aimed to investigate and compare the physiological, cognitive and cardiovascular responses during explosives ordnance disposal (EOD) type activity in moderate and hot environments whilst wearing an EOD suit and phase change material cooling garments on either the head or torso.

METHODS: Following ethical approval from Coventry University's Ethical Committee, and after providing informed consent, six healthy, unacclimatised males took part in the study (age: 23 (3) yrs; height: 1.74 (0.05) m; mass: 65.1 (2.0) kg). Each participant underwent 9 sessions performed on separate days consisting of; three pre-trial practice sessions (no EOD suit worn), one trial familiarisation session (light-weight EOD suit worn) and six experimental sessions (consisting of 6 experimental trials; light-weight EOD suit worn), with a week separating the familiarisation and each experimental session. The experimental trials involved six separate conditions, two without cooling (20NC and 40NC), two with head cooling (20HC and 40HC) and two with torso cooling (20TC and 40TC) performed at 20 °C and 40 °C. Conditions were applied in a randomised cross-over type design. Cooling consisted of a phase change material (PCM) scrum cap (head cooling) and PCM vest (torso cooling) donned by the participant prior to wearing a light-weight 3010 Ergotec EOD suit 15 minutes before each trial. Each trial consisted of 6 activity stations; 1. Treadmill walking (4 km·hr^{-1}); 2. Manual loading; 3. Searching and crawling; 4. The postural challenge; 5. Unloaded arm ergometry (60 rev·min^{-1}); 6. The spatial working memory (SWM) test, performed 4 times through to make up 4 cycles lasting a total of 80 minutes per trial.

RESULTS: There was an increase in physiological, perceptual and cardiovascular strain with duration in all conditions. Physiological strain was greater in 40 °C air than in 20 °C air ($p<0.001$). The heart rate (HR), core temperature (T_{cP}), skin temperature (T_{sk}), chest temperature (T_c), rate of percieved exertion (RPE), thermal sensation (T_{hS}) and thermal comfort (T_{hC}) responses (excluding T_f) were lowest during the 20TC trial when compared to 20HC and 20NC. At 40 °C, the physiological strain was reduced with both cooling condidions (40HC and 40TC). During 40HC, T_{cP}, T_f, and PhSI, were lowest for upto 60 minutes of activity (3 cycles) when compared to 40NC. 40TC produced the lowest T_{sk} responses for up to 60 minutes of activity (3 cycles) and T_c responses throughout the 80 minute trial, compared to 40NC and 40HC. The recovery of mean arterial blood pressure (MAP) was not comprimised in response to standing at 40 °C, however during both cooling trials within the first cycle at 20 °C MAP did not recover back to the pre-stand reponse. At 40 °C, HR peaked significantly post-stand and remained greater than that during the pre-stand response. Completion speed of the cognitive spatial working memory test was greatest during the final cycle of activity, ($p<0.017$).

CONCLUSION: At 20 °C torso cooling created the most benefit when compared to head cooling at reducing the physiological and perceptual strain experienced. At 40 °C, both cooling methods (TC and HC) were effective at lowering the physiological, perceptual and cardiovascular strain when compared to the non-cooling control (40NC). The majority of this benefit was observed within the first hour of activity. It is recommended that the torso cooling garment be used within the light-weight EOD suit to reduce the thermal strain experienced at 40 °C, and that when using the light-weight EOD suit at 20 °C the PCM cooling garments are not required as the physiological strain experienced at this temperature is less than that experienced at 40 °C.

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ACRONYMS & ABBREVIATIONS

20NC – No phase change material worn within the EOD suit at 20 °C

20HC – Head cooling scrum cap worn within EOD suit at 20 °C

20TC – Torso cooling vest worn within EOD suit at 20 °C

40NC - No phase change material worn within the EOD suit at 40 °C

40HC - Head cooling scrum cap worn within EOD suit at 40 °C

40TC - Torso cooling vest worn within EOD suit at 40 °C

ANOVA – Analysis of Variance

BP – Blood Pressure

EOD – Explosive Ordnance Disposal

HC – Head cooling

HR – Heart Rate

HS – Heat Storage

MAP – Mean Arterial Pressure

n – Number of Sample

NC – No cooling

PCC – Personal Protective Clothing

PCM – Phase Change Material

PeSI – Perceptual Strain Index

PhSI – Physiological Heat Strain Index

Q – Cardiac Output

RH – Relative Humidity

RPE – Rating of Perceived Exertion

SkBF – Skin Blood Flow

$S\dot{R}$ – Sweat Rate

T_{au} – Aural Temperature

T_{amb} – Ambient Temperature

T_c – Chest Temperature

TC – Torso cooling

T_{cP} – Gastrointestinal Pill Temperature

T_f – Forehead Temperature

T_{hC} – Thermal Comfort

T_{hS} – Thermal Sensation

T_{re} – Rectal Temperature

T_{sk} – Skin Temperature

T_{ty} – Tympanic Temperature

UHS – Uncompensable Heat Stress

1. INTRODUCTION

Personal protective clothing (PPC) is impermeable and designed to protect operatives from harmful and in some cases potentially life-threatening environments. The type (weight, thickness, and coverage) of clothing depends on the level of protection required. Problems arise because the PPC results in a thermal layer of air that forms between the suit and skin surface. This layer is known as the microclimate which can potentially limit the rate of heat exchange between the skin and external environment (Holmer *et al.* 1999; Parsons *et al.* 1999). When the evaporative capacity of the environment is less than the required evaporative capacity for efficient skin surface cooling, a situation of uncompensable heat stress (UHS) ensues (Cheung, McLellan and Tenaglia 2000). The body can no longer thermoregulate efficiently; heat becomes stored, increasing physiological and perceptual strain. UHS is exacerbated by the impermeable properties, and the mass of PPC worn, high ambient temperatures (>35 °C), physical activity (increasing metabolic heat production), and ineffective cooling; leading to hyperthermia, heat illness and if untreated – death (Taylor 2006). Operatives' safe work time is therefore determined by the severity of UHS which further determines the rate of onset of hyperthermia. Thus, reducing the severity of UHS and rate of increase in heat storage is key to maintaining operative performance and extending safe work limits (Taylor and Orlansky, 1993).

Cooling methods have been devised to attenuate the rise in heat storage, and reduce the consequent heat strain of individuals that can arise whilst wearing protective clothing. Examples of these include conductive and convective mechanisms that use air, water, ice or a combination of air and water as a means of cooling the skin surface in an attempt to lower the rate of rise in core body temperature during periods of exercise and/or enhance heat loss during rest.

Research has been based upon the effectiveness of localised skin cooling of different regions of the body, as well as whole body cooling. In particular many studies have been conducted surrounding cooling of the torso and/or the head, and in addition whilst wearing personal protective clothing. This is presumed to be because the chest, back and head are high in thermal sensitivity and thus are likely to produce greater reductions in body temperature. By not cooling the entire body the mass of any cooling garment worn is lighter, possibly improving comfort of the wearer, there is a reduction in the layers that need to be worn (if conductive cooling) and potentially cost of use.

Cooling the head and torso beneath PPC has been found to be effective at reducing body temperature, sweating rate, and the perceived exertion, whilst also improving the thermal comfort of individuals. This thesis sets out to compare the physiological, cardiovascular, perceptual and cognitive responses to both types of cooling when worn beneath an Explosives Ordnance Disposal suit during various representative activities within moderate and hot environments. Thus, the following aims, objectives and hypotheses were determined:

1.1. AIMS

1. To investigate and compare the physiological, perceptual and cognitive responses to EOD related activity in a light-weight EOD suit in 20 °C and 40 °C
2. To investigate and compare the cardiovascular response to standing (from kneeling) during an EOD related activity sequence in a light-weight suit in 20 °C and 40 °C

3. To investigate and compare the influence of cooling the head to cooling the chest upon these responses (physiological, perceptual, cognitive and cardiovascular) to EOD activity in a light-weight EOD suit in 20 °C and 40 °C

1.2. OBJECTIVES

1. To assess these aims using six conditions; head cooling at 20 °C and 40 °C, chest cooling at 20 °C and 40 °C, no cooling at 20 °C and 40 °C.
2. To measure physiological responses using three core temperature sites, five skin temperature sites, heart rate (HR), and body mass.
3. To measure perceptual responses using the rate of perceived exertion (RPE) scale, thermal sensation (T_{hS}) and thermal comfort (T_{hC}) scales.
4. To measure cognitive responses using a specific psychological spatial working memory (SWM) test on a touch screen computer.
5. To measure cardiovascular responses to standing using a digital-arterial non-invasive blood pressure device known as the Portapres Model II.
6. To apply conductive localised skin cooling to the head and chest with the use of phase change material set to a phase change (solid $\longleftrightarrow$ liquid) of 25 °C .

1.3. HYPOTHESES

1. Physiological and perceptual responses will increase, with a reduction in cognitive performance at 40 °C when compared to 20 °C.
2. Cardiovascular strain (HR and BP) in response to standing (from kneeling) will be greatest in 40 °C when compared to 20 °C.
3. Torso cooling will produce the greatest reduction in physiological strain and perception of strain, when compared to head cooling at both 20 °C and 40 °C.

4. Torso cooling will produce the greatest reduction in cardiovascular strain when compared to head cooling at both 20 °C and 40 °C.

2. LITERATURE REVIEW

2.1. THERMOREGULATION AND THE PRINCIPLES OF HEAT TRANSFER

At rest, within most cells of the human body, a state of thermal equilibrium (core body temperature of ≈37±0.5 °C) is present (Taylor 2006; Lim, Byrne, and Lee 2008). The hypothalamus in the brain receives afferent information from the thermoreceptors in the skin and dictates whether the body should initiate the process of cooling down (through the stimulation of sweat glands and increased skin blood flow by vasodilatation) or warming up (by vasoconstriction of the cutaneous blood vessels, increasing metabolic activity, and thermogenesis (Charkoudian 2003). The inability of an individual to thermoregulate can result in serious consequences, such as the onset of hypothermia or hyperthermia and ultimately death. Thus, the transfer and removal of heat, both within the human body and between the skin and the surrounding environment is vital for survival (Taylor 2006).

Conduction, convection, radiation and evaporation are all forms of heat exchange. At normal room temperature (≈22 °C) and during rest, heat is transferred internally from the core to the periphery by vascular conductance where it is lost to the environment (Benzinger 1959). When the body comes into contact with cooler objects heat will be lost through conductive transfer. In addition, convective air flow, and electro-magnetic radiation also dissipate heat to the surrounding environment provided the air and surrounding objects are cooler than skin surface temperature (≈27 °C to 35 °C; Burton 1935).

In hotter climates, where the surrounding environmental temperature is greater than skin temperature, heat is gained by the process of radiation, conduction and convection and in such conditions; the body has to rely solely on the evaporation of sweat for cooling. However, the evaporation of sweat can be limited by the evaporative capacity of the surrounding environment. Increases in the relative humidity (RH) reduce the capacity for water vapour resulting in increases in skin wettedness and a reduction in the rate of heat removal (Cheung, McLellan and Tenaglia 2000).

The rate of heat gain or removal between humans and the environment is governed by thermal gradients. The gradient between the core and the skin and the skin surface and external environment is ever changing and influenced by many factors (see Figure 2.1), for example; the rate of metabolic heat production (effected by level of activity), ambient temperature (T_{amb}; °C), core temperature (T_{re}; °C), skin temperature (T_{sk}; °C), wind speed (m s^{-1}), radiant heat (the sun), including types of clothing worn and the number of layers (creating additional micro-environments). All of these factors in combination dictate the rate and direction of heat exchange (Havenith 1999).

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Figure 2. 1: Schematic of the microclimate-skin-core relationship in relation to heat transfer. M=Metabolic Heat Production (internal heat source). T_{amb} = Ambient Temperature (external heat source; Cheung, McLellan and Tenaglia 2000).

2.2. MEASURING STRAIN WITHIN PROTECTIVE CLOTHING

2.2.1. PHYSIOLOGICAL STRAIN

Heart rate (HR) measured by the use of a heart rate monitor (Sports Tester; Polar Electro Oy) or Electrocardiogram (ECG) has been used as an index of physiological strain during a range of laboratory and field based settings both with and without personal protective clothing (PPC; Barnett and Maughan 1993; McLellan *et al.* 1996; Lafrenz *et al.* 2007) and has been shown to increase, when wearing PPC, compared to normal sports-wear, within physically active males (Turpin-Legendre and Meyer 2006).

Core temperature has been measured using various sites around the body. The rectum is one example, whereby a rectal thermometer is inserted past the anal sphincter and taped to the skin. This method is a valid and reliable measure of core temperature, widely used to monitor fluctuations in core temperature of humans under various conditions, most commonly within sporting environments to monitor temperature fluctuations in athletes (Casa *et al.* 2007). However brain temperature is usually slightly greater in temperature than any other site, and the delay that can occur as heat dissipates through deep body tissue means safety is an issue with increasing core temperature and anyone using a rectal thermometer should be aware of this by setting low hyperthermic cut-off limits (Lim, Byrne and Lee 2008).

Thus, in the interest of safety, when measuring core temperature, some studies have combined the use of the rectal thermometer with the use of an aural thermistor (Thake *et al.* 2009b). The aural thermistor is placed close to the tympanic membrane and responds faster to fluctuations in core temperature than the rectal thermometer. This therefore allows for a more immediate indication of whether heat is being stored or lost by the body.

However in a further interest of safety, the difference in the temperature measured rectally compared to aurally should be noted, especially if the aural thermistor was used as a standalone measure of core temperature. This is due to the position of these sites within the body and that deep tissue temperature is likely to be greater than that of superficial tissue temperature (Lim, Byrne and Lee 2008).

Oesophageal temperature (Tes) measures may not always be appropriate if participants are ingesting water or are the type that could interfere with breathing apparatus or oxygen consumption ($\dot{V}O_2$) measures. Telemetric pill sensors measure core body temperature from within the gastrointestinal (GI) tract (Casa *et al*. 2007). They are more comfortable for the participant and easier to administer than the T_{re} but are limited by the affect of water ingestion and time. They require swallowing approximately two hours before experimental testing, for the pill to be thoroughly within the GI tract and to produce reliable readings for approximately 8 hours, (Waterhouse *et al*. 2005; Lim, Byrne and Lee 2008).

Skin temperature can be measured using thermistors, placed at different sites of the body. Attaching thermistors to specific sites such as the forehead, or chest, make it possible to assess the direct impact of passively or actively cooling or heating those areas. Mean skin temperature (T_{sk}) can be calculated from individual skin temperatures using various methods that assign skin sites with specific weightings according to their body surface area (BSA) and/or thermal sensitivity (Ramanathan 1964). Overall body temperature (Tb) can be used to assess how the localised cooling/heating effects the whole body, by combining specified weightings of T_{sk} (0.2) and core temperature (0.8). Furthermore, changes in heat storage capacity of the body over time can be calculated from these variables and used as an additional measure of physiological strain. Although this method is potentially flawed as during UHS the core to skin gradient reduces and thus the specified weightings would need to change in accordance with this.

It has been found that careful attention should be paid when affixing skin thermistors to the participant and that uncovered thermistors produce the most accurate readings of skin temperature, with covered thermistors preventing heat loss surrounding the measured site and consequently causing an increase in the readings. The greatest difference was found to be 1.3 °C between the covered vs. uncovered sites when compared within a thermoneutral environment. This impact may be less when the EOD suit is worn due to its encapsulating nature. Difficulty arises when conducting studies in the heat, and covering them is required to ensure they remain in position. Therefore, when tape is required the application of skin thermistors should be conducted in the same way each time with the same type and amount of tape (Buono and Ulrich 1998).

2.2.2. PERCEPTUAL STRAIN

Subjective measures of physiological and thermal strain, include Borg's (1974) 15 point rate of perceived exertion (RPE; 6 to 20) scale and the perceptions of thermal strain (PTS) scales by Young *et al*. (1987). Smith *et al*. (2001) used these to measure the effects of strenuous live fire-fire fighting drills. They were also used to assess thermal comfort, and effort of men when exercising in EOD protective clothing (Thake and Price 2007). Other methods of measuring thermal comfort have been for the participant to draw lines between 0 (perfectly comfortable) to 10 cm (absolutely intolerable) that equate to the extent of comfort experienced (known as a semantic differential; Nunneley and Maldonado 1983). These measures need to be clearly explained as they are open to misinterpretation by the participant, and so all participants need to understand the scales before experimental tests commence. The scales used by Nunneley and Maldonado (1983) may be difficult to include in the following study for a combination of reasons; the participants will be exercising whilst in moderate and hot environments, thus they are likely to have sweaty palms and fingers and so a verbal response may more feasible and require less time. However, if the scales used required a verbal response then this may influence the responses of others if more than one participant was being tested at any one time and so the scale used by Nunneley and Maldonado would be the better one to use. This emphasises that the scales used need to be selected carefully based on the design of the study.

2.2.3. PHYSIOLOGICAL AND PERCEPTUAL STRAIN INDICES

Physiological strain can be determined from a range of variables including; T_{re}, HR, $\dot{V}O_2$ and $S\dot{R}$. When observing the changes over time with any one of these variables there is a noticeable rise with increasing intensity of exercise and ambient temperature. To see the main effect that exercise or environmental stressors have on the whole body, these variables need to be combined. Thus, a physiological strain index (PSI) was developed (Moran, Shitzer and Pandolf 1998) that combined normalised HR and T_{re} responses and calculated a value representing on a scale of 0 (no strain) to 10 (very high strain) the degree of whole body physiological strain experienced. The PSI has shown to successfully differentiate between the physiological strain experienced over a range of different hydration status' and exercise intensities extending to heat stress environments, (Moran, Shitzer and Pandolf 1998). However, the PSI uses upper limits of 180 beats·min^{-1} and 39.5 °C for HR and T_{re}, respectively. Therefore, the extent of physical exertion and heat storage experienced by each participant is limited.

Thus, a different Physiological Strain Index (PhSI) was devised (Tikuisis, McLellan and Selkirk 2002) in an attempt to reduce such limitations. The PhSI used a standard baseline value of 60 beats·min^{-1} for resting HR with participants measured HR max as the upper limit, making the index more specific to the individual, although it may still be limiting to physically trained individuals, due to them usually having a lower than the 60 beats·min^{-1} resting heart rate included here.

A perception based strain index (PeSI) that was thought to parallel increases in PhSI, was also developed (Tikuisis, McLellan, and Selkirk 2002). Findings in support of this, have shown significant correlations under different conditions between thermal sensation (0 to 8 scale) and T_{re} (0.72; $p<0.001$; Casa *et al*. 2007). The PeSI also used a 0 (no strain) to 10 (very high strain) scale. PeSI was obtained through calculating normalised ratings of perceived exertion (RPE) and thermal sensation (TS) responses. However, PeSI did not appear to parallel increases in PhSI of individuals that were endurance trained ($\dot{V}O_2$Max; 59.0±6.2 ml·min^{-1}·kg^{-1}) vs. individuals that were untrained ($\dot{V}O_2$Max; 43.6±3.8 ml·min^{-1}·kg^{-1}), and so it is thought that highly trained individuals must underestimate their RPE constituting an underestimated PeSI value. This therefore should be taken into account for safety when testing aerobically fit individuals, although this was within 40 °C 30 % RH ambient environment. Fire-fighters within moderate ambient climates (25 °C and 30 °C) under varying intensities of exercise (Selkirk and McLellan 2003), showed PeSI to also be underestimated when compared to the physiological strain measured (PhSI), of which was not the case at 35 °C, (PeSI, 6.80±1.52; and PhSI, 6.91±0.67). Therefore it would be interesting to compare the disparity (if any) present between PhSI and PeSI at 20 °C and 40 °C and between cooling conditions in the current study.

2.2.4. CARDIOVASCULAR STRAIN (BLOOD PRESSURE CHALLENGES)

When the cardiovascular system has to work hard to meet the demands of the body, heart rate (HR; beats·min^{-1}) increases, and blood pressure (BP; mmHg) fluctuates (dependent upon the situation), both of which indicate a level of cardiovascular strain, (Imholtz *et al.* 1998). Therefore when working within PPC at high ambient temperatures, with increased physical exertion over time, there is a lot of stress placed on the cardiovascular system with regard to attempting to cool the body and maintain BP and as a consequence cerebral blood flow may become compromised, leading to an increased risk of syncopal symptoms as body temperature increases (light-headedness, loss of consciousness, Latzka *et al.* 1998). Syncope presents dangers to EOD operatives in the field with regard to safety and so reducing the risk of syncope with heat stress is of high importance. Therefore, it would be useful to investigate the risk of syncope within the current study and if present, whether skin cooling could provide benefit by reducing the thermal load and consequent cardiovascular strain, (Cui, *et al*. 2005; Wilson, *et al*. 2006).

Measuring HR and BP simultaneously is one method that allows the monitoring of the current cardiovascular state of an individual in response to specific situations or stressors (exercise, orthostasis; Imholtz 1990). Specifically, researchers have detailed the difficulty with supine to or sit to standing manoeuvres and the large drop in BP that results within the first 30 seconds post manoeuvre in moderate environments (Borst, *et al*. 1982; Tanaka, Sjoberg, and Thulesius 1996) and in the heat (Lucas *et al*. 2008). In many instances it is not uncommon that an operative would need to bend down to assess a situation during an operation and thus these findings suggest it would be useful to incorporate a postural challenge manoeuvre within the current study to assess the risk of syncope whilst wearing the EOD suit particularly when the cardiovascular system is under stress and the benefit that cooling may have upon reducing that cardiovascular strain, if present.

The methods that can be used to monitor and measure changes in BP can be categorized into two parts; i) direct invasive methods, ii) indirect non-invasive methods. Direct invasive methods include the measurement of intra-arterial pressure which involves a hollow needle inserted into the brachial or radial artery of the arm or even aortic arch. The needle contains a long thin liquid filled catheter that gets positioned inside the artery, and is ideally stiff, short in size, with a large diameter for accuracy. The catheter is attached to a manometer (pressure gauge) which detects changes in pressure (Van Burgen 1954; Langewouters *et al*. 1998). This method is beneficial with regard to gauging a direct measurement of blood pressure, but requires a trained individual to conduct the procedure; ethical approval and like any invasive procedure carries a risk of infection. There is also incidence for error due to the size and type of catheter used which may cause an overestimation of systolic pressure (Gardner 1981). This would also be a very difficult method to use on exercising volunteers wearing PPC.

Indirect non-invasive methods include the auscultatory, oscillatory and Penaz/Wessling techniques. Using a sphygmommanometer is an example of an auscultatory method, whereby a cuff is applied to the upper arm over the brachial artery and a stethoscope to the artery at the elbow, the cuff is inflated until no pulse is felt at the wrist and then deflated until Korotkoff sounds can be heard (systolic pressure detected), when the sounds are no longer present or muffled, this is taken as the diastolic pressure reading. This method has found to underestimate systolic or overestimate diastolic pressure when compared to invasive methods, (Langewouters *et al*. 1998). Furthermore, earlier research found that accuracy of indirect measurements compared to direct measurements decreased with increasing pressure (Van Burgen *et al*. 1954).

In contrast, later studies have shown that measuring finger arterial pressure (non-invasively) is as reliable in the tracking of BP variability with regard to MAP and Diastolic pressures as invasive methods (Imholtz *et al.* 1998), and in one orthostatic study in response to several orthostatic manouvers, the BP response by Finapres was almost identical to the invasive intra-brachial waveforms (Imholtz *et al.* 1990).

Devices such as the Finapres and (most recent) Portapres (developed for ambulatory use) use the Penaz/Wessling technique to measure non-invasive finger arterial pressure and to allow for continuous 24 hr recordings to be made (Imholtz *et al.* 1998). Furthermore, the most recent Finapres and Portapres devices include a hydrostatic height correction mechanism for correcting that of finger arterial pressure to that of brachial arterial pressure leading to greater alignment with invasive methods, (Guelen *et al*. 2003).

In summary, the Portapres model 2 device has been considered as a reliable and accurate measure of BP during low to moderate levels of stress brought on by exercise (Eckert *et al*. 2002), and appears to be the most reasonable tool to use to monitor cardiovascular strain in response to standing within the current investigation. To date and to current knowledge it has also not so far been used to test the orthostatic response of participants wearing protective clothing.

2.3. PHYSIOLOGICAL RESPONSES TO VARIOUS INTERNAL AND EXTERNAL VARIABLES WHILST WEARING PERSONAL PROTECTIVE CLOTHING (PPC)

Air force pilots (Faerevik and Reinersten 2003), explosive ordnance disposal (EOD) personnel (Frim and Morris 1992), nuclear biological and chemical (NBC) protective workers (Cheung and McLellan 1998), army soldiers (Rayson *et al.* 2000), certain sports players (Godek *et al.* 2004), and fire fighters (Eglin 2006) all wear a form of PPC that has been specifically designed to protect them from harm as a result of the tasks they are required to undertake.

Explosives ordnance disposal (EOD) personnel are required to wear a highly protective encapsulating suit, the type of suit ranges according to the task and manufacturer, two examples are the 3010 and 4010 Ergotec (NP Aerospace Ltd, Coventy, UK) weighing ≈18 kg and ≈37 kg in mass respectively. The EOD personnel are highly trained individuals that will work for as long as it takes to dispose of a potential threat, taking breaks where necessary. They can be deployed to countries all over the world and thus be subjected to environments with high ambient temperatures (≈40 °C). Due to the encapsulating nature of the suit and the weight of the suit, this can lead to UHS. Thus, the internal (metabolic rate, hydration status, fitness capacity) and external (ambient temperature, exercise intensity, load and encapsulation properties of the PPC) factors that may exacerbate or reduce the extent of UHS have been discussed.

2.3.1. LOAD AND ENCAPSULATION

Increasing and decreasing load can influence physiological strain, by contributing to the overall energy expenditure of the individual. Wearing a 20 kg load with normal clothing compared to wearing just normal clothing alone, has shown to result in significant increases in HR and oxygen consumption ($\dot{V}O_2$) of exercising participants, (Keren *et al.* 1981). In support of this HR was found to be ≈ 70beats·min^{-1} greater during the arm ergometry station of the final cycle of activity (after approximately 60 minutes of activity) when a full EOD suit (≈ 37 kg) was worn vs. no EOD suit (Thake and Price 2007), emphasising the physiological strain brought on by wearing an EOD suit during exercise. Therefore, wearing PPC such as the light-weight (≈ 18 kg) or heavy-weight (≈ 37 kg) EOD suit will increase the metabolic rate of the exercising participant and consequently increase the potential for heat storage within the body, as they will be working at a higher percentage of their physical capacity.

Thake and Price (2007) demonstrated the impact of load on an increase in metabolic activity when a lighter-weight trouser configuration was worn compared to that of a full EOD ensemble, with regard to physiological and psychological performance at 40 °C. Both were compared to a control trial whereby no EOD suit was worn. Wearing the suit caused a considerable increase in physiological and perceptual stain (HR, T_{re}, T_{sk}, RPE; $p<0.01$), with sweat production being twice as great as when no suit was worn. This reflected how the encapsulating nature of the suit combined with its mass increased metabolic work rate, impeded necessary heat dissipation, and increased the risk of dehydration. The lighter-weight trouser ensemble helped to reduce this physiological strain by reducing the increase in T_{re} ($p<0.05$), thus, reducing the rate of heat storage that could subsequently allow personnel to work safely for longer (Thake and Price 2007).

Furthermore, a similar study (n=4; Thake *et al.* 2009c) using the same protocol duration as Thake and Price (2007) conducted the manual loading and search and crawling with fixed work rates, whilst exploring the benefits of wearing a lighter EOD suit (3010; ≈18 kg) vs. a heavier EOD suit (≈37 kg) within two ambient temperatures, once at 20±1 °C and once at 40±1 °C. It was evident that both suit type and ambient temperature (T_{amb}) affected the physiological strain experienced by participants. Strain was greater at 40 °C than at 20 °C, ($p<0.001$). The rate of rise in T_{re}, and HR whilst wearing the 3010 (light-weight) suit was less, reducing heat storage with a lower PhSI index that could be attributed mainly to the differences in HR. Lower RPE responses and subsequent PeSI values were also found when wearing the lighter weight suit. Furthermore, overall RPE during the final cycle of activity was the same for the 3010 suit at 40 °C when compared to the 4010 suit at 20 °C. Thus, emphasising the impact of both T_{amb} and load on physiological strain and how reducing the load (-19 kg) can be highly beneficial at reducing the physiological stress experienced at these temperatures (20 °C and 40 °C).

Not only load but also encapsulation leads to significant physiological strain. The nuclear, biological, and chemical (NBC) protective suit is moderately lightweight (≈9 kg; McLellan 1999) when considering other forms of personal protective clothing (EOD suit; ≈37 kg; Thake and Price 2007) yet fully encapsulates its wearer. Encapsulating the wearer in an NBC suit contributed to an increase in expired minute ventilation (V_E $l \cdot min^{-1}$), metabolic heat production ($kj \cdot m^{-2} \cdot h^{-1}$), and sweat production ($kg \cdot h^{-1}$), vs. normal combat clothing. Untrained (UT) and endurance trained (ET) heat-acclimated subjects wore normal combat clothing (4.4kg) and NBC clothing (8.2 kg; a difference of 3.8 kg) whilst exercising at $4.8 km \cdot h^{-1}$ on a motorised treadmill in a hot ambient temperature (40 °C 30 % RH). The difference noted above highlights the extra strain that is placed on nuclear, biological and chemical protective workers by being completely contained within the suit. The evaporative efficiency of the suit was 30 % which was less than half that of the combat clothing which was reduced further with an increased sweat production, emphasising that sweat is wasted as evaporation is restricted within the impermeable layer leading to a greater rate of heat storage, which in this case consequently lead to reduced tolerance times of workers by greater than half that of the normal combat clothing trials (Aoyagi, McLellan, and Shephard 1994).

Reducing the load and encapsulation should therefore help to improve tolerance times, by reducing the rate of heat storage and physiological strain. In support of this, a study by Montain *et al*. (1994), found that male subjects wearing full PPC walking on a treadmill in the heat (43 °C; 20 % RH), presented lower T_{re} at exhaustion ($p<0.05$), when compared with subjects partially covered in PPE. Noted in this study, was that the partially clothed subjects exposed their neck, face and hands, (12 % of the skin surface area) and presented similar T_{re} at exhaustion to those subjects not wearing PPC under the same conditions. Therefore, emphasising either the areas of the body that are useful for dissipating heat and/or that only a small reduction in load may be required to reduce physiological strain.

In support of the latter, the forehead, check bones, and chin have been found to have the highest convection coefficients and so it is plausible that cooling through evaporative sweat was increased with the greater exposure to convective air flow creating a greater evaporative capacity (Clark and Toy 1975; Holmer *et al*. 1999), however in contrast it is also plausible that the additional load of the helmet once removed reduced metabolic heat production (Dorman and Havenith 2005), and a combination of the two reduced the physiological strain experienced.

