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THE INTERACTION OF THE THERMAL ENVIRONMENT, CLOTHING AND AUXILIARY BODY COOLING IN THE WORKPLACE

A thesis submitted in partial fulfilment of the
requirements for the award of the degree

Masters of Science (Research)
from

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by

Joanne Nellie Caldwell, BSc.

School of Health Sciences
2008

I, Joanne Nellie Caldwell, declare that this thesis, is submitted in partial fulfilment of the requirements for the award of Masters of Science (Research), in the School of Health Sciences, University of Wollongong, is wholly my own work unless otherwise referenced or acknowledged. The document has not been submitted for qualifications at any other academic institution.

______________________________ Date:_______________

Joanne Nellie Caldwell

THE INTERACTION OF THE THERMAL ENVIRONMENT, CLOTHING AND AUXILIARY BODY COOLING IN THE WORKPLACE

Abstract

Extensive research into the physiological impact of wearing thermal protective clothing has been conducted for many years. However, the current literature does not provide a consensus concerning the interaction of heat strain and cognitive function. This project sought to investigate the problems associated with personnel working in uncompensable environmental conditions while wearing Australian Defence Force (ADF) protective clothing. Four separate investigations were conducted. The first was a field based study evaluating the thermal influences of operating a helicopter simulator. The second was a laboratory study evaluating the impact of wearing body armour on physiological and cognitive function. Thirdly, a theoretical evaluation of, the problems associated with performing work in an uncompensable heat stress environment and, the physical characteristics of various coolants and cooling systems were investigated. Finally, a laboratory investigation on the physiological and cognitive consequences of wearing a personal protective ensemble while performing exercise with and without an activated liquid-cooling garment. A significant reduction in flying performance was evident when pilots were heated to a mean skin temperature ($\overline{T}_{sk}$) of $\sim 39°C$ compared to the other two conditions ($\sim 33°C$ and $37°C$, $P < 0.05$), using a water perfusion garment to achieve these target $\overline{T}_{sk}$. However no obvious detriments in cognitive performance were observed for the two laboratory based studies even though subjects were exposed to a significant thermal load, as determined by increases in T_C, $\overline{T}_{sk}$ and f_c ($P < 0.05$). For the final study, where thermal strain was significantly higher in the hot-dry trial without cooling ($P < 0.05$), resulting in a terminal rectal temperature that was $1.6°C$ higher than the thermoneutral condition, the liquid-cooling garment (water temperature $15°C$) successfully prevented all detriments in physiological function observed during the hot-dry trial without cooling. It can therefore be concluded from this investigation that, individuals exposed to extreme environmental conditions while wearing protective ensembles, are at risk of developing increased thermal strain that may lead to heat illness. In terms of cognitive function assessment, this project failed to determine specifically, which areas of cognitive function are in fact adversely affected. However, a reduction in thermal strain can be achieved with the use of an auxiliary cooling device.

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CHAPTER 1: INTRODUCTION

1.1 Introduction

Humans can tolerate a vast range of thermal environments using both physiological and behavioural strategies. However, body core temperature (T_c) must be held within a very narrow range, and is normally regulated around 36.7°C±0.3°C (Ivy, 1944). From a clinical perspective, if T_c varies greater than 2°C either side of 37°C, then one assumes thermoregulatory failure to have occurred. In this state, the regulation of body temperature has been transiently compromised or lost (dysthermia: hypothermia ($T_c < 35$°C), or hyperthermia ($T_c > 39$°C)), with the possibility of death accompanying a reduction of ~10°C, or an elevation of only ~5°C (Pugh *et al.*, 1967; Robinson, 1963).

The first law of thermodynamics states that energy can neither be created nor destroyed, but is transferred from one form to another. In the case of humans, when working or exercising, stored chemical potential energy (carbohydrates and lipids) is converted into kinetic and thermal energy (heat). Since we are only about 20% efficient, approximately 80% of this chemical energy will appear in the body as heat. Unless this heat is able to be readily dissipated, then the average tissue temperature of the body will rise, and thermal homeostasis may be compromised. In this project, we focus upon the problems and possible solutions associated with clothed military personnel working under hot climatic conditions, where air and skin temperatures ($\overline{T}_{sk}$) may be equal.

1.2 Mechanisms of heat exchange

The thermodynamics of this problem are dictated by the avenues through which thermal energy is exchanged between the body and its physical environment, and also by the interactions of the thermal environment and physiological function. The principal avenues for heat flux are conduction (K), convection (C), radiation (R) and evaporation (E), with thermal input from metabolism and the performance of physical work. Each of the mechanisms with which heat is exchanged is discussed below.

Conduction (K) occurs when objects come into physical contact. Heat is exchanged from molecule to molecule, and down the thermal gradient from the heat source to the heat sink.

The quantity of heat removed by conduction is a function of the thermal conductivity of the heat sink, the distance through which the heat must travel, the size of the thermal gradient, and the contact surface area. Conductive heat losses from an individual can be achieved by placing their skin in direct contact with a coolant such as ice, which has a high thermal conductivity, and due to its low temperature a large thermal gradient is possible.

There are two forms of convective heat transfer (C), both of which involve mass transfer: free and forced convection. The latter is the only form to be considered in this report, and it involves the exchange of thermal energy between an object and its environment by the movement of a fluid (liquid or gas), which has a different thermal energy content (temperature), across the surface of that object. The quantity of heat extracted by convection is a function of the size of the thermal gradient and the heat transfer coefficient of the fluid (coolant). The latter is a function of the density of the coolant, its flow at the skin surface and the contact surface area. This form of heat exchange occurs when cool air is moved over the skin surface.

Individuals may gain or lose heat through radiative heat exchange. Radiative heat exchange occurs as a results of objects emitting electromagnetic waves of energy that are passed between objects of different temperatures. For example, the sun emits hot radiative waves that results in an increase in the temperature of the earth's surface, and hence an increase in skin temperature of an individual exposed to the sun's rays.

Evaporative heat exchange, in humans, is the only avenue that cannot lead to a nett increase in heat storage. That is, humans can only lose heat to the environment through evaporation. Heat is lost through evaporation of sweat, from the conversion of the liquid form (on the skin's surface) to the gaseous form (water vapour). It is the heat required for this conversion that allows the cooling effect of evaporation. However, this conversion is dependent on the water vapour pressure[1] gradient between the skin surface and the surrounding environment and at any given air temperature. A rise in relative humidity

[1] Water vapour pressure: the partial pressure exerted by water molecules in the gaseous form.

results in increased vapour pressure, thereby reducing the potential water vapour pressure gradient.

When body temperature rises, as a result of increased metabolic heat production or increased environmental conditions, the autonomic nervous system activates the sweat glands to secrete sweat onto the surface of the skin. As sweat evaporates, heat is lost to the environment, which results in lowered skin temperatures. However, evaporation of sweat from the skin is highly dependent upon the temperature and relative humidity of the surrounding environment, and where there is a reduced water vapour pressure gradient, less heat sweat is evaporated, hence less heat loss. For each gram of sweat evaporated, 2.43 kJ of heat is lost (Wenger, 1972 and Lide, 2008).

However, during work in the heat, the avenues for non-evaporative (dry) heat dissipation are impeded (R, C, K), and can even be reversed, leading to heat influx. For instance, under a full solar load, the body experiences radiative heat gains from the sun and nearby surfaces. Similarly, natural convective losses cease when air temperature approximates $\overline{T}_{sk}$ (31-33°C). Under these conditions, the body becomes heavily, if not totally, reliant upon evaporative cooling for heat dissipation, and the capacity of the body to continue its rate of endogenous heat production, without sustaining a progressive elevation in tissue temperature, is dictated by the compensability of the thermal environment (Pascoe *et al.*1994).

Thermal compensability defines the interaction of the body and the environment, such that it specifies the conditions under which the body is most likely to enter a state of dysthermia. For example, when personnel work in hot environments, thermal compensability is dictated by the ratio of the required evaporative heat loss (E_{req}) to the maximal evaporative cooling that the environment, including clothing, will permit (E_{max}). If E_{req} is greater than E_{max}, then the conditions are uncompensable (Belding and Hatch, 1955).
When working in such conditions, where heat losses are reduced or impeded, the rate of

heat storage[2] is increased. As a result physiological strain is increased and individuals exposed to uncompensible environments are at risk of developing heat stress illness.

1.3 The nature of the problem

In most military scenarios, personnel wear clothing covering the majority of the skin surface, and all clothing impacts upon heat exchanges with the environment. Many personnel also use personal protective ensembles that are designed to reduce exposure to hazardous environments, by minimising the surface area of exposed skin. In some cases, such protective clothing is totally encapsulating (*e.g.* Biological and Chemical (BC) clothing), with very high insulation and poor moisture permeability characteristics.

Although these personal protective ensembles greatly reduce the risk of injury or illness during exposure to hazardous materials or environments, consideration is often not given to the implications for heat strain. Ensembles are designed with many impermeable and semi-permeable fabric layers. These layers trap air, creating a microclimate between the skin and the environment. This microclimate is a very powerful insulator, and has significant implications for heat exchange. The trapped air is warmer, it contains more water vapour, and its movement across the skin surface is limited. Each of these clothing properties can markedly reduce heat loss capabilities and therefore potentially create a condition of uncompensible heat stress. Thus, clothing will markedly affect heat and water vapour transfer. Knowing this, it becomes critical to understand two physical properties of clothing.

The first factor is the thermal insulation provided by the ensemble. This relates to the characteristics of the garment that allow it to trap a layer of insulating air (air is an

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[2]Heat storage: Is dictated by the avenues through which heat is exchanged between the envionment and the individual and is calculated by the heat balance equation:

$S=M-(\pm W)\pm E \pm R \pm C \pm K$ [$W.m^{-2}$]..Equation 1

S = heat storage [$W.m^{-2}$]
M = endogenous heat production (metabolism) [$W.m^{-2}$]
W = work leaving or entering the system [$W.m^{-2}$]
E = heat exchange by evaporation [$W.m^{-2}.kPa^{-1}$]
R = heat exchange by radiation [$W.m^{-2}$]

extremely good insulator). The thicker the garment, the more air that is trapped, and the greater is its insulating capacity. For instance, the personal protective ensembles of firefighters is generally about 0.465 $m^2.K.W^{-1}$ (3 clo). In the situation of the firefighter, such insulation is designed to exclude heat from the surrounding environment. However, when such powerfully insulating garments are worn, they are also equally effective in trapping metabolically-produced heat, and several studies have shown that wearing a fire fighter protective uniform results in increased thermal strain (O'Connell *et al.*, 1986, Montain, *et al.*, 1994 and Smith and Petruzzello, 1998). This is why, when working whilst wearing such ensembles, one need not be in the heat to suffer from heat illness; one may actually be overheating from the inside.

Second, the vapour (moisture) permeability of the garment is important. This is the ability of the fabric from which the garment is made to allow water vapour to pass through. Since skin and air temperatures (T_a) are very similar in hot environments, then evaporative cooling becomes the dominant means through which to dissipate heat, and this is affected not just by covering the body, but also by the ability of the fabric to allow moisture to pass through the clothing, and so facilitate evaporation at the skin surface by allowing the water vapour pressure of the trapped air to remain below that at the skin surface.

Nagata (1978) demonstrated that the greater the amount of clothing worn, the lower the evaporative sweat rate, but the greater the sweat production (Budd, 1981). For a heat-acclimatized individual who will produce more sweat than one who is not, where the clothing worn creates a barrier to sweat evaporation, heat acclimatization is of little benefit (Givoni and Goldman, 1973) and may simply contribute to more rapid rate of dehydration and earlier onset of heat exhaustion (Goldman, 1994, and Cheung and McLellan, 1998). This increase in sweat rate, but reduced sweat evaporation (due to reduced water vapour pressure gradient) will cause sweat to accumulate on the skin surface and therefore increase skin wettedness. Furthermore, sweat secretion in extreme conditions may result in reduced blood volume (Sawka, *et al.,* 1985 and 1996).