2.3.2. AMBIENT TEMPERATURE AND EXERCISE

T_{re} has been shown to increase with exercise time, under hot ambient conditions as well as cold ambient conditions whilst wearing PPC (McLellan et. al. 1996; Rissanen and Rintamäki 2007). Despite the severe cold (-33 °C), participants marching at a high intensity within an NBC suit managed to increase their core temperature to just below 38°C, highlighting the impermeable encapsulating nature of the suit to the extent that metabolic heat gains could not be dissipated at a rate that would maintain a thermal equilibrium (Rissanen and Rintamäki, 2007). This is because the micro-environment within the suit has only a limited evaporative capacity, that when the environment is saturated will no longer aid the dissipation of metabolic heat, despite the large temperature difference present between the skin and external ambient air (≈-60 °C). This further emphasises the influence of the rate of metabolic heat production within PPC upon the degree of physiological strain experienced. However, the mean skin temperatures were considerably low (25 °C) particularly when measured at the extremities (15 °C), which would have initiated vasoconstriction of the blood vessels reducing the rate of convective and conductive heat loss from the core to the environment, and localised initiation of sweating, leading to an increase in heat storage and core temperature.

Exercise combined with high ambient temperatures, places demands on the body that increase physiological stress. The extent of the stress experienced is dependent upon the mode, frequency, duration, and the volume and the intensity of exercise performed. Whilst wearing NBC clothing (≈8kg) in hot dry environments (40 °C 15 %RH), heavy intensity (500W) exercise caused a greater increase in HR and sweat rate ($\dot{SR}$; 39 %) when compared to light intensity (350 W) exercise, and that tolerance time was reduced during the heavy intensity exercise trial (within the NBC ensemble) to half (63.5 minutes) that found at the end of the lighter intensity exercise trial (120 minutes; McLellan 1996). Reasons for this are that the increase in intensity increases the metabolic rate, and consequent metabolic heat production per unit time, and therefore the rate of heat storage, leading to a greater physiological strain. Wearing EOD clothing and varying the exercise intensity (by comparing the different activity stations used) has also shown with increases in intensity comes an increase in oxygen consumption, HR and physiological strain (Thake and Price 2007). Thus by reducing exercise intensity whilst wearing EOD clothing it is possible to maintain a slower increase in heart rate, reduce the rate of rise in T_{re} and prolong safe operational performance times of workers. An alternative method to reducing the intensity would be the introduction of work:rest cycles, although this may be ineffective at improving tolerance times due to the continuous increase in heat storage that is present under hot ambient conditions at rest (Cheung, McLellan, and Tenaglia 2000).

2.3.3. HYDRATION

One of the physiological consequences of wearing PPC is the risk of dehydration, caused (as previously described) by the great volumes of sweat that can be lost over a working period ($1.30\ l \cdot h^{-1}$; McLellan *et al.* 1999). Being dehydrated by 2.3 % body mass whilst performing treadmill walking ($4.8 km \cdot h^{-1}$) under hot ambient conditions (35 °C 50 % RH) in PPC, has lead to significant reductions in sweat rate (-37 %), and tolerance times (-11.3 minutes) vs. individuals that were adequately euhydrated, (McLellan *et al.* 1999).

Sweat rate measured 1.30 $kg \cdot h^{-1}$ during the euhydrated trial reduced to 0.95 $kg \cdot h^{-1}$ during the dehydrated trial. There were no differences in final core temperature responses between the euhydrated trial (38.52±0.39 °C) and the dehydrated trial (38.43±0.45 °C). Thus, hydration status of participants should be checked prior to trials whereby hydration is or is not the dependant variable. Although there was a tendency towards a higher HR in the dehydrated trial, there was no significant difference in HR between trials. Core temperature (T_{re}) at the end of both euhydrated and dehydrated trials were similar (38.52±0.39 °C and 38.43±0.45 °C), meaning the rate of increase in T_{re} was greater in the dehydrated trial. Thus, the resultant effect of being dehydrated is a reduction in the heat storage capacity of the body, potentially due to a reduced blood volume causing cutaneous vasoconstriction in an attempt to maintain blood pressure (Charkoudian 2003). To maintain physiological performance NBC workers should be adequately hydrated before being deployed to deal with specific tasks. Although further research shows that additional water intake prior to exercise in chemical protective ensembles did not increase the capacity for heat storage or reduce the rate of rise in T_{re} (Latzaka et. al. 1998).

2.3.4. FITNESS AND TRAINING

Endurance exercise training reduced the rate of rise in T_{re} over long durations of exercise in the heat (walking at 4.8$km \cdot h^{-1}$ with 2 % grade; 40 °C 30 % RH) significantly between 110 and 120 mins when wearing normal protective clothing, however, when conducting the same exercise in the heat wearing NBC clothing no obvious reduction due to training was found, (Aoyagi, McLellan and Sheppard, 1994). This possibly reflects the impermeable nature of the clothing, and its total encapsulation preventing any physiological adaptations due to training, such as increased sweat production, from benefiting subjects due to the limited evaporative capacity within the micro-environment.

Participants that are highly trained with greater aerobic capacities (46.0±2.9; vs. 59.5±0.4 $l \cdot min^{-1}$) have been linked to the ability to tolerate higher rectal temperatures (T_{re}) during exercise testing, and associated with lower T_{re} prior to exercise testing when compared to moderately trained individuals. Thus, providing them with a greater heat storage potential vs. untrained/sedentary individuals. Tolerance times whilst wearing PPC were greater by ≈22 minutes with the highly trained individuals. The 'fitter' subjects were stopped due to reaching the ethical limit of 39.3 °C, when compared to the moderately fit subjects that 'gave-up' due to voluntary exhaustion below 39.3 °C. This highlights that significant changes to tolerance time (TT) whilst exercising in the heat, can be achieved when wearing PPC, if the training is long enough to induce significant changes in aerobic capacity, and/or if subjects already have a high aerobic capacity ($\dot{V}O_{2max}$). Training has shown to increase blood volume, and trained athletes posses greater cardiac outputs during exercise compared to untrained individuals (Convertino 1991). Therefore, trained individuals are able to work at a lower level of physiological and cardiovascular strain due to a more efficient oxygen delivery vs. untrained participants, and can afford to compromise a greater volume of blood for cutaneous cooling.

In summary, high intensity exercise, greater degrees of encapsulation and load, and greater ambient temperatures have shown to reduce the physiological tolerance of participants wearing PPC. These variables do so by increasing the metabolic rate, and rate of rise in heart rate, T_{re} and T_{sk}. Internal individual factors such as being dehydrated, and possessing a low level of aerobic fitness contribute to this reduction in tolerance. Thus, the physiological responses observed emphasise the need for personnel to be aerobically trained with regular monitoring of well being (physiological responses), for workers to ensure adequate hydration before beginning tasks, and to take breaks during higher intensity exercise, without compromising the work required per unit time. The use of cooling systems within PPC ensembles to enhance heat dissipation and physiological performance by skin surface cooling have been investigated, and further investigations are required to determine the best methods and types of cooling garments that may be worn.

2.4. COGNITIVE RESPONSES TO EXERCISE IN MODERATE AND HOT ENVIRONMENTS WHILST WEARING PPC

The extent to which UHS impairs cognitive performance is debatable, and many researchers have found either; differences in cognitive performance under situations of UHS due to changes in deep core body temperature, or no differences in cognitive performance. However, this may be a consequence of the type of cognitive task chosen and the aspects of performance they assess, such as, memory, reaction time, vigilance, and tracking performance, it may also be down to the skill level and experience of the participants being tested, whereby those who have practiced and over-learned a specific task will have developed stronger automotive processes that are better able to withstand high levels of stress, (Hancock and Vazmatzidis 2003).

It has been suggested that the fluctuation and rate of rise in core body temperature appears to influence changes in cognitive performance, but that sustained attention can be maintained if participants establish a stable thermic state (Hancock and Vazmatzidis 2003). Furthermore, the ability to sustain attention and keep a pointer aligned with a target marker under warm humid conditions (41 °C) was shown to deteriorate over time (30 minutes) with steady increases in T_{re} (Pepler 1959). PPC has been shown (when worn by pilots), to cause a rise in rectal core body temperature (T_{re}; 1.2 °C) with ambient temperatures of 40 °C at 19 % relative humidity (RH). This rise in T_{re} was correlated with an increase in the number of incorrect reactions as performed on a vigilance test ($r = 0.907$; $P<0.002$), chosen to assess concentration, reaction time and accuracy, and to mimic tasks commonly performed by Norwegian Air force pilots. The number of incorrect reactions were greatest within the 40 °C condition when compared to both 23 °C ($P<0.006$) and 0 °C ($p<0.03$). Furthermore, it was found that the ambient temperatures that caused the greatest deviation in T_{re} from normal range (40 °C and 0 °C) were more likely to cause incorrect reactions, (Faerevik and Reinersten 2003).

Simmons *et al.* (2008) suggested that high core body temperature is a limiting factor of cognitive performance in the heat. They conducted cognitive performance tests based on reaction times and accuracy. The first battery of cognitive tests were performed under conditions of initial low skin and core temperatures (LL) where the environmental chamber was set to 25 °C 50 % RH for 30 minutes, followed by passive heating of skin temperature (HL) for a further 30 minutes as the chamber temperature was increased to 45 °C 50 % RH, whereby a second battery of cognitive tests were conducted, finally a third battery of cognitive tests were conducted once core body temperature had risen by 1 °C. This was repeated on separate days either with (HC) or without (CON) a liquid cap providing head and neck cooling. Faster reaction times with a decrease in accuracy were observed with increased core and skin temperature, however due to the experimental design the duration of exposure and fatigue may have influenced these findings. Head cooling did not improve upon these decrements in cognitive performance.

A study by Thake and Simons (2009a) investigated men working in a pressurised breathing air suit (PBAS) at 20 °C and 40 °C for three hours at a time (6 x 30 minute activity cycles). There was an increase after two hours at 40 °C in the total number of errors made on a cognitive, touch screen spatial working memory (SWM) test. The test took longer to complete at 40 °C vs. 20 °C, where the rate of rise in T_{re} was greatest, reflecting a reduction in attention due to the increase in errors made, however, the duration required to complete the test at 40 °C (6.32±1.24 min vs. 5.64±0.68 min) when comparing the 1st cycle to the 6th cycle was generally faster, supporting the findings of Simmons *et al.* (2008) that increases in core temperature results in faster reaction times, but with increased errors.

However, it has also been found that despite steady increases in T_{re} (0.45 $°C \cdot h^{-1}$) the ability of trained military personnel to perform rifle marksmanship and target detection tasks were maintained for up to 4 hours within the heat (42 °C; passive liquid cooling suit) whilst hydrated and dehydrated. Thus, skill level and practice may be enough to eliminate the effects of thermal strain on cognitive performance. However, it should be noted that controlling core temperature, maintaining a thermal balance, or stabilising core temperature at a certain hyperthermic level, may also reduce the number of errors of cognitive performance.

2.5. COOLING METHODS USED TO BENEFIT WORKERS WITHIN UNCOMPENSABLE HEAT STRESS (UHS) ENVIRONMENTS

A range of microclimate cooling methods have been devised and tested with the aim of reducing UHS, and preventing work induced hyperthermia. Types of microclimate cooling include; liquid conditioned suits, ice packs and ice vests, convective air flow, and phase change materials (PCM). Further investigation has arisen with regard to the body parts selected for cooling. Various cooling applied to the head, neck, chest, back and extremities (Kissen *et al*. 1976; Nunneley and Maldonado, 1983; Cohen, Allan, and Sowood 1989; McLellan, Frim and Bell 1999; House 2003) have shown to reduce heat stress experienced by exercising humans and occupational workers (including EOD, NBC, and Flight Crew), and the extent to which is discussed with reference to defining which methods, body parts, and temperatures have the best outcome for operative workers.

2.5.1. METHOD OF COOLING

Different types of cooling such as liquid, ice and air based systems have been investigated with regard to reducing physiological strain whilst working in protective clothing (Kissen *et al*. 1976; Frim and Morris 1992; McLellan, Frim and Bell 1999; McLellan 2007). Air (AC; 23±0.5 °C), water (WC; 20±1 °C) or air and water combined (AWC) as types of applied cooling have shown to reduce T_{re}, HR, heat storage and sweat loss when participants wore Nomex flight coveralls and helmet whilst sat in a heated environmental chamber (46.1 ±0.5 °C). The cooling was focused on the back and crown of the head with liquid tubes for water based cooling and slits within the top of a helmet whereby (≈ 200 l/min) air based cooling was administered (Kissen *et al*. 1976).

Combining air and water (AWC), reduced the rise in HR by 54 % vs. the no cooling (NC) condition, and with air and water cooling separately by 30 % vs. NC. The T_{re} increased by 0.74 °C overall within the NC condition and this increase was reduced to less than half that (0.32 °C) with the use of AWC combined. Futhermore, the 50 % reduction in sweat loss by the combination of air and water head cooling only reinforces the degree of thermal sensitivity surrounding the head, and face (Crawshaw *et al.* 1975; Cotter and Taylor 2005) and how effective it can be in reducing physiological strain amongst workers.

The face (including forehead and cheeks), has been found to have a high convective coefficient (Clark and Toy 1975) combined with a high sweat production from the forehead (Nunneley and Maldonado 1983), and as evaporative cooling is the most beneficial form of heat loss (Havenith 1999; Flouris and Cheung 2006) explains why AWC provided the ideal conditions for heat removal, when compared to NC with both types providing the potential for a greater evaporative capacity. The participants were not exercising or physically active during these trials, and so the greatest improvements to physiological strain may be due in part to the low level of metabolic heat production, therefore with greater metabolic rates such benefits may not occur.

The use of micro-climate cooling by air vests (McLellan 2007) has shown to benefit those exercising within protective clothing by maintaining T_{re} after 3 hours of work (in either hot dry or warm humid environments), to that measured at rest (prior to the commencement of the trial). This was compared to the same trial without cooling, where T_{re} increased by 2 °C in the hot dry condition, and 1 °C in the warm humid condition. Thus, despite the extra layer presented by the air-vest, micro-climate conditioning was effective in maintaining core body temperature (T_{re}), which was probably due to the air-vest aiding heat dissipation by sweat evaporation, and providing a sufficient evaporative capacity within the suit. This type of cooling may also assist in the thermoregulation of those wearing EOD suits, and appears to be more effective at maintaining a body temperature throughout exercise that is close to the response given at rest, when compared to the liquid based head-cooling methods (Watanuki 1993).

In contrast to the study by McLellan (2007) where air was used as the main cooling type, one favourable method with respect to the EOD suit was found to be the liquid-based Exotemp® Personal Cooling System. Frim and Morris (1992) evaluated a liquid cooled undergarment (Exotemp® Personal Cooling System) and an air vest, within three experimental conditions; 18 °C and 40 % relative humidity (RH); 34 °C and 40 % RH; and 34 °C and 80 % RH. Each trial involved 90 minutes of repeating simulated EOD tasks with approximately a 5:4 work:rest ratio. One of the tasks included treadmill walking at 3.5 $km \cdot h^{-1}$ for 10 minutes, followed by unstacking, carrying and re-stacking weighted boxes (15 kg) across a distance of 2.5 m.

The liquid-based suit brought about reductions in physiological strain under warm humid conditions (34 °C; 80 % RH) comparable to that measured when no protective clothing was worn. The highest fluid loss (2.8kg) was present in the EOD suit trial without cooling, (34 ºC 80 % RH) combined with the highest percentage of dehydration (1.98 %). Thus, placing emphasis on the contribution of an EOD suit to overall thermal stress, and the importance of cooling garments in general as well as specifically the Exotemp® Personal Cooling System at maintaining thermoneutrality and subsequent performance of workers.

It was noted that these results (fluid loss and dehydration) were obtained from the 'fittest' participant, reinforcing the advantage physically trained individuals have over physically untrained individuals with regard to dissipating heat through greater levels of sweat production. However, this advantage becomes a disadvantage when working in high ambient temperatures, especially when wearing impermeable PPE, due to the increased sweat response leading to a decrease in time to dehydration and an increased risk of heat illness without fluid ingestion (Montain *et al.* 1994). Thus, cooling methods as opposed to acclimation and/or training methods can actually reduce the loss of sweat, and consequent dehydration that hinders performance and exacerbate feelings of nausea and discomfort.

2.5.2. THE EFFECT OF COOLING DIFFERENT BODY REGIONS ON THERMAL AND PHYSIOLOGICAL RESPONSES

There has been a lot of research based around head and torso cooling within PPC, cooling of the extremities (hands and feet), and the use (as previously stated) of full body cooling suits. Research has shown that the perception of physiological strain in terms of thermal sensation and comfort, to be significantly reduced with the aid of cooling portions of the head (frontal; occipital and temporal) whilst participants were seated within an environmental chamber (40 °C; 50 % RH), (Katsuura 1992). Forearm skin blood flow and sweat rate also had a tendency to be higher without head cooling, although the rise in T_{re} did not change, therefore this could imply that cooling the head can significantly influence subjective responses more so than physiological responses, and may present dangers if an individual were to misjudge their own thermal state. In support of these findings, further research by Hayashi and Tokura (1996) found significantly reduced thermal sensation and comfort when using similar subjective scales with two positioned (250 g each) frozen gel strips as the head cooling device, both with and without PPE.

In contrast to the previous aforementioned studies, head cooling during exercise in the heat and within protective clothing, has been found to be 2-3 times more effective than torso cooling at reducing the rate of rise in HR, T_{re}, total body sweat rate (SRT) and forehead sweat rate (SRF; 49 vs. -29 $g/m^2 \cdot h$) when compared to torso cooling, (Nunneley and Maldonado, 1983). However, these responses for the head and torso were compared in relation to 1 % of the total body surface area (BSA) covered, and torso cooling resulted in the greatest physiological strain reductions overall. Cooling was administered using a liquid-cooling garment (15.5 °C) a flow rate of 0.8 l/min for the cap (XH) and 1.0 l/m for the vest (XT).

In support of the latter, the face has been found to be 2-5 times more thermosensitive than the torso, forearm, thigh, leg and foot, with regard to sudomotor response, (Cotter and Taylor 2005). Cotter and Taylor (2005) found that a combination of cooling presented the best responses producing near baseline responses for all measured variables with a significantly lowered T_{sk} at the forehead and chest (25 °C to 26 °C).

In relation to BSA, and in support of Nunneley and Maldonados' (1983) findings, head cooling (7.5 °C; 12 % BSA) has also been found to be more effective than suit cooling alone (torso, arms and thighs; 9.9°C; 60 % BSA) or head and suit cooling combined (head; torso, arms, and thighs; 9.9 °C; 72 % BSA), as head cooling only required 0.5 % BSA to be cooled for a reduction of 1 heart beat per minute compared to 1.6 % and 2.6 % for suit cooling and hood and suit cooling combined. This is most likely due to the difference in head vs. torso heart rate responses to localised cooling. However, the overall effect of the hood and suit cooling combined was the finding of the greatest magnitude of reduction in physiological strain compared to hood and suit cooling separately.

The benefits of torso and head cooling have been emphasised further with findings from a study that was conducted using an original liquid-conditioned vest (flow rate of 1 l/min) under Aircrew Chemical Defence (ACD) clothing, (Cohen, Allan, and Sowood 1989). Trials were performed wearing the vest only (V; 15±0.57 °C), or combining the vest with either a neck cooling collar (NV; 13±0.73 °C) or head cooling cowl (HV; 13±2.06 °C). Trials were ≈2 hours in duration, and consisted of six cycles of 15 minutes exercise and 5 minutes rest, within an experimental chamber (40 °C; 25 % RH). Head and torso cooling (HV) were more effective at reducing thermal comfort to a cooler and more tolerable range (3 to 5) when compared to neck and torso cooling (NV; 5 to 6.5), reasons for this as previously discussed may have been due to the increased thermosensitivity of the head, and chest vs. head and neck and/or a result of the greater surface area being cooled.

2.5.3. THE EFFECT OF THE TEMPERATURE OF THE COOLING SYSTEM USED UPON THERMAL AND PHYSIOLOGICAL RESPONSES

The temperature of the cooling materials is also a significant factor when investigating the benefits of cooling on reducing thermal strain. House (2003) demonstrated that hand immersion in 10 °C of water could help improve safe work tolerance times of NBC workers by 62.5 %, with rest periods and by 37.5 % with the use of an ice-vest when activity was continuous. It was suggested that combining the ice-vest with hand immersion and/or lower temperatures may increase the rate of heat removal by increasing the surface area being cooled or increasing the thermal gradient, improving tolerance times even further but that it may possibly impede the rate of heat removal due to vasoconstriction.

Whole body immersion in water of varying temperatures (2 °C, 8 °C, 14 °C and 20 °C) for post exercise-induced hyperthermia (T_{re} of 40 °C) showed temperatures as low as 2 °C offering the highest rate of heat removal, (Proulx, Ducharme, Kenny 2003). However, it should be noted that the study covered the extremities (hands and feet) in mits and that participants were only immersed up to their clavicle, leaving their head exposed. Thus, it may be possible that if the hands and/or feet were involved, vasoconstriction may have resulted due to the heads high thermosensitivity initiating vasoconstriction and shivering (Crawshaw *et al.* 1975; Cotter and Taylor 2005; Wilson 2007).

In contrast, excessive cooling (15 ºC) of the head has shown to cause a significant increase in core temperature (tympanic temperature; T_{ty}) and torso temperature (T) during cycling activity when compared to 20 °C head cooling (Watanuki 1993), presenting possibly dangerous consequences, especially because of the association of head cooling producing lower perceptual responses. However, Katsuura *et al.* (1992) when using 10ºC of cooled liquid on either the frontal, occipital or temporal portions of the head, 5ºC cooler than that of Watanuki (1993), found no significant increase in core temperature (T_{re}). This could be due to the difference in core temperature measure site (T_{re} vs. T_{ty}) whereby according to Desruelle and Candas (2000) T_{ty} is thought to be influenced by air temperature.

However, in Katsuura *et al.*'s (1992) study partial cooling of the head provided less of an overall cooling effect by covering less surface area of the head, the participants were also stationary (compared to cycling in Watanuki's study) and so there would have been less metabolic heat production, and a smaller thermal gradient present between the liquid tubules, scalp and blood vessels within the brain. It is useful however, to note that head cooling could potentially cause an adverse affect on body temperature. Suggestions of selective brain cooling (Cabanac and Caputa 1979a) support this further whereby reductions in T_{ty} were in contrast to the increases found in Tes during face fanning of exercising humans in an ambient temperature of 10 °C, thus cooling of the brain was proposed to produce an upper re-setting of core temperature (Tes). Leading to possible implications preventing the use of cooler temperatures (<10 °C) surrounding the head.

Phase-change vests of various temperatures (0 °C (CV_0), 10 °C (CV_{10}), 20 °C (CV_{20}) or 30 °C (CV_{30}) have been investigated when worn under fire-fighter protective clothing in the heat. Participants did 45 minutes of light-stepping followed by 45 minutes of rest-recovery (House 2009). All cooling vests maintained lower T_{re} at rest when compared to the control trial ($P<0.05$). The PCM cooling vest with a melting temperature of 10 °C was the best option of all temperatures when considering participant thermal comfort. Both the CV_0 and CV_{10} vests with regard to physiological responses helped to reduce heat strain with the removal of 66 W and 69 W of heat respectively. However, cooling benefits were seldom during exercise and mainly observed during rest therefore the cooling rate during exercise provided by the PCM vests was not sufficient enough to manage the rate of metabolic heat production, this can be supported by findings from previous research (Carter 2007), whereby during continuous fire-fighting activity at moderate ambient temperatures a PCM vest of 28 °C did not benefit workers with regard to heat storage, and the rise in T_{re} remained unchanged between conditions.

2.5.4. THE USE OF PHASE-CHANGE MATERIAL (PCM) WITHIN PPC

PCM garments have been investigated with regard to reducing physiological thermal strain of occupational workers, as they are easier to manage, less costly, and easier to apply than most liquid based cooling systems (Flouris and Cheung 2006). PCM garments are made from a variety of different substances, such as, crystalline dehydrate of sodium sulphate, glauber's salt, or sodium acetate trihydrate (Cabeza, *et al.* 2003; Reinertsen 2008) and are currently used commercially as methods of latent heat storage. They can be made to melt and subsequently absorb and store heat at a range of different temperatures, (Sharma, *et al.* 2007), and so have the potential to be a highly beneficial source of heat removal for workers wearing protective clothing.

The use of PCM vests (28 °C) under fire-fighter clothing during activities representative of the work conducted by fire-fighters (Carter, *et al.* 2007), has shown to be of no benefit with regard to reducing thermal strain, with no differences found in T_{sk}, final T_{re}, sweat rate, thermal sensation or comfort vs. a control trial. The fire-fighters carried equipment (≈ 35 kg), whilst participants walked in pairs (≈ 4.2 $km \cdot h^{-1}$) along an underground rail service tunnel for a duration of 2 hrs. The phase-change material (PCM) vest had a melting point set to ≈ 28 °C, and was stored for two hours prior to use at 10 °C to 15 °C, with a mass of ≈ 3.0 kg. Furthermore, fire-fighting activities were conducted within a firehouse that was either heated (170 °C measured at a height of 1.2 m) or not heated (15 °C to 20 °C), either wearing or not wearing a PCM vest (different manufacturer to latter study with the only difference being a mass of 2.5 kg). There was also no change in work duration in the heated condition between the vest cooling trial and no cooling control trial.

A combination of reasons may have accounted for the aforementioned findings; the contribution of load (2.5 kg to 3 kg) by the PCM vest could have added to the metabolic heat production, the temperature of the PCM melting point may have been set too high for significant rate of heat removal to be achieved, and thus the rate of metabolic heat production must have outweighed the rate of heat removal.

However, in contrast to the previous study, there have been reductions in the rate of rise of T_{sk}, thermal comfort, thermal sensation, and in sweating rate of the back of participants, when a PCM suit was worn vs. a placebo suit, underneath well-insulated protective clothing, while sat within an environmental chamber (27±0.5 °C; 50±5 % RH) for 120 minutes, supporting that PCM can effectively reduce thermal load when worn within PPC (Reinertsen 2008).

Reasons for this reduction may have been related to the PCM melting point, as it has been found that PCM melting and freezing points are an important factor with regard to heat removal (House 2009), with the lower melting points providing the most benefit (10 °C), although again this benefit was greatest at resting recovery and minimal during exercise. It was also suggested that the amount and distribution of the PCM garment were related to the reduction, (Reinertsen 2008). Thus, it would be interesting to see if the same findings could be reproduced during exercise within hotter ambient climates.

The benefits of the PCM vest over other cooling methods are that it can be easily donned and is cheaper to maintain over other liquid and air based cooling methods. The downfalls are that once melted the capacity to remove heat reduces and the PCM has potential to act as a thermal insulator (Shim and McCullough 2000). Furthermore, the use of PCM garments for heat removal is limited to the duration they can be worn and by their maximum heat storage capacity. It has also been found that condensation from the garment can increase humidity of the microclimate and subsequently reduce the capacity for evaporative cooling (Flouris and Cheung 2006), of which is already limited within the PPC micro-climate. In summary, it is evident that more information is required to draw conclusions, with regard to the potential benefit that PCM may provide to workers exposed to UHS, in particularly what areas are best such as, cooling the head vs. cooling the chest.

Thus, once again the current study aims to investigate this by comparing the physiological, perceptual and cognitive responses to EOD related activity of participants wearing either a PCM skull cap or PCM vest.

2.6. SUMMARY

The use of both liquid tubes and air ventilated systems have been shown to reduce or maintain subjective and physiological measures of thermal strain when wearing PPC (McLellan, Frim and Bell, 1999). Workers within PPC tended to benefit more from the Expotemp® Personal Cooling System (liquid based), when compared to personally pumped air, or air vest systems (Kissen *et al*. 1976; Frim and Morris 1992; McLellan, Frim and Bell 1999; McLellan 2007). However, liquid cooling systems are complicated and costly when compared to air or PCM, it is also difficult in the hotter based climates to supply cool liquid through the suit, therefore the use of PCM instead of liquid based cooling may be preferred as it is more logistically feasible and the PCM material can be re-charged within a commercial fridge for re-use (Reinertsen 2008).

Head cooling managed to significantly reduce subjective measures of thermal strain in all head cooling studies, despite the portion of the head that was covered, combined with significant reductions in sweat rate (SRT and SRF) and in few cases core and/or body temperature (Nunneley and Maldonado, 1983; Katsuura *et al*. 1992). Cooling the torso was less effective when compared to head cooling when they were compared proportionally with BSA, although when not compared proportionally to BSA the torso cooling garment resulted in the better outcome, and combined, both managed to improve thermal strain significantly due to the larger surface area covered. Monitoring temperatures of the cooling systems has shown to be an important factor, especially with regard to cooling the head and/or different regions of the body. The success of these cooling systems at maintaining resting core temperature and/or a thermoneutral environment depends upon a variety of factors and all studies show benefits of implementing cooling when compared to no cooling within a PPC (NBC and EOD) ensemble. This re-enforces the need for cooling systems in the field, to maintain performance, and reduce the risks of heat illness. The need for careful consideration of study design when testing these systems is also an important factor.

3. METHOD

3.1 PARTICIPANTS

With approval from Coventry University Ethics Committee, six male volunteers (n = 6; Table 3.1) took part in the current study. All were non-heat acclimated, non-smokers and in accordance with the completion of a PAR-Q Health Screen Questionnaire had no history of illness (cardio-respiratory or metabolic disease) or injury. Three of the six participants were current members of the Officer Training Corps (OTC) and all six participants took part in regular activity (a combination of running and cycling for greater than 120 minutes per week).

Table 3. 1: Anthropometric characteristics (mean ± SD) of each participant (n=6).

Participant	Sex	Age (yrs)	Height (m)	Body Mass (kg)	+Body Mass Index (BMI)	*Body Surface Area (BSA; m^2)
1	Male	21	1.72	65.2	22.0	1.77
2	Male	22	1.78	67.6	21.3	1.84
3	Male	21	1.63	64.3	24.2	1.69
4	Male	29	1.74	67.0	22.1	1.81
5	Male	19	1.78	64.6	20.5	1.81
6	Male	22	1.77	62.1	19.9	1.77
MEAN±SD	-	22±3	1.74±0.05	65.1±2.0	21.7±1.5	1.78±0.05

+BMI was calculated using weight (kg)/height (m^2). *BSA was calculated using the method of DuBois and DuBois (1916), {BSA (m^2) = 0.20247 x Height(m)$^{0.725}$ x Weight(kg)$^{0.425}$}.

3.2 STUDY DESIGN

The study ran from February through to June. It consisted of three pre-trial familiarisation sessions, one trial familiarisation session and six experimental trials for each participant. All of which took place within the same laboratory housed in the James Starley Building at Coventry University. The six experimental trials consisted of two no cooling (NC) control trials, two torso cooling (TC) trials, and two head cooling (HC) trials. Each conducted on separate occasions at ≈20 °C and 40 °C (in a randomised format). Thus, the six trials are annotated as; 20NC; 40NC; 20TC; 40TC; 20HC; and 40HC, respectively. A Latin square design was used to allocate the chronological order of trial completion in a randomised format, for each participant, thus eliminating any potential order effect (Table 3.2). The trials were completed at the same time of day for each participant (either 10 am or 2 pm) to account for circadian rhythm changes in core temperature and cardiovascular responses (Waterhouse, Drust, Weinert, *et al.*, 2005) and were separated by one week to reduce the risk of heat acclimation to participants (Barnett and Maughan 1993).

Table 3.2: A Latin square design was used to allocate participants (n=6) to a trial order for the six conditions (NC = No Cooling; HC = Head Cooling; TC = Torso Cooling; Order1-6).

CONDITON	**NC**	**HC**	**TC**	**NC**	**HC**	**TC**
TEMP (°C)	**20**	**40**	**20**	**40**	**20**	**40**
PARTICIPANT NO.						
1	1	2	3	4	5	6
2	6	1	2	3	4	5
3	5	6	1	2	3	4
4	4	5	6	1	2	3
5	3	4	5	6	1	2
6	2	3	4	5	6	1

3.2.1 PRE-TRIAL TEST SESSIONS

Three pre-trial test sessions were conducted on separate days at 20 °C. A session lasted one hour in duration. After donning the light-weight EOD suit (Ergotec 3010), participants completed a spatial working memory (SWM) test (CANTAB® neuropsychological tests; Cambridge Cognition Ltd; Cambridge; UK). The test lasted ≈ 6 minutes and was repeated four times per session. Within the same session participants practised a postural challenge test (2 min 10 sec in duration; see section 3.2.4, for a description and explanation of the test), that was repeated three times per session. The purpose of conducting three pre-trial test sessions was to establish a clear baseline of performance on the SWM test and for the participants to perform the postural challenge manoeuvre in a reproducible manner.

3.2.2 FAMILIARISATION SESSION

The familiarisation session was completed by participants one week prior to commencing the experimental phase of the project. The familiarisation session was used as a tool for each participant to practice the required trial activities and sequence of events that would take place during each of the six experimental trials, (see section 3.2.3). The ambient temperature of the experimental chamber was set to 30ºC and the light-weight EOD suit with no phase change material (PCM) was worn. The reasoning for an ambient temperature of 30ºC was to ensure completion of the trial (4 activity cycles), and because it was between the temperatures that the participants were going to be exposed to (20 °C and 40 °C).

3.2.3 EXPERIMENTAL TRIALS

Each laboratory trial consisted of a series of four activity cycles each containing six activity stations. One cycle lasted 20 minutes resulting in a total trial duration of 80 minutes. The six activity stations (1. to 6.) are described below (Figure 3.1).

1. **Treadmill walking (4 km·hr^{-1}; 3 min)**

The participants walked on the treadmill for a total duration of 3 minutes with a 0 % incline, which equated to 200m in distance, (Figure 3.1).

2. **Manual loading (2 min)**

This involved the participants kneeling in front of a shelving unit, lifting up and putting down metallic disc shaped weights to the beat of a metronome (30 beats·min^{-1}; Seiko DM-20, Hattori Seiko Co. Ltd; Japan) four 1.25 kg weights, whereby one beat equalled one action. The weights were positioned side by side on a top shelf situated 64 cm from the floor and were moved in turn on to a bottom shelf situated 27 cm from the floor, this was then repeated so that the weights were moved back on to the top shelf and so forth, until two minutes had past. The participant then progressed within 30 seconds over to the searching and crawling station, (Figure 3.1).

3. **Searching and crawling (2 min)**

Involved the use of a 2.25 m ‘ladder’ marked out in black tape along the experimental chamber floor, (Figure 3.1). The starting position for the participant required them to be situated on their hands and knees with both hands shoulder width apart. Their hands were in line with the first black line of the ladder, and all movement was completed in time to a metronome (30 beats·min^{-1}; Seiko DM-20, Hattori Seiko Co. Ltd; Japan), with one movement to the next rung per beat. Participants began by ‘searching,’ which required looking to the left, down, right, and then down again, to the beat of the metronome, before proceeding to crawl forwards. Crawling involved moving their left hand followed by their right to each marked rung on the ladder. Each rung was staggered 24 cm apart and one stretch of the ladder (including one search) took 30 seconds to complete. Once the participant reached the end of the ladder they repeated the ‘searching’ task before commencing backwards leading with their feet. The participant moved their hands to each rung in time with the metronome. The participants went back and forth along the ladder twice (2 min) to complete the searching and crawling station.

4. The postural challenge (2 min 10 sec)

Participants stopped searching and crawling and knelt upright distributing their weight evenly on their knees and balls of their feet (shoulder width apart situated on the first rung of the ladder). In this position the participants gluteals were resting on their heels, (see Figure 3.1; image 4.B), and the blood pressure recording device fitted to the participant. The blood pressure (BP) response was measured using a Portapres Model-2 device (Beatscope FMS, Finapres Medical Systems BV, Amsterdam; The Netherlands). An appropriately sized finger cuff (either small, or medium) was applied to the left hand of each participant. The cuff was positioned on the middle phalanx of the index or forefinger and remained fixed for each participant.

To normalise the system for hydrostatic pressure the following procedure was used: The left arm and finger were lifted forwards (at 90º parallel to the floor) away from the body and in line with a previously determined marker (on a meter rule; set per participant) that was in line with the participant’s heart, this was determined as the height null, and the distance between the forefinger and the height null was continuously measured throughout the manoeuvre. This height null was carried out so that during analysis, corrections and conversions could be made of the blood pressure (mmHg) measured in the digital artery of the participants forefinger to that of blood pressure (mmHg) measured in the brachial artery of the upper arm. This height null was followed by an internal system calibration that was conducted within 60 seconds from the initiation of kneeling. A three second count down was given from 86 seconds and the participant asked to stand to the beat of the metronome (30 beats·min^{-1}), in three stages beginning with the first beat at 90 seconds as follows:

- Stage 1) – (90 sec) the right arm was placed on the adjacent treadmill (Figure 3.1; image 4.A);
- Stage 2) – (92 sec) the participant then rolled back onto the balls of their feet into a squat-like position (figure 3.1; image 4.B; using their right arm to balance - hence first stage);
- Stage 3) – (94 Sec) from balancing in a squat-like position on the balls of their feet the participant moved vertically to a standing position instructed to do so in a relaxed manner as fast as physically possible, (Figure 3.1; image 4.C).

The three stage manoeuvre from kneeling to standing, took a total of approximately 6 seconds and the participant was then instructed to remain standing as relaxed as possible without talking or holding their breath for a further 34 seconds, while post-stand digital-arterial blood pressure (mmHg) was recorded. The station lasted a total of 2 minutes 10 seconds leaving 20 seconds transfer time to the arm ergometer.

5. Unloaded arm ergometry (60 rev·min^{-1}; 3 min; Thake and Price 2007)

The participant stood at an arm ergometer with one hand on either handle, and when instructed to do so, rotated the handles at a speed of 60 rev·min^{-1} for a total duration of three minutes (Figure 3.1).

6. The SWM test (6 min)

A cognitive spatial working memory (SWM) test was conducted, on a touch screen computer whilst the participant was seated at rest, (Figure. 3.2). The test measures the ability of an individual to retain and manipulate spatial information within their working memory whilst testing the participants' heuristic strategy (Cambridge Cognition Ltd 2009). The test began with a series of coloured square boxes (n=3) positioned randomly on the screen, the participant would press on each of these boxes in turn, to reveal a blue square 'token.' Once the blue square token was found it was placed into a clear black column on the right hand side of the screen, (Figure 3.2). The number of tokens to find per stage and the size of the clear black column corresponded to the number of boxes available, *e.g.* 3 boxes = 3 blue tokens; 6 boxes = 6 blue tokens. The token would never appear in the same box twice and the number of boxes per stage increased from 3 through to 8 boxes, increasing test difficulty at each stage. The test lasted for as long as it took for the participant to complete all of the available stages. The participants were instructed to use either hand and/or finger they felt comfortable with and to complete the test as fast as they felt were possible with some using two hands as developed in the familiarisation session. Pilot studies prior to commencing any trials indicated that completion time was generally between 4 minutes 30 seconds and 5 minutes 30 seconds dependent upon the individual and so 6 minutes was provided as the overall station time.

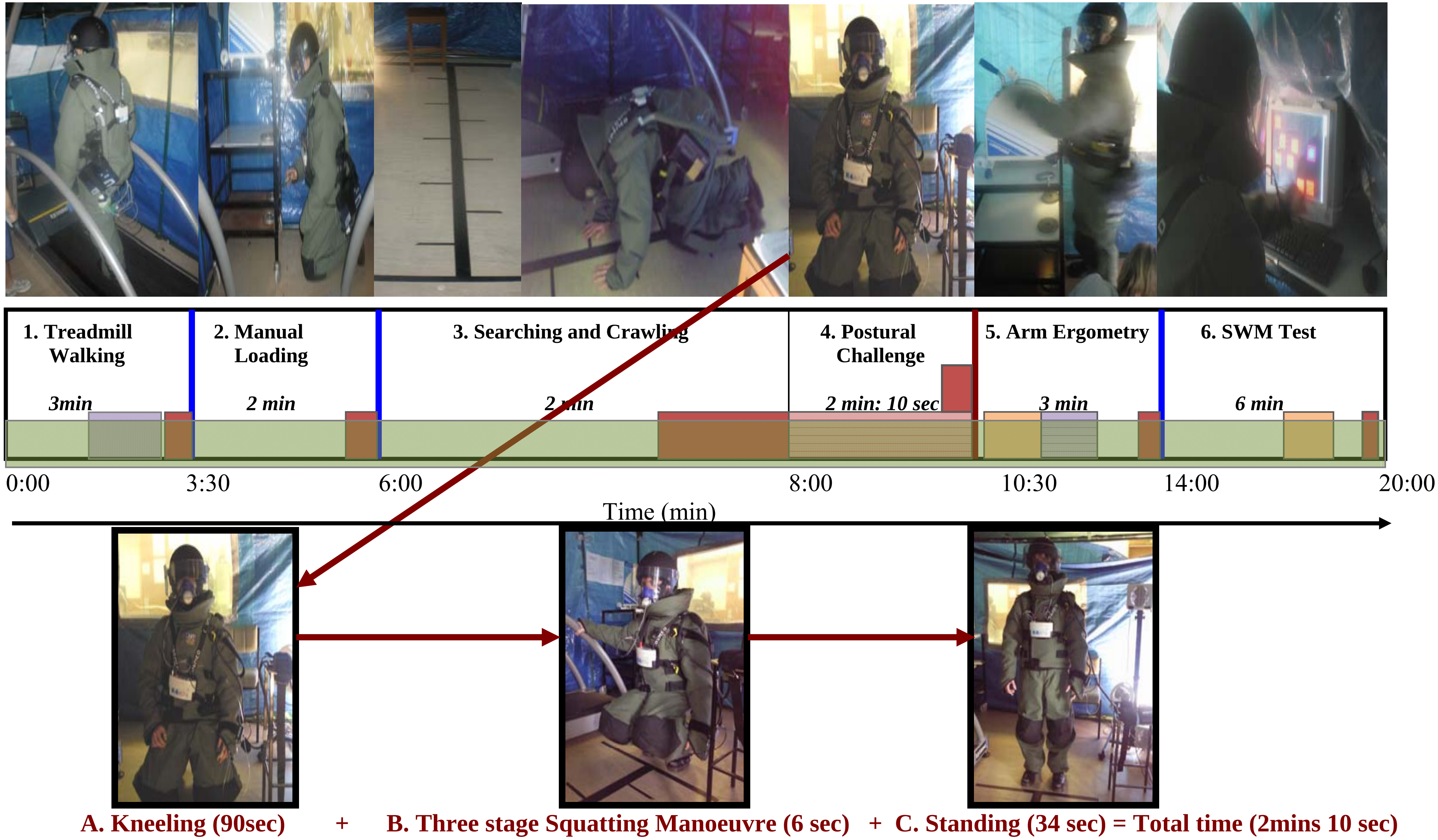

Figure 3. 1: Schematic diagram of one 20 minute cycle (6 stations). A complete experimental trial is 4x20 min cycles (80 minutes). Solid blue lines represent 30 seconds of transfer time between activity stations, and the solid red line represents 20 seconds of transfer time between activity stations. A break-down of the postural challenge (2 min 10 sec) manoeuvre is also included. Time represents start time of each station. Coloured boxes represent (not to scale) when in the cycle variables were measured; T_{hS}, T_{hC}, RPE (purple); HR manually recorded (red); BP & HR(light red); temperatures manually recorded (orange); PCM, $T_{sk,}$, T_{au}, T_{re}, T_{cP} (transparent green); & HR (transparent green).

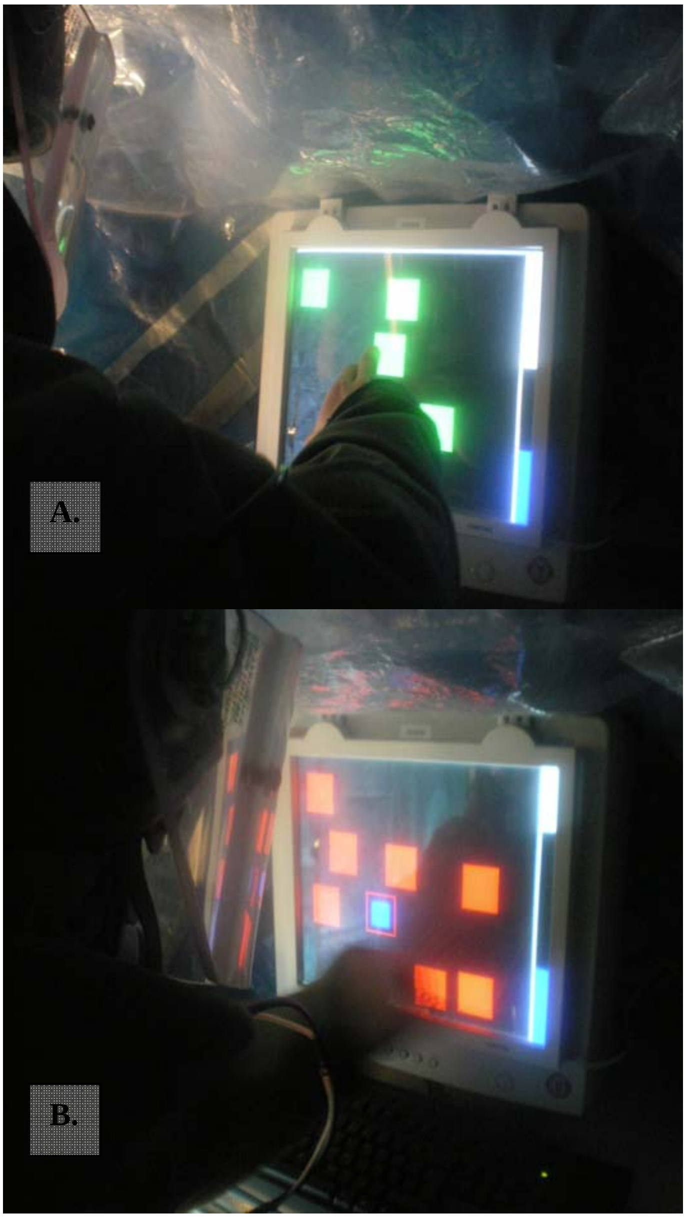

Figure 3. 2: The SWM test (station 6) completed on a touch screen computer. Two different stages (A and B) are shown with an example of the found blue tokens visible within the black right hand column.

3.2.4 EXPLANATION OF TRIAL PROTOCOL

The laboratory based protocol included manual, and cognitive tasks representative of EOD type activity based on previous research (Thake and Price 2007; Thake, *et al*., 2009b). Changes made to the previous EOD protocols (Thake and Price 2007; Thake, *et al*., 2009b), included the incorporation of a postural challenge station (2 min:10 sec; Figure 3.1; section 3.2.3) situated directly after the searching and crawling task and the inclusion of a cognitive spatial working memory (SWM) test (6 min) in place of previous physical seated rest (5 min; in lew of previously used tests of inadequate sensitivity/specificity).

The postural challenge represents an operative moving from kneeling to standing (after searching and crawling), and was introduced and standardised especially for this study to examine the impact of thermal stress on orthostatic tolerance. The SWM test and physical seated rest (touch screen computer; 6 min) assesses the area of cognition thought to be integral to EOD related tasks and was incorporated into the following study to examine how this cognition may change in relation to increasing thermal strain.

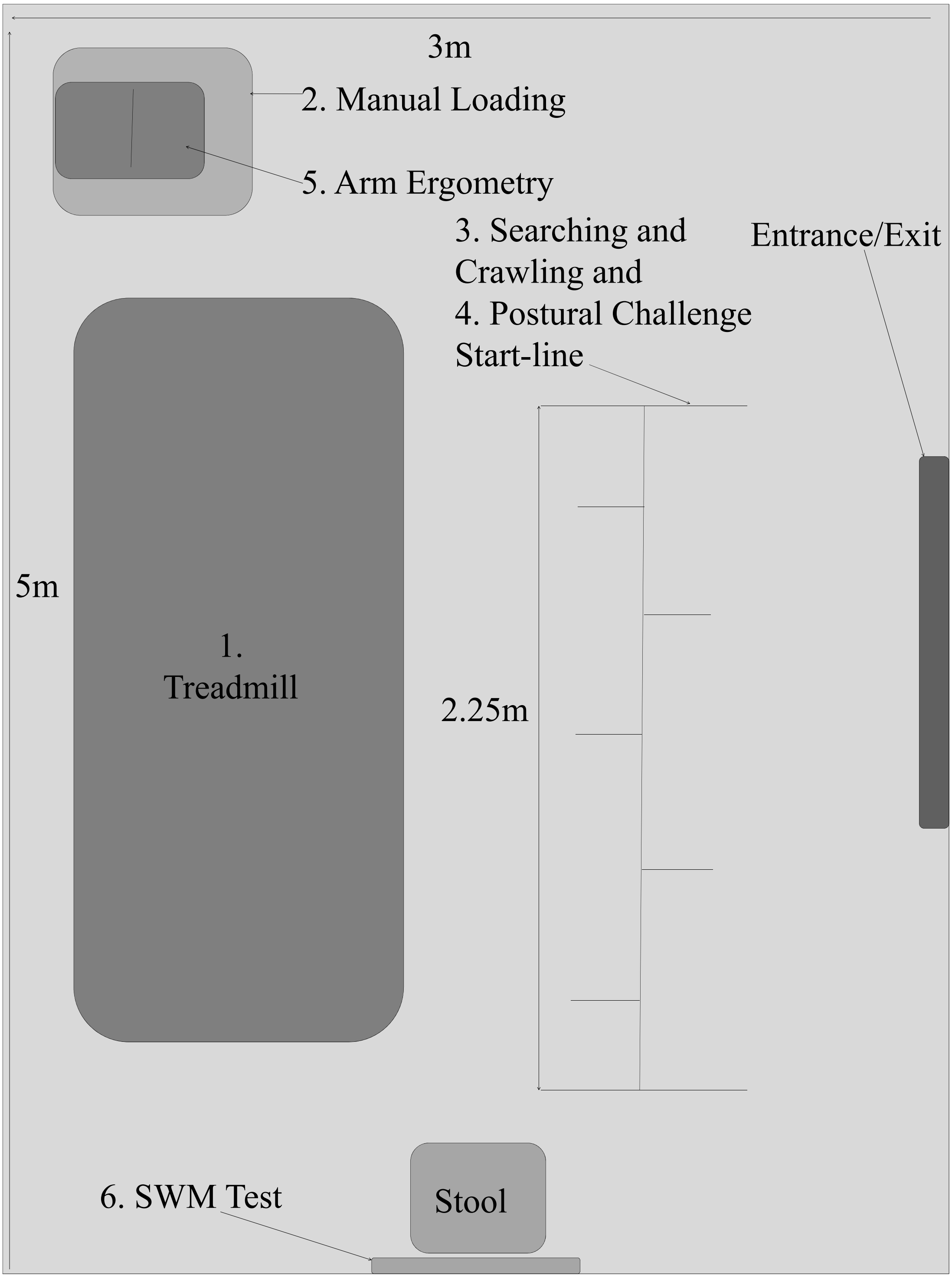

Figure 3. 3: A schematic diagram (not to scale) outlining the layout of the experimental area with stations (1.-6.).

3.3 STUDY ATTIRE

3.3.1 EOD UNDERGARMENTS

The participants wore shorts while thermistors were fixed to the skin (see section 3.5). During the pre-trial preparation and before donning the EOD suit the participants wore a set of normal combat clothing, consisting of t-shirt, trousers, and boots (size 8, 9, or 11 dependant on the participant).

3.3.2 EOD SUIT

The EOD suit (3010 Ergotec; NP Aerospace Ltd; Coventry; UK), was worn during the pre-trial sessions, familiarisation session and experimental trials. The suit consisted of trousers, jacket, helmet, and boots, with a total mass of ≈ 18 kg. The helmet of the 3010 Ergotec was equipped with visor and did not fully encapsulate the head (Figure 3.4). The suit was also equipped with a single internal fan unit powered by a battery pack (16 AA batteries). The internal fan unit blew ambient air (≈ 200 l/min^{-1}) through the suit that was dispersed across the participants' back.

3.4 PHASE CHANGE MATERIALS (PCM)

Phase change material (PCM) is used commercially as a form of latent heat storage (Mondal 2008). The PCM used in this study had a melting point of 25 ºC, and was thus solid below 25 ºC; whereas above 25 ºC it was in the liquid phase. This process of changing state was initiated mainly by the conductive heat transfer between the PCM, undergarments and/or skins surface, and additionally by the ambient air of the internal fan.

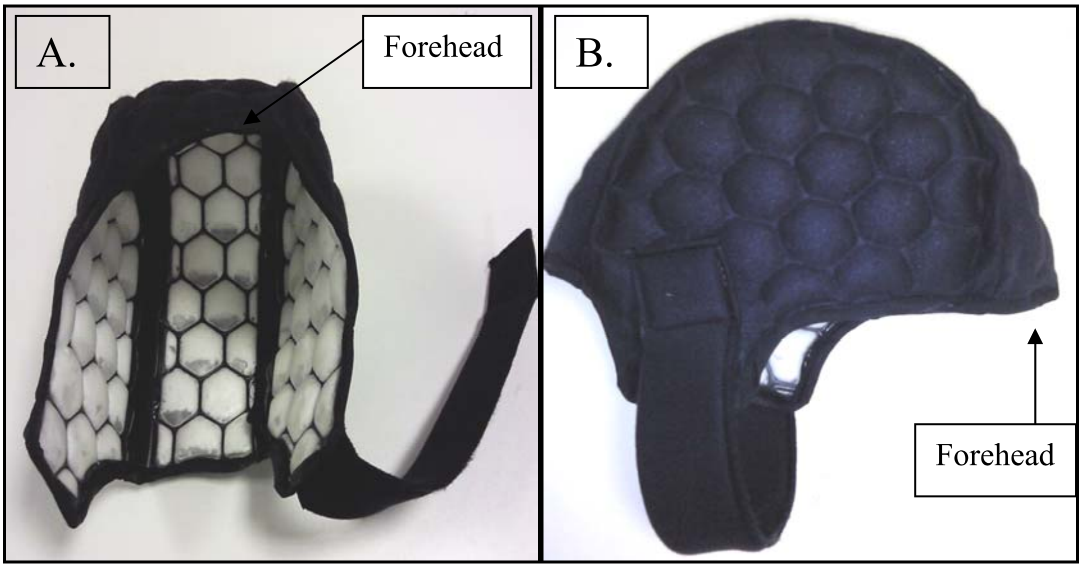

Figure 3. 4: Picture A. the inside of the 'Scrum Cap' from a front view, and picture B. the outside of the 'Scrum Cap' from a side view. The 'Scrum Cap' was used as a head cooling method covering the hairline and ears of each participant during both head cooling trials (20HC and 40HC).

PCM was used as head and torso cooling in the experimental trials (20HC, 40HC, 20TC and 40TC). The scrum cap was designed to cover the participants' head, and had a total mass of 402 g. The vest was designed to cover the participants' torso (back and chest) and had a mass of 1122 g.

The PCM vest and scrum cap were designed with a honeycomb (hexagon shaped) type structure, (Jackson Technical Solutions Ltd, Norfolk, UK; Figures 3.4 and 3:5). The scrum cap covered the hairline of the head and the ears. A soft strap went under the chin of each participant, and attached (with Velcro) to both sides of the scrum cap over either ear to ensure the cap was secure, (Figure 3.4 A. and B.). The vest had two sides (back and chest) and four straps with velcro attachments to connect them together over and around the participants' torso, (Figure 3.5 C. and D.).

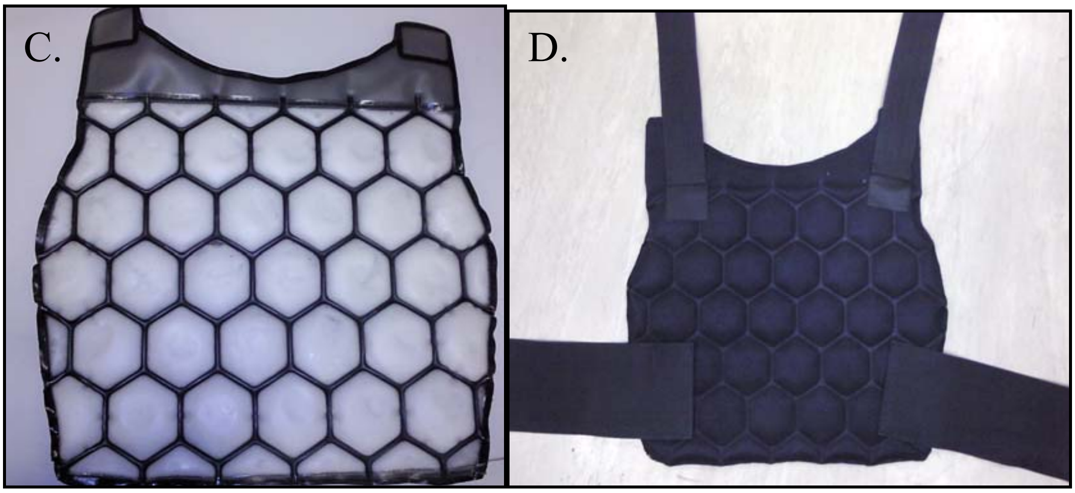

Figure 3. 5: Pictures C. and D. the PCM vest used in all torso cooling trials (20TC and 40TC). Pictures C. and D. the chest and back panel of the of the PCM vest. Picture C. the inside of the vest, and Picture D. the outside of the vest, with velcro strap attachments used to connect the chest and back panels over and around the participants' torso.

3.4.1 PCM STORAGE AND APPLICATION

Both the PCM vest and scrum cap were cooled in a commercial Fridge set to 5 ºC prior to usage. The recommend commercial guidelines (as instructed by NP Aerospace Ltd) stated the time required to 'charge' the PCM material was no less than 30 minutes. The PCM charging duration was kept the same per participant per trial but varied between participants due to the initial speed at which they managed to dress and prepare themselves for the trial (34 to 50 minutes) this was to avoid long periods where the participant could have been standing or waiting. The PCM was applied over the undergarment t-shirt for the chest and back and over the hairline for the head. The PCM was donned by the participant 15 minutes before each experimental trial commenced and remained on throughout the entire 80 minute trial.

3.5 TRIAL INSTRUMENTATION

3.5.1 PREPARATION

Upon arrival to the lab the participants completed a PAR-Q health screen questionnaire. Each participant was required to swallow a gastrointestinal pill (CorTemp™ Ingestible Core Body Temperature Sensor HT150002; HQ Inc. Wireless Sensing Systems and Design; Palmetto, USA) two hours prior to arrival time into the lab. A check was conducted using the CorTemp™ Data Recorder (with Polar® Heart Rate HTT150016; HQ Inc. Wireless Sensing Systems and Design; Palmetto, USA), to ensure the appropriate read-out (≈37 °C) could be attained on arrival at the laboratory. The participant then proceeded into the experimental chamber (Figure 3.3; 20 °C) to execute a baseline SWM test on the touch screen computer (section 3.2.3; 6), followed by a baseline postural challenge digital-arterial blood pressure measurement (section 3.2.3; 4). For hot trials (30 °C to 40 °C) the experimental chamber was then heated, using five commercially available heaters positioned at two opposing corners of the experimental chamber with two heaters situated in one corner and three heaters in another. The PCM was then placed in a fridge (5 °C) on the same shelf each time and a clock was started to ensure the PCM was charged for the set duration required per participant. A helmet check was then carried out to ensure the EOD helmet would be fitted correctly to the participants head prior to donning the EOD suit, with a specific configuration set per participant that was then kept the same for each of their trials.

The participants then proceeded into the bathroom, to don a pair of shorts kept the same per participant and continued with the pre-trial preparation. The participants were asked to insert a flexible translucent PVC rectal probe (Grant Instruments (Cambridge) Ltd, Shepreth, UK) into their rectum (approximately 10 cm beyond the anal sphincter). Record three nude body mass measurements (kg; to obtain an average) using the same balance each time and one mid-flow urine sample to monitor the hydration status of each participant prior to each experimental trial.

Once the participant returned to the lab, stainless steel temperature thermistors (Grant Instruments (Cambridge) Ltd, Shepreth, UK) were applied to the lateral calf, medial thigh, upper arm, and chest; (Ramanathan 1964) followed by the forehead. The thermistors were fixed using self adhesive tape. An aural thermistor (Grant Instruments (Cambridge) Ltd, Shepreth, UK) was inserted into the outer ear and held in place using cotton wool and self adhesive tape. All thermistors were then connected to the Squirrel SQ data logger (2020 series; Grant Instruments (Cambridge) Ltd, Shepreth, UK) and checked to ensure they were working correctly.

A Polar® heart rate chest belt (Polar Accurex Plus, Polar electro Oy; Kempele, Finland) was moistened, applied and tightened around the participants' torso in line with the bottom of the sternum. The undergarment t-shirt, trousers and boots were then donned by the participant. Once dressed, the Cosmed K4b$_2$ head strap and mask (Cosmed Pulmonary Function Equipment; Rome, Italy) were fitted to the head and face, (Figure 3.6).