1.4 The consequences of this problem

Reductions in heat loss, in combination with increased metabolic workloads, can have catastrophic physiological, psychological and pathophysiological consequences. These are expressed most dramatically in the development of heat illness. In epidemiological analyses, one can identify factors that directly lead to, or cause, various clinical conditions; these factors are called **agents**. These are largely dictated by the conditions of the working environment, and form a basis for this thesis. In addition, certain genetic, physical, physiological or behavioural characteristics of an individual may predispose that individual to a particular clinical condition; such characteristics are known as **host factors**. The agents and host factors associated with heat illness are summarised in Figure 1.1.

One likely consequence of this heat stress problem is that work tolerance times are likely to decrease and many studies have shown this. Reduced tolerance times were observed in a study by McLellen *et al* (1993) who showed that as metabolic rate and environmental temperature increased, work time was reduced. In fact, after testing this theory with three different uniforms, it was not only the work and environmental conditions that altered exposure time, but tolerance times were decreased further with the heaviest uniform possibly imposing greater metabolic demands.

Similarly, physical and cognitive performance may be adversely affected. Recently, Faerevik and Reinertsen (2003) showed there was a correlation between increased T_c and a reduction in cognitive performance with a rectal temperature (T_{re}) of 37.7°C being the threshold of cognitive decrement and 39.6°C being the suggested functional limit. When T_{re} reaches approximately 37.9°C, manual dexterity is likely to decrease, and temperatures of 38.8°C will lead to loss of tracking skills. Rectal temperatures of 39.5°C will result in a 50% chance of heat casualties (Goldman, 2001). The effect of heat on cognitive function is critically important in the military environment, since the successful operation of sophisticated equipment will often dictate both operational success and the health and safety of personnel. Ultimately, the health and capability of the individual will be threatened.

1.5 A possible solution

The occupational health and safety of individuals exposed to heat stress conditions is of great concern to the military. However, many constraints exist within military trades, as with the most emergency services, which mean that individuals will invariably be placed within high-risk environments, the nature of which may not be able to be modified. Thus, whilst it is relatively easy to ensure that the host factors are modified to reduce strain experienced by the individual, modification of the agents of thermal strain is highly unlikely. For this reason, other methods must be sought to optimise health of the individual and task performance (capability). These principles will be discussed in detail in Chapter 5.

Please see print copy for figure

Figure 1.1: The agents and host factors of heat illness relevant to military personnel (Taylor, 2006).

1.6 Aims and hypotheses

This project was designed to explore the physiological and cognitive changes associated with exercising in extreme environmental conditions while wearing personal protective ensembles. Four different investigations were performed. The first was a field based study evaluating the thermal influences of operating a helicopter simulator. The second was a laboratory study evaluating the impact of wearing body armour on physiological and cognitive function. Thirdly, a theoretical evaluation of the problems associated with performing work in an uncompensible heat stress environment and, the physical characteristics of various coolants and cooling systems were investigated. Finally, a laboratory investigation on the physiological and cognitive consequences of wearing a personal protective ensemble while performing exercise with and without an activated auxiliary cooling system.

It was hypothesised that:

(i) An increased thermal strain, as measured by core temperature, skin temperature, cardiac frequency and sweat loss, would result in decreased pilot flight performance.

(ii) The addition of combat body armour would cause reduced physiological and cognitive function. However, no additional reduction in performance would be observed with the addition of the combat helmet.

(iii) Cognitive function detriments would be observed in individuals required to perform very light exercise in an uncompensable environment while wearing the ADF Biological and Chemical personal protective ensembles.

(iv) The use of a liquid-cooling device (water temperature 15°C) would successfully reduce the thermal strain and cognitive function detriments observed during the hot-dry trials.

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CHAPTER 2: THE INTERACTION OF TRANSCUTANEOUS HEATING AND HELICOPTER FLIGHT SIMULATOR PERFORMANCE.

2.1 Introduction

The Australian Defence Force (ADF) deploys personnel to countries in which the summer climates are very hot (>40°C). When the air temperature is greater than skin temperature (critical air temperature), heat is gained from the environment. Exercise and clothing lower this critical temperature, since clothing impedes heat gain from, and heat loss to, the environment. When wearing military clothing (combat fatigues: insulation 0.29 $m^2K.W^{-1}$) and working at a moderate exercise intensity, the critical air temperature can be as much as 10°C lower than for an unclothed, resting person, and exercise in such conditions is physiologically uncompensable[1].

It is known that elevations in body temperature can impair both physical and cognitive performance (Epstein, *et al.*, 1980; Hancock, 1981; Nunneley *et al.*, 1982). The target personnel for this research were Royal Australian Navy (RAN) helicopter pilots, for whom the major heat source during flight originates from solar radiation (Gibson *et al.*, 1979; Froom *et al.*, 1991), with aircraft cockpit temperatures under a full solar load, exceeding 50°C (Nunneley and Myhre, 1976). Yet, under times of nuclear, biological or chemical (NBC) threat, personnel must wear appropriate protective clothing. Such garments prevent the flushing of clothing with relatively cool external air, and will also eliminate evaporative cooling, once the water vapour partial pressure of the microclimate reaches that of the skin. Furthermore, metabolic heat generated during the pre-flight period, and during the mission, is trapped, exacerbating thermal strain. The combination of these states places personnel at risk of elevated thermal strain, even during light work, with the possibility of reduced operational capability and heat illness. Thus, heat illness in the military is an on-going operational problem (Bricknell, 1995; 1996; House *et al.*, 2003; Carter *et al.*, 2005).

A progressive elevation in thermal strain is known to impact upon physiological function,

[1] An uncompensable state occurs when the thermal load to which a person is exposed exceeds the capacity of that person to dissipate heat by an elevation in sweat production and evaporation.

but our understanding of the affect of heat strain upon cognitive function is less certain (Hancock, 1981). Indeed, while the literature contains a wide range of experimental observations concerning this relationship (Hancock, 1981), there is no consistent trend within those observations that would enable the ADF to fully understand the problem, or to implement appropriate preventative strategies. This is due largely to design limitations of previous research, and the fact that much of the research in this area has not been specifically targeted at operational scenarios. Nevertheless, slight changes in the physiological or cognitive function of pilots can have a catastrophic impact upon personnel, equipment and operational capability.

2.1.1 Aims of the study

The focus of the current project was upon the impact of the thermal loading of helicopter pilots on subsequent physiological and flight performance. It was hypothesised that elevations in body heat content, as reflected by skin, core and mean body temperatures, would degrade flight performance. This was tested using RAN helicopter pilots, who completed three, two-hour flight simulations (Sea King simulator) under three levels of external thermal strain.

2.2 Methods

2.2.1 Subjects

Six healthy, physically active, Sea King helicopter pilots from the Royal Australian Navy volunteered to participated in this research (Table 2.1). Each subject completed each of three trials, acting as their own control, but only after providing a signed, written informed consent. All procedures were approved by the Human Research Ethics Committee, University of Wollongong.

2.2.2 Experimental conditions

2.2.2.1 Determination of water temperature for the water perfusion garment

Prior to the flight simulations, preliminary trials were undertaken at the University, using civilian personnel. The purpose of these trials was to determine the upper, but realistic, mean skin temperature that a pilot may reasonably be expected to experience during

Table 2.1: Physical characteristics of the RAN pilots.

Characteristics	Mean (range)
Age (y)	32.3 (27-39)
Height (m)	182.5 (176-190)
Mass (kg)	81.6 (71-102)
Flight experience (y)	6.25 (5-8)
Flight hours last 3 months (h)	42.5 (30-50)

mid-summer flights in a hot-dry climate, with a full solar load. Froom *et al.* (1992) have previously reported mean skin temperatures in the range 34.7-35.4°C for cockpit temperatures of 28°C and 33°C, but skin temperature data were required for much hotter operational conditions (48°C).

Five volunteer subjects, wearing the full NBC ensemble and military clothing, were exposed to a hot-dry environment (48°C, 20% relative humidity), whilst performing low-intensity cycling (~30 W; total heat production: ~240 W). This workload closely approximates that of a helicopter pilot. Three, 350-W infra-red lights were directed onto each subject. The target skin temperature was taken as the steady-state mean skin temperature observed over the last 15-20 min of each 90-min exposure. This steady-state skin temperature was approximately 39°C. From these trials, it was determined that three experimental conditions would be evaluated, representing the typical mean skin temperature observed during thermoneutral rest (33°C: control), a realistically-hot state (37°C: ~2°C less than steady-state peak recorded during this testing) and an extreme, but not unrealistically-hot state (39°C).

2.2.3 Experimental procedures

Each pilot completed three, two-hour flight simulations (Sea King simulator: SK50A Simulator, Link-miles, Somerset, U.K.) under each of three levels of thermal strain (Table 2.2). Trials were conducted at HMAS Albatross, and were delivered in a balanced order. Pilots were tested in pairs with each wearing a water-perfusion garment (Cooltube suit, Med-Eng, Canada), normal flight clothing and NBC clothing (Figure 2.1). The water-perfusion garment covered the subject's whole body except for their hands, feet and face. Thermal strain was induced by modifying the temperature of water pumped (Deltawing pump, Med-Eng, Canada; 325 $ml.min^{-1}$) to the perfusion garment (water bath: Type VFP, Grant Instruments, U.K.), covering the whole body except the hands, feet and face, such that three target skin temperatures could be achieved: 33°C (control), 37°C (moderately hot) and 39°C (hot). Prior to commencing each trial, fully-clothed volunteer subjects (Figure 2.1C) performed 10 min of bench stepping (cadence: 18 $steps.min^{-1}$, step height: 18 cm). This was designed to replicate typical pre-flight physical activity. Volunteer subjects then moved directly to the helicopter simulator.

2.2.3.1 Experimental standardisation

Volunteers subjects were instructed to refrain from strenuous exercise, and the consumption of alcohol and tobacco during the 12-h period prior to each trial. Before each trial, volunteer subjects were requested to eat an evening meal, and breakfast, high in carbohydrate and low in fat, and to drink 20 $ml.kg^{-1}$ of additional water before retiring. Caffeine was avoided for 2 h prior to each trial. On arrival at the preparation room, volunteer subjects provided a urine sample and hydration status was confirmed by having a urine specific gravity $\leq$1.020. Before leaving the laboratory, volunteer subjects were rehydrated, consuming a flavoured, sodium-chloride drink equivalent to 150% of the body mass change observed during the experiment.

2.2.3.2 Flight simulation

Each flight sortie was comprised of eight different simulated circuits, with each circuit lasting approximately 15 min, but variable among pilots, and involving separate takeoff and landing exercises. These simulations were programmed and controlled by the flight simulator training officer, who was blind to the order of experimental treatments. This officer had 32 y of flight experience and 26 y experience as a flight instructor.

During each simulated flight circuit, the pilots were required to identify and solve two different operational problems, graded in difficulty as “easy”, “moderate” and “hard” (Table 2.3), based upon the following criteria:

- ***easy:*** simple task involving single switch activation (“on” or “off”);
- ***moderate:*** requires a degree of decision making, such as choosing the correct lever or switch to operate to solve the problem;
- ***difficult:*** problems that were not likely to happen in routine flights, and had greater potential to elicit an incorrect response.