3.5.2 BASELINE MEASURES (WITHOUT SUIT)

Baseline measures (B1; without the suit) were conducted once the Cosmed $K4b_2$ mask and head strap were in place, prior to the participant donning the EOD suit. Heart rate (HR), skin temperature ($T_{sk,}$), aural temperature (T_{au}), rectal temperature (T_{re}), gastrointestinal temperature (T_{cP}), thermal comfort (T_{hC}) and thermal sensation (T_{hS}) were manually recorded, (Section 3.6).

3.5.3 DONNING THE EOD SUIT

The participant donned the EOD trousers two minutes before the end of the cooling charge duration. Once the relevant time for charging the PCM had been completed, the PCM (either scrum cap or vest) was removed from the fridge. A temperature thermistor was then attached to the PCM using adhesive tape and the PCM fitted to the participant. In the instance of no cooling (control trials; 20NC and 40NC) the EOD trousers were donned, followed directly by the rest of the EOD ensemble. The EOD jacket was then donned followed by the helmet. Once dressed in the full EOD ensemble the Cosmed $K4b_2$ control unit was added and fixed over the jacket using the Cosmed $K4b_2$ strap, (Figure 3.6).

Figure 3. 6: The 3010 Ergotec EOD ensemble with instrumentation prior to entering the experimental chamber.

3.5.4 BASELINE MEASURES (WEARING THE SUIT)

Baseline measures (B2; wearing the EOD suit) were conducted once the Cosmed K4b$_2$ was started and set to record breath-by-breath data telemetrically, prior to entering the experimental chamber. Thermal measures and HR, $T_{sk,}$ T_{au}, T_{re}, T_{cP}, T_{hC} and T_{hS} were manually recorded, (see section 3.6). Participants proceeded into the experimental chamber ≈ 3 minutes before starting the trial. Three suited body mass values (to gain an average) were obtained using the same balance each time and the participant proceeded onto the treadmill to commence the 80 minute experimental trial.

3.6 MEASUREMENTS AND CALCULATIONS

3.6.1 TEMPERATURE MEASUREMENTS

The experimental chamber temperature was measured using a Kestrel® 4100 Pocket Air Flow Tracker (Richard Paul Russell Ltd; Lymington; UK). Relative humidity (RH; %), and temperature (ºC) were monitored regularly throughout the trial and recorded manually (instrument accuracy of ± 1 ºC for temperature and ± 3 % for RH) at the beginning of every station within each cycle by the investigator (Table 3.3). The average temperature and RH measured at the beginning of each trial was as follows; 22.2±0.4 (20NC), 22.3±0.6 (20HC), 22.0±0.4 (20TC), 40.3±0.3 (40NC), 40.2±0.6 (40HC), 40.5±0.4 (40TC), (see Appendix A).

The gastrointestinal pill data was logged manually at B1, B2 and at the SWM test station (once per cycle). The CorTemp™ Data Recorder was worn by the participant on the outer side of the EOD Jacket, and was set to log both HR (beats·min^{-1}) and T_{cP} (ºC) every 20 seconds throughout the trial. All core temperature ingestible sensors came coded meaning that they could then be tracked by using this code once it had been typed into the data recorder at the beginning of each trial. Tre, T_{au}, $T_{sk,}$ and PCM temperatures were logged manually at B1, B2 and the arm ergometry and SWM test stations (twice every cycle), and every 15 seconds throughout the trial by the Squirrel SQ 2020 series data logger (Grant Instruments (Cambridge) Ltd, Shepreth, UK; section 3.2.3, Figure 3.1).

3.6.2 MEAN SKIN TEMPERATURE AND HEAT STORAGE CALCULATIONS

Mean skin temperature ($T_{sk,}$; ºC), was calculated from the lateral calf, medial thigh, upper arm, and chest temperatures (Equation 1; Ramanathan 1964). Heat storage ($J \cdot g^{-}1$) was calculated using $T_{sk,}$ and T_{cP} as the core temperature (T_c) variable (Equation 2; Havenith, Luttikholt and Vrijkotte 1995).

Equation 1:

$$\text{Mean Skin Temperature (ºC)} = 0.30\,(\text{Chest} + \text{Arm}) + 0.20\,(\text{Thigh} + \text{Calf})$$

Equation 2:

$$\text{Heat Storage } (J \cdot g^{-1}) = [(0.8 \times \Delta\, T_{cP}) + (0.2 \times \Delta\, T_{sk,})] \times CB$$

CB denotes specific heat capacity of the body (3.49 $J \cdot g^{-1}$)

3.6.3 CARDIOVASCULAR MEASUREMENTS

Digital-arterial blood pressure (bp; mmHg) and HR (beats·min^{-1}) were recorded and monitored non-invasively by the volume-clamp method (Penaz, 1973) and plethsmography, using a Portapres Model-2 device (Beatscope FMS, Finapres Medical Systems BV, Amsterdam; The Netherlands). Participants wore one finger cuff on the middle phalanx of either the index or forefinger. The cuff was connected to a front-end unit by an air hose and cuff cable, and the front-end unit to the main unit and pump. At the start of each recording a ‘physiocal’ (calibration) was automatically conducted to detect a ‘set point’ diameter of the digital-artery. This included the cuff inflating and deflating accordingly to adjust to changes in intra-arterial pressure. The diameter of the digital-artery was ‘clamped’ when the transmural pressure equated to zero. The physoical was then turned off while the participants' digital-arterial BP was measured and displayed using Plethsmography.

Embedded and aligned parallel within the cuff was a light emitting diode (LED) and infrared photodiode sensor. Changes in the volume of light passing through the artery are directly proportional to the changes in diameter, thus, changes in arterial diameter were compared to the participants 'set point,' and a BP waveform was computed using an algorithm embedded within the software.

3.6.5 CALCULATIONS OF PHYSIOLOGICAL STRAIN

HR (beats·min^{-1}) and core temperature (T_{re} and T_{cP}; ºC) were used to calculate the physiological strain experienced by each participant within each condition. Physiological strain was calculated using the physiological heat strain index (PhSI; Equation 3; Tikuisis, McLellan and Selkirk 2002), first with T_{re} then again with T_{cP} as the core temperature variable. The index provides physiological strain on a scale of 0 to 10, with 0 representing no physiological strain and 10 representing maximal physiological strain.

Equation 3:

$$PhSI = 5[(TCt^* - TC0^*) \div (39.5 - TC0^*)] + 5[(HRt - 60) \div (HRmax - 60)]$$

t denotes values at a given time point. 0 denotes baseline value.

max denotes maximum HR value seen from all trials. *substitute with T_{cP} or T_{re}

3.6.6 SUBJECTIVE MEASUREMENTS

A 15-point scale (6 to 20; Borg 1970; Appendix B) was used to monitor the participants overall ratings of perceived exertion (RPE) of three individual body segments (upper back and shoulders, lower back, and legs). Thermal sensation (TS; Appendix C; Young, Sawka, and Epstein *et al.* 1987) and thermal comfort (TC; Appendix D; modified from Epstein and Moran 2006) were rated by participants using a 9-point scale (0-8). Participants were asked to provide values for TS and TC referring to their overall body followed by 5 other body segments (head, back, chest and arms, groin, and legs). RPE, TS and TC were recorded manually by the investigator at B1, B2 and during the treadmill and arm ergometry stations of every cycle.

3.6.7 CALCULATIONS OF PERCEPTUAL STRAIN

Ratings of perceived exertion (RPE) and thermal sensation (T_{hS}) from the treadmill and arm ergometry stations (twice per cycle) were used to calculate an overall perception based strain index (PeSI; 0-10). For the PeSI to be calculated (equation 4; Tikusis, McLellan and Selkirk 2002) the RPE and T_{hS} scores were altered from 15 (6 to 20) and 9 (0 to 8) point scales to 11 (0 to 10) and 7 (7 to 13) point scales, respectively.

Equation 4:

$$PeSI = 5[(T_{hS}t - 7) \div 6] + 5[RPEt \div 10]$$

T_{hS} and RPE denote thermal sensation and perceived exertion respectively.

t denotes values at a given time point.

3.8 BP ANALYSIS

The BP portapres waveforms from each cycle were merged to produce one portapres file per trial using BeatScope 1.1a software (FMS, Finapres Medical Systems BV, Amsterdam, The Netherlands). A beat-to-beat analysis was then conducted on the merged file using BeatFast (within BeatScope). The level correction was turned on (correcting pressure from finger to brachial level using the height null information) with the analysis execution speed set to very high (>10 times real time; with no effect to original readings). This produced a beat data file (showing pulsatile BP values and HR) aligned with the original portapres file (showing height null and the BP waveform). Both the Portapres file and Beat data file were viewed together using Beatscope (Figure 3.8) and saved as a session file (one session file equated one trial) for analysis. Each BP waveform was viewed and analysed as follows (Figure 3.8):

- A 10 second mean of HR (beats·min^{-1}), and BP (Sys, Dia, MAP; mmHg) were obtained prior to the event marker (standing). In an attempt to eliminate artefact the mean was obtained from >4 seconds prior to the event marker and when the height null measured was constant (*i.e.* 34cm).
- Once stood (>2 seconds after event marker and when the height null was constant) recovery values (HR and BP) were obtained closest to 25 seconds after the event mark. The lowest (trough) and highest (peak) recorded BP values and the highest (peak) HR values obtained within the 25 second recovery phase were noted with the time point at which they occurred.

- Means of each data point for each cycle and trial were then calculated using Microsoft Office Excel (versions 2003 and 2007). Graphs were drawn to represent the pre-stand mean, peak and recovery HR and the pre-stand mean, trough, peak and recovery BP response to the postural challenge, per cycle and trial.

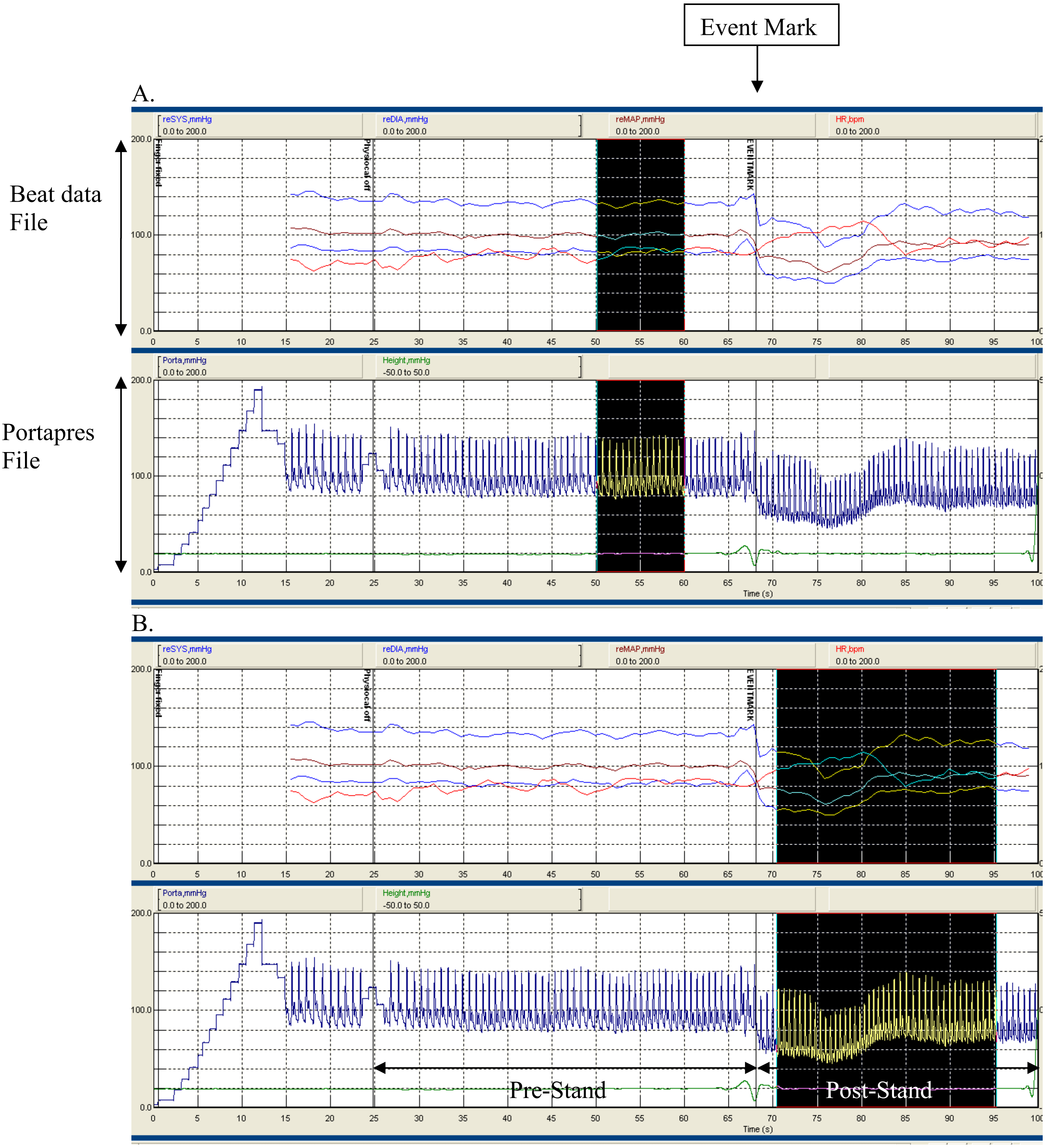

Figure 3. 7: An example BP waveform from one participant during a baseline measurement, prior to an experimental trial. Two viewports are shown (A. and B.) to aid explanation; A. highlights a 10 second period before the event mark (pre-stand) and B. highlights a 25 second period after the event mark (post-stand) used in the analysis.

3.9 TRIAL DISCONTINUATION CRITERIA

For the participants safety, an experimental trial was terminated when; participants heart rate exceeded 95 % of maximum (220-AGE) for 3 minutes, gastrointestinal, rectal, or aural temperature reached 39.5ºC. If perceptual scores reached maximum on either the RPE (19/20), T_{hC} (8), T_{hS} (8), and/or GSQ (3) scales, and if a participant elected to withdraw at any point throughout the trial/study the current trial was terminated and/or participation in the study discontinued.

3.10 STATISTICS

The management and calculations of experimental data collected from all trials and conditions within the current study were performed using Microsoft Office Excel (versions 2003 and 2007). Once managed, a general linear model analysis of variance (GLM ANOVA) statistical test was conducted (with the use of MINITAB 15 software) separately on the thermal, subjective, cognitive, and postural challenge data, for time (points 0 to 24), and then again for cycle (1 to 4). The model was set to include main effects for condition (20TC, 20HC, 20NC, 40TC, 40HC, 40NC), participant (n=6), and order (1 to 6). If a significant *P* value ($P \leq 0.05$) was obtained for any main effect or interaction (condition x time; condition x cycle), then a Tukey post hoc test was conducted to determine the exact points of significance within the data.

4. RESULTS

4.1 HEART RATE

Heart rate (HR; beats·min^{-1}; Figure 4.1) varied within each activity cycle and between conditions with the greatest response achieved in the 40 °C compared to the 20 °C trials ($P<0.001$; condition*time) during the arm ergometry station (not including the postural challenge station). There are noticeable peaks and troughs within each cycle relative to the different workloads, for example, HR was lowest during the 6th station (SWM test) and highest during the 1st (treadmill) and 5th (arm ergometry) stations of each cycle.

Within the 20 °C trials, HC resulted in the greatest HR response ($P<0.001$ vs. 20NC and 20TC) throughout the 80 minute trial, with a peak HR of 107±16 beats·min^{-1} during the arm ergometry (5th) station of the final cycle when Tf measured was lowest and T_{cP} was greatest.

At 40 °C, HR remained lowest during both the HC ($P<0.001$ vs. NC) and TC conditions ($P<0.001$ vs. NC) throughout the 80 minute trial. Towards the end of the trial during the 5th (arm ergometry) station of the 3rd cycle (≈ 50 mins) and the 1st (treadmill) station of the 4th cycle (≈ 60 mins), HR was lower with TC compared to HC (111±14 vs. 121±18 beats·min^{-1} and 118±12 vs. 125±21 beats·min^{-1}). The greatest HR occurred within 40NC during the postural challenge station of the final cycle 148±12 beats·min^{-1} (see section 4.7.3).

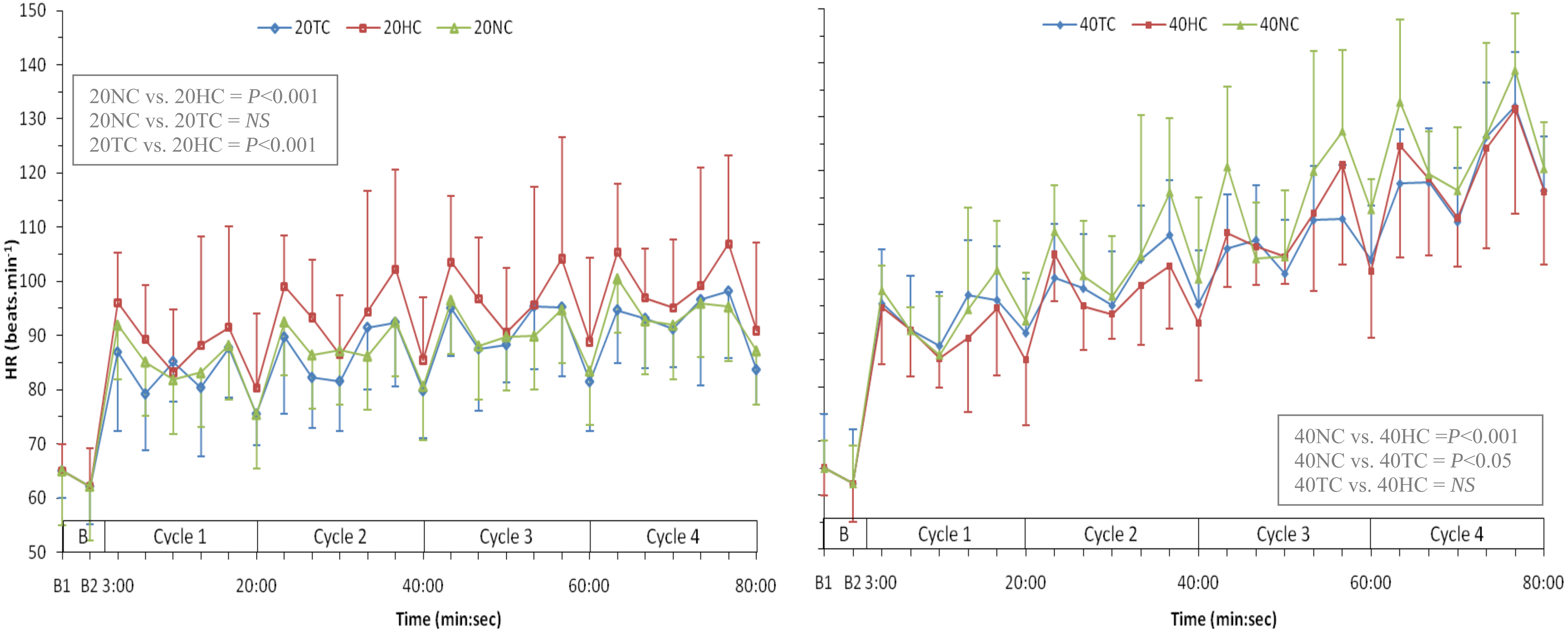

Figure 4. 1: Heart Rate (HR; beats·min^{-1}; mean±SD; n=6). Significant main effects for condition, time, and condition x time, (P<0.001). 80 minutes of explosives ordnance disposal related activity in 20 °C and 40 °C. (TC=torso cooling; HC = head cooling; NC = no cooling)

4.2 TEMPERATURE MEASUREMENTS

4.2.1 GASTROINTESTINAL, AURAL, AND RECTAL TEMPERATURE

Core temperature remained within safe limits, measuring below 38 °C within all conditions, with no significant increases from B1 to the end of exercise at 20 °C with either T_{re} or T_{cP} measures. A summary of the response variables at 80 minutes is presented in Table 4.7.

Core body temperature measured by a gastrointestinal pill (T_{cP}; Figure 4.2) transiently declined in all conditions within the first 10 minutes of the 1st cycle, (e.g. minus 0.02 to minus 0.09 °C). Thereafter, T_{cP} remained below that measured at rest (37.10±0.15 °C) in 20TC only, for the entire 80 minute duration. The magnitude of rise was greatest in 40°C trials (TC 0.51±0.21°C; HC 0.66±0.33°C; NC 0.59±0.11°C) when compared to the 20 °C trials (TC, minus 0.06±0.26°C; HC, minus 0.03±0.10°C; NC, 0.05±0.25°C; $P<0.05$).

At 20 °C, T_{cP} responses during TC were significantly lower than HC and NC during the 80 minute sequence ($P<0.001$). HC and NC did not significantly vary. At 80 minutes, T_{cP} did not vary between trials (37.00±0.21 °C for TC, 37.22±0.23 °C for HC and 37.19±0.21 °C for NC).

In the 40 °C trials, T_{cP} was lowest overall with HC ($P<0.05$ vs. TC; $P<0.001$ vs. NC) however, the difference between HC (37.70±0.31 °C) and TC (37.65±0.27 °C) was no longer evident at 60 minutes.

The magnitude of rise with T_{au}, T_{re} and T_{cP} was greatest at 40 °C when compared to 20 °C for the NC and TC conditions ($P<0.001$; post hoc for condition; Table 4.1). At 20 °C, T_{au} and T_{re} were greatest with HC when compared to NC and TC, whereas the opposite was present at 40 °C, with the lowest T_{re} and T_{au} responses measured during HC when compared to NC and TC, ($P<0.001$; post hoc for condition; Table 4.1). Core temperature measured at baseline with an aural thermistor was approximately 1 °C lower than that measured with T_{re} or T_{cP}, with T_{au} detecting the greatest rise between B1 and 80 minutes within all conditions (20NC, 0.35 °C; 20HC, 0.31 °C; 20TC, 0.27 °C; 40NC, 1.13 °C; 40HC, 1.04 °C; 40TC, 0.93 °C). T_{au} continued to increase with no evidence of an initial decrease within the first cycle, which differs to that of the overall trend found with the T_{re} and T_{cP}, with an initial decrease present typically between B1 and the end of the first cycle before rising again between the 2nd and 4th cycle (Table 4.1).

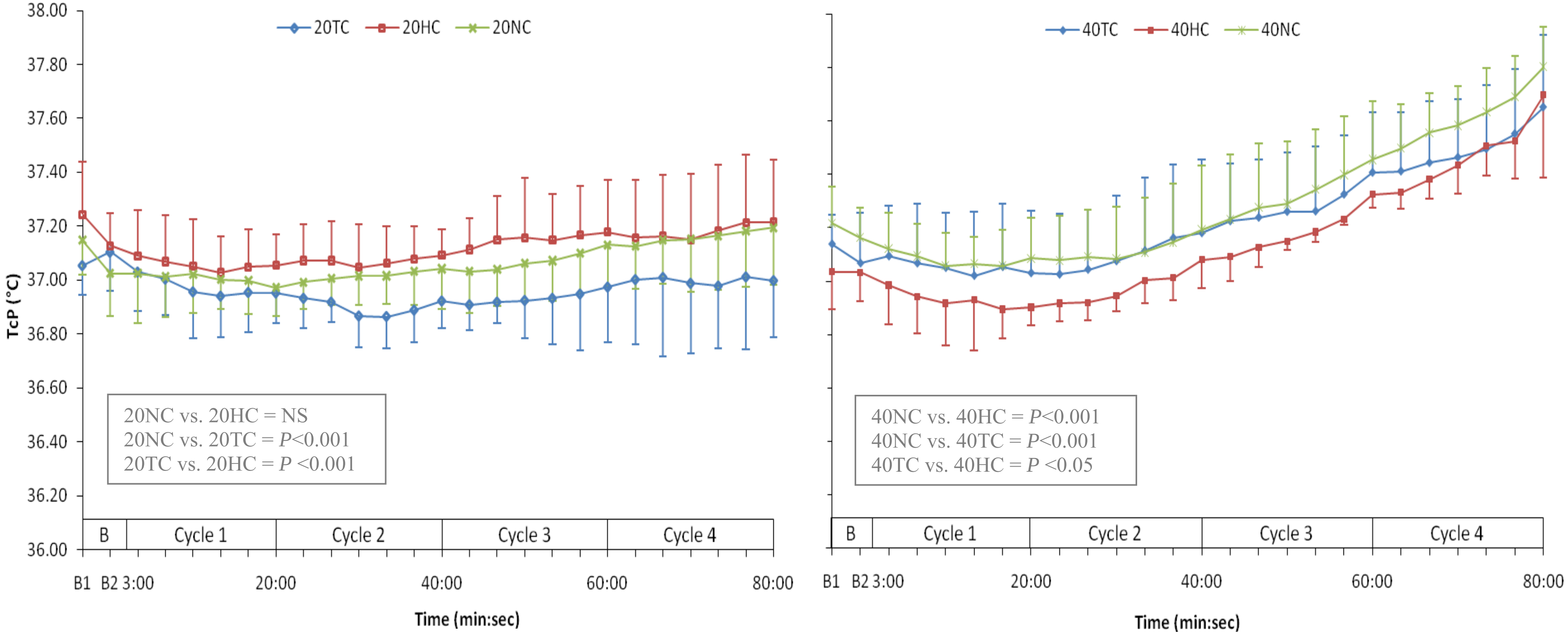

Figure 4. 2: Core temperature (T_{cP}; °C; mean±SD; n=6). Significant main effect for condition, time, and condition x time, (*P*<0.001). 80 minutes of explosives ordnance disposal related activity in 20 °C and 40 °C. (TC=torso cooling; HC = head cooling; NC = no cooling).

Table 4. 1: Three core temperature variables (T_{cP}; T_{re}; T_{au}; °C; mean±SD) (n=6). Significant main effect for condition, time, condition x time, ($P<0.001$) with all conditions. Responses taken from baseline without the suit, prior to trial start (B1; PRE), and at the end of each cycle throughout 80 minutes of explosive ordnance activity (1, 20; 2, 40; 3, 60; 4, 80).

Condition	Cycle	Time (min)	Core Temperature at 20°C			Core Temperature at 40°C		
			T_{cP}	T_{re}	T_{au}	T_{cP}	T_{re}	T_{au}
NC	**B1**	**PRE**	37.15±0.13	37.06±0.09	36.11±0.45	37.22±0.11	37.10±0.09	36.25±0.32
	1	**20**	36.97±0.11	36.94±0.14	36.19±0.30	37.09±0.15	36.97±0.09	36.55±0.26
	2	**40**	37.04±0.15	36.95±0.12	36.34±0.28	37.19±0.24	37.06±0.17	36.84±0.31
	3	**60**	37.13±0.16	37.01±0.23	36.42±0.35	37.46±0.22	37.32±0.17	37.07±0.30
	4	**80**	37.19±0.21	37.09±0.28	36.46±0.35	37.80±0.15	37.59±0.22	37.38±0.28
HC	**B1**	**PRE**	37.24±0.19	37.23±0.22	36.31±0.48	37.04±0.14	37.01±0.14	36.00±0.33
	1	**20**	37.06±0.12	37.04±0.21	36.27±0.31	36.90±0.07	36.90±0.10	36.15±0.28
	2	**40**	37.09±0.10	37.01±0.16	36.41±0.30	37.08±0.10	37.01±0.11	36.41±0.26
	3	**60**	37.18±0.19	37.09±0.21	36.53±0.30	37.33±0.05	37.20±0.10	36.69±0.21
	4	**80**	37.22±0.23	37.20±0.28	36.63±0.30	37.70±0.31	37.49±0.16	37.05±0.22
TC	**B2**	**PRE**	37.05±0.11	37.00±0.05	36.10±0.40	37.14±0.11	37.22±0.22	36.35±0.24
	1	**20**	36.95±0.11	36.81±0.17	36.13±0.33	37.03±0.23	37.15±0.15	36.65±0.12
	2	**40**	36.92±0.10	36.86±0.30	36.25±0.27	37.18±0.28	37.15±0.18	36.91±0.13
	3	**60**	36.97±0.21	36.93±0.25	36.34±0.27	37.41±0.05	37.31±0.22	37.05±0.14
	4	**80**	37.00±0.21	37.04±0.27	36.38±0.28	37.65±0.27	37.58±0.26	37.28±0.16

4.2.2 MEAN SKIN TEMPERATURES

T_{sk} (Figure 4.3) increased throughout the 80 minute trial duration (4 activity cycles) in all conditions ($P<0.001$; main effect for time). In all conditions the greatest rise in T_{sk} occurred within the first 20 minutes of activity (ranging from 1.15 °C to 1.93 °C), with a gradual incline thereafter. However, the magnitude of rise overall was greatest in 40 °C compared to the 20 °C trials ($P<0.001$). In both 20 °C and 40 °C, T_{sk} was lowest with TC when compared to HC and NC during the 3rd activity cycle and values were equivalent to those of HC and NC during the 2nd activity cycle.

In 20 °C, T_{sk} was lowest overall with TC (vs. 20HC & 20NC $P<0.001$; post hoc for condition) this was similar to the response in 40 °C, whereby T_{sk} was lowest in 40TC when compared to both 40HC and 40NC, ($P<0.001$; post hoc for condition). Although, in 40°C after the 3rd cycle of activity (60 minutes) T_{sk} did not vary between conditions and T_{sk} at the end of each trial was 37.19±0.17 °C 40NC; 37.09±0.15 °C 40HC; and 36.94±0.18 °C 40TC.

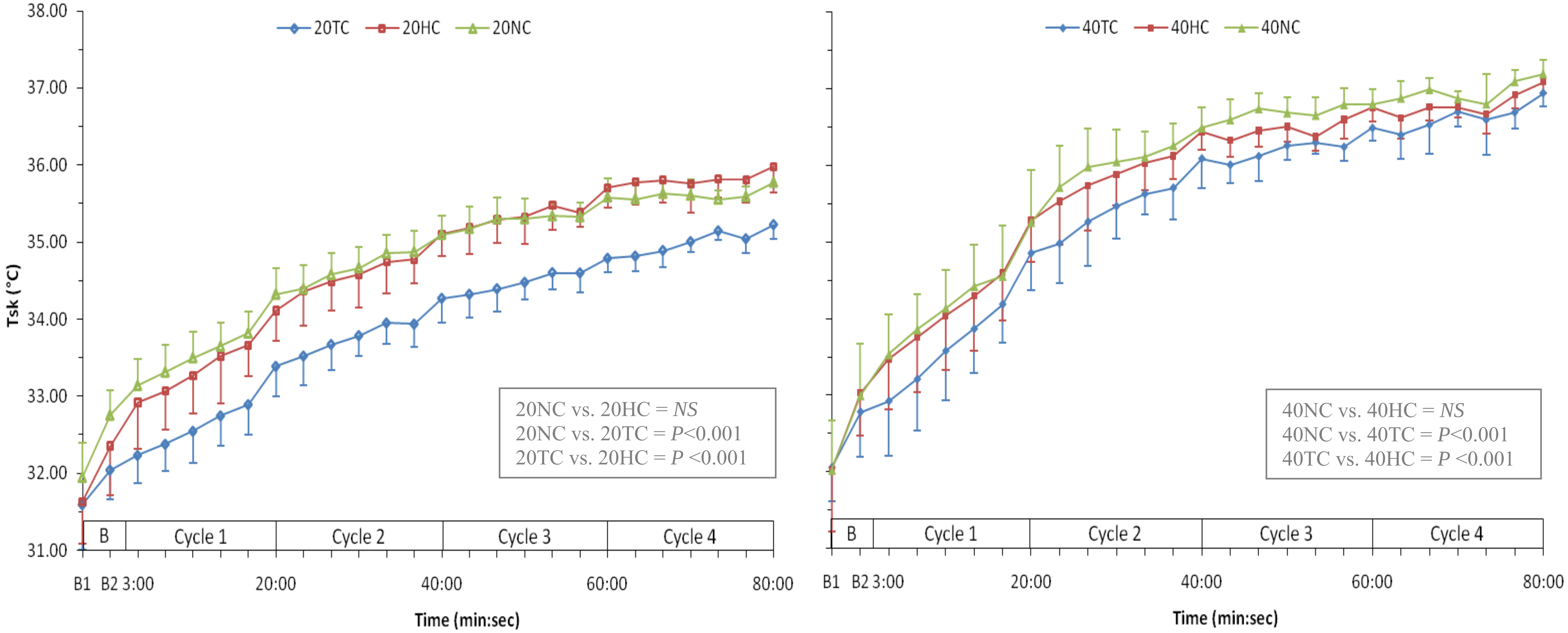

Figure 4. 3: Mean Skin temperature (T_{sk}; °C; mean±SD; n=6). Significant main effects for condition, time, and condition x time, (P<0.001). 80 minutes of explosives ordnance disposal related activity in 20 °C and 40 °C. (TC=torso cooling; HC = head cooling; NC = no cooling).

4.2.3 SKIN TEMPERATURES

Temperature (PCM, upper arm, thigh and calf; °C; Table 4.2) increased over the 80 minute activity duration with the magnitude of rise being greatest in the 40 °C vs. 20 °C (*P*<0.001; main effect for time) and varied between conditions (*P*<0.001). At 20 °C, upper arm and thigh temperatures were lowest with TC when compared to both HC (*P*≤0.05) and NC (*P*<0.001) conditions. Calf temperatures did not vary between conditions. At 40 °C, upper arm, thigh and calf temperatures were lowest with HC when compared to TC (*P*<0.001) and NC (*P*<0.001; upper arm only). The rise in PCM temperature over the 80 minute duration was greatest with 20HC (≈6 °C) when compared to 20TC (≈3 °C), and greatest with 40HC (≈9.5 °C) when compared to 40TC (≈8 °C).

Table 4. 2: Temperatures (°C) recorded at baseline (B2; -5 minutes prior to trial start; equating to 10 minutes of wearing the PCM; responses were taken before entering the experimental chamber), and end of trial (Cycle 4; 80 minutes). Significant main effects for time, condition, condition x time, (P<0.001; all variables).

Condition	**Cycle**	**Time (min)**	**Temperature Variable (°C)**			
			PCM	**Upper Arm**	**Medial Thigh**	**Lateral Calf**
20NC	**B2**	**-5**		32.45±0.52	32.51±0.57	32.89±0.33
	4	**80**		35.67±0.48	35.35±0.37	35.68±0.44
20HC	**B2**	**-5**	26.86±0.85	32.02±1.08	32.04±1.26	32.53±0.71
	4	**80**	32.94±2.26	36.04±0.44	35.28±0.64	35.73±0.47
20TC	**B2**	**-5**	24.12±1.02	32.14±0.61	32.12±0.79	32.44±0.39
	4	**80**	27.75±2.66	35.54±0.25	35.02±0.44	35.74±0.38
40NC	**B2**	**-5**		33.00±0.88	32.36±0.96	33.06±0.70
	4	**80**		37.30±0.15	37.25±0.18	37.16±0.16
40HC	**B2**	**-5**	27.22±1.76	32.84±0.61	32.64±0.70	33.36±0.77
	4	**80**	36.82±0.17	36.71±1.13	37.10±0.20	37.16±0.21
40TC	**B2**	**-5**	25.89±0.40	33.03±0.32	33.20±0.31	33.49±0.49
	4	**80**	33.78±0.75	37.27±0.13	37.20±0.12	37.19±0.30

4.2.4 CHEST TEMPERATURES

T_c (Figure 4.4) increased in all conditions, with the magnitude of rise being greatest during the 40 °C trials compared to the 20 °C trials, ($P<0.001$). In both 20 °C and 40 °C conditions, chest temperature was lowest with TC by >1 °C when compared to HC and NC ($P<0.001$; main effect for condition). However, at 40 °C this was less evident after the 3rd cycle (60 minutes) with the end of trial temperatures being; 36.98±0.35 °C NC; 36.87±0.47 °C HC; and TC; 36.28±0.46 °C. At 20 °C chest temperature increased over the 80 minute trial by 2.41 °C with TC, 3.81 °C with NC, followed by and 4.32 °C with HC, of which the majority of the increase occurred during the first two cycles of activity (85 % NC; 82 % HC; 54 % TC). At 40 °C the increase overall was greatest with NC (4.41 °C) followed by HC (4.33 °C) and TC (3.49 °C), of which the majority of the increase occurred during the first 40 minutes of activity, (89 % HC; 86 % NC; 59 % TC).

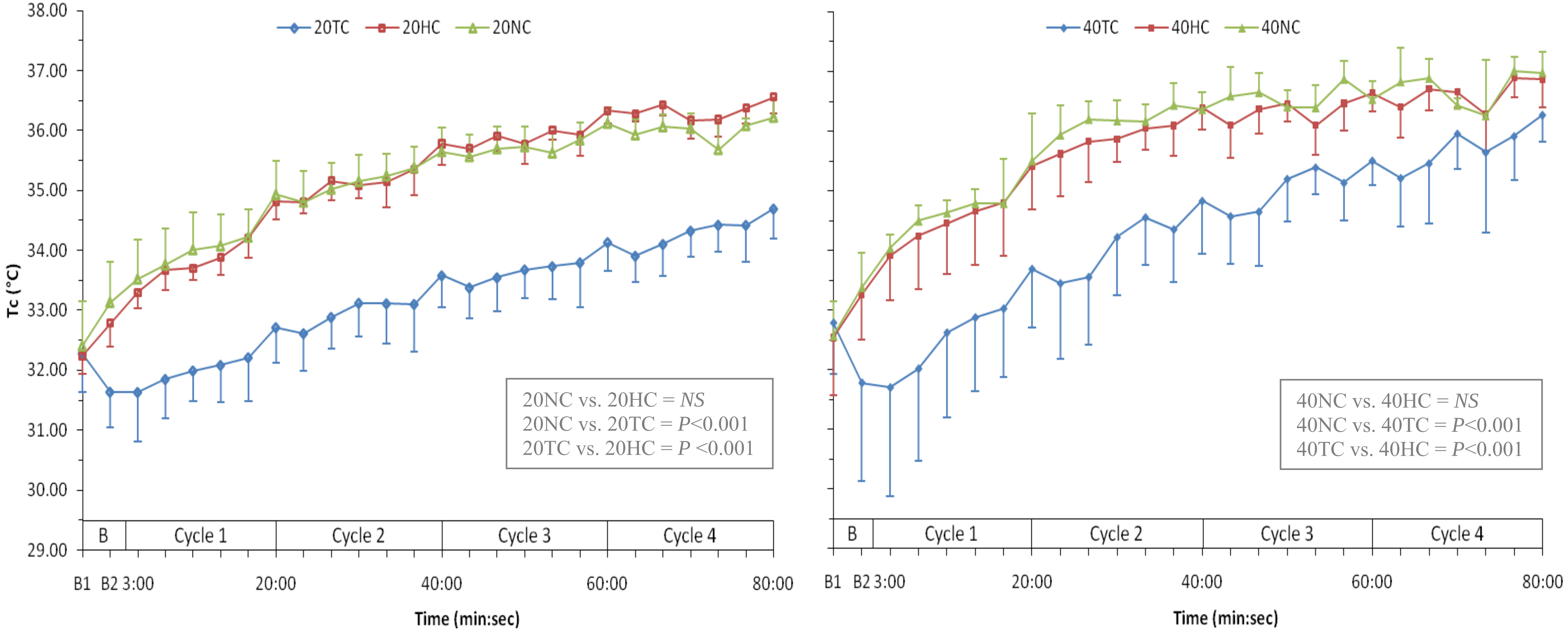

Figure 4. 4: Chest temperature (T_c; °C; means±SD; n=6). Significant main effects for condition, time, and condition x time, (*P*<0.001). 80 minutes of explosives ordnance related activity in 20 °C and 40 °C. (TC=torso cooling; HC=head cooling; NC=no cooling).

4.2.5 FOREHEAD TEMPERATURES

T_f (Figure 4.5) increased in all conditions, with the magnitude of rise being greatest during the 40 °C trials compared to the 20 °C trials, (*P*<0.001; main effect for condition). In both 20 °C and 40 °C conditions, after cycle 1 (20 minutes), T_f was ≈1.0°C lower in HC compared to TC and NC, (*P*<0.001). Within the 20 °C conditions, T_f was the lowest during 20HC, (*P*<0.001 vs. 20TC and 20NC) which was evident throughout the trial with end of trial temperatures of 35.10±0.50 °C (20HC), 35.72±0.17 °C (20TC), and 35.97±0.44 °C (20NC). At 40 °C, HC maintained the lowest T_f throughout the 80 minute trial (*P*<0.001 vs. 40TC and 40NC) however at the end of the forth cycle there was no significant difference between 40HC (36.99±0.17 °C), and 40TC (37.12±0.11 °C).

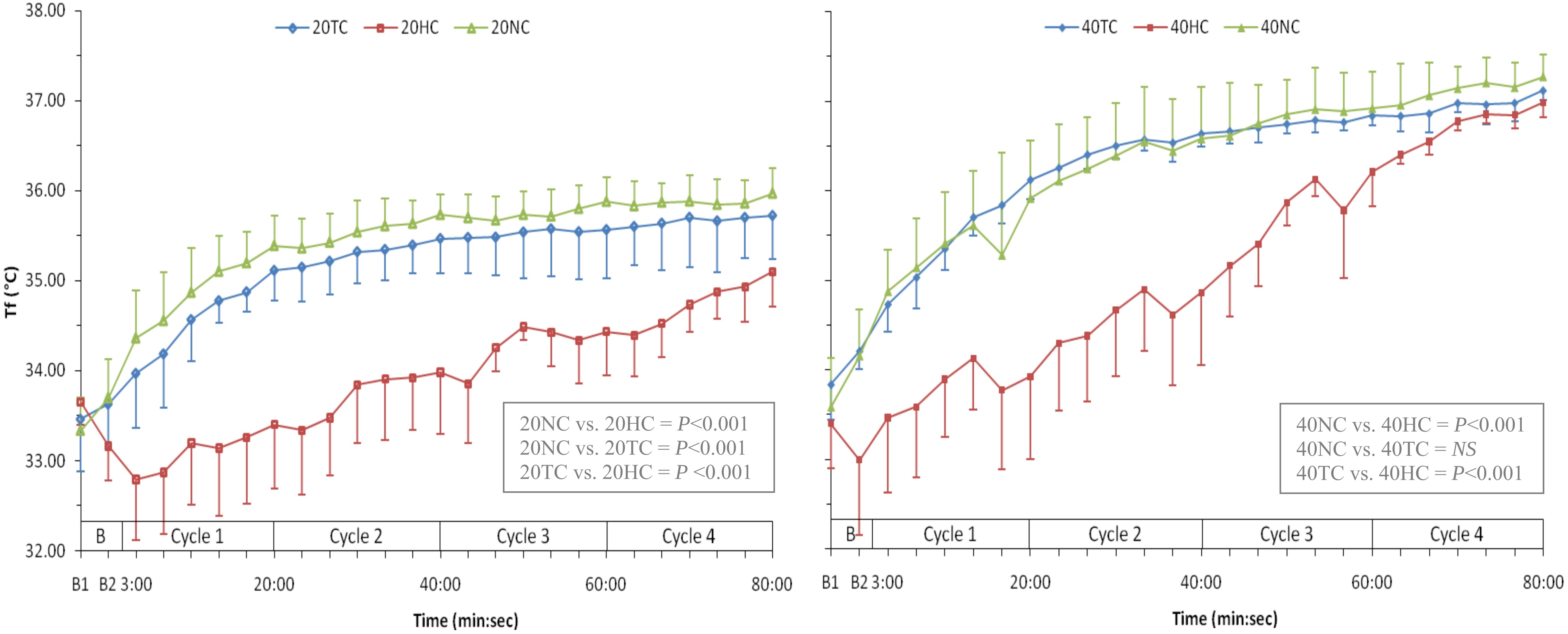

Figure 4. 5: Forehead temperature (T_f; °C; mean±SD; n=6). Significant main effects for condition, time, and condition x time, ($P<0.05$). 80 minutes of explosives ordnance disposal related activity in 20 °C and 40 °C. (TC=torso cooling; HC = head cooling; NC = no cooling).

4.3 HEAT STORAGE

Heat storage (HS; $J \cdot g^{-1}$; Figure. 4.6) was greater at 40 °C compared to 20 °C, (*P*<0.001; post hoc for condition). Heat storage was lowest throughout the 20 °C trials with TC, compared to HC and NC (*P*<0.001; post hoc for condition), the difference between TC and NC was no longer evident during the fourth activity cycle (after 60 minutes). Heat storage at the end of the 80 minutes of activity was 3.16 $J \cdot g^{-1}$ with HC; 2.59 $J \cdot g^{-1}$ with 20NC; and 2.51 $J \cdot g^{-1}$ with 20TC).

Within the 40 °C trials, heat storage increased significantly between cycles in all conditions (*P*<0.001; post hoc for cycle). The heat storage during 40TC was significantly lower than that found during 40HC and 40NC (*P*<0.001; post hoc for condition). The rise in heat storage was approximately twice as great during the first 40 minutes of activity, compared to the last 40 minutes of activity, (40TC 2.88 $J \cdot g^{-1}$ vs. 1.00 $J \cdot g^{-1}$; 40NC 3.20 vs. 0.89 $J \cdot g^{-1}$; and 40HC 3.25 vs. 0.73 $J \cdot g^{-1}$).

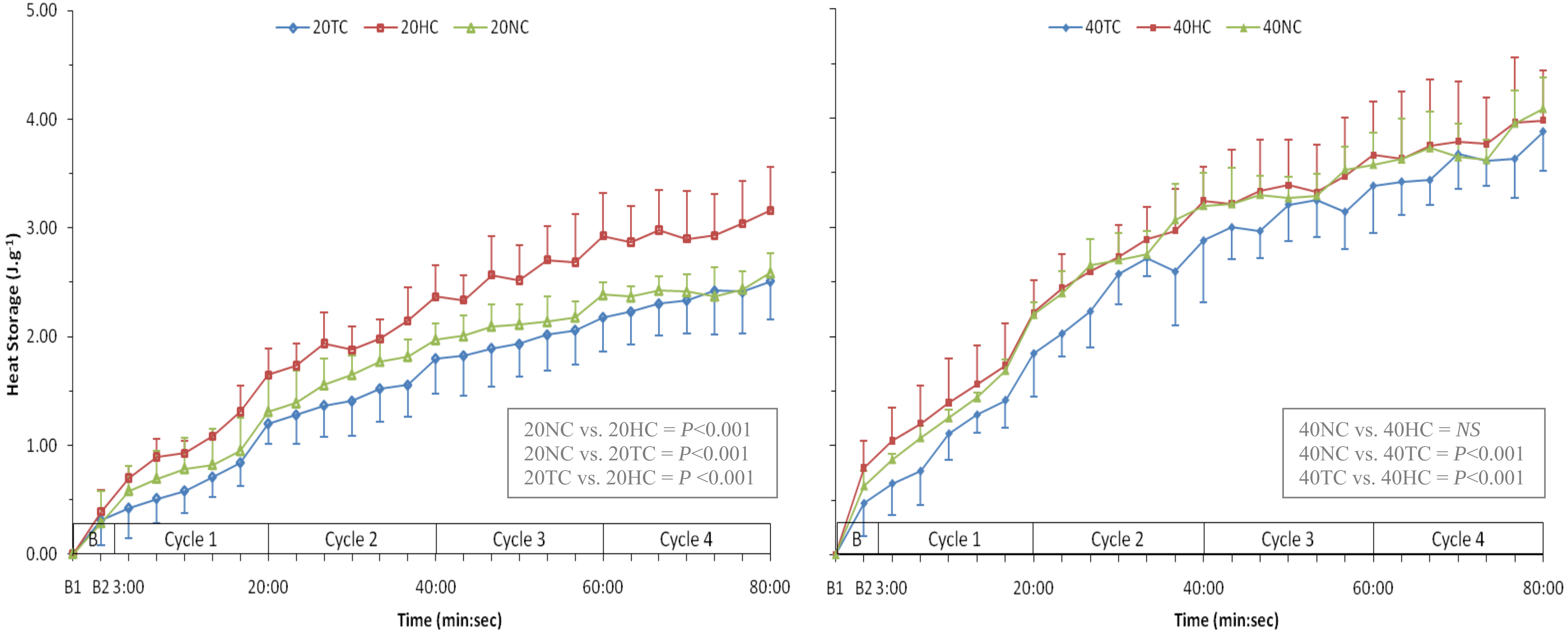

Figure 4. 6: Heat Storage (J·g^{-1}; mean±SD; n=6). Significant main effects for condition, time, and condition x time, (P<0.001). 80 minutes of explosives ordnance disposal related activity in 20 °C and 40 °C. (TC=torso cooling; HC = head cooling; NC = no cooling).

4.4 SWEAT RATE

Sweat rate ($\dot{SR}$; L·hr^{-1}; Figure 4.7) in the 40 °C trials was approximately double that during the 20 °C trials, ($P<0.005$). TC produced the largest inter-individual difference (Figure 4.6) in SR compared to HC and NC, both at 20 °C (±0.112 L·hr^{-1}) and 40 °C (±0.181 L·hr^{-1}).

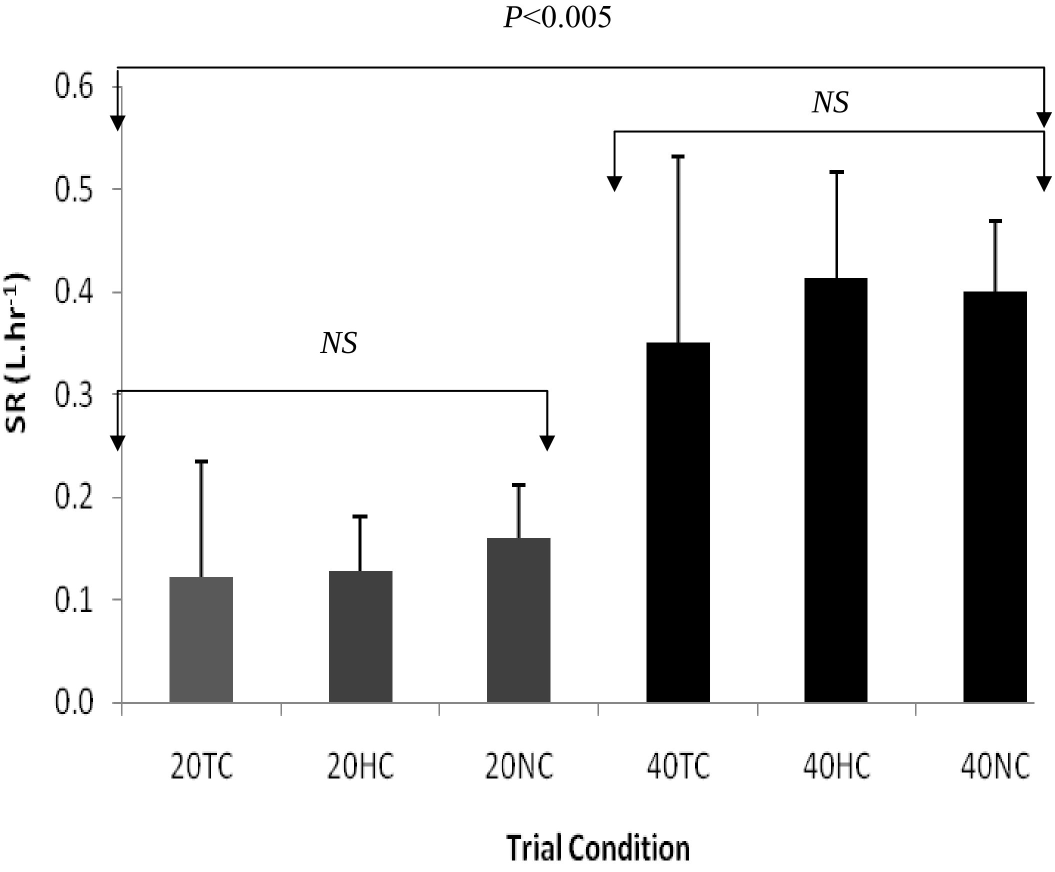

Figure 4. 7: Sweat Rate ($\dot{SR}$; L·hr^{-1}; mean (SD); n=6). Significant main effect for condition, ($P<0.001$). 80 minutes of explosives ordnance disposal related activity in 20 °C and 40 °C. (TC = torso cooling; HC = head cooling; NC = no cooling).

4.5 PHYSIOLOGICAL STRAIN INDEX

There was an overall increase in the physiological strain index (PhSI; Figure 4:8) throughout the 80 minute trial duration (4 activity cycles) in all conditions except 20TC with the magnitude of rise being greatest in 40 °C when compared to 20 °C, (*P*<0.001). PhSI values calculated at the end of each trial at 40 °C (NC 3.46±0.36; HC 3.37±1.09; TC 3.12±0.70), were twice as high as the PhSI calculated at the end of each trial at 20 °C, (NC 1.22±0.63; HC 1.05±0.65; TC 0.69±0.68).

In all conditions and within each cycle (20 minutes of activity) there are peaks and troughs relative to the changes in workload, whereby the PhSI is lower during the final station of activity (SWM test with physical seated rest), and higher during the 1st and 5th (treadmill walking and arm ergometry) stations of activity, predominately due to fluctuations in HR (see section 3.6.4 for the PhSI calculation).

In 20 °C, PhSI was found to be lowest within 20TC (*P*<0.001; post hoc for condition, cycle) when compared to 20HC and 20NC which were no different to each other. There was a significant increase in PhSI within the 20HC and 20NC trials between B2 and 80 minutes of activity (*P*≤0.01; post hoc for time), thus emphasising further that the least physiological strain was experienced during 20TC.

In 40 °C, although PhSI did not significantly vary between conditions; after 40 minutes of activity, PhSI tended to be lowest with 40HC than 40NC and 40TC (≈0.3 units) with no change from the value calculated at the first activity station of the first cycle.

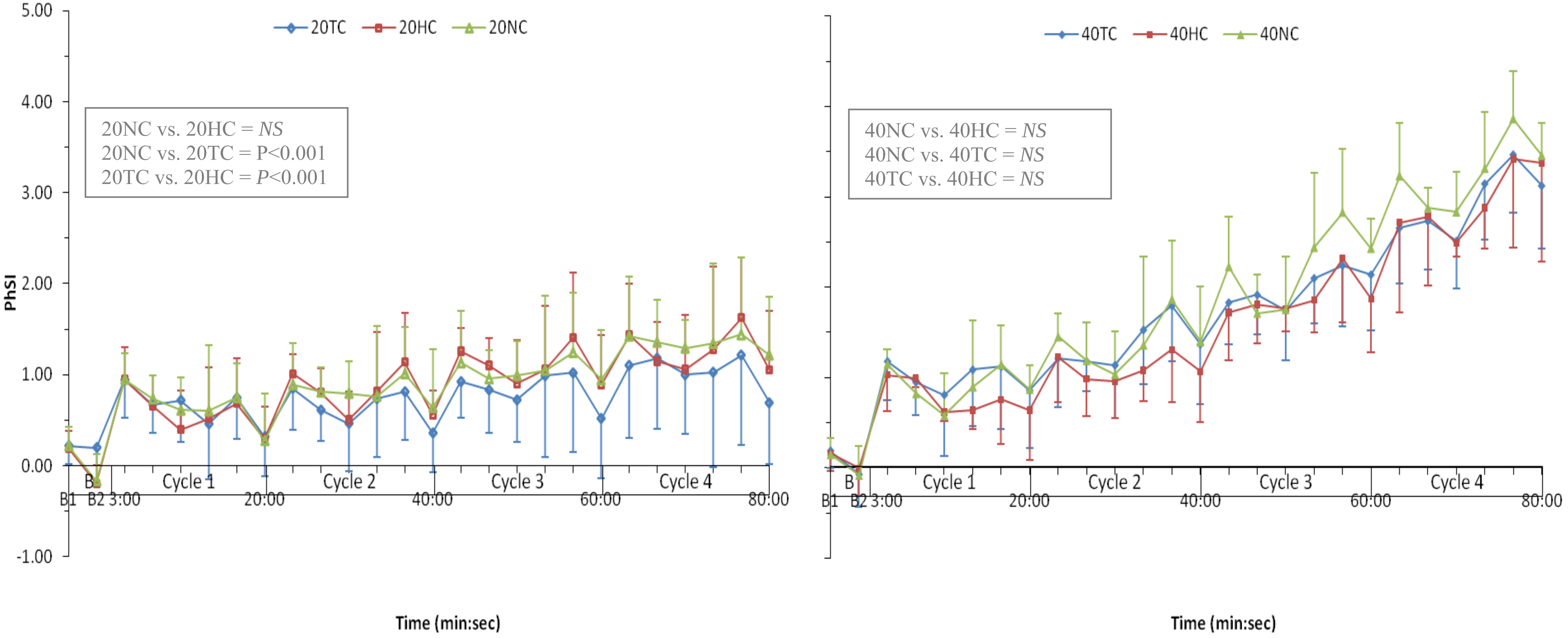

Figure 4. 1: Physiological strain index (PhSI; mean±SD; n=6). Significant main effects for condition, time, and condition x time, (*P*<0.001). 80 minutes of explosives ordnance disposal related activity in 20 °C and 40 °C. (TC=torso Cooling; HC = head Cooling; NC = no cooling).

4.6 PERCEPTUAL AND COGNITIVE RESPONSES

4.6.1 PERCEIVED EXERTION

Perceived exertion (RPE; Table 4.3) was greatest at the end of the 40 °C trials when compared to the 20 °C trials, ($P<0.01$). RPE increased at a greater rate during the NC trials when compared to the cooling trials (HC and TC). The greatest RPE mean values were given in response to 'overall' and 'upper back and shoulders' questions when compared to 'lower back' and 'legs'. The overall RPE was greatest in 40NC when compared to both 40HC and 40TC, within the arm ergometry (5th) station of the 4th cycle.

4.6.2 THERMAL SENSATION

The greatest differences in thermal sensation (T_{hS}; Table 4.4) response were between the 20 °C conditions. At 20 °C, the responses were lowest during TC in response to T_{hS} 'overall' ($P<0.001$ vs. NC and $P<0.05$ vs. HC) and T_{hS} 'back' ($P<0.01$ vs. NC). As expected, T_{hS} in response to 'chest and arms,' was lowest with the TC condition at both 20 °C and 40 °C ($P<0.001$ vs. NC). At 20 °C, T_{hS} in response to 'head' was lower within both cooling conditions (TC and HC) than with no cooling ($P<0.001$ vs. NC) and at 40 °C, when compared to NC, both HC ($P<0.001$) and TC ($P=0.006$) had lower T_{hS} 'head' responses.

4:6:3 THERMAL COMFORT

Thermal Comfort (T_{hC}; Table 4.5) responses given to 'overall,' at 20 °C were lowest with TC when compared to NC ($P\leq0.05$), and at 40 °C, both cooling conditions (HC and TC) produced lower T_{hC} responses for 'overall,' when compared to NC ($P\leq0.05$). By the 4th activity cycle, during NC, the groin (20 °C) and the chest & arms (40 °C) were perceived to be 7.7±0.5 which was associated with the verbal anchor, ‘uncomfortably hot’.

By the 4th activity cycle, at both 20 °C and 40 °C, TC resulted in the lowest responses when compared to HC in response to all body segments.

Table 4. 3: RPE (mean±SD) responses (n=6) for ‘overall,’ ‘upper back and shoulders,’ ‘lower back,’ and ‘legs,’ during the treadmill (1st) and arm ergometry (5th) stations of the 1st and 4th cycles of activity, within all conditions (20TC, 20HC, 20NC; 40TC, 40HC, 40NC). Main effects for condition, cycle, condition*cycle are annotated as; ***P<0.001. Differences in RPE within each condition were located by Tukey post hoc tests between cycles 1 and 4 of the relative activity stations and are annotated as; ###P<0.001, ##P<0.01, #P<0.05.