Both the simulated circuits and the operational problems were presented in a different order for each of the three trials, to minimise learning effects. Between each circuit, a rest period of 5 min was scheduled (Table 2.2). During this time, pilots answered the psychophysical questionnaires, under the direct supervision of the experimenter, and were permitted to drink water *ad libitum*, though drinking through the NBC mask made drinking quite difficult, so fluid consumption was minimal.

2.2.4 Data collection procedures

2.2.4.1 Physiological measures

Body core temperature

Core temperatures (T_c) were measured using radiotelemetry (gastric pill (HQ Inc., U.S.A.) and receiver (FitSense, U.S.A.). Pilots swallowed a gastric pill about 30 min before commencing a trial.

Skin temperatures

Skin temperatures were measured using thermistors taped to eight skin sites (Type EU, Yellow Springs Instruments Co. Ltd., Yellow Springs, OH, U.S.A.). These sites were: right scapula, right chest, right upper arm, left forearm, left dorsal hand, right anterior thigh and left posterior calf (ISO 9886, 1992). Data were sampled at 0.25 Hz using a data logger (1206 Series Squirrel, Grant Instruments Pty Ltd., Cambridge, U.K.). Mean skin temperature ($\overline{T}_{sk}$) was derived using skin surface area weightings (ISO 9886, 1992).

$$\overline{T}_{sk} = 0.07 \cdot T_{sk\text{-}1} + 0.175 \cdot T_{sk\text{-}2} + 0.175 \cdot T_{sk\text{-}3} + 0.07 \cdot T_{sk\text{-}4} + 0.07 \cdot T_{sk\text{-}5} + 0.05 \cdot T_{sk\text{-}6} + 0.19 \cdot T_{sk\text{-}7} + 0.2 \cdot T_{sk\text{-}8}$$

where:

$T_{sk\text{-}1}$ = forehead

$T_{sk\text{-}2}$ = chest

$T_{sk\text{-}3}$ = scapula

$T_{sk\text{-}4}$ = arm

$T_{sk\text{-}5}$ = forearm

$T_{sk\text{-}6}$ = hand

$T_{sk\text{-}7}$ = thigh

$T_{sk\text{-}8}$ = calf.

Figure 2.1: Clothing configuration: (a) water-perfusion garment (upper left); (b) flight clothing (upper right) and (c) nuclear, biological and chemical clothing (bottom).

Table 2.2: Experimental time line.

Time (min)	Activity summary
0	Subject arrival
0-5	Subject hydration and body mass check
5-25	Subject preparation (22°C)
25-27	Thermoneutral baseline data collection
27-30	Move to stairs for bench stepping
30-40	Bench stepping exercise
40-42	Move into the simulator
50	Start flight simulations
50-65	Circuit 1
65-70	Rest
70-85	Circuit 2
85-90	Rest
90-105	Circuit 3
105-110	Rest
110-125	Circuit 4
125-130	Rest
130-145	Circuit 5
145-150	Rest
150-165	Circuit 6
165-170	Rest
170-175	Circuit 7
175-180	Rest
180-195	Circuit 8
195-200	Rest and terminate experiment

Table 2.3: Flight simulator operational faults, graded by difficulty.

Fault	Difficulty
Single booster pump failure	Easy
Droop cancel	Difficult
Fuel bi-pass	Easy
Auxiliary hydraulic failure	Moderate
ECU fire	Moderate
Single generator failure	Easy
Double generator failure	Difficult
Yaw sense link failure	Moderate
Tail rotor control failure	Difficult
Single ECU failure in manual	Difficult
Fluctuating oil pressure: <4 psi	Easy
TX oil temperature gauge failure (60°C)	Easy
Single TQ gauge failure	Moderate
Computer run up	Difficult

Mean body temperature

Mean body temperature ($\overline{T}_b$) was determined from the weighted summation of gastric and skin temperatures, using the following equation (Vallerand *et al.*, 1992):

$$\overline{T}_b = 0.9\ T_c + 0.1\ \overline{T}_{sk} \quad [°C]$$

Thermistor calibration

All skin thermistors were calibrated before testing. Probes were placed in a 38-litre water bath (Grant, U.K.) with a National Association of Testing Authorities certified thermometer (Dobbie Instruments, Dobros total immersion, Australia). Calibration covered the range 21-46°C, in 2°C increments, with calibration data recorded after water temperature had stabilised for 5 min. Linear regression equations were derived for each thermistor, using the recorded thermistor data and known temperatures from the certified thermometer (r=0.99). Thermistor data recorded during the experimental trials were corrected using these calibration equations.

Cardiac frequency (f_c)

Cardiac frequency was measured from ventricular depolarisation (Polar Electro Sports Tester, Finland) and later downloaded onto a computer.

Whole-body mass changes

Mass changes were taken as the difference between the pre- and post-experimental mass measurements (fw-150k, A&D scale, Australia). These were recorded to estimate sweat rate over the duration of each trial.

2.2.4.2 Psychophysical measures

Four psychophysical measurements were taken throughout each sortie, and during the between-circuit rest periods. These indices included: thermal sensation; thermal discomfort; flight performance effort and flight performance quality. Volunteer subjects were provided with copies of the relevant subjective scales prior to the start of each sortie, with written and oral instruction on how to use each scale.

Thermal sensation

Thermal sensation was monitored using a modified version of the Gagge scale (Gagge *et al.*, 1967). Pilots were asked to describe whole-body sensation of temperature using a 13-point scale: 1 (unbearably cold), 7 (neutral sensation), 13 (unbearably hot). Sensation votes were recorded following the question: "How does the temperature of your body feel?"

The 13-point thermal sensation scale

1	Unbearably cold
2	Extremely cold
3	Very cold
4	Cold
5	Cool
6	Slightly cool
7	Neutral
8	Slightly warm
9	Warm
10	Hot
11	Very hot
12	Extremely hot
13	Unbearably hot

Thermal discomfort

Whole-body thermal discomfort was evaluated using another modified scale (Gagge *et al.*, 1967; 1.0 = comfortable and 5.0 = extremely uncomfortable) in response to the question: "How comfortable do you feel with the temperature of your body?"

The 5-point thermal discomfort scale

1.0	Comfortable
1.5	
2.0	Slightly uncomfortable
2.5	

3.0 Uncomfortable

3.5

4.0 Very uncomfortable

4.5

5.0 Extremely uncomfortable

Flight performance effort

Pilots were asked to describe how the experimental conditions impacted upon the effort required to sustain the required quality of flight performance. The focus was upon how much effort was required to sustain each pilot's normal flight performance. The performance effort scale ranged from 0 (minimal effort) to 5 (maximal effort), and pilots responded to the question: "How much effort is required to maintain the required quality of your flight performance?"

The 5-point flight performance effort scale

0.0 Minimal effort (no effort)

0.5

1.0 Very little effort

1.5

2.0 Little effort

2.5

3.0 Moderate effort

3.5

4.0 Considerable effort

4.5

5.0 Maximal effort

Flight performance quality

Pilots were then asked to describe how the experimental conditions impacted upon the quality of flight performance, using a rating scale ranging from -5 (performance has been dramatically reduced), through to 0 (no change in performance quality), and to 5 (performance has dramatically improved). Performance quality ratings were given in response to the question: "How has the temperature of your body affected the quality of your flight performance?"

The 11-point flight performance quality scale

-5	Dramatically reduced
-4	
-3	Reduced
-2	
-1	Slightly reduced
0	Performance quality unchanged
1	Slightly improved
2	
3	Improved
4	
5	Dramatically improved

2.2.4.3 Independent flight performance scores

The flight simulator training officer independently graded pilot performance for each circuit (overall performance), and on problems presented within a circuit. Rating scores ranged from 0-8. This is a routine procedures used by the simulator officer.

2.2.5 Statistical analysis

This project was based upon a repeated-measures experimental design, with volunteer subjects acting as their own controls, and participating in each of the three trials. Testing was performed under blinded conditions since, while there were clear and perceptible differences in the temperature of each of the water perfusing garments, neither the volunteers subjects nor the simulator flight instructor were informed about which treatment condition was used for any given trial. Between-trial differences were analysed using two-way analyses of variance for repeated measures, with Tukey's *HSD post hoc* procedure used to identify sources of significant differences. Paired and student *t*-tests were also performed. *Alpha* was set at the 0.05 level for all statistical comparisons, with data reported as means with standard deviations (SD) or standard errors of the means. Persons Product-Moment correlations between dependent variables were also undertaken.

2.3 Results

All volunteers subjects completed the control and moderately-hot trials. However, all trials under the hot condition were terminated prematurely due either to physiological strain or subject discomfort. Since testing occurred in pairs, when either subject achieved the point of subjective trial termination, the flight simulation was aborted for both pilots. Thus, instead of the hot trials lasting approximately 110 min, one sortie was terminated at 49 min, another lasted 70 min and the third continued until 82 min.

2.3.1 Gastric temperature

Under the current conditions, significant treatment by time interactions were evident for comparisons among each the three trials ($P<0.05$; Figure 2.2). Table 2.4 shows the average gastric temperatures for each of these trials. The terminal gastric temperatures for each trial were: 37.4°C (±0.1; control), 38.4°C (±0.2; moderate) and 38.8°C (±0.2; hot). The last two temperatures represented a significant thermal strain, with the latter being in excess of the cut-off points used for occupational settings.

2.3.2 Skin temperature

When averaged across the entire experimental period, the resultant mean skin temperatures for each of the three treatments were: control: 34.2°C (SD 0.7); moderately hot: 36.7°C (SD 0.5); and hot: 38.1°C (SD 0.5). Each of these temperatures differed significantly from one another ($P<0.05$). Two key observations are immediately apparent from these data. First, based upon the distribution of temperatures across both trials and volunteers subjects, the clamping of the skin temperature was successful. Second, the attainment of the control and moderately hot targets (33°C and 37°C, respectively) was also very successful. However, while the average skin temperatures differed significantly, it was not possible to obtain the desired separation between the moderately-hot and hot (39°C) trials, due to the attainment of a lower than desired target temperature. That is, the treatment by time

Table 2.4: Overall physiological responses during three, two-hour flight simulations, performed under three levels of thermal strain: control (34.2°C); moderately hot (36.7°C); hot (38.1°C). Data are means with standard errors of the means derived across complete trial durations.

Variable	Control	Moderate	Hot
Cardiac frequency (b.min^{-1})	84.8 (±6.0)^{M,H}	109.3 (±6.1)	125.7 (±6.2)
Gastric temperature (°C)	37.5 (±0.1)^{M,H}	37.9 (±0.1)	38.2 (±0.2)

Note: Sources of significant differences ($P<0.05$) are indicated using the superscripts M (different from the moderate trial) and H (different from the hot trial).