Condition	**Cycle**	**Station**	**RPE**			
			Overall* **	**Upper Back & Shoulders*** **	**Lower Back*** **	**Legs*** **
20NC	**1**	**Treadmill**	10.0±0.9	10.3±1.4	10.0±0.9	9.8±1.0
		Arm	10.7±1.4	11.3±1.4	9.8±1.0	9.8±1.0
	4	**Treadmill**	12.2±1.9##	11.8±1.7	10.7±1.0	11.2±1.6
		Arm	12.0±1.8	12.2±1.5	11.0±2.0	11.0±1.8
20HC	**1**	**Treadmill**	10.0±1.3	10.7±1.0	9.7±1.0	10.0±0.8
		Arm	10.7±1.0	11.2±0.9	10.2±0.9	10.2±0.8
	4	**Treadmill**	12.0±0.9##	12.3±1.3	11.3±1.0	11.2±1.0
		Arm	12.0±0.9	12.2±1.4	11.0±0.8	10.7±0.8
20TC	**1**	**Treadmill**	9.8±1.0	10.3±1.0	9.7±1.0	9.8±0.8
		Arm	10.7±1.0	11.0±0.9	10.0±0.9	9.8±0.8
	4	**Treadmill**	12.0±0.9##	12.0±1.3	11.2±1.0	11.3±1.0
		Arm	12.2±1.5	12.3±1.4	11.2±0.8	11.2±0.8
40NC	**1**	**Treadmill**	9.8±1.0	10.3±1.5	9.7±1.2	10.0±0.9
		Arm	10.7±1.6	11.2±1.5	9.8±1.0	10.0±0.9
	4	**Treadmill**	14.2±1.5###	14.2±1.9###	12.8±1.5###	12.3±1.2###
		Arm	14.5±1.5###	14.7±1.9###	13.0±1.4###	12.7±1.2###
40HC	**1**	**Treadmill**	10.8±1.1	11.2±1.1	10.0±1.0	10.4±0.9
		Arm	11.0±1.3	11.3±1.4	9.8±1.0	10.0±1.3
	4	**Treadmill**	13.2±1.2###	13.0±0.9##	11.5±0.5	11.8±0.4
		Arm	13.5±1.2##	13.7±1.4##	12.0±0.9###	11.8±0.8#
40TC	**1**	**Treadmill**	10.3±1.0	11.0±1.3	10.2±0.9	10.0±0.9
		Arm	11.0±1.8	11.8±1.5	10.2±1.0	9.8±1.0
	4	**Treadmill**	13.3±1.4###	13.2±1.7##	12.2±1.0##	11.8±1.5#
		Arm	13.5±1.5###	13.3±2.1	11.8±2.0	11.2±1.9

#

Table 4. 4: T_{hS} (mean±SD) responses (n=6) for ‘overall,’ ‘head,’ ‘back,’ ‘chest & arms,’ ‘groin,’ and ‘legs,’ during the treadmill (1st) and arm ergometry (5th) stations of the 1st and 4th cycles of activity, within all conditions (20TC, 20HC, 20NC; 40TC, 40HC, 40NC). Main effects for condition, cycle, condition*cycle are annotated as; ****P*<0.001. Differences in TS within each condition were located by Tukey post hoc tests between cycles 1 and 4 of the relative activity stations and are annotated as; ###*P*<0.001, ##*P*<0.01, #*P*<0.05.

Condition	**Cycle**	**Station**	**Thermal sensation**					
			Overall***	**Head*****	**Back*****	**Chest & Arms*****	**Groin*****	**Legs*****
20NC	**1**	**Treadmill**	4.2±0.4	4.2±0.4	3.7±0.5	4.2±0.4	4.2±0.4	4.0±0.0
		Arm	4.5±0.5	4.5±0.5	4.0±0.0	4.7±0.5	4.5±0.5	4.5±0.5
	4	**Treadmill**	5.5±0.8#	5.3±0.8	5.3±1.0##	5.7±0.5#	5.8±1.0###	5.8±1.0###
		Arm	5.5±0.8	5.8±1.0#	5.5±0.8#	5.7±0.5	5.8±1.0##	5.8±1.0##
20HC	**1**	**Treadmill**	4.0±0.0	3.5±0.5	3.8±0.4	4.0±0.0	4.0±0.0	4.0±0.0
		Arm	4.0±0.0	3.5±0.5	3.8±0.4	4.0±0.0	4.2±0.4	4.2±0.4
	4	**Treadmill**	5.3±0.5#	4.8±0.4#	5.3±0.5#	5.3±0.5#	5.7±0.5###	5.3±0.8##
		Arm	5.2±0.4	5.2±0.4###	5.3±0.5#	5.7±0.5##	5.5±0.5##	5.2±0.8
20TC	**1**	**Treadmill**	4.7±0.5	4.0±0.0	3.0±0.6	3.2±0.8	4.0±0.0	3.8±0.4
		Arm	3.8±0.4	4.0±0.0	3.5±0.5	3.5±0.5	4.0±0.0	4.0±0.6
	4	**Treadmill**	4.8±0.4	4.8±0.8	4.7±0.5##	4.7±0.5##	5.0±0.9	5.0±0.6
		Arm	5.0±0.6	5.0±0.6	4.8±0.8	5.0±0.6##	5.3±0.8##	5.5±1.0###
40NC	**1**	**Treadmill**	5.0±0.6	5.0±0.6	4.7±0.5	4.7±0.5	4.8±0.8	4.5±0.5
		Arm	5.3±0.8	5.2±0.8	5.3±0.8	5.7±0.5	5.2±0.8	5.3±0.8
	4	**Treadmill**	7.0±0.6###	6.7±0.8###	7.0±1.1###	7.2±0.8###	7.0±0.6###	7.0±0.6###
		Arm	7.0±0.6###	7.0±0.6###	7.0±0.6#	7.2±0.8##	7.0±0.6###	6.8±0.8###
40HC	**1**	**Treadmill**	4.5±0.5	3.8±0.8	4.0±0.0	4.5±0.5	4.7±0.5	4.3±0.5
		Arm	5.2±0.8	4.5±0.5	5.2±0.8	5.3±0.5	4.8±0.8	4.7±0.8
	4	**Treadmill**	7.0±0.6###	6.7±1.0###	6.7±1.0###	7.0±0.6###	7.0±0.6###	7.0±0.6###
		Arm	7.2±0.4###	6.8±0.8###	7.0±0.6###	7.2±0.4###	7.2±0.4###	7.0±0.6###
40TC	**1**	**Treadmill**	4.7±0.5	4.7±0.5	3.8±0.8	3.8±0.4	4.5±0.5	4.3±0.5
		Arm	5.2±0.8	5.0±0.0	4.3±0.5	4.5±0.8	5.0±0.6	5.0±0.6
	4	**Treadmill**	6.8±0.4###	6.5±0.5###	6.3±0.8###	6.5±0.8###	6.8±0.4###	6.7±0.5###
		Arm	6.8±0.4###	6.7±0.5###	6.7±0.8###	6.8±0.4###	7.0±0.6###	6.8±0.8###

Table 4. 5: T_{hC} (mean±SD) responses (n=6) for 'overall,' 'head,' 'back,' 'chest & arms,' 'groin,' and 'legs,' during the treadmill (1st) and arm ergometry (5th) stations of the 1st and 4th cycles of activity, within all conditions (20TC, 20HC, 20NC; 40TC, 40HC, 40NC). Main effects for condition, cycle, condition*cycle are annotated as; ***P<0.001. Differences in TS within each condition were located by Tukey post hoc tests between cycles 1 and 4 of the relative activity stations and are annotated as; ###*P*<0.001, ##*P*<0.01, #*P*<0.05.

Condition	**Cycle**	**Station**	**Thermal Comfort**					
			Overall* **	**Head*** **	**Back*** **	**Chest & Arms*** **	**Groin*** **	**Legs*** **
20NC	**1**	**Treadmill**	4.0±0.0	4.0±0.0	4.0±0.0	4.0±0.0	4.0±0.0	4.0±0.0
		Arm	4.2±0.4	4.0±0.0	4.0±0.0	4.3±0.5	4.2±0.4	4.2±0.4
	4	**Treadmill**	5.3±1.0#	5.2±1.0	5.3±1.0	5.5±0.8	5.7±1.0###	5.7±1.0###
		Arm	5.5±0.8#	5.5±1.0#	5.3±1.0	5.5±0.8#	5.7±1.0###	5.8±0.8###
20HC	**1**	**Treadmill**	4.0±0.0	3.8±0.4	4.0±0.0	4.0±0.0	4.0±0.0	4.0±0.0
		Arm	4.2±0.4	3.8±0.4	3.8±0.4	4.2±0.4	4.2±0.4	4.2±0.4
	4	**Treadmill**	5.2±0.8#	4.7±0.8	5.0±0.6	5.0±0.6	5.2±0.4##	5.0±0.6
		Arm	5.2±0.8#	4.8±0.8#	5.3±0.8	5.5±0.8#	5.3±0.5##	5.2±0.8
20TC	**1**	**Treadmill**	4.0±0.0	4.0±0.0	3.7±0.5	3.5±0.8	4.2±0.4	3.8±0.4
		Arm	4.0±0.0	4.0±0.0	3.8±0.4	3.7±0.5	4.0±0.0	4.0±0.0
	4	**Treadmill**	4.8±0.8	4.8±0.8	4.5±0.5	4.5±0.5	4.8±1.0	5.0±0.9
		Arm	5.0±0.9#	4.8±0.8	4.8±0.8	4.8±0.8#	5.2±1.0##	5.2±1.0###
40NC	**1**	**Treadmill**	4.3±0.5	4.5±0.5	4.5±0.5	4.3±0.5	4.2±0.4	4.2±0.4
		Arm	5.2±0.8	5.3±0.8	5.8±1.0	5.8±0.4	5.2±0.8	4.8±1.0
	4	**Treadmill**	7.0±0.6###	7.0±0.6###	7.2±0.8###	7.3±0.8###	7.0±0.6###	6.8±0.8###
		Arm	7.5±0.5###	7.5±0.5###	7.3±0.5###	7.7±0.5###	7.5±0.5###	7.5±0.5###
40HC	**1**	**Treadmill**	4.0±0.0	3.5±0.5	4.0±0.0	4.2±0.4	4.2±0.4	4.0±0.6
		Arm	5.2±0.8	4.7±0.8	5.2±0.8	5.2±0.8	4.8±0.8	4.5±0.8
	4	**Treadmill**	7.0±0.6###	6.7±1.0###	6.7±1.0###	7.0±0.6###	7.0±0.6###	7.0±0.6###
		Arm	7.2±0.4###	6.8±0.8###	7.0±0.6###	7.2±0.4###	7.2±0.4###	7.0±0.6###
40TC	**1**	**Treadmill**	4.0±0.0	4.0±0.0	3.8±0.4	3.7±0.5	4.2±0.4	4.0±0.0
		Arm	5.0±0.0	5.0±0.0	4.3±0.5	4.3±0.5	4.8±0.4	5.0±0.6
	4	**Treadmill**	6.8±0.4###	6.5±0.8###	6.2±1.2###	6.7±0.5###	6.8±0.4###	6.7±0.5###
		Arm	6.8±0.4###	6.7±0.5###	6.7±0.8###	6.8±0.4###	7.0±0.6###	6.8±0.8###

4.6.4 PERCEPTUAL STRAIN INDEX

The perceptual strain index (PeSI; Figure 4.9) increased throughout the 80 minute period and the rate of rise in PeSI was greatest in 40 compared to 20 °C (*P*<0.001; main effect for time, condition). At 20 °C, perceptual strain was lowest in the TC condition (*P*<0.001 vs. NC). At 40°C perceptual strain was lowest in the TC and HC conditions during the 2nd and 3rd cycles of activity, when compared to NC. However, by the 5th station (arm ergometry) of the forth activity cycle, within 20 °C (6) and also within 40 °C (8) PeSI was the same regardless of the condition (HC/TC/NC).

4.6.5 SPATIAL WORKING MEMORY (SWM) TEST

Individual differences in cognition (SWM; Table 4.6) were found within strategy, test duration and total errors (*P*<0.001; main effect for participant). The total number of errors made by the participants were directly proportional to the test difficulty (number of boxes displayed). Less than 6 % of the total errors made were attributed to working with 4 boxes and >64 % of the total errors made were attributed to working with 8 boxes.

Time taken to complete the SWM test decreased from cycle 1 to cycle 4 for all conditions except 20NC (*P*=0.017; main effect for cycle). The greatest decrease in test duration between cycle 1 and 4 was with 40HC (minus 0.41 min) and 40NC (minus 0.35 min). The SWM test took the least time to complete within 20NC (4.69±0.32 min; cycle 1) and longest to complete during 40HC (5.24±0.76 min; cycle 1) and 40NC (5.22±0.62 min; cycle 1).

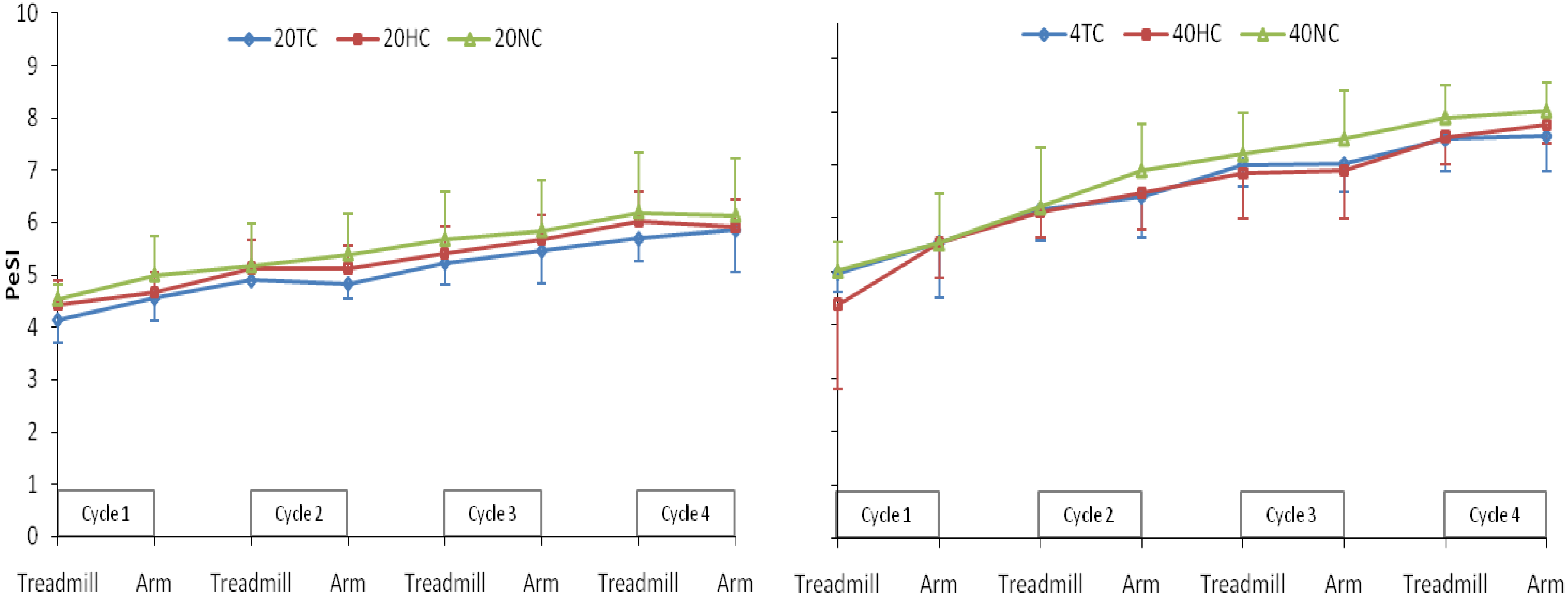

Figure 4. 2: PeSI (mean±SD) responses (n=6). Significant main effects for condition, time, and condition x time, (*P*<0.001). Six experimental trials (20TC; 20HC; 20NC; 40TC; 40HC; 40NC), with a trial duration of 80 minutes. SD error bars are omitted for clarity.

Table 4. 6: Spatial working memory results (mean±SD; n=6) for strategy, test duration (min), total errors and percentage of total errors for 4, 6 and 8 boxes, for cycles 1 and 4 only, within all conditions (20TC, 20HC, 20NC; 40TC, 40HC, 40NC). Main effect for cycle is annotated as ***P*=0.017.

Condition	**Cycle**	**Spatial Working Memory**					
		Strategy	**Duration****	**Total Errors**	**% of Total Errors (4 Boxes)**	**% of Total Errors (6 Boxes)**	**% of Total Errors (8 Boxes)**
20NC	**1**	27.6±6.8	4.69±0.32	6.2±13.9	0	16	84
	4	29.0±6.5	4.92±0.51	8.2±13.4	0	20	80
20HC	**1**	29.2±6.9	5.01±0.63	8.0±14.5	0	17	83
	4	29.0±7.3	4.86±0.73	5.7±9.4	0	32	68
20TC	**1**	29.8±6.6	5.15±0.63	7.2±7.4	2	16	81
	4	29.7±7.6	5.00±0.80	9.3±20.5	0	36	64
40NC	**1**	27.8±5.8	5.22±0.62	5.8±8.9	0	20	80
	4	28.5±6.0	4.87±0.41	6.8±9.2	5	12	83
40HC	**1**	28.2±6.9	5.24±0.76	7.2±16.1	0	16	84
	4	28.2±6.4	4.83±0.50	5.8±9.7	6	11	83
40TC	**1**	29.5±6.1	4.97±0.52	5.5±10.6	0	36	64
	4	28.3±5.2	4.85±0.54	4.0±7.1	0	21	79

4.7 CARDIOVASCULAR RESPONSE TO STANDING (BP AND HR)

4.7.1 RESPONSE AT BASELINE (WITHOUT THE SUIT)

At baseline (20 °C, ≈1 hour prior to trial), blood mean arterial pressure (BP; mmHg; Figure 4.10 & 4.12) initially ranged from 87±5 to 96±4mmHg (pre-stand). Post-stand; MAP declined to a nadir ($P<0.001$; main effect for time) ranging from 55±11 to 63±9mmHg between 3.16±1.31 and 5.64±1.21 seconds, before reaching a MAP response, similar to the pre-stand phase, ranging from 85±5 to 95±10 mmHg between 15.24±2.32 and 20.85±4.35 seconds. This was followed by recovery pressures (ranging from 80±5 to 89±13 mmHg) at 25 seconds that ranged from 88±6 to 95±13 % of the initial pre-stand MAP.

At baseline; heart rate (HR; beats$\cdot$min^{-1}; Figure 4.11 & 4.13) prior to standing (PRE) ranged from 73±10 to 79±21 beats$\cdot$min^{-1}. Once stood heart rate began to rise, peaking ($P<0.001$; main effect for time) from 102±9 to 111±19 beats$\cdot$min^{-1} between 9.14±3.50 and 10.53±2.96 seconds into the post-stand recovery period (25 seconds) before declining to a recovery rate ranging from 85±14 to 95±21 beats$\cdot$min^{-1} between 6±9 and 28±18 % greater than the pre-stand rate. There were no significant differences found for either MAP or HR response between conditions at baseline.

4.7.2 WITHIN CYCLES (FIGURES 4.10 TO 4.13)

At cycle 1, there was a significant fall in MAP (ranging from minus 29 to minus 39 %) and rise in HR (ranging from plus 39 to plus 59 %), from the pre-stand response within all conditions ($P<0.001$). MAP varied between 20 °C and 40 °C, and within the 20 °C conditions only ($P<0.001$; main effect for condition). MAP was higher within 40TC when compared to 20TC ($P<0.01$), during the nadir (68±7 vs. 58±11 mmHg), peak (94±11 vs. 78±11 mmHg), and recovery phases (81±4 vs. 70±13 mmHg). At 20°C, MAP was lower within 20TC ($P<0.01$; vs. 20NC), with peak (PK) responses of 78±11 mmHg (TC) vs. 94±11 mmHg (NC). MAP did not recover back to that of the pre-stand response within 20TC and 20HC ($P\leq0.05$), with recovery

MAPs being only 77±5 % (TC) and 74±14 % (HC) of that found during the pre-stand phase, compared to 87±5 % during 20NC.

At cycle 4, in all conditions, a nadir in MAP (ranging from minus 7±13 to minus 20±7 %) below the pre-standing response (ranging from 72±8 to112±14 mmHg) and a peak in HR (ranging from plus 32±5 to plus 53±13 %) greater than the pre-standing rate (66±7 to 83±13 beats·min^{-1}) was found ($P<0.001$; main effect for time). Recovery MAPs were equivalent to the pre-stand response. However, at 40°C, the recovery HR did not return to that measured during the pre-stand phase ($P \leq 0.05$; ranging from plus 22±9 to plus 25±8 % of the pre-stand response) remaining greatest at 112±14 beats·min^{-1}.

Within cycle 4, MAP varied between 20 °C and 40 °C, and within the 40 °C conditions only ($P<0.001$; main effect for condition). MAP was greatest throughout within 40HC ($P<0.01$; vs 40NC). However, MAP was also lowest at cycle 4 within 40NC when compared to 20NC and 20HC ($P<0.05$).

4.7.3 BETWEEN CYCLES (FIGURES 4.10 TO 4.13)

There were no significant differences in MAP found between activity cycles at 20 °C and 40 °C. HR did not vary between cycles at 20 °C within either condition (20NC, 20HC, 20TC). At 40 °C, HR response throughout cycle 4 was greater than the HR response throughout baseline and cycle 1 ($P<0.001$), with similar peak HRs of 148±12 beats·min^{-1} (40NC), 148±8 beats·min^{-1} (40TC) and 140±16 beats·min^{-1} (40HC).

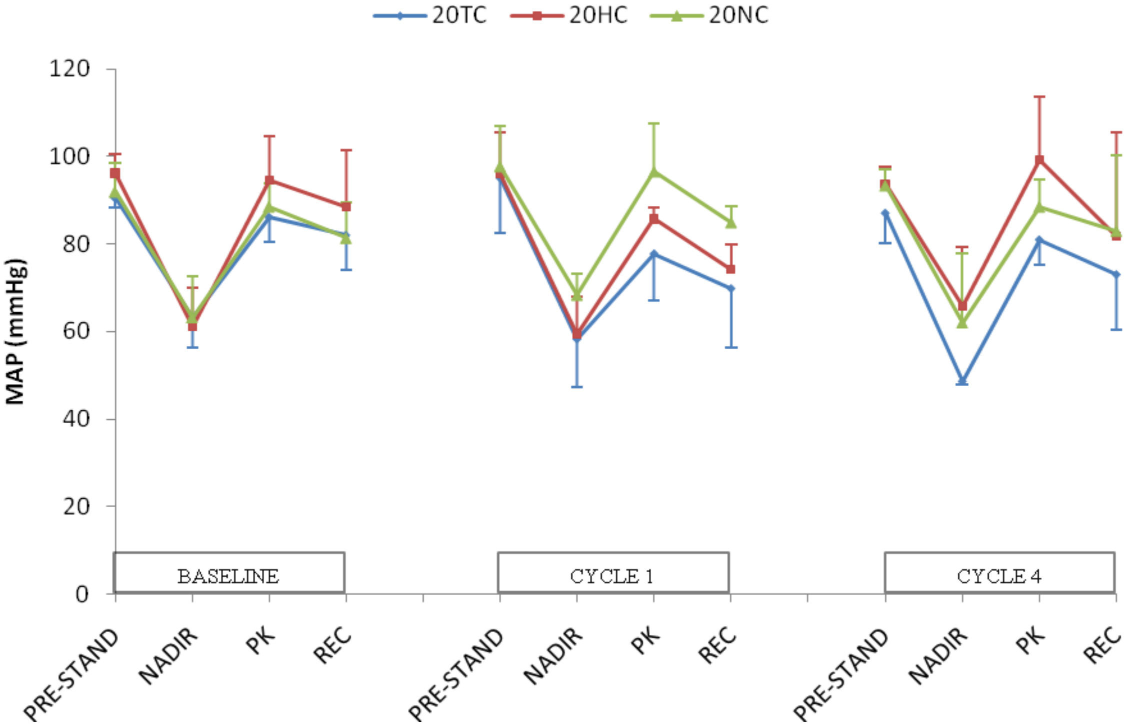

Figure 4. 3: MAP response (means±SD) to the postural challenge station (kneeling to standing) at 20 °C. PRE-STAND = mean of 10 seconds kneeling before stand; NADIR = lowest response (within 25 seconds) post stand; PK = highest response (within 25 seconds) post stand; REC = response at 25 seconds post stand.

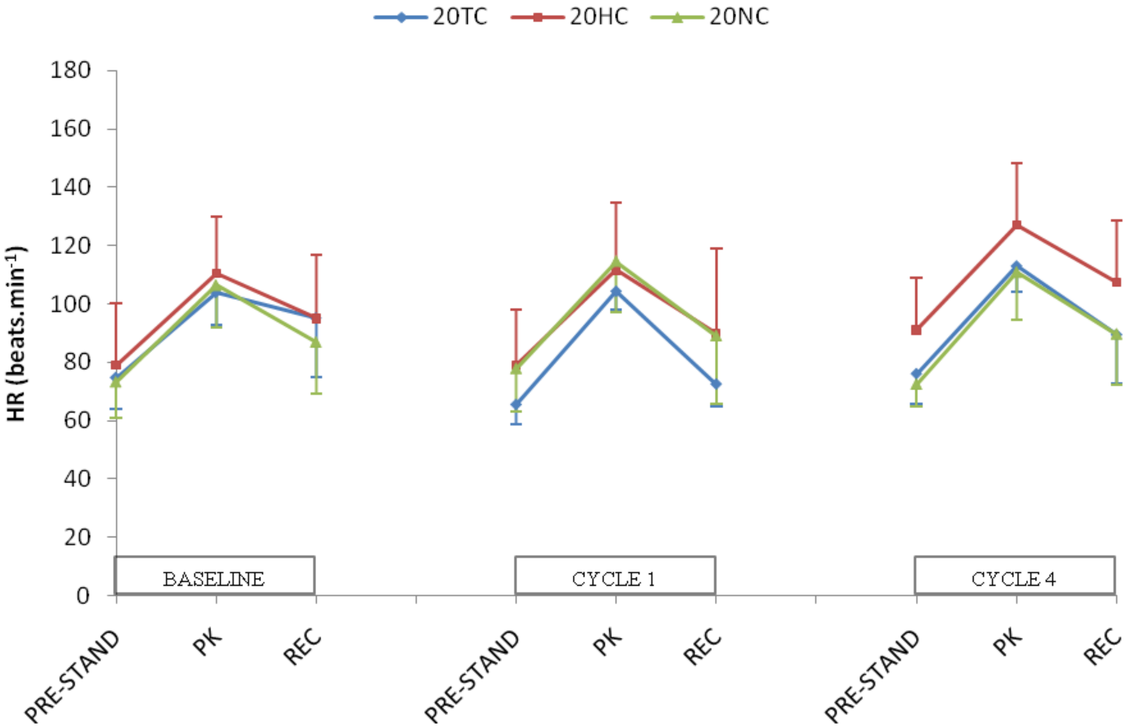

Figure 4. 4: HR response (means±SD) to the postural challenge station (kneeling to standing) at 20 °C. PRE-STAND = mean of 10 seconds kneeling before stand; PK = highest response (within 25 seconds) post stand; REC = response at 25 seconds post stand.

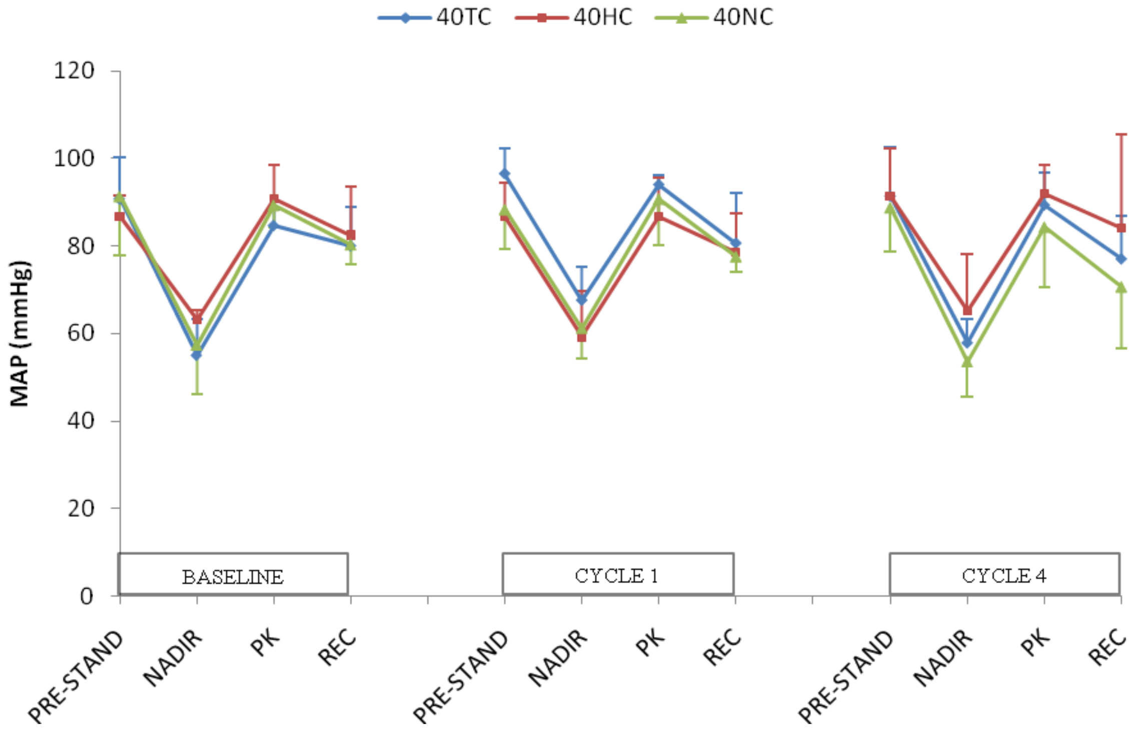

Figure 4. 5: MAP response (means±SD) to the postural challenge station (kneeling to standing) at 40 °C. PRE-STAND = mean of 10 seconds kneeling before stand; NADIR = lowest response (within 25 seconds) post stand; PK = highest response (within 25 seconds) post stand; REC = response at 25 seconds post stand.

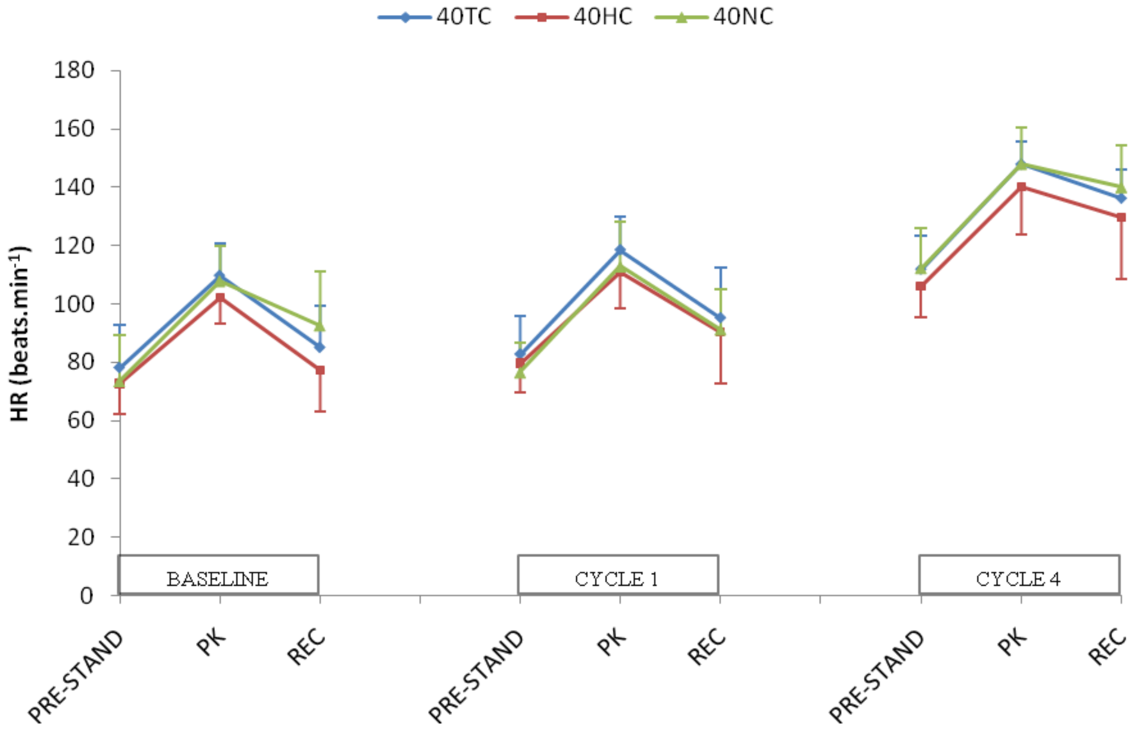

Figure 4. 6: HR response (means±SD) to the postural challenge station (kneeling to standing) at 40 °C. PRE-STAND = mean of 10 seconds kneeling before stand; PK = highest response (within 25 seconds) post stand; REC = response at 25 seconds post stand.

4.8 RESULTS SUMMARY (TABLE 4.7)

An increase in thermal strain over the 80 minute trial duration was observed in all conditions with the greatest increase at 40 °C vs. 20 °C.

At 20 °C, baseline values for the T_{cP} and PhSI during 20TC were preserved throughout each trial. At 40 °C, both 40HC and 40TC reduced the physiological strain observed in 40NC. 40TC maintained the lowest T_{sk} for upto 60 minutes of activity (3 cycles) and Tc throughout the 80 minute trial (see Table 4.7).

Indicators of perceptual strain; RPE, T_{hS}, T_{hC} and the conseqent PeSI, also increased over the 80 minute trial duration in all condtions. Both cooling conditions (TC and HC) were effective at reducing the percieved thermal strain experienced by partciapants, when compared to NC at 20 °C and 40 °C. The lowest T_{hS} and T_{hC} reponses to 'head,' were present throughout TC and HC when compared to NC, with TC resulting in the lowest T_{hS} and T_{hC} responses to 'overall,' 'chest & arms,' and 'back,' by the 4th cycle of activity at both 20 °C and 40 °C, which was, in part, reflective of the physiological responses mentioned above.

In relation to the postural challenge station, 20TC resulted in the lowest MAP response post-stand (Nadir; PK; REC) throughout cycle 1 when compared to 20NC that was lower than that recorded at baseline. MAP did not recover back to pre-stand response in either cooling condition (20HC and 20TC). HR did not recover back to the pre-stand response during cycle 4 at 40 °C in either of the three conditions, although MAP did, emphasising further that the greatest cardiovascular strain was present within 40 °C vs. 20 °C.

Table 4. 7: Rankings (scale from 1 = least strain; to 6 = greatest strain) for condition (20NC, 20HC, 20TC, 40NC, 40HC, 40TC) in relation to physiological and perceptual responses at 80 minutes of explosive ordnance disposal (EOD) activity. The greatest response at 80 minutes indicates the greatest strain (6).

Strain	**Rank**	**Physiological Variables**							**Perceptual Variables**				**Overall Outcome**
		HR	**T_{cP}**	**PhSI**	**T_{sk}**	**T_f**	**T_c**	**HS**	**PeSI**	**T_{hC}**	**T_{hS}**	**RPE**	
Lowest	**1**	20TC	20TC	20TC	20TC	20HC	20TC	20TC	20TC	20TC	20TC	20NC=20HC	20TC
	2	20NC	20NC	20HC	20NC	20TC	20NC	20NC	20HC	20HC	20HC	20NC=20HC	20HC=20NC
	3	20HC	20HC	20NC	20HC	20NC	20HC	20HC	20NC	20NC	20NC	20TC	20HC=20NC
	4	40HC	40TC	40TC	40TC	40HC	40TC	40TC	40TC	40TC	40TC	40TC=40HC	40TC
	5	40TC	40HC	40HC	40HC	40TC	40HC	40HC	40HC	40NC	40NC	40TC=40HC	40HC
Greatest	**6**	40NC	40NC	40NC	40NC	40NC	40NC	40NC	40NC	40HC	40HC	40NC	40NC

5. DISCUSSION

5.1 PHYSIOLOGICAL STRAIN

All participants (n=6) completed all trials (n=6) in 20 °C and 40 °C. Physiological strain as indicated by the PhSI calculation and as hypothesised (section 1.3) was greater in 40 °C when compared to 20 °C, (Figure 4.9). This was as a consequence of the greater core temperatures (T_{cP}; Figure 4.1) and heart rates (HR; Figure 4.8) measured at 40 °C, and relates to findings by Thake *et al*. (2009c) whereby despite the PhSI calculation using a different core temperature site (T_{cP} vs. T_{re}) the PhSI of participants whilst in the 3010 light-weight suit after 66 minutes of EOD related activity was more than twice as great at 40 °C when compared to the PhSI calculated at 20 °C.

At 20 °C, when considering PhSI it is evident that the physiological response to working in the EOD suit was not a cause for concern, which is in agreement with findings from the aforementioned study (Thake *et al*. 2009c). At this temperature, without applied cooling there was only a slight rise in HR (Figure 4.8) and T_{cP} did not significantly change over the 80 minutes of activity in either cooling, (TC, HC) or no cooling (NC) trials. T_{cP} during 20TC was significantly lower than within either of the HC or NC conditions (Figure 4.1). This could be related to measurement site whereby localised cooling of the torso may have influenced the gastro-intestinal tract temperature or simply due to a greater rate of heat removal when the PCM vest was worn. The greater surface area being cooled during TC vs. HC is also likely to result in these responses which can be supported by previous research (Nunneley and Maldonado 1983) whereby the overall effect of hood and suit cooling combined was the finding of the greatest magnitude of reduction in physiological strain compared to hood and suit cooling separately when worn by aircrew members within a simulated cockpit heat stress environment.

At 40 °C, there was a significant rise in HR (Figure 4.8) and T_{cP} (Figure 4.1) by the end of the each trial (40NC, 40HC, 40TC). Cooling of the head and torso produced the lowest HR and T_{cP} responses when compared to no cooling. This is in contrast to previous research (Carter, *et al.* 2007), as when cooling was applied with a PCM vest (set to melt at 28 °C) under fire-fighter PPC in moderate and hot environments, no differences were found in T_{sk}, and final T_{re}, vs. a control trial (when no cooling vest was worn). The cooling vest increased the total load by ≈ 3 kg vs. the control trial and the duration of the trials in the moderate environment were 73.17±26.6 min and 88.77±16.7 min for the cooling vest and control trial, respectively. It is possible the extra 3 kg may have caused an increase in the metabolic rate and heat production and this could have outweighed any potential benefit of the cooling upon reducing core temperature. In addition, research by House *et al.* (2009) state that higher PCM temperatures can reduce the efficiency of the cooling garment and the rate of heat removal and so may explain why no differences were found.

Other research supports the findings of the current study and have found HRs to be reduced with head cooling and then again with torso cooling vs. a control trial when worn during simulated cockpit heat stress. Although this difference was found with liquid-conditioned garments and not PCM (Nunneley and Maldonado 1983) and to the authors knowledge the current study is the first study to find a reduction in T_{cP} during exercise in response to PCM cooling when worn beneath PPC in the heat.

Thus, cooling with PCM at 40 °C using either cooling garment would be physiologically beneficial to operatives working at similar work rates for up to 80 minutes in a hot environment, although the majority of benefit was observed within the first hour. This can be attributed to the majority of cooling benefit being present at the point at which the PCM changes phase and begins to melt (House *et al*. 2009). Thus, after 60 minutes, the slower rate of heat removal at this stage would have resulted in the greater rise in T_{cP} (Figure 4.2) found during the final cycle. Thus, cooling the torso during the first 60 minutes of activity can be perceived as beneficial to the operative with regard to delaying the potential rise in core temperature, within both moderate and hot environments.

5.1.1 PHYSIOLOGICAL RESPONSES AT 20 °C AND 40 °C WITHOUT PCM

The physiological differences found between 20NC and 40NC can be partly attributed to the direction of heat transfer (between the skin and ambient air) with the contribution of air flow from the internal fan either hindering (at 40 °C) or enhancing (at 20 °C) the cooling down process depending upon the environmental temperature. High ambient temperatures (40 °C; greater than skin temperature) will have been detected by thermal receptors in the skin (Arens and Zhang, 2006), and will have reacted accordingly by increasing vasodilatation (by neural release of sympathetic cutaneous vasoconstrictor tone) and blood flow to the periphery, initiating localised sweating. This would have allowed for better heat exchange throughout the body by convective and conductive pathways, which in turn will have become counterproductive at 40 °C due to the increased blood flow increasing the rate of heat gained by the body (Passlick-Deetjen and Bedenbender-Stoll 2005; Arens and Zhang, 2006).

The magnitude of rise in HR was greatest in the hotter environment (20 °C vs. 40 °C; Figure 4.8), which would have occurred in order to meet the greater demand for skin blood flow (SkBF) required for cooling, (Gonzalez-Alonso et al. 1998). HR (station 1, cycle 1 vs. station 1, cycle 4) increased by ≈3 beats·min^{-1} at 20 °C and by ≈22 beats·min^{-1} at 40 °C. The difference in the magnitude of rise in HR between moderate and hot environments has been demonstrated in other studies by Faerevik and Reinertsen 2004 (23°C vs. 40°C) and Thake, *et al.* 2009b (20°C vs. 40°C), in response to exercise in PPC, and together serve to emphasise the effects of ambient temperature on physiological and cardiovascular strain.

However, HR in relation to the other stations at 20 °C and 40 °C, peaked per cycle; at station 1 (treadmill) and station 5 (arm ergometry) and was lowest at station 6 (SWM test and physical seated rest) regardless of environmental temperature. The work rate was standardised for each station and thus this highlights that the 1st, and 5th stations were the most physically demanding. This trend is very similar to that found within the study by Thake and Price (2007) whereby work rates were not standardised yet HR still peaked during the walking, crawl and search and arm ergometry stations and was lowest during the seated psychological testing which places further emphasis that stations 1 and station 5 were the most physically demanding, and a greater blood flow was required in order to meet the demand for oxygen supply to the muscles.

The rate of sweat lost at 40 °C ($\approx 4 l \cdot hr^{-1}$) was more than double that compared to 20 °C ($\approx 1.5 l \cdot hr^{-1}$; Figure 4.6). The stated differences were most likely due to the earlier initiation of an increased SkBF and localised sweating, as a result of greater skin and core temperatures found at 40 °C (Arens and Zhang 2006). The increased sweat that will have accumulated in the microenvironment will have increased the humidity leading to a reduced evaporative capacity and an increase in skin wettedness which would consequently result in a reduced evaporative efficiency (McLellan, *et al.* 1996). In support of the latter, the t-shirt worn beneath the EOD suit became saturated in sweat, and was stuck to the skin, which will have limited the convective air flow beneath the t-shirt. The saturated t-shirt was evident at the end of each trial once the vest and suit were removed, particularly within the 40 °C trials.

There was a greater rate of increase in T_{sk} present during the 40NC condition when compared to the 20NC condition. Reasons for this are related to there being fewer avenues for heat loss at 40 °C vs. 20 °C. At 20 °C, the main source of heat gain was through metabolic heat production, with heat loss (by convection and evaporation) aided by the ambient air flow in to the suit, (Benzinger 1959). At 40 °C, in addition to the metabolic heat production, the suit that was worn would have also heated up over time, and the air temperature between the suit and the clothing layer will have been greater than that at 20 °C, due to the fan blowing ambient air into the suit, leading to heat gain by convective and conductive pathways. These differences help to explain why T_{sk} and heat storage were greatest at 40 °C vs. 20 °C.

Gastrointestinal pill temperature (T_{cP}; °C) declined from the initiation of exercise to the end of the first cycle at both 20 °C and 40 °C (Figure 4.1). This reduction was expected due to the mixing of blood from the cooler periphery with blood from the core, combined with a redistribution of flow to the working muscles at the onset of exercise (Ho, Beard, Farrell, *et al.* 1997). It is likely however that the measured decrease (minus 0.02 °C to minus 0.09 °C) could be due to error as the accuracy of the instrument was stated to be ± 0.1 °C (HQ, Inc., n. d.). After 40 minutes the rate of increase was much greater within 40 °C than 20 °C, as a consequence of a hotter skin surface temperature and a reduced thermal gradient between the skin and core.

In summary, and in relation to the previously stated hypothesis (section 1.3) the data support the hypothesis in that it was expected that conducting such physical work within a light-weight EOD suit would produce greater physiological strain at 40 °C when compared to 20 °C. Core temperatures remained well within the safety cut off limits (section 3.8) and there was a greater strain present within a hotter working environment (40 °C). The greater heat stress, such as, the higher ambient temperature of 40 °C, lead to a greater strain on the cardiovascular system represented by an increase in HR which resulted in an increase in T_{sk} and heat storage, consequently leading to an increase in T_{cP} over time.

5.1.2 PHYSIOLOGICAL RESPONSES TO 20HC AND 20TC

Torso cooling resulted in a lower HR than head cooling (Figure 4.8). The HR peaks were 'dampened,' by ≈10 beats·min^{-1} as a result of TC when comparing the 1st station (treadmill) of each cycle to that during 20HC. Considering the relationship between HR and T_{re} is shown to be linear (Gonzalex-Alonso, *et al.* 1999), a lower T_{cP} during TC when compared to HC may be the reason for the 'dampened,' HR peaks, reflecting how cooling the torso meant there was less of a demand for SkBF, resulting in a lower HR required to maintain Q when compared to work done during the HC trials.

Cabanac and Capatua (1979b) stated the idea that brain temperature is reflected by tympanic (T_{ty}) temperature, and that the HR response is altered by changes in brain temperature (by central control of blood flow through the hypothalamus). Therefore, if this was the case it would help to further explain the greater HRs found with HC when compared to TC, as T_{au} was greater with HC ($P<0.001$; Table 4.1), which could imply there was greater brain temperature that initiated an increase in HR through central control. In support of this, T_{cP} was also greater with HC ($P<0.001$; Figure 4.1), which further supports the idea of a linear relationship between T_{re} and HR (Gonzalex-Alonso, *et al.* 1999).

In addition, the greater proportion of body surface area (BSA) cooled during TC vs. HC could have meant mixing of a greater volume of cooled blood from the chest and back, than from the head, which would have resulted in a relative increase in the core to skin thermal gradient, aiding conductive and convective heat loss, increasing the heat storage capacity, and reducing the rate of heat stored (Figure 4.5).

Cooling of the torso resulted in a lower T_{sk} throughout the 80 minute trial duration, when compared to the 20HC and 20NC trials (section 4: Figure 4.2). Within the 20 °C trials the fan blew 20 °C air onto the participants' back of which depending on vest fit to the participant would have aided evaporative cooling of sweat and maintained the PCM charge, especially during crawling, as participants were able to arch their backs more so during this station. This leads to the conclusion that TC was better than HC, however, the chest of the torso was involved in the T_{sk} calculation and the forehead temperature was not, therefore it is possible the method used in the current study to calculate T_{sk} may have been more focused towards the changes in temperature during TC than HC.

The weighting (an approximation of the regional area distribution) given to the forehead in a formula used by Godek, Godek, and Bartolozzi (2004), (equation 5.1) was 0.058 vs. 0.335 for the chest, they also incorporated back temperature with a weighting of 0.335. Thus, if equation 5.1 was used in the current study along with the corresponding measurements, T_{sk} would have still been lower during 20TC and 20HC, than 20NC, yet with the addition of back temperature (not measured in this study), the difference between conditions would have been greater still at 20 °C and less than that at 40 °C. This is due to the back and chest temperature weighting combined in equation 5.1 being greater than the weighting given for forehead temperature. Therefore, you could conclude that with either calculation, TC was the better of the two cooling methods at reducing overall T_{sk} and consequent heat storage within 20 °C.

Equation 5.1:

$$(T_{sk}; \text{ºC}) = 0.058\ T_f + 0.335\ T_c + 0.335\ Tb + 0.136\ Tarm + 0.136\ Tcalf$$

(Godek, Godek and Bartolozzi 2004)

Equation 5.2:

$$(T_{sk}; \text{ºC}) = 0.30\ (Chest + Arm) + 0.20\ (Thigh + Calf)$$

(Ramanathan 1964)

No significant differences were found with regard to sweat rate ($S\dot{R}$) between conditions (TC vs. HC) which in part contradicts the initial hypothesis (section 1.3; point 3.) that torso cooling would produce the greatest reduction in physiological strain experienced when compared to head cooling and no cooling. Due to the same findings being present at 40 °C, the differences between sweat rate responses for 20 °C and 40 °C environments are discussed further within the 40 degree section (5.1.3) of this discussion.

In summary, at 20 °C, TC resulted in the lowest T_{cP} at the end of the trial, maintaining a lower T_{cP} overall when compared to HC. Thus, cooling the torso with a PCM vest whilst wearing protective clothing, within a 20 °C ambient environment, resulted in the dissipation of enough heat to maintain thermal balance whilst wearing EOD protective clothing. This is a key finding, as previous research relating to the use of PCM vests (melting temperature of 25 °C) under fire fighter protective clothing within cool ambient temperatures (16.5±1.8 °C; 44±3 % RH) found them ineffective, with no differences in HR or T_{re} vs. a control (Carter, *et al.* 2007). The lack of benefit found in the aforementioned study when compared to the findings of the current study, may have been due to a greater metabolic rate present in the fire fighter workers vs. the EOD workers as a result of a greater load, (≈35 kg fire fighter suit > ≈18 kg EOD suit), that the work done was continuous vs. intermittent. In addition to this, it is probable that within the current study, the internal fan contributed to maintaining charge in the PCM vest and aided skin cooling by convective air flow (20 °C) over the back. Therefore, when considering these factors, the use of a PCM vest, during intermittent low intensity exercise, within a moderate environment whilst wearing a light-weight EOD suit, was able to reduce T_{cP} below baseline temperature.

5.1.3 PHYSIOLOGICAL RESPONSES TO 40HC AND 40TC

HR remained lowest with cooling (40HC and 40TC) than with no cooling (40NC), throughout the entire 80 minute trial (*P*<0.001; Figure 4.8). HR had a tendency to be lowest within 40HC than 40TC up to about 60 minutes of activity, although from then onwards the peaks in HR remained lowest within the 40TC trials. Core temperature (T_{cP}; T_{au}; Table 4.1) were also lowest up to approximately 60 minutes of activity with HC vs. TC. Thus, it is likely that temperature of the blood flowing through the hypothalamus will have been lower, contributing to the lower HR findings (Cabanac and Capatua 1979b). Interestingly, HC caused a greater decrease in T_{cP} during the 1st cycle compared to the 40TC trials, which would have lead to a greater heat storage capacity from the beginning of the trial. This is due to the difference in the response of the vasculature surrounding the head and torso. There is evidence that the vessels in the head are less likely to vasoconstrict in response to cold whereas the vessels in the torso have a much stronger vasoconstrictor response (Fox, Goldsmith and Kidd 1961). Thus, with head cooling it is likely that there was more blood flow present close to the periphery of the head when compared to the blood flow present at the periphery of the torso during the first cycle of activity.

As previously stated, despite the difference in BSA coverage between the torso and head (not estimated in this study) (Arens and Zhang 2006) findings have shown that HC can be more efficient at heat removal and physiological strain reduction when compared to torso cooling in hot environments. Nunneley and Maldonado (1983), showed that cooling 1 % BSA of the head vs. the torso resulted in a decrease of 3.7 vs. 1.1 beats·min^{-1} in HR and a decrease of 0.10 vs. 0.03°C in T_{re}, stating that head cooling was 2 to 3 times more effective than torso cooling. Therefore, the greater reductions in T_{cP} and HR at the beginning of the current study with HC may be due to a greater rate of heat removal from the head vs. the torso per unit area.

In support of the aforementioned, PCM temperature increased by 9.5 °C in the scrum cap vs. 8 °C in the vest over the entire trial, although the size of the vest and cap need to be considered this may still provide an indication of a greater heat removal at the head per unit area. Shvartz (1976) also found that a liquid conditioned hood covering 12 % BSA was more efficient at reducing thermal strain vs. a liquid conditioned suit (60 % BSA). When cooling the head a smaller surface area (0.6 %) was required to reduce HR by 1 beat·min^{-1} compared to the rest of the body (2.6 %). However, the temperature used in the hood was 13 °C lower than that of the suit, and House, *et al.* (2009) have shown that when using cooler PCM vests there was an increase in the heat removed by conduction. Thus, the lower temperature in the hood may be the cause of a more effective heat removal.

There are many possibilities for the reduced physiological strain and greater rate of heat removal at the head. 1) the forehead and face convey little evidence of vasoconstriction during cooling (Fox, Goldsmith and Kidd 1961; Arens and Zhang 2006; Flouris and Cheung 2006), 2) it is possible that localised vasoconstriction of the vessels at the chest may have reduced the cooling efficiency at the torso, (Flouris and Cheung 2006; Wilson *et al.* 2007), however in contrast to this a study by House *et al.* (2009) concluded that there was no localised vasoconstriction present when exercising participants in fire-fighter clothing wore a PCM vest with a phase change temperature as low as 0 °C, 3) it may also be possible that as previously predicted face cooling or in this case cooling of the forehead may reduce brain temperature, by counter-current exchange in the neck as indicated by T_{au} (Cabanac and Capatua 1979b; Nunneley and Maldonado 1983; Arens and Zhang 2006). Thus, a lower temperature detected by the hypothalamus would lead to a reduction in HR by central control. In support of this, cooling the forehead and face has shown to reduce HRs (Allen, Shelley, Boquet 1992).

T_{sk} and heat storage were lowest throughout the 80 minute activity trial within the 40TC trials when compared to 40HC trials, despite findings that localised skin temperatures during HC (upper arm, thigh and calf) were significantly lower than TC, ($P<0.001$). Thus, the 1 °C reduction in chest temperature with TC must have influenced the overall T_{sk}, and as previously stated, the calculation to determine T_{sk} did not include the back or forehead temperatures resulting in a heat storage response that may be bias towards TC. This may also help to explain why heat storage was shown to be greatest during the 40HC trials. However it is unlikely as the rate of rise in T_{cP} was greatest during the final cycle of activity with HC when compared to TC which suggests the participants' periphery was also hotter at this time.

The manufacturer of the PCM garments estimated a total usage time of approximately 75 minutes for the scrum cap and the participants wore the PCM garment 15 minutes before starting each trial. Thus, it is possible therefore that the HC scrum cap may have lost the majority of it's 'charge,' by 60 minutes of activity (cycle 3; 34.60 °C), affecting the rate of heat removed. This loss of charge could be due to a greater initial rate of heat removed. After the treadmill station of the first cycle the PCM within the scrum cap was already 1.49 °C greater than the PCM within the vest which was reflected in the greater inital drop in T_{cP} during this time within 40HC (0.14 %) vs. 40TC (0.07 %).

Unexpectedly at both 20 °C and 40 °C sweating rates were found to be no different between conditions. There was also no difference in sweat rate with either cooling condition (HC and TC) vs. the no cooling condition (NC), despite the differences found between conditions with T_{cP} and temperature. This is surprising as there have been many findings of a reduced sweat rate with cooling of the skin within warm ambient climates (McLellan 2007). Hayashi and Tokura (1996) found that whilst exercising in protective clothing the forearm sweat rate of participants was significantly lower with head cooling than without.

Reasons for this indifference may be due methodological factors. The participants were not instructed as to when they should use the lavatory prior to recording body mass, which may have had an influence over the pre and post differences, for example, if the participant was to use the lavatory after the trial, before weighing themselves, the loss in body mass would have been greater than the loss in body mass caused by sweating alone. It is also difficult to gauge the changes in sweat rate over time using the method of calculating sweat rate by recording body mass; as it only provides an average sweat rate per hour and therefore it is difficult to determine the points within the 80 minutes that sweat rate was greatest. Thus, the lack of significant difference between conditions may have been due to the method used, and that this method was not accurate enough to detect differences.

The great inter-individual variation with regard to $S\dot{R}$ (Figure 4.7) during TC may have been due to the fit of the PCM vest to the participant. During certain stations of activity, such as the searching and crawling station it was possible for the participant to allow more air flow under the PCM vest and onto their back due to the arched position of their back whilst crawling. This will have increased the convective air flow under the PCM vest and over the participants back, (40 °C; ≈ 200 $\text{ml}\cdot\text{min}^{-1}$) consequently affecting skin wettedness surrounding the back and chest of the participant and thus influencing $S\dot{R}$ (McLellan, *et al.* 1996). Thus, how tightly the vest fit to the participant due to the size of each participant, will have affected the volume of air that could have passed under the PCM vest during the searching and crawling station.

In summary, with the physiological responses at 40 °C, it is clear that both cooling methods (HC and TC) were beneficial at reducing physiological strain when compared to a control trial (without cooling – 40NC) for up to one hour of intermittent exercise within a light-weight EOD suit. When looking at the results summary (Table 4.7; section 4.8) TC appeared to provide the most benefit within 40 °C by the end of 80 minutes of activity, when compared to HC with both cooling methods providing benefit when compared to NC.

5.2 PERCEPTUAL RESPONSES AT 20 °C AND 40 °C:

Perceptual responses were used as a subjective measure of physiological strain within each condition. Thus, the responses have been compared between conditions and to the physiological responses within those conditions.

5.2.1 PERCEIVED EXERTION

The increase in RPE over time was greatest at 40 °C vs. 20 °C for all body segments. Cooling appeared to attenuate the rise in RPE at 40 °C as the end values for 'overall' were lowest with cooling than without, with no difference between conditions at 20 °C. It is interesting to note that as no differences in RPE responses were found within the 20 °C conditions or within the 40 °C conditions that the RPE responses contradict slightly with the HR and T_{cP} findings. It is likely therefore that a greater difference in the HR and T_{cP} responses between conditions was required in order to initiate a greater and significant difference in RPE between conditions. Generally the upper back & shoulders tended to have greater RPE responses by the end of the trial when compared to the lower back and legs, which most likely will have been related directly to the distribution of the external load of the EOD suit over the body.

5.2.2 THERMAL SENSATION

The greatest differences in T_{hS} over time were present at 40 °C vs. 20 °C. Cooling of the head resulted in the lowest initial baseline sensation response for ‘head,’ and as expected cooling the torso resulted in the lowest initial baseline sensation response for ‘chest’ and ‘back’ when compared to NC. This is reflected by the ‘forehead’ and ‘chest’ having the lowest measured skin temperatures during these conditions (HC and TC).

T_{hS} in response to ‘head’ was lowest at 20 °C and 40 °C with both HC and TC (vs. NC), suggesting that torso cooling influenced the perception of cooling among other regions of the body other than the region being cooled. This also coincides with the measured skin temperature of the forehead being lower with both types of cooling than NC at the end of exercise (T_f; Figure 4.3). T_{hS} has been previously shown to be an inaccurate estimate of skin temperature (Patterson, *et al.* 2007), which could mislead participants with regard to their thermal state. T_{hS} seemed to correspond with skin temperature when comparing relative sites (‘head’ vs. T_f; ‘chest’ vs. T_c), however when comparing the final measurements (T_{cP} vs. T_{hS} ‘overall’) made at the end of the 80 minutes, using Table 4.7, it is clear that there is a slight discrepancy between the perceptual data and physiological data when the head is being cooled. T_{cP} and PhSI at 20 °C were greatest with HC but the overall T_{hS} indicated that the perceived hottest condition was NC. At 40 °C, it was different still with T_{cP} and PhSI being greatest during NC and the overall T_{hS} responses indicating that the perceived hottest condition was HC. This indicates that the temperature of the head can influence the overall T_{hS} that is experienced which can be potentially dangerous to operatives.

By the end of the 80 minute trial at 40 °C, it appears that torso cooling maintained the lowest T_{hS} responses compared to HC, and NC which relates to the physiological data as shown in Table 4.7. This is likely due to the PCM scrum cap losing most if not all of its cooling capacity vs. the vest and because the torso vest would have had a greater cooling capacity due to the greater volume of coolant available within the vest vs. the scrum cap (Table 4.2).

5.2.3 THERMAL COMFORT

T_{hC} was lowest at 20 °C vs. 40 °C. At the end of the 80 minute trial, both cooling of the torso and head resulted in lower T_{hC} responses to all body segments vs. NC, however, TC especially at 20 °C, produced the lowest responses of all conditions, which were closer to the comfortable range (4 to 5) than uncomfortably hot (7).

For 20NC, the ‘groin’ was perceived as the most uncomfortably hot area of the body, whereas for 40NC, the ‘chest and arms,’ were perceived as being the most uncomfortably hot area of the body. This was most likely due to many of the activities involving movement of the arms and so the muscles would have been working harder around that area of the body, this would have lead to greater heat production and possibly sweat production in that area vs. the other areas of the body and in addition to this the fan at 20 °C could have aided cooling of the chest to a greater extent than the air flow present at 40 °C. When looking at Table 4.4, 4.5, and

4.7 it is clear that the T_{hS} and T_{hC} responses coincided reflecting a directly proportional relationship.

5.2.4 PERCEPTION OF STRAIN

At 20 °C perceptual strain was lowest with TC vs. NC. At 40 °C both TC and HC for the 2nd and 3rd cycles of activity resulted in the lowest PeSI values when compared to the NC condition. At 40 °C, HC resulted in a lower initial PeSI vs. TC and NC, which would be related to the lower T_{cP} and HRs observed and a greater heat storage capacity with HC vs. TC at the onset of exercise. The PhSI was much lower than the PeSI and shows that these two indexes do not completely relate and that the participants' perception of the physiological strain was worse than the physiological measurements (T_{cP} and HR) implied. It should be noted that as PhSI increased there was an increase in PeSI and so the PeSI does provide some indication of the physiological strain experienced by participants. The PeSI is also useful when attempting to predict when a participant is likely to discontinue with a trial or with exercise.

Thus, in summary for the perceptual responses, cooling of the torso at 20 °C and cooling of both the head and torso at 40 °C, has shown to provide benefit to the individual, by reducing the perceived physiological strain experienced whilst performing EOD related activities in a light-weight suit.

5.3 COGNITIVE RESPONSES AT 20 °C AND 40 °C:

A key finding from the cognition test was that there was a reduction in the duration taken to complete the SWM test over time (Figure 4.6). Thus, completion of the test was faster at cycle 4 than cycle 1 (*P*=0.017), with a tendency to be faster at 40 °C vs. 20 °C. Cooling had no effect on total errors or duration, however, when T_{cP} remained at baseline temperature (within 20TC) the time taken to complete the test was longest. Highlighting the relationship present between T_{cP} and reaction time. Thake and Simons (2009) found a decrease with duration over time when using the same SWM test, which may have been related to an improved reaction time with an increase in body temperature (T_{sk} and T_{re}).