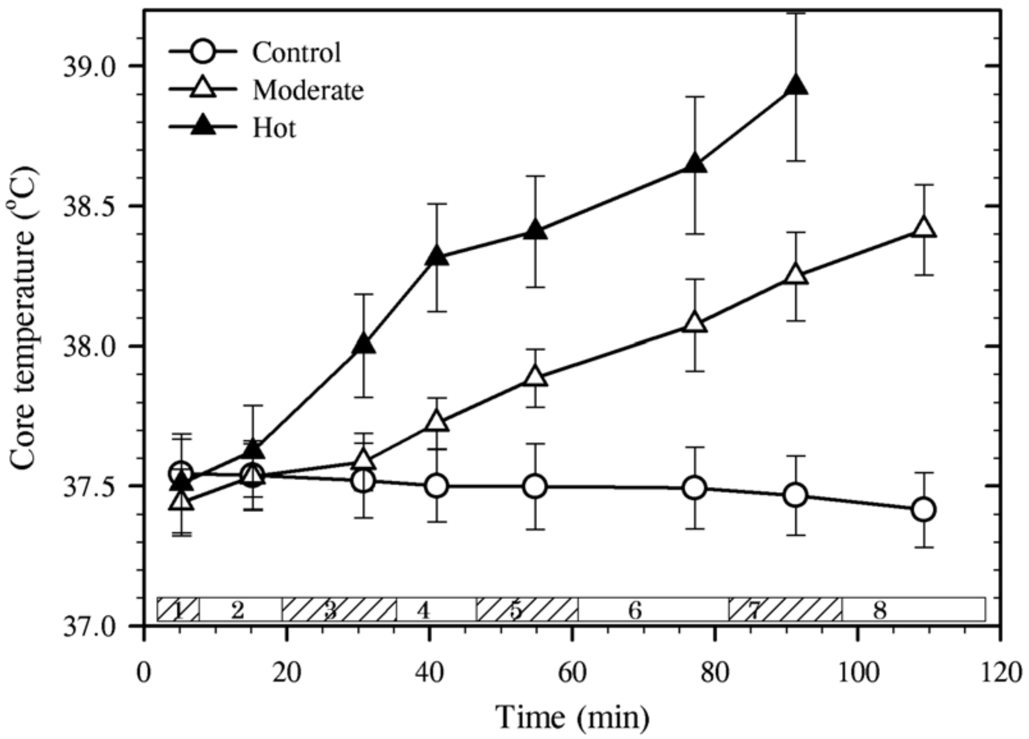

Figure 2.2: Gastric temperatures during three, two-hour flight simulations comprised of eight flight circuits (labelled 1-8), performed under three levels of thermal strain: control (34.2°C); moderately hot (36.7°C); hot (38.1°C). Data are means with standard errors of the means from each flight circuit.

interactions differed significantly for each comparison except the moderately-hot and hot sorties ($P>0.05$).

Examination of the time series data for skin temperature (Figure 2.3), again revealed the stability of the control trial. This is not surprising, since 33°C is very close to the thermoneutral skin temperature of a resting person. The significant separation of the treatment effects is now more evident, but so too is the approximately exponential rise in mean skin temperature in both the moderate and hot trials. That is, a steady state temperature had not been obtained prior to the commencement of each sortie.

2.3.3 Mean body temperature

When skin and gastric temperature data were combined to derive mean body temperature (Figure 2.4), three distinct and significantly divergent response patterns were evident. Now, for each between-trial comparison, the time by treatment interactions differed significantly ($P<0.05$). These observations confirm that not only had the three different skin temperatures (thermal stress) been achieved, but that the heat applied to the pilots had elicited significantly different states of thermal strain across the three treatments.

2.3.4 Cardiac frequency

This thermal strain was also reflected in the average (Table 2.4) and terminal cardiac frequencies of the current volunteers subjects: 85.0 b.min^{-1} ($\pm$5.2; control), 126.0 b.min^{-1} ($\pm$5.0; moderate) and 147.3 b.min^{-1} ($\pm$6.0; hot). These terminal data represented 45%, 67% and 78% (respectively) of the age-predicted maximal heart rates for this group of volunteer subjects. The time series data for each trial differed significantly for the time by treatment interactions ($P<0.05$; Figure 2.5).

2.3.5 Psychophysical responses

2.3.5.1 Thermal sensation and discomfort

Whilst clear separation was evident for the physiological strain indices between the two hotter conditions, this was not evident for either thermal sensation (Figure 2.6) or thermal discomfort (Figure 2.7). The former index is believed to be closely associated with changes

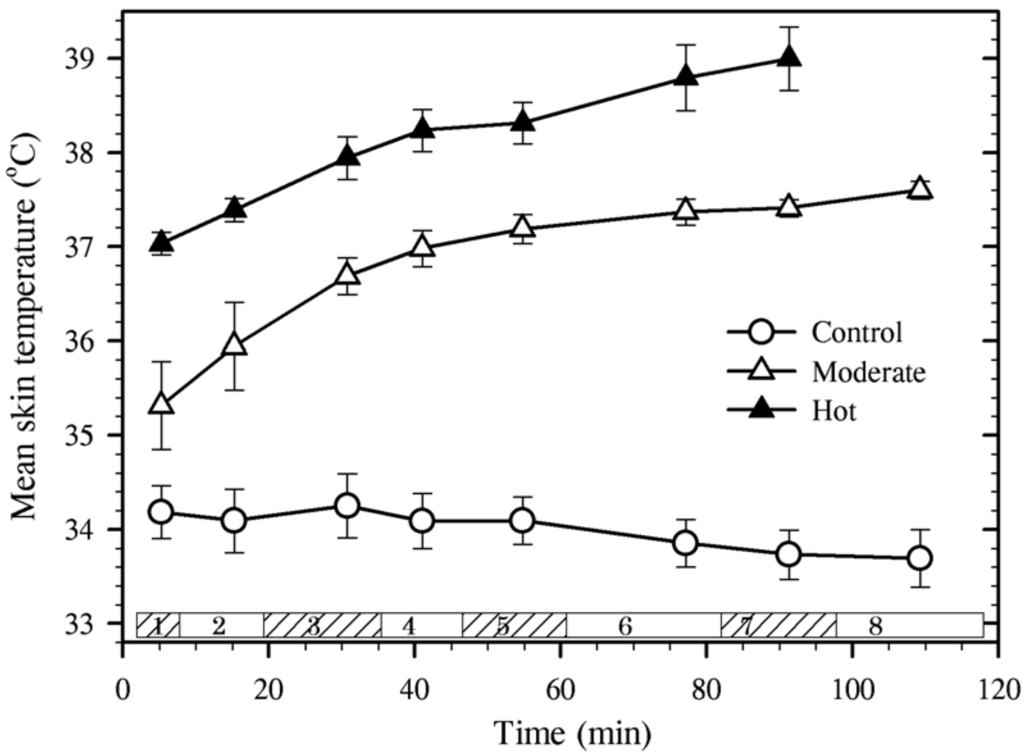

Figure 2.3: Mean skin temperatures during three, two-hour flight simulations comprised of eight flight circuits (labelled 1-8), performed under three levels of thermal strain: control (34.2°C, N=6); moderately hot (36.7°C, N=6); hot (38.1°C, N=5). Data are means with standard errors of the means from each flight circuit.

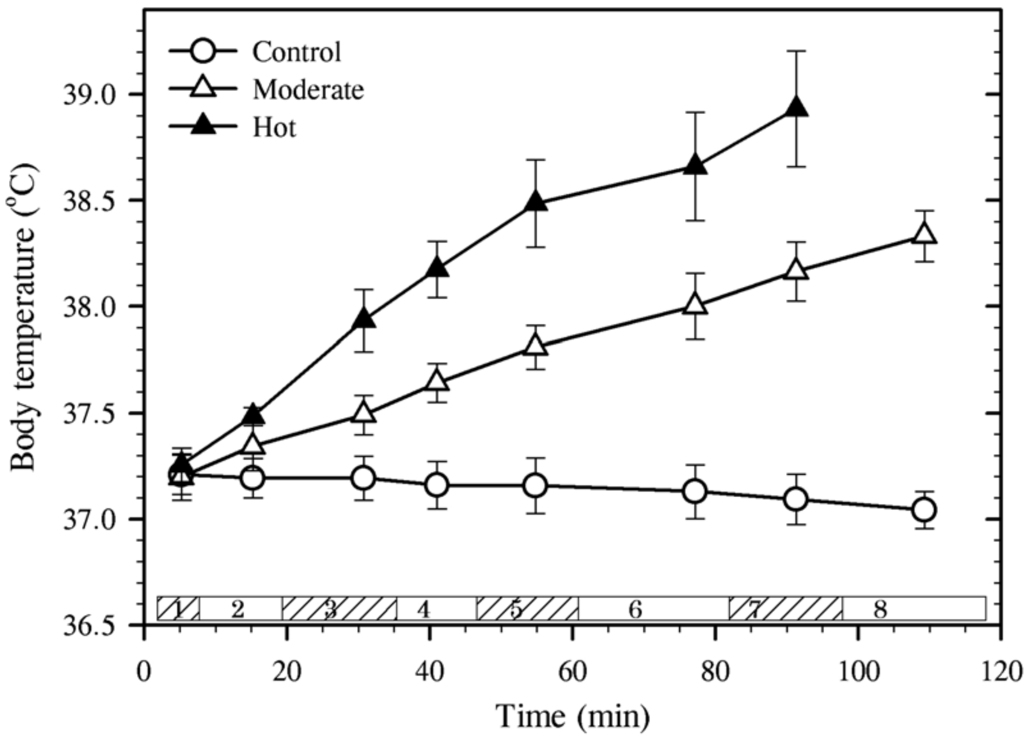

Figure 2.4: Mean body temperatures during three, two-hour flight simulations comprised of eight flight circuits (labelled 1-8), performed under three levels of thermal strain: control (34.2°C, N=6); moderately hot (36.7°C, N=6); hot (38.1°C, N=5). Data are means with standard errors of the means from each flight circuit.

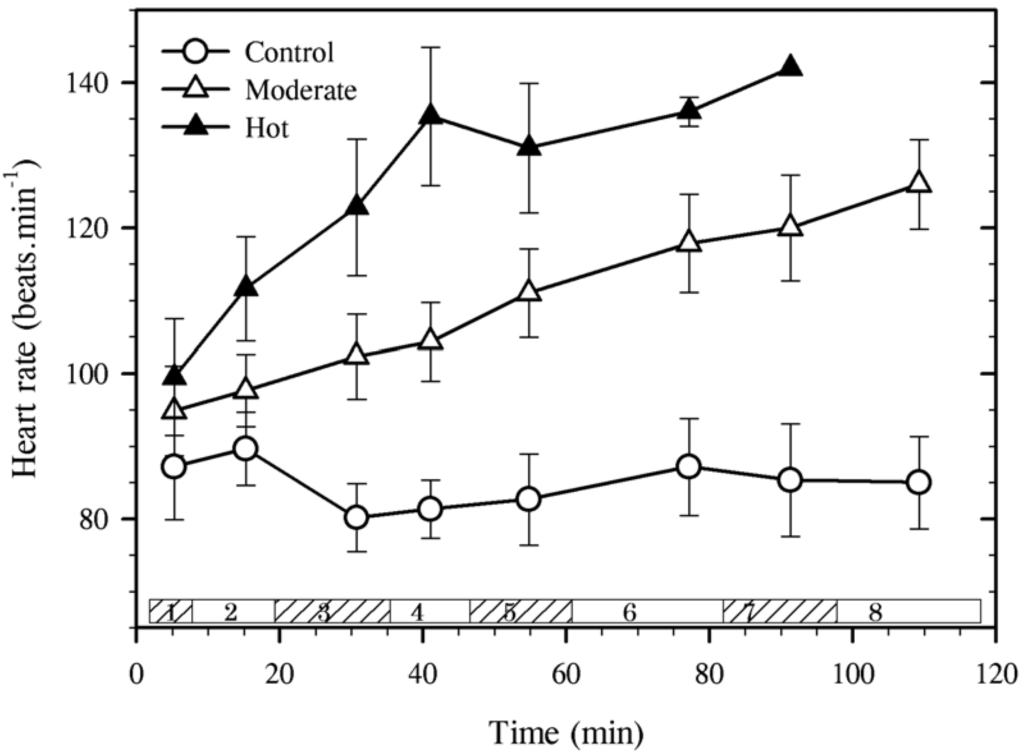

Figure 2.5: Cardiac frequencies during three, two-hour flight simulations comprised of eight flight circuits (labelled 1-8), performed under three levels of thermal strain: control (34.2°C); moderately hot (36.7°C); hot (38.1°C). Data are means with standard errors of the means from each flight circuit.

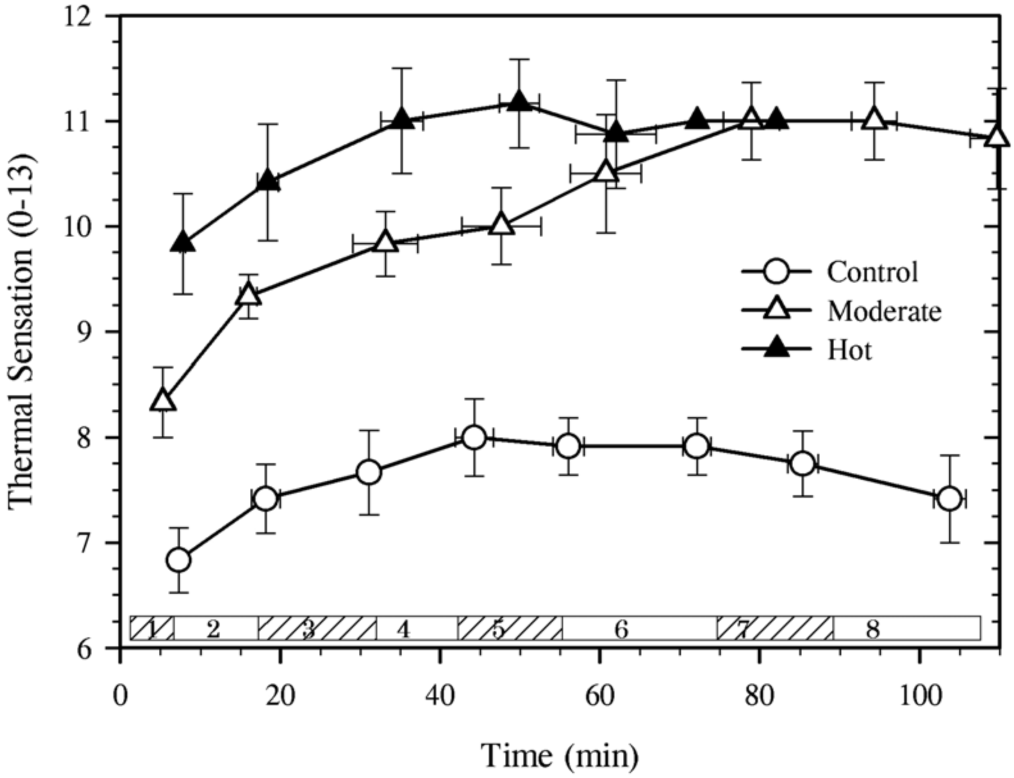

Figure 2.6: Thermal sensation (range: 0-13) during three, two-hour flight simulations comprised of eight flight circuits (labelled 1-8), performed under three levels of thermal strain: control (34.2°C); moderately hot (36.7°C); hot (38.1°C). Data are means with standard errors of the means from each flight circuit.

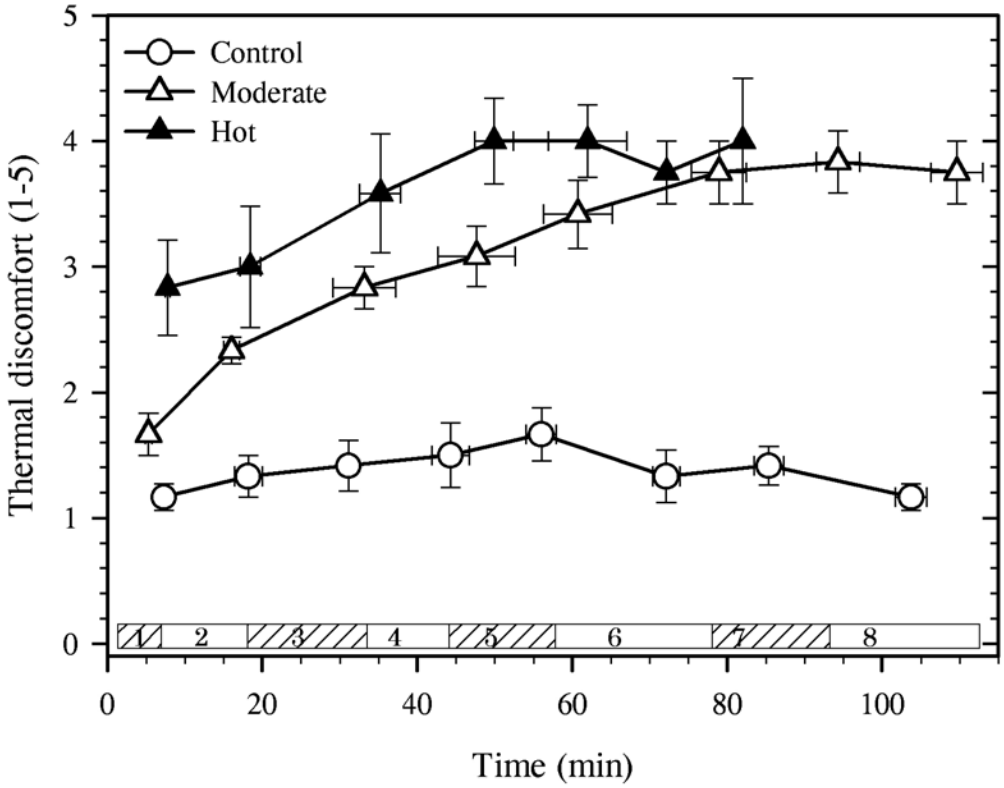

Figure 2.7: Thermal discomfort (range: 0-5) during three, two-hour flight simulations comprised of eight flight circuits (labelled 1-8), performed under three levels of thermal strain: control (34.2°C); moderately hot (36.7°C); hot (38.1°C). Data are means with standard errors of the means from each flight circuit.

uncomfortable" (discomfort vote = 4). For neither of in body temperature, while the latter is more affected by conditions at the skin surface (Hensel, 1981). For thermal sensation, at least 50% of the time during the two hot sorties was described by the pilots as being "very hot" (sensation vote = 11), while thermal discomfort was reported as "very these variables was there a significant separation of the time by treatment interactions between the hot and moderately-hot trials ($P>0.05$), though each differed significantly from the control trial ($P<0.05$). Thus, whilst the subjects could probably differentiate between the two water bath temperatures, if comparisons were made at the same time in the laboratory, their thermal sensation and discomfort votes indicated that they were unable to distinguish one treatment from the other during the different sorties.

2.3.5.2 Perceived flight performance measures

All pilots indicated that the thermal load had adverse effects upon perceived flight performance quality, such that, beyond 40 min in the hot trial, pilots indicated that the performance quality decrement ranged between "reduced" and "dramatically reduced" (Figure 2.8). The time by treatment interactions were significantly different between the two hot conditions and the control trial ($P<0.05$), but not between the two hot trials ($P>0.05$). At no time did thermal loading enhance performance quality or effort perception. In parallel with this change, pilots also reported that a greater ("moderate" to "considerable") effort was required to sustain the desired performance quality (Figure 2.9), with significant interactions between the hot and control trials ($P<0.05$), but not between the two hot trials ($P>0.05$).

Two generalisations are evident from these data. First, both hot conditions resulted in equivalent decrements in perceived flight performance quality and elevations in the amount of effort needed to support that quality. Second, these points were reached much faster during the hotter trials. Taken collectively, these trends have significant operational implications when pilots are required to direct attention to many different tasks.

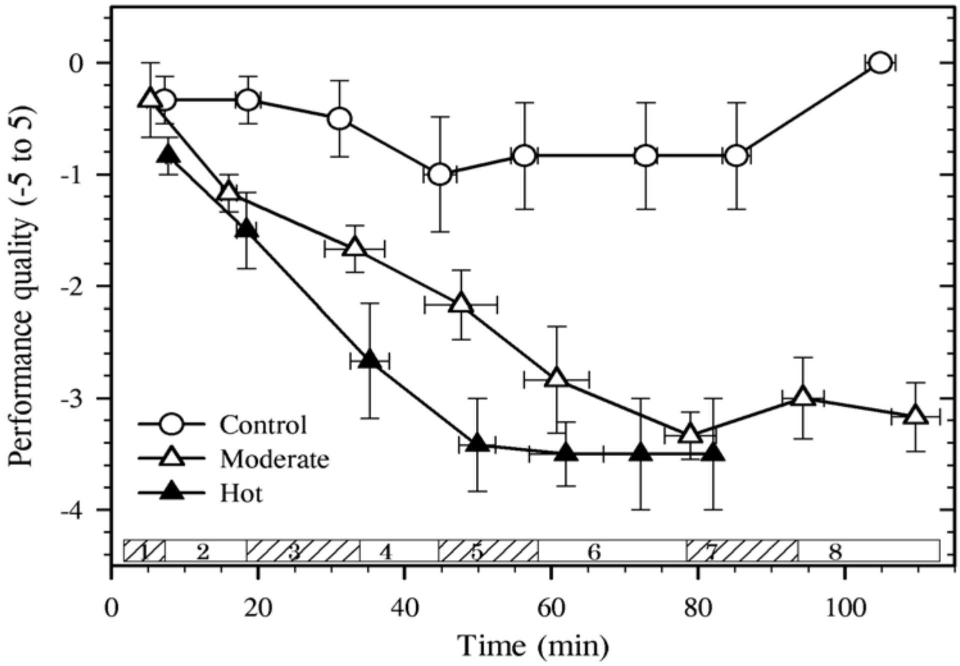

Figure 2.8: Flight simulator perceived performance quality (range: -5 to +5) during three, two-hour flight simulations comprised of eight flight circuits (labelled 1-8), performed under three levels of thermal strain: control (34.2°C); moderately hot (36.7°C); hot (38.1°C). Data are means with standard errors of the means from each flight circuit.

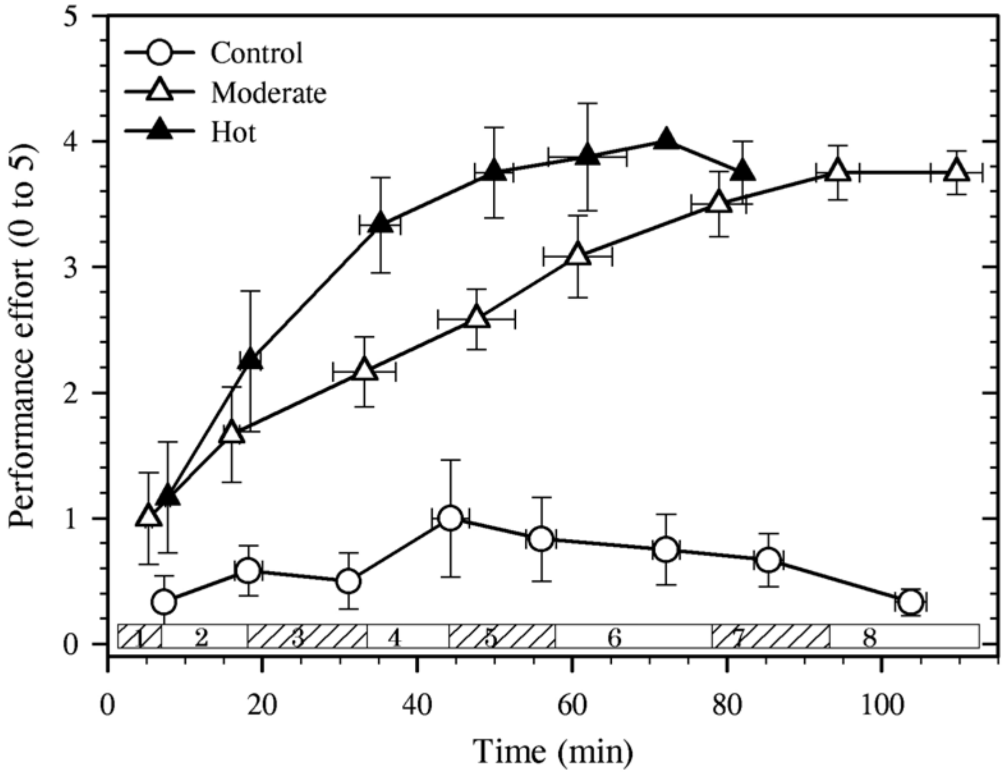

Figure 2.9: Flight simulator perceived performance effort (range: 0-5) during three, two-hour flight simulations comprised of eight flight circuits (labelled 1-8), performed under three levels of thermal strain: control (34.2°C); moderately hot (36.7°C); hot (38.1°C). Data are means with standard errors of the means from each flight circuit.

2.3.6 Independent flight performance scores

During each sortie, the simulator training officer (blind to the treatment order) rated the performance of each pilot as the operational problems were identified and solved. This procedure is a routine practise during flight simulator training, and the performance scores are summarised in Figure 2.10. The hot treatment resulted in a significantly reduced flight performance score, relative to the control state ($P<0.05$). Performance appeared to be unaffected by the moderately-hot condition ($P>0.05$). Thus, the thermal load not only had a significant impact upon the pilots' perception of their own performance, and perceived effort to sustain performance, but significant performance decrements were apparent to an experienced flight officer.

2.3.7 Inter-relationships between physiological and psychophysical responses

The relationship between each of the subjective flight performance assessments (effort, quality and score) and the thermal strain (core, skin and mean body temperature) were investigated. The strongest correlation was found between the flight performance effort and mean body temperature (Figure 2.11), where more than 70% of the variance in perceived performance effort could be explained on the basis of changes in mean body temperature (Table 2.5). Since skin temperatures were essentially clamped beyond 40 min, this relationship is assumed to have been driven by changes in core temperature. This relationship was also strong between perceived performance quality and mean body temperature (Figure 2.12, Table 2.5), with the latter accounting for more than 65% of the former. However, the relationship with flight performance score, as independently assessed, was very weak (Table 2.5).

2.4 Discussion

2.4.1 Evaluation of the thermal stimulus

The focus of this project was upon the impact of thermal loading on simulated helicopter flight performance. To evaluate this, high, but realistic, mean skin temperatures that might be encountered during mid-summer operations in a hot-dry climate, with a full solar load were used. From preliminary trials, it was determined that three experimental conditions would be evaluated, representing the typical mean skin temperature observed during

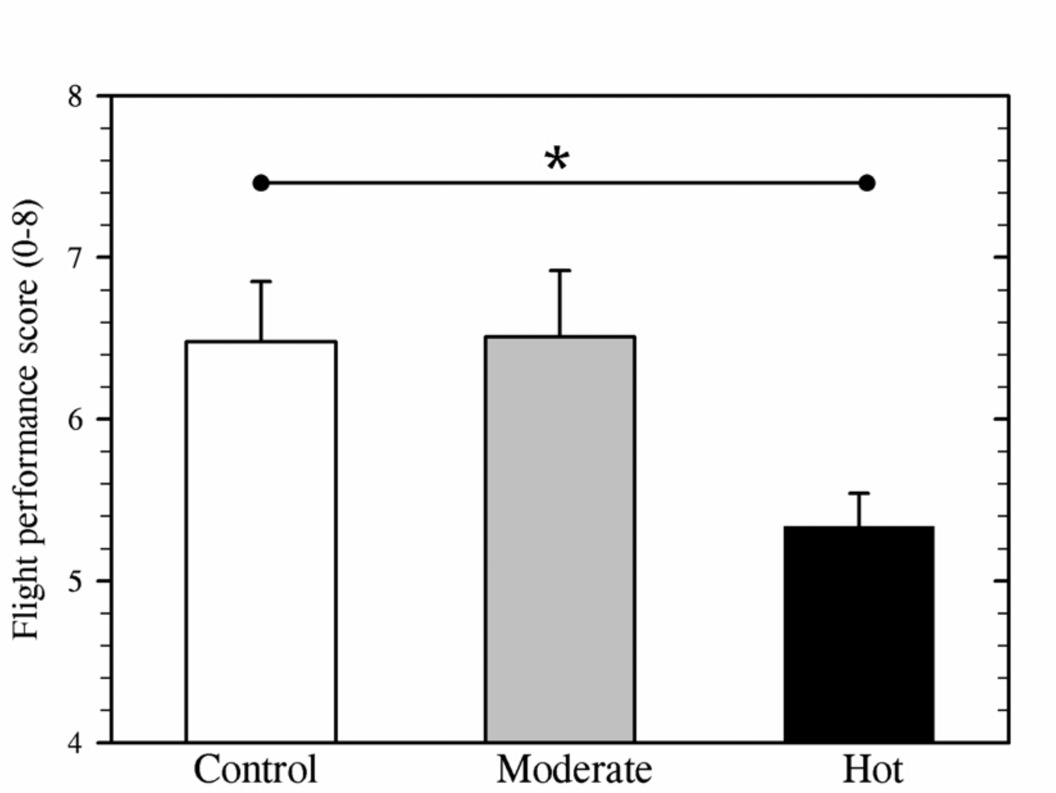

Figure 2.10: Flight simulator performance ratings (scores ranged: 0-8) as evaluated by an independent flight simulator training officer (26 y as flight instructor), during three, two-hour flight simulations comprised of eight flight circuits (labelled 1-8), performed under three levels of thermal strain: control (34.2°C); moderately hot (36.7°C); hot (38.1°C). Data are means with standard errors of the means from each flight circuit.

Table 2.5: Overall correlation coefficients for perceived performance quality and effort, and overall flight performance scores (assessed by flight officer) during three flight simulations. Data were analysed across three treatment skin temperatures: control (34.2°C); moderately hot (36.7°C); hot (38.1°C).

Physiological variable	Performance quality	Performance effort	Performance score
Mean skin temperature	-0.78	0.8	-0.29
Core temperature	-0.71	0.75	-0.1
Mean body temperature	-0.81	0.85	-0.2

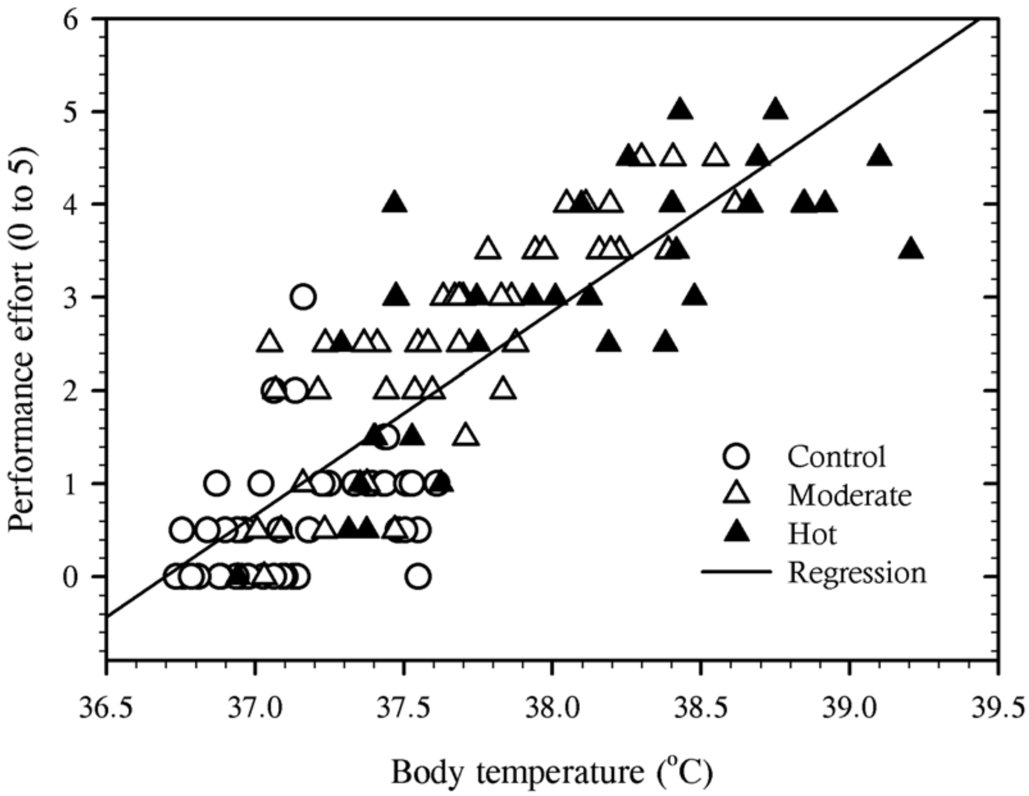

Figure 2.11: The correlation between perceived flight performance effort and mean body temperature during three, two-hour flight simulations, performed under three levels of thermal strain: control (34.2°C); moderately hot (36.7°C); hot (38.1°C).

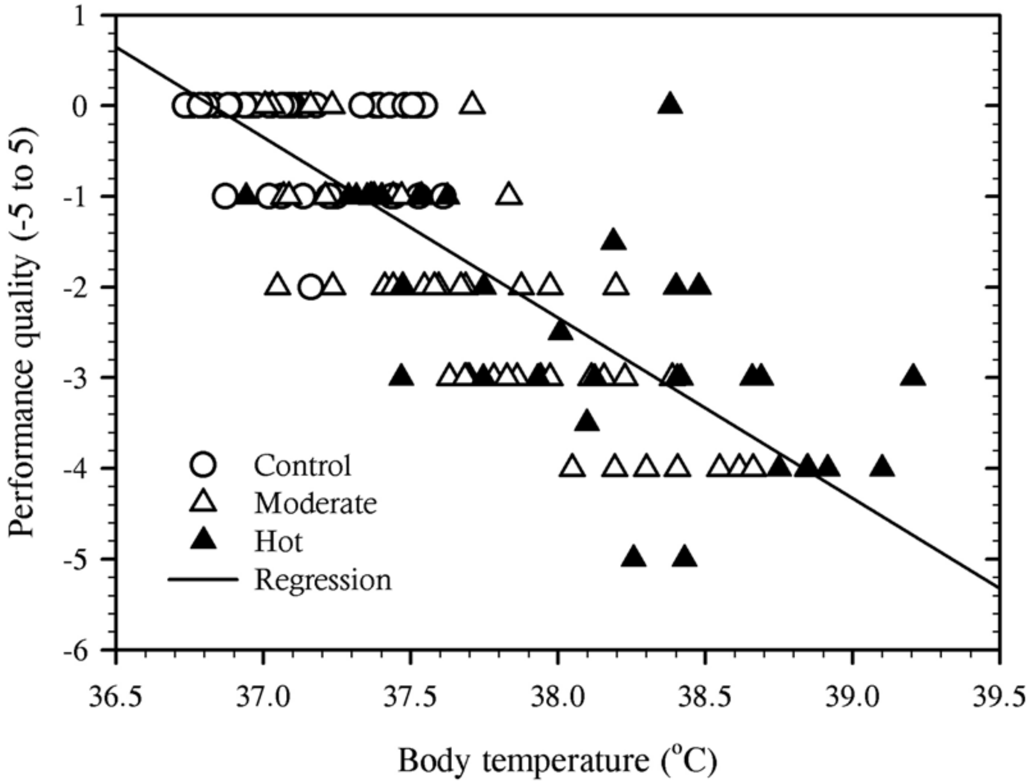

Figure 2.12: The correlation between perceived flight performance quality and mean body temperature during three, two-hour flight simulations, performed under three levels of thermal strain: control (34.2°C); moderately hot (36.7°C); hot (38.1°C).

thermoneutral rest (33°C: control), a realistically-hot state (37°C: ~2°C less than steady-state peak recorded during this testing) and an extreme, but not unrealistically-hot state (39°C).

However, the comparisons between the moderately-hot and hot sorties for mean skin temperature did not differ significantly. This was possibly due to differences in perfusion suit fit across the subjects. While attainment of steady state was not achieved, and was not an unexpected trend, there was no attempt to prevent its occurrence. Therefore it is worth more serious consideration in the design for future trials of this nature. Indeed, it may be likely to impact upon the changes in both physiological and cognitive function, since it takes about 40-50 min for a steady-state mean skin temperature to be approximated.

Although differences between the moderately-hot and hot sorites were not observed for the skin temperature measurements, tolerance times were affected and the reduction in tolerance time to the hot sortie was not surprising. Thornton and Caldwell (1993) and Reardon *et al.* (1998) similarly reported reduced flight simulator durations for subjects wearing NBC clothing in the heat.

Whilst clear, between-trial separations were evident for physiological strain, this trend was not apparent for the flight simulator performance indices (required effort, perceived performance quality or performance score). The time by treatment interactions for both the hot and moderately-hot trials differed significantly from the control trial, but not from one another. However, the hot treatment resulted in a significantly reduced flight performance score. Consequently, the thermal load not only had a significant impact upon perceived performance quality, and the effort to sustain performance, but significant performance decrements were apparent to an experienced flight officer.

2.5 Conclusion

The current investigation involved an evaluation of the interaction of thermal loading of helicopter pilots on subsequent physiological and flight performance. It was hypothesised that elevations in body heat content, as reflected by skin, core and mean body temperatures, would degrade flight performance. This was tested using six Royal Australian Navy (RAN) helicopter pilots, who completed three, two-hour flight simulations (Sea King simulator) under three levels of external thermal strain, with skin temperature elevated and clamped to produces the three different treatment states: control, moderately-hot and hot.

From the physiological observations, four general conclusions may be drawn:

- three significantly different target skin temperatures were achieved for the control (34.2°C), moderately-hot (36.7°C) and hot treatments (38.1°C);
- the application of external heat elicited significantly different states of thermal strain, with respective terminal core temperatures averaging: 37.4°C, 38.4°C and 38.8°C;
- three divergent mean body temperature responses were evident, confirming that pilots were exposed to three significantly different states of thermal strain; and
- this thermal strain was reflected in the terminal heart rates, which represented 45% (control), 67% and 78% (hot) of the age-predicted maximal heart rates for these pilots at the end of the flight simulations.

Taken collectively, these observations lead us to accept the working hypothesis. Furthermore, these data appear to have significant operational implications, since, when pilots are required to direct attention to many tasks, slight changes in the physiological or cognitive function of pilots can have a catastrophic impact upon personnel, equipment and operational capability. Whilst these observations do not identify the possible sources of flight performance decrement, they do highlight the need for the ADF to consider the use of auxiliary cooling systems for helicopter pilots during deployment in hot climates.

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CHAPTER 3: THE THERMAL CONSEQUENCES OF WEARING BODY ARMOUR DURING EXTENDED EXERCISE IN THE HEAT

3.1 Introduction

It is well documented that individuals working in hot environments experience an increase in body core temperature due to metabolic (endogenous) and external heat sources. This elevation can be restricted to a safe and manageable level if physiological heat loss mechanisms (sweating and skin blood flow) can be sustained, allowing for dissipation of heat to the external environment. When evaporation of sweat on the skin surface is impeded by the addition of clothing and protective equipment, the risk of exertional heat stress is greatly increased. The combination of increased metabolic heat production, and reduced heat dissipation, will eventually lead to an elevation in core temperature and progressive dehydration, resulting in a degradation of both physical and cognitive performance, and ultimately exertional heat illness.

Heat is produced as a by-product of metabolism, where stored chemical energy is liberated to fuel daily activities. This process is very inefficient, with approximately 80% of the energy conversion being lost as heat. This heat is removed from the body by dry and evaporative pathways, mediated by increases in cutaneous blood flow and sweat secretion. Heat reaching the skin surface can be transferred to the surrounding external environment by conduction, radiation and convection, but only if the immediate environment is cooler than the skin (<31-33°C). That is, since heat flows down a thermal gradient (from warmer to cooler regions), tropical environments will impede dry heat loss. Thus, as the external temperature rises, heat loss will progressively become more reliant upon the evaporation of sweat. However, this process is dependent upon the water vapour pressure gradient between the skin and the external environment, and physical barriers to evaporation. One impediment to evaporation is created by clothing, regardless of its moisture permeability.

When clothing is added, evaporation at the skin surface will be reduced. The extent of this reduction is a function of the properties of the fabric that is used to manufacture the clothing, with less permeable fabrics permitting less water vapour movement through a garment. Water can move through a fabric in the form of water droplets (wicking) or as water vapour. Water vapour can pass through holes (pores) within the fabric. Some fabrics are designed to allow water vapour, but not water droplets, to pass through, while other garments are designed to protect the user from chemical, biological and nuclear agents; these are totally encapsulating and totally impermeable to water. Therefore, once the water vapour pressure of the micro-environment (space between the skin and clothing) becomes saturated, evaporation ceases and sweating is ineffective. Sweat now accumulates within the clothing layers. Since the insulating power of air is about 2800 times greater than that of water, then water absorption into the fabric displaces air, and garment insulation is dramatically reduced. Thus, moisture reduces clothing insulation in proportion to the volume of air that it displaces from the garment. This added moisture will make the clothing uncomfortable to wear and, at the feet, it leads to the formation of blisters.

Excessive heat storage, due to the combination of reduced heat loss and increased metabolic heat production, will lead to fatigue and decreased tolerance time (Ramsey, 1975). This increase in heat storage will not only have detrimental effects on physiological function, but may also adversely impact upon cognitive performance (Ramsey and Morrissey, 1995; Caldwell *et al.,* 1997).

To gain a better understanding of the heat stresses imposed on an individual by the environmental conditions, and to reduce the incidence of heat illness during military training, the wet bulb globe temperature (WBGT) index was developed by Yagloglou and Minard (1957). General use of the WBGT index was recommended by the Occupational Safety and Health Administration (1974), and subsequently adopted by the International Standards Organisation for quantifying thermal stress (ISO 7243:1982), the National Institute for Occupational Safety and Health (1986), and the American College of Sports Medicine (1996). The index is currently used by the Australian Defence Force (ADF) to evaluate the severity of environmental conditions.

Notwithstanding the almost ubiquitous adoption of the WBGT index, several studies have identified significant limitations of this method; these are summarised below for completeness. First, the index tends to over-emphasise the effects of dry bulb temperature towards the top end of the scale (Belding, 1970). Second, it does not adequately consider air velocity under hot-humid conditions (Belding, 1970), and is insensitive to this affect once air velocity exceeds 1.5 $m.s^{-1}$ (Azer and Hsu, 1977), yet this can have a significant impact upon heat dissipation. Third, the index lacks the capacity to accommodate different rates of metabolic heat production (Belding, 1970; Wenzel, 1978; Wenzel *et al.*, 1989), or variations in skin temperature or skin wettedness (Azer and Hsu, 1977). Wenzel (1978) demonstrated that the physiological influence of air humidity, at a fixed air temperature, was elevated when metabolic rate was increased. Fourth, Wenzel *et al.* (1989) found that body mass loss (gross sweating) was not independent of climatic conditions, and it invariably diverged from the changes in core temperature and heart rate. That is, physiological responses varied within and among climatic conditions, such that conditions that elicited equivalent mass losses did not simultaneously evoke predictable changes in core temperature and heart rate. Fifth, the usefulness of the WBGT index for clothed workers is questionable, ranging between inferior (Lotens and van Middendorp, 1986) to wholly inappropriate (encapsulation: Goldman, 1994).

At present, the ADF follows standard work-rest guidelines when operating under more stressful environments. These guidelines are based upon the WBGT index, and are designed to reduce the risk of exertional heat illness by reducing metabolic heat production when wearing standard military clothing. When clothing changes from this standard, these guidelines are modified. For instance, when clothing of greater insulation is used (*e.g.* nuclear, biological and chemical clothing), or when heavier garments are worn (*e.g.* helmets and body armour), rest periods are lengthened and work periods are shortened. While some adjustment factors have previously been determined (Kenny, 1987; Bernard *et al.*, 2004), there is a paucity of experimental data upon which such modifications may be based, and two possible adverse outcomes may exist. First, the risk of exertional heat illness may be increased if thermal strain is under-estimated. Second, operational capability will be compromised if thermal strain is over-estimated.

Elevations in body temperature can impair both physical and cognitive performance. For military workers, these elevations in body core temperature can be from radiant heat from the sun, or from metabolic heat produced during work. With the addition of protective clothing, heat gains within the individual are exacerbated. For an individual required to wear combat armour, the possibility of heat strain is elevated. For example, Majumdar *et al.* (1997) found that body armour, when worn during work in hot-humid environments, significantly increases physiological strain, as reflected by an increased in heart rate and skin temperatures. Previously, Haisman and Goldman (1974) investigated the effects of exercise and different combinations of body armour under two hot environments (35°C, 70% relative humidity, and 47°C, 21% relative humidity). Based on their experimental observations, a mathematical model was developed for predicting thermal strain, as reflected by changes in core temperature and heart rate, when wearing protective clothing, and performing work in warm-to-hot environments. Further predictive models have been used to show that wearing combat armour can potentially change a compensable environment to an uncompensable heat stress (Goldman, 2001). Based upon this method, the ADF has recommended that a further 2.8°C should be added to the measured environmental conditions to enable the prediction of the appropriate work and rest durations.

However, the affects of combat body armour on physical work capacity, and physiological and cognitive function remain largely unexplored. Although some experimental data are available, and predictive models have been developed to enable the prescription of work schedules, these models lack the precision, detail and climatic diversity required by the ADF. This study aims to initiate the provision of these data.

3.1.1 Aims of the Study

The principal aim of this project was to provide advice to the ADF on the risks of exertional heat illness when an individual is required to wear combat body armour in environments typical of the northern Australian summer. To achieve this aim, we investigated the effects of the combat body armour upon physiological, psychophysical and cognitive function. This was achieved by exposing volunteer subjects to hot-wet conditions, whilst performing 'very light' and 'light' work intensities. Furthermore, we explored the additional thermal impact of wearing a combat helmet.

3.2 Methods

3.2.1 Subjects

Ten physically-active males volunteered to commence this project, following the provision of written, informed consent. All procedures were approved by the Human Research Ethics Committee (University of Wollongong). However, due to an incomplete data set for one subject, data from only nine subjects (Table 3.1) were used for this report.

3.2.2 Experimental conditions

Volunteer subjects completed three trials in a hot-humid environment (36°C, 60% relative humidity) with a substantial radiant heat source (infra-red lamps ~750 $W.m^{-2}$: solar heat is typically ~800 $W.m^{-2}$).

3.2.3 Experimental procedures

Within each trial, subjects completed work at two different intensities: treadmill walking to simulate urban patrol activities. For the first 1.5 h, subjects walked at a very light intensity (2 $km.hr^{-1}$ (7.2 $m.s^{-1}$)), followed by a further 1 h of work at a light intensity (4 $km.hr^{-1}$ (14.4 $m.s^{-1}$)). A large-diameter fan was used to simulate natural airflow during walking, and was set to produce wind speeds equivalent to the target walking speeds. The three trials differed only through the clothing and equipment that was worn:

1. disruptive pattern (camouflage) combat uniform (all clothing: **2.05** ±0.02 kg; insulation 0.29 $m^2K.W^{-1}$),
2. disruptive pattern combat uniform plus combat body armour (6.07 ±0.07

kg; Hellweg, Australia; total mass **8.12 kg**); and

3. disruptive pattern combat uniform, combat body armour and combat helmet (1.29 kg; Rabintex Industries Pty. Ltd., Australia; total mass **9.41 kg**).

To minimise order effects, subjects performed trials in a balanced order, determined using a Latin square. Physiological data were collected continuously, while psychophysical and cognitive function data were collected intermittently (Table 3.2).

3.2.3.1 Experimental standardisation

Subjects were required to refrain from strenuous exercise and consumption of alcohol and tobacco during the 12 h prior to each trial. For the night prior to each trial, subjects were instructed to drink 15 $ml.kg^{-1}$ of additional water before retiring, and to eat an evening meal and breakfast high in carbohydrate and low in fat. Subjects also refrained from using caffeine for 2 h prior to each trial. On arrival at the laboratory, subjects were provided with supplementary drinking water (500 ml). During each trial, subjects consumed 500 ml of water (at chamber temperature) every 30 min. Before leaving the laboratory, subjects were rehydrated, consuming an iso-osmotic drink equivalent to 150% of the body mass change (100% in the laboratory and 50% taken away).

3.2.4 Data collection procedures

Physiological and cognitive-function measures included: body core and skin temperatures, heart rate, whole-body sweat and evaporation rates, psychophysical responses and six cognitive-function indices. The cognitive-function measures were included within the current experiment to trial these procedures during an exercising heat stress, since they are to be used also in Chapter 5. subsequent collaborative project with the ADF (Caldwell, 2006). The methods used will be described in detail, but these indices will not be covered in detail within the results or discussion.

Table 3.1: Subject characteristics

Subject	Age (y)	Height (m)	Mass (kg)
S1	24	184.5	74.76
S2	38	185	85.42
S3	28	172.5	77.02
S4	29	182.5	57.62
S5	26	182.3	93.62
S6	21	179.8	72.64
S7	33	185.6	91.46
S8	25	172.2	74.12
S9	22	178	87.78
Mean	27.33	180.27	79.38
S.D.	5.43	5.11	11.34

Table 3.2: Experimental timeline.

Time (min)	Activity summary
0	Subject arrival
38472	Subject hydration check
38491	1^{st} set of cognitive function tests
20-60	Subject preparation (22°C), 500 ml water consumed
60-65	Thermoneutral baseline data collection
65	Enter climate chamber (36°C, 60% RH)
65-70	Don military clothing
70-84	Commence first work (very light) intensity
84	Psychophysical questionnaires
85-99	2^{nd} set of cognitive function tests
99	Psychophysical questionnaires
100-114	500 ml water consumed
114	Psychophysical questionnaires
115-129	3^{rd} set of cognitive function tests
129	Psychophysical questionnaires
130-144	500 ml water consumed
144	Psychophysical questionnaires
145-159	4^{th} set of cognitive function tests
159	Psychophysical questionnaires
160	Commence second work (light) intensity
160-174	500 ml water consumed
174	Psychophysical questionnaires
175-189	5^{th} set of cognitive function tests
189	Psychophysical questionnaires
190-204	500 ml water consumed
204	Psychophysical questionnaires

Time (min)	Activity summary
205-219	6th set of cognitive function tests
220	Psychophysical questionnaires
220-235	Terminate experiment: supervised recovery

3.2.4.1 Physiological measurements

Auditory canal temperature

Auditory canal temperatures (T_{au}) were measured using an ear moulded plug, with a thermistor protruding 1 cm from the mould (Edale Instruments Ltd, U.K.). A large piece of cotton wool was secured over the ear to minimise the effect of the environment temperature. Data was recorded throughout each trial at 0.2 Hz using a portable data logger (Grant Instruments Ltd., 1206 Series Squirrel, U.K.). This measure was taken to be the primary index of core temperature.

Rectal temperature

Rectal temperature (T_{re}) was also measured (Edale Instruments Ltd, U.K.) continuously (0.2 Hz), at a depth of 12 cm beyond the anal sphincter. This measure was used only as a back-up index to auditory canal temperature.

Skin temperatures

Skin temperatures were measured (0.2 Hz) using thermistors taped to eight skin sites (Type EU, Yellow Springs Instruments Co. Ltd., Yellow Springs, OH, USA). These sites were: right scapula, right chest, right upper arm, left forearm, left dorsal hand, right anterior thigh and left posterior calf (International Standards Organisation, 1992). Mean skin temperature ($\overline{T}_{sk}$) was derived using standard skin surface area weightings (International Standards Organisation, 1992):

$$\overline{T}_{sk} = 0.07 \cdot T_{sk\text{-}1} + 0.175 \cdot T_{sk\text{-}2} + 0.175 \cdot T_{sk\text{-}3} + 0.07 \cdot T_{sk\text{-}4} + 0.07 \cdot T_{sk\text{-}5} + 0.05 \cdot T_{sk\text{-}6} + 0.19 \cdot T_{sk\text{-}7} + 0.2 \cdot T_{sk\text{-}8}$$

where:

$T_{sk\text{-}1}$ = forehead

$T_{sk\text{-}2}$ = chest

$T_{sk\text{-}3}$ = scapula

$T_{sk\text{-}4}$ = arm

$T_{sk\text{-}5}$ = forearm

$T_{sk\text{-}6}$ = hand

$T_{sk\text{-}7}$ = thigh

$T_{sk\text{-}8}$ = calf.

Mean body temperature

Mean body temperature ($\overline{T}_b$) was determined from the weighted summation of auditory canal (T_{au}) and skin temperature ($\overline{T}_{sk}$) using the following equation (Vallerand *et al.*, 1992):

$$\overline{T}_b = 0.9\ T_{au} + 0.1\ \overline{T}_{sk} \quad [°C]$$

Thermistor calibration

All thermistors were calibrated before testing. Probes were placed in a 38-litre water bath (Grant, U.K.) with a National Association of Testing Authorities certified thermometer (Dobbie Instruments, Dobros total immersion, Australia). Thermistors used to record skin temperature were calibrated over a range 21-46°C, in 2°C increments, with calibration data recorded after the temperature had stabilised for 5 min. The core temperature thermistors were calibrated over the range 30-40°C. Linear calibration equations were derived for each thermistor, using the recorded thermistor data and known temperatures from the certified thermometer ($r > 0.99$). Raw thermistor data were corrected using these calibration coefficients.

Cardiac frequency

Cardiac frequency was monitored from ventricular depolarisation throughout each trial (0.2 Hz; Polar Electro Sports Tester, Finland).

Whole-body sweat rate

Gross mass changes, minus sweat retained within the clothing and body armour, were used determine sweating and evaporation rates. Mass changes were recorded at the completion of each trial, and following complete drying of the subject (fw-150k, A&D scale).

3.2.4.2 Psychophysical measures

Subjects were asked, at 15-min intervals, to rate perceived work effort (exertion), thermal sensation, thermal discomfort, perceived skin wetness and skin wetness discomfort. Subjects were provided with the relevant subjective scales prior to the start of each trial, and with written and oral instruction on how to use each scale.

Perceived exertion

Perceived exertion was evaluated using the 15-point Borg scale (Borg, 1962), and in response to the question: "How hard are you exercising?".

Please see print copy for scale

Thermal sensation

Thermal sensation was monitored using a modified version of the Gagge scale (Gagge *et al.*, 1967). The question: "How does the temperature of your whole body feel?":

13-point thermal sensation scale

1	Unbearably cold
2	Extremely cold
3	Very cold
4	Cold
5	Cool
6	Slightly cool
7	Neutral

8	Slightly warm
9	Warm
10	Hot
11	Very hot
12	Extremely hot
13	Unbearably hot

Thermal discomfort

Thermal discomfort was evaluated using another modified scale (Gagge *et al.*, 1967), and in response to the question: "How does the temperature of your body feel?".

The 5-point thermal discomfort scale

1.0	Comfortable
1.5	
2.0	Slightly uncomfortable
2.5	
3.0	Uncomfortable
3.5	
4.0	Very uncomfortable
4.5	
5.0	Extremely uncomfortable

Perceived skin wetness

Perceived skin wetness was evaluated using a modification of the 13-point thermal sensation scale, and in response to the question: "How wet or moist does your skin (clothing) feel?".

13-point wetness sensation scale

1	Unbearably dry
2	Extremely dry
3	Very dry
4	Dry
5	Slightly dry
6	Very slightly dry

7	Neutral
8	Slightly moist
9	Moist
10	Wet
11	Very wet
12	Extremely wet
13	Totally saturated

Perceived skin wetness discomfort

Perceived skin wetness discomfort was evaluated using a modification of the 5-point Gagge thermal discomfort scale (Gagge *et al.*, 1967), by responsing to the question: "How comfortable are you with the wetness of your skin (clothing)?".

The 5-point skin wetness discomfort scale

1.0	Comfortable
1.5	
2.0	Slightly uncomfortable
2.5	
3.0	Uncomfortable
3.5	
4.0	Very uncomfortable
4.5	
5.0	Extremely uncomfortable

3.2.4.3 Cognitive-function indices

Cognitive function was evaluated using the Mini-Cog rapid assessment battery (Shephard and Kosslyn, 2005) administered by a personal digital assistant (PDA, PalmOne, Tungsten C). Subjects performed six cognitive-function tests during each trial, and following about 8-10 h of preliminary training. Training was designed to provide learning curves from which the number of trials necessary to learn each test could be determined. Accordingly, each subject performed the complete cognitive-function test battery on ten occasions prior to commencing the present trials, since it was deemed that 5-7 trials would be necessary to ensure task learning was complete. Within each of the experimental trials, the cognitive-function tests were administered at 30-min intervals. Subjects continued walking during each test administration.

Vigilance

Vigilance is the ability to concentrate for a sustained period, whilst waiting for a specific event to occur (Kruegar, 1989; Leproult *et al.*, 2003; Ballard, 2001). A series of geometric shapes (rectangles, parallelograms and trapezoids) was randomly presented (500 ms) to the subjects, followed by an inter-trial interval of 1, 2 or 3 s. The subject responded during this interval. ***The task:*** Subject was required to recognise and identify the correct (and incorrect) shapes as quickly as possible; the shape must be in the same form and orientation as the target shape. ***Test duration:*** For each administration, 90 trials were presented, lasting about 3-4 min.

Three-term reasoning

This is a classical cognitive function test (Yama, 1986) in which three simple statements are made, and the subject was required to answer whether or not the third statement was "true" or "false". ***Test duration:*** Eight trials were presented, with 45 s allotted to each response.

Filtering

This test focusses upon the ability to select relevant (important) information from a range of stimuli, such that attention is only directed to that information which is relevant to the current task. This test is a modification of the classical Stroop test (Stroop, 1935), and appears as a black and white version (numbered Stroop). ***The task:*** Subject was presented with arrays of three numbers (4, 5 or 6). The numbers were always the same within an array, but the number of digits within a presentation varied (either 4, 5 or 6 numbers). The subject had to choose how many numbers were presented by attending to the total number, and not the actual numbers being presented (*e.g.* four 5s: 5555). The subject had 10 s to respond. ***Test duration:*** 84 trials were presented, with each lasting a maximum of 10 s. This test lasted 2-3 min.

Verbal working memory

This test also evaluates the ability to recall and use information held within the working memory (two-back test: Baddeley, 1986; Flowers, 1985): digit recall. ***The task:*** Four numbers were presented to the subject (1, 2, 3, 4), each in the centre of the screen. The subject must recall whether or not the digit is the same as that presented two-back in the sequence. ***Test duration:*** 60 trials were provided, with each stimulus lasting just 1 s. The subject had only 1 s to respond (the inter-trial interval).

Divided attention

This test is part of the vigilance test battery