Faster reaction times (Simmons, *et al.* 2008), and greater alertness and mental performance have been correlated with increases in T_{sk} and T_{re}, (Wright, Hull and Czeisler 2002), which help to support the findings in this study that the greatest duration of time taken to complete the test was during the 20TC trials with the tendency for the test to be completed at a faster rate in 40 °C. However, findings by Thake and Simons (2009) showed it took longer to complete the test after 3 hours in 40 °C than 20 °C. Thus, these findings lead to the idea of the existence of a critical turning point, or optimal body temperature for mental performance. Previous research has shown that addition performance improved with an initial rise in core temperature but decreased when temperatures rose to as great at 38.5 °C and it was suggested that different areas of the brain may differ in thermal sensitivity and thus affect the cognitive performance of those areas, (Wright, Hull and Czeisler 2002).

In addition, cognitive performance has been found to be negatively affected with increases in T_{re} of >1°C above baseline, (Faerevik and Reinertsen 2004). In support of the latter and a critical turning point, Thake and Simons (2009) found there was an increase in the total number of errors made during 2 hours of activity at 40 °C ($P<0.05$), that was not present at 20 °C. T_{re} was greater than 1 °C above baseline at this point and may have had an impact on the spatial working memory of participants. It is possible then that because T_{cP} did not increase beyond 1 °C above baseline, the temperature of the brain was not great enough to negatively impact upon the spatial working memory and may help to explain the lack of difference observed between conditions, with regard to errors.

With passive heating (50 °C 50 % RH) an increase of greater than 1.5 °C in T_{re}, impaired working memory capacity and visual memory (Racinais, Gaoua, and Grantham 2008). However, when T_{re} only rose by 1 °C with the application of head and neck cooling, the working memory capacity was preserved but the visual memory was not. Which as previously stated could relate to different areas of the brain having different levels of thermal sensitivity and/or to a transition period in frontal lobe activity that is triggered by the changes in core temperature. In addition, when high skin temperatures were combined with low core temperatures accuracy was preserved, supporting suggestions that core temperature is an influential factor in cognitive performance (Simmons, *et al*. 2008).

The findings above lead to suggestions of an optimal body temperature for mental performance (greater reaction times and accuracy), with a greater weighting on core temperature rather than T_{sk}. Cheung and Sleivert (2004) suggest that very high core temperatures reduce arousal. It is likely therefore that this reduction in arousal would impair spatial working memory and reaction speed, increasing the chances of error. Thus, there is a stressed importance of maintaining low core temperatures during EOD work in the heat, and that cooling may help to increase the heat storage capacity and as noted earlier in this section with regard to head and neck cooling, consequently reduce the rate of rise in core temperature, limiting errors in cognitive (working memory) performance of which is an essential part of explosives ordnance disposal. Further work would be required using the spatial working memory (SWM) test to support this.

5.4 CARDIOVASCULAR RESPONSE TO STANDING (WITHOUT THE SUIT)

The cardiovascular response after the sit to stand manoeuvre recorded at baseline, (section 4.7, Figure 4.10), resulted in a decline in MAP (3 to 5 seconds) followed by a transient increase in HR, peaking at approximately 9 to 10 seconds, leading to a consequential peak in MAP between 15 to 20 seconds. At 25 seconds both HR and BP appeared stable and similar to pre-standing values (despite the different positions from which they were measured; kneeling then standing; Figure 3.1). Previous research (Borst, *et al.* 1982; Rossberg and Penaz 1988) reports a similar BP response to active standing from squatting, with a fall in BP at between 7 and 9 seconds, and a rise within 15 seconds thereafter, with more often than not biphasic response in HR, peaking at ≈2 seconds and 12 seconds post-stand.

The reasons behind this cardiovascular pattern of response to standing are complex. An exercise-reflex response due to the contraction of muscle is thought to be the cause of an initial HR increase between <1 to 2 seconds post-stand. This increase in HR is likely to be detected by the baroreceptors of the aorta or endocardium, leading to increased vascular compliance and a fall in BP, of which could lead to greater withdrawal of parasympathetic vagal tone and a compensatory rise in HR. From then on it may be a combination of plasma catecholamines and baroreceptor activity that result in the recovery of both HR and BP, (Borst, *et al.* 1982; Rossberg and Penaz 1988). In support of this, findings have shown significant decreases (58 %) in total peripheral resistance (measured using a Finapres) upon standing, which can be explained by systemic vasodilation initiated by the baroreceptor response in response to an initial increase in BP upon standing with the contraction of calf and abdominal muscle, (Tanaka, Sjoberg, and Thulesius 1996).

In the current study, we did not observe a biphasic HR response as the measurements were only taken from >2 seconds after the initiation of standing, in an attempt to reduce the impact of any movement artefact. HR peaked earlier (9 to 10 seconds) than has been previously observed (11 to 12 seconds), which may be due to the initial drop in BP (between 3 to 5 seconds) also occurring earlier than previously observed (7 and 9 seconds). Prolonged rest in a supine position prior to standing has been suggested to account for a delayed HR peak (Borst, *et al.* 1982), and as there was minimal rest in a kneeling position prior to the postural challenge manoeuvre it is possible that this may have been the cause of a faster response. Reasons for the faster initial drop in BP in the current study may be due to the characteristics of the postural challenge vs. the previous squat-stand protocols used in other research such as Borst, *et al*. (1982), but this cannot be accounted for and more research would be needed to explore this further.

5.4.1 CARDIOVASCULAR RESPONSE TO STANDING AT 20 °C AND 40 °C:

Within cycle 1 and cycle 4 at 20 °C and 40 °C, as found at baseline, a significant fall in MAP and rise in HR was found in all conditions (section 4.7, Figures 4.10 to 4.13). However, when cooling (HC and TC) was applied at cycle 1 at 20 °C, it appeared to hinder the recovery of MAP, as demonstrated by MAP not returning to the pre-stand response when compared to the 20NC condition. It is interesting however that this was not an issue at cycle 4 within 20 °C or 40 °C, and that during cycle 4, MAP recovered to that measured prior to standing. This could be because during cycle 4 prior to the standing manoeuvre, HRs were greater than that recorded during cycle 1, and so cardiac output was sustained, aiding the recovery of MAP.

Within 20TC, T_{sk} was lowest when compared to 20NC (greatest), thus, vasoconstriction of the vessels local to the chest and torso may have been already present to an extent whereby any additional vasoconstriction would not have aided the maintenance of MAP. Skin-surface cooling (water perfused tubes; 15 °C to 18 °C) has been found when applied to supine individuals within a 21 °C to 23 °C environment to elict an increase in vasoconstriction of the peripheral and visceral arteries (Wilson, *et al*. 2007), reduce skin blood flow and maintain central venous pressure (Cui, *et al*. 2005) therefore in support of the aforementioned, this mechanism must have already occurred by the time the manoeuvre took place. Furthermore, any rise in HR that occurred must not have been sufficient enough to return the MAP back to that measured during the pre-stand phase. In support of this, HR during 20TC, although not significantly so, appears to be generally lower than the other conditions at recovery during cycle 1.

At cycle 4, at 20 °C the HR and MAP responses between conditions did not differ, possibly due to the PCM heating up to a point whereby there was less of a cooling induced vasoconstriction present when compared to cycle 1. At cycle 4 at 40 °C, HR did not return to that measured during the pre-stand phase in either condition, indicating a greater degree of cardiovascular strain was imposed on the worker in order to maintain MAP after an hour of activity in the heat in response to standing vs. the response to standing in a moderate climate. There was a slight tendency for peak HRs to be lowest within the 40HC condition, but overall cooling did not appear to benefit the wearer when compared to the no cooling condition at either 20 °C or 40 °C.

The increase in core temperature at 40 °C and the degree of cardiovascular stress prior to standing did not appear to compromise the recovery of MAP in response to standing during the no cooling trial. Previous research highlights that during heating of the body and forced lower body negative pressure, the vascular system partially retains the vasoconstriction mechanism, (Johnson, *et al.* 1973). Therefore, reasons for this recovery in MAP are that it is likely the participants' average heart rate reserve was still great enough (60 %) and the participants' were ‘warm,’ so that an increase in heart rate and peripheral vasoconstriction were able to occur to an extent sufficient enough to counteract the drop in MAP. Findings may have been different if the participants’ core temperatures had been greater during the no cooling trial, offering a greater comparison to the cooling conditions.

It should be mentioned that the peak HRs measured during the postural challenge during the 4th cycle at 40 °C were the greatest of all cycles (within the postural challenge) and stations (throughout the trial) by $\approx$10 beats·min^{-1} with and without cooling. Emphasising the degree of cardiovascular stress brought about through changes in posture as an individual goes from kneeling to standing compared to the other exercises involved; (walking on a treadmill, crawling and arm ergomentry), reinforcing the usefulness of this challenge to exert acute cardiovascular stress upon an individual within protective clothing in the heat.

Thus, in summary at 20 °C it appears there is no need for applied cooling to be worn within the 3010 EOD suit and that it may hinder rather than benefit the wearer with regard to maintaining suitable cardiovascular function. At 40 °C, there was a tendency for lower HRs when cooling was applied, and so although there was no difference found between the cooling or no cooling trials with regard to MAP, wearing either the vest or scrum cap did not hinder cardiovascular function and as cooling has shown in other studies to maintain central venous pressure and reduce the demand for skin blood flow (Cui *et. al*., 2005) it could potentially be useful if worn within high ambient temperatures.

5.5 RECOMMENDATIONS FOR COMMERCIAL USE

The results from this study provide many reasons for workers to incorporate the use of PCM cooling within the light-weight EOD suit and so for maximum benefit the following recommendations apply:

- For this particular type of PCM cooling garment (melting temperature 25 °C), it should be worn for 60 minutes at a time (after 30 minutes stored in a freezer, ice bucket or fridge) to gain full benefit as it is likely that after 60 minutes the rate of heat removal is greatly reduced. The PCM temperatures recorded at 80 minutes were only just less than the relative skin temperatures recorded at that time.
- The fan in the EOD light-weight 3010 suit should be turned off throughout any duration of work completed at 40 °C, to prevent the cooling garment from losing charge and to reduce sweating rate and consequent fluid loss.
- For work completed in a moderate environment this fan should be kept on, as the cooler air appears to aid cooling and maintain the charge of the PCM (provided air temperature is lower than the melting temperature of the garment).
- For work completed in moderate environments, the PCM vest would be the better garment to use as it stated to be the most comfortable garment when worn by the participants, and was found to reduce cardiovascular, physiological, and the general perception of strain more so than when the scrum cap was worn.

- For work completed in hot environments both cooling garments could be worn, however this could add more mass and increase the metabolic rate, and possibly decrease comfort, but on the other hand it could potentially reduce the rise in core temperature to a greater extent than when wearing only one garment due to the greater surface area being cooled.

5.6 FUTURE RESEARCH

From completing the current study many questions have been answered alongside many others that have arisen with regard to requirements for further work. It is clear that within the aspect of physiological responses more work could be done to investigate various continuous and intermittent exercise protocols (with prolonged rest/work cycles) to find out how they affect the efficiency of the PCM cooling garment and consequent physiological strain whilst wearing protective clothing. A number of different ensembles; such as; fie-fighter clothing, various EOD suit models, nuclear biological and chemical, and bio-chemical ensembles could be compared to discover if the benefit observed in the current study would be present under heavier, and thicker, more restrictive suits. It would also be useful to investigate whether turning the fan off at 40 °C would improve the efficiency of the torso cooling garment by preventing additional heat gain.

In this study core temperature did not reach greater than 38 °C and so cognitive spatial working memory appeared to remain unaffected by the physiological strain experienced when wearing the light-weight EOD suit. Thus, questions arose regarding a transition period in cognitive performance with increasing core temperature, specifically regarding working and visual memory. Research could be carried out to investigate this further, such as; gradually increasing the participants core temperature and monitoring their cognitive function (errors and reaction time) using the spatial working memory test, and/or when their core temperature is kept constant at various degree levels (0.5 °C, 1 °C, 1.5 °C, 2 °C) above normerthermia. This could help to determine the risk of errors that could potentially arise as an operative comes under greater thermal physiological strain, the reason behind them and further reinforce the need for cooling.

Further work that would be required is to measure skin and core temperatures and the perception of strain of operatives while they work within a 'test' environment, such as outside or inside within their training environment. This would allow comparisons to be made to results that have been obtained from within the laboratory environment and also help to determine more accurately when cooling may be required.

6. CONCLUSIONS

When exercising within the 3010 EOD suit at 40 °C, as expected, the physiological and perceptual responses were greater when compared to 20 °C, reflected in the greater PhSI and PeSI values found at 40 °C.

Cardiovascular strain in relation to the HR response to standing (from kneeling) had a tendency to be greatest within 40 °C vs. 20 °C in all conditions during the final cycle of activity. However as BP was not affected by the difference in environmental temperature this leads to refuting the second hypothesis as stated in section 1.3.

At the end of the 80 minute trial TC produced the greatest reduction in physiological and perceptual strain when compared to HC, at both 20 °C and 40 °C, as highlighted in Table 4.7.

It is evident that the cooling garments did not seem to be required whilst wearing the 3010 EOD suit at 20 °C. However, at 40 °C for the first 60 minutes of activity, TC and HC reduced the extent of physiological and perceptual strain experienced when compared to NC. When comparing cooling conditions; TC provided greater benefit than HC.

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8. APPENDICIES

APPENDIX A

Table 8. 1: Ambient temperature (ºC) and relative humidity (%) (mean ± SD) experienced by all participants (n = 6), during the 1st station (Treadmill) of each cycle (1-4) within each experimental condition (20NC, 20HC, 20TC, 40NC, 40HC,40TC).

Condition	Cycle	Ambient Temperature (°C)	Relative Humidity (RH;%)
20NC	1	22.2±0.4	34±4
	2	22.4±0.3	35±4
	3	22.4±0.4	34±4
	4	22.4±0.3	34±4
20HC	1	22.3±0.6	35±4
	2	22.2±0.5	35±3
	3	22.3±0.3	35±4
	4	22.3±0.3	35±4
20TC	1	22.0±0.4	35±6
	2	22.4±0.5	34±5
	3	22.5±0.5	34±4
	4	22.5±0.3	34±4
40NC	1	40.3±0.3	10±1
	2	40.3±0.3	12±2
	3	40.3±0.3	13±2
	4	40.2±0.4	13±2
40HC	1	40.2±0.6	11±2
	2	40.5±0.2	11±1
	3	40.2±0.3	12±1
	4	40.1±0.3	12±1
40TC	1	40.5±0.4	9±1
	2	40.2±0.3	10±1
	3	40.4±0.3	11±1
	4	40.4±0.2	11±1

APPENDIX B

APPENDIX C

Appendix D

0.0 VERY UNCOMFORTABLY COLD

1.0 UNCOMFORTABLY COLD

2.0 SLIGHTY UNCOMFORTABLY COLD

3.0

4.0 COMFORTABLE

5.0

6.0 SLIGHTLY UNCOMFORTABLY HOT

7.0 UNCOMFORTABLY HOT

8.0 VERY UNCOMFORTABLY HOT

Figure 8. 3 Thermal Comfort (T_{hC}) Scale (modified from Epstein and Moran 2006)

APPENDIX E

INFORMED CONSENT FORM

FACULTY OF HEALTH AND LIFE SCIENCES
Department of Biomolecular and Sports Sciences

THE INFLUENCE OF HEAD VS. CHEST COOLING ON PHYSIOLOGICAL AND COGNITIVE RESPONSES TO EXPLOSIVES ORDNANCE DISPOSAL (EOD) TYPE ACTIVITY IN MODERATE AND HOT ENVIRONMENTS

Principal Investigator: **Fiona Brown**
Principal Supervisor: **Dr Doug Thake**

Thank you for showing interest in participating in this study. It is important that before you volunteer to participate you are absolutely clear on the intentions of the study and the protocol involved. All the relevant information is provided below and within the participant information sheet (see attached) and requires your close attention prior to your participation. Do not hesitate to ask any questions that you may have regarding information provided here or other queries you may have.

PURPOSE OF THE RESEARCH

The main purpose of the current research is to investigate the use of cooling worn within personal protective clothing (EOD suits) that will potentially benefit explosives ordnance disposal (EOD) personnel through maintenance of physical and cognitive working performance in the heat. The aims of the current study are to investigate the impact of cooling (with PCM) on physiological and psychological responses to EOD type activity in both 20°C and 40°C environments. Predominantly the studies will investigate the impact of head and chest cooling, on blood pressure, cognitive performance and body temperature. Both head and chest cooling will be investigated, with the use of a phase change material 'scrum-cap', and vest (worn under the EOD suit, over the skin).

PARTICIPATION IN THIS RESEARCH WILL INVOLVE

Study Outline: Two studies will be conducted, one with the ‘heavy weight’ EOD suit and one with the ‘light weight’ EOD suit. There will be a total of 6 participants per study. You (the participant) will only be required for one of these studies (see *participant information sheet*). Each study will require a total of 18 hours commitment, split into seven sessions, with each session lasting 2 ½ hours. There will be one habituation/familiarisation session followed by six experimental sessions. Each session will be separated by one week, and include an 80 minute experimental trial, plus 70 minutes of preparation and cool down/showering time. The protocol will involve two control trials (CON; at 20°C and 40°C), two head cooling trials (HC; at 20°C and 40°C) and two chest cooling trials (CC; at 20°C and 40°C), conducted in a randomised order.

Participant Requirements: Participants will need to be non-smokers, with no reported illness or injury, non-heat acclimated and physically active (more than 120 minutes of physical exercise per week). Participants will need to be available for a period of seven weeks during mid-February to the End of March (1st Study) and Mid-April to the first week in June (2nd Study). They will need to ensure they; avoid consuming alcohol or undertaking vigorous exercise at least 24 hours before each test day. They will be asked to follow their usual sleep routine combined with their usual dietary habits ensuring they are adequately hydrated, the night before and the morning prior to each test day. Due to the daily fluctuations in body temperature, heart rate, and sweat rate for example (as a result of our internal circadian bio-rhythm), participants will be required and asked to ensure they are available at the same time period on each test day, i.e. if the first session is conducted at 2pm all remaining sessions will be conducted at 2pm.

Measurements: A combination of physiological, subjective, and cognitive measures will be monitored and recorded during the current study (Old/New). Baseline measures of heart rate, body temperature (core and skin), blood pressure, with local and whole body perceived thermal comfort (PTC), and perceived thermal sensation (PTS), with and without the suit (and/or cooling) will be made. Throughout the trial measurements of these variables at regular intervals with the addition of breath by breath analysis and rate of perceived exertion (RPE) will also be made. N.B. For a full explanation of measurements see the attached *participant information sheet*.

FORESEEABLE RISKS OR DISCOMFORTS

You may experience discomfort from performing EOD type activities in both the moderate (20°C) and hot (40°C) conditions, due to the nature of the suit and the duration of activity. You may also feel a little discomfort from the rectal thermistor probe but this should be less noticeable as the trial progresses. There is a possibility of fainting occurring during the postural challenge and/or at any point due to the onset of sweating, and subsequent dehydration. However, in all cases there will be regular monitoring of physical and subjective responses throughout each trial. If deemed necessary by the investigator or if requested to by the participant the trial will be terminated, (see *trial discontinuation criteria* on the *participant information sheet*).

DATA PROTECTION

Any information provided in response to questionnaires, along with all your data, will be kept strictly anonymous. Your name will never be used in conjunction with your data instead each participant will be assigned a code recognisable by the principal investigators only. Paperwork will be stored in a locked filing cabinet and data will be kept on a password-secured computer only accessible to the principal investigators, Fiona Brown or Dr. Doug Thake. Data may also be published in scientific works, but your name or identity will not be revealed. Your data may be made available to the participant(s) coaches if required and with prior consent by you the participant.

If you have any further questions regarding your participation in this study please do not hesitate to ask Fiona Brown – brownf8@coventry.ac.uk or Dr. Doug Thake

If you have any questions about your rights as a participant or feel you have been placed at risk you can contact Dr Doug Thake.

I confirm that I have read the above information. The nature, demands and risks of the project have been explained to me.

I have been informed that there will be no benefits / payments to me for participation

I knowingly assume the risks involved and understand that I may withdraw my consent and discontinue participation at any time without penalty and without having to give any reason.

Subject’s signature ____________________________________Date _____________

Investigator’s signature ____________________________________Date _____________

The signed copy of this form is retained by the student, and at the end of the project passed on to the supervisor.
A second copy of the consent form should be given to the subject for them to keep for their own reference.

PARTICIPANT INFORMATION SHEET

FACULTY OF HEALTH AND LIFE SCIENCES
Department of Biomolecular and Sports Sciences

THE INFLUENCE OF HEAD VS. CHEST COOLING ON PHYSIOLOGICAL AND COGNITIVE RESPONSES TO EXPLOSIVES ORDNANCE DISPOSAL (EOD) TYPE ACTIVITY IN MODERATE AND HOT ENVIRONMENTS

Investigator: **Fiona Brown**
Principal Supervisor: **Dr Doug Thake**

Thank you for showing interest in participating in this study. It is important that before you volunteer to participate you are absolutely clear on the intentions of the study and the protocol involved. All the relevant information is provided below and requires your close attention prior to your participation. Do not hesitate to ask any questions that you may have regarding information provided here or other queries you may have.

BY ANSWERING OUR QUESTIONS AND SIGNING THE CONSENT FORM, YOU ARE CONSENTING TO YOUR DATA BEING USED IN THIS STUDY. NO RECORD WILL BE MADE OF YOUR NAME SO INFORMATION IS STRICTLY ANONYMOUS.

What is the purpose of the study?

The main purpose of the current studies are to investigate the use of cooling worn within personal protective clothing (EOD suits) that will potentially benefit explosives ordnance disposal (EOD) personnel through maintenance of physical and cognitive working performance in the heat. For the protective EOD clothing to serve its purpose it is required to be impermeable, strong (made from Aramid), and thus very heavy. Heat loss is very limited when wearing the EOD suit and can lead to conditions known as uncompensable heat stress. Heat stress leads to serious medical problems, such as, heat illness, loss of consciousness and cases of death. Thus, the introduction of cooling material in to the EOD suit should result in reduced heat stress and subsequent improvements in personnel performance, (duration and efficiency).

These studies aim to investigate the impact of cooling (with PCM) on physiological and psychological responses to EOD type activity in both 20°C and 40°C environments. Predominantly the studies will be investigating the effect of head and chest cooling, on blood pressure, cognitive performance and body temperature. Both head and chest cooling will be investigated, with the use of a phase change material 'scrum-cap', and vest (worn under the EOD suit, over the skin).

What does it involve?

Study Outline: Each participant will undergo one study (heavy/light weight EOD suit) involving seven sessions (one 2 ½ hour session; made up of 70 minutes preparation and cool down/shower time and 80 minutes EOD activity). The seven sessions are inclusive of one habituation/familiarization session followed by six experimental trials (inclusive of two control, two with head cooling, and two with chest cooling). **NB: the order of expected participation in the six experimental trials will be different to that written below**:

OVERVIEW OF SESSIONS

1. Habituation/Familiarization Session as 30°C without cooling (FAM)
2. 20°C without cooling (20CON)
3. 40°C without cooling (40CON)
4. 20°C with head cooling (20H)
5. 40°C with head cooling (40H)
6. 20°C with chest cooling (20C)
7. 40°C with chest cooling (40C)

Each trial will last 80 minutes in total, and will involve six activity stations, repeated four times (4 cycles). The stations are as follows:

TRIAL ACTIVITIES (Representative of 1 Cycle)

1. Treadmill walking (4 km.hr^{-1}; 3min:30sec),
2. Manual activity (standardised movement of 1kg weights; (2min:30sec),
3. Crawling and Searching (2min),
4. Postural Challenge (standardised kneeling to standing; (2min:30sec),
5. Arm Ergometry (3min:30sec)
6. Spatial Working Memory (SWM) test whilst undertaking physical seated rest (6min)

Inclusive of 30 seconds transfer time between activity stations.

Familiarization Session:
Participants will undergo an initial familiarisation session (FAM) related to the Old 'heavy-weight' or New 'light-weight' suit dependent upon which study they are involved with (1st or 2nd respectively). This session will be conducted in the same laboratory used to conduct experimental trials (JS309). Participants will wear shorts while the following anthropometric data are measured and recorded; height (cm), body mass (kg), skin folds and limb girths from which fat-mass and muscle-mass will be estimated and estimated body surface area (%).

During the familiarisation session participants will take part in one full trial, with either the, Old 'heavy-weight' or New 'light-weight' suit dependent upon which study they are involved with (1st and 2nd respectively). To account for the initial anxiety that may come with first exposure to the laboratory and 'hot' ambient temperatures (40°C), an ambient temperature of 30°C will be used. The familiarisation trial will also enable the participant and the investigator to practice and run through the activities and measurements, respectively.

Experimental Protocol:
Each trial will involve arriving at the required test time (e.g. 2pm), the ingestible pill will have been given to the participant during the familiarisation session and/or previous session, and should be taken 2 hours before test time (e.g. 12pm), while at home or at university or at work for example. Upon arrival the participant will be given a standard PAR-Q Health Screen Questionnaire to assess general well-being and fitness. One practice of the cognitive spatial working memory (SWM) test will be carried out (6min). The participant will then retire to a private lavatory to insert the rectal thermistor probe, take nude body weight, a mid-stream urine sample, and change into the required (supplied) combat trousers and t-shirt. Once returning to the laboratory (JS309), the participant will need to give the urine sample to the investigator along with the recorded nude body mass (kg). The participant will remove the t-shirt, and skin thermistors will be placed on the calf, thigh, chest and upper arm with self-adhesive tape, followed by the aural thermistor, inserted like an ear plug into the ear and secured with cotton wool and self-adhesive tape. A heart rate monitor will be placed around the chest with a strap. The participant may put the t-shirt back on and baseline measurements (without the suit) will be recorded. The suit (old or new) will then be applied (in trials with cooling, either the head or chest cooling material will be applied over the t-shirt before donning the suit). The gas analyser breathing mask will be applied over the mouth (lips), and secured with a strap over the head under the helmet, the participant will be able to breathe freely in and out. The boots and helmet will then be donned and made comfortable and secure. A second baseline measurement will be made (whilst wearing the suit) and body mass will also be recorded. The participant will then make their way into the experimental chamber tent (set to either 20ºC or 40ºC). The trial will commence when instructed to do so by the investigator and will begin with treadmill walking activity (4km.h^{-1}).

Measurements:
Physiological, cognitive and subjective measurements will be recorded at regular intervals during each trial. Physiological measurements include; Heart rate, skin and core temperature, oxygen consumption, and non-invasive digital arterial blood pressure (from the finger during the postural challenge). Subjective measurements will be based on number scales whereby higher numbers represent higher intensity of response and include; Perceived thermal comfort (PTC: 0-8), perceived thermal sensation (PTS: 0-8), perceived exertion (RPE: 6-20) and a general symptoms questionnaire (GSQ: 0-3). These scales and questionnaires will be explained prior to testing and made visible to the participant during each trial. The cognitive measurement includes a spatial working memory (SWM) test (this will be practised during the FAM session), completed with the use of a touch screen computer and will last 6 minutes (times may vary).

Trial Discontinuation Criteria:
For the participants safety, an experimental trial will be terminated if; participants heart rate exceeds 95% of maximum (220-AGE) for 3 minutes, gastrointestinal, rectal, or aural temperature reach 39.5ºC or 2ºC greater than initial baseline temperature. If perceptual scores reach maximum on either the RPE (19/20), PTC (8), PTS (8), and/or GSQ (2/3) scales, physiological data will be considered and the trial may be terminated. A participant may also elect to withdraw at any point throughout the trial/study.

What do I have to do?

Time: You will be required to commit a total of 18 hours of your time, spread out over a number of weeks (one session a week is ideal). There are seven trials in total, and you will be required to attend each trial lasting between 2 hours and 2 hours 30mins each. The actual EOD type activity will last 80 minutes, and the rest of the time will be for preparation prior to beginning the trial (getting dressed, weighed, and the application of equipment such as, the thermistors, heart rate monitor, phase change material and cooling down/showering etc. at the end of the trial. The participant should let the investigator know if there are any problems with attending a scheduled session well in advance (if possible) of the testing session.

Health and Fitness: You will need to be a non-smoker, currently participating in > 120 minutes of aerobic exercise per week (2 hours). Free from any injuries, or illness, such as, cardiovascular disease. Core temperature capsules slightly larger than paracetamol capsules will be used for assessment of gastrointestinal temperature, and therefore the participant will need to be able to swallow them comfortably. Feel free to ask questions if you are not sure about whether you are eligible to participate.

Diet: Before every trial it is important to ensure that you are hydrated efficiently, and that you adhere to your usual eating and drinking habits. It is important that you try to keep a regular pattern of eating and drinking on the day of the trial and that this pattern is the same each week. No alcohol should be consumed at least 24 hours before testing time, and no vigorous exercise should be undertaken at least 24 hours before testing time. Aim to maintain a similar sleeping duration (i.e. 8 hours) the night before test days.

Do I have to take part?

No, participation is on a **voluntary basis**. However, once committed to the study it is greatly appreciated if you could attend all requested testing days at the stated time, and adhere to the required guidelines concerning potential confounding variables (alcohol use, hydration status etc.) and participant behaviour prior to and during testing (as above). **You may withdraw yourself from the study at any time.**

What are the possible disadvantages or risks in taking part?

There is a possible risk of fainting (syncope), due to working in the heat, during the postural challenge in particular. There is also a risk of heat illness, however, appropriate safety measures (see: Trial Discontinuation Criteria) are in place to ensure minimal risk. Heart rate and Core temperature will be continuously monitored. The subjective questionnaires (mentioned above) are there to ensure the investigator (myself) and the participant (you) are aware of the level of comfort, and physical exertion, experienced throughout each trial. **If the participant (you) are unable to continue with a trial for any reason let the investigator know as soon as possible and the trial will be stopped.** General well-being will also be monitored as described previously using the GSQ.

What will I get out of the study?

You will gain an insight into the investigative methods used in the laboratory, along with possible improvements in general fitness. Furthermore, you may ask questions about the scientific aspects of the study and you may find it interesting to know what we are trying to achieve or how various measurements are recorded.

Who has reviewed the study?

Coventry University Ethics Committee

If you have any further questions regarding your participation in this study please do not hesitate to ask (e-mail) FIONA BROWN (Investigator) – brownf8@coventry.ac.uk or DR. DOUG THAKE (Principal Supervisor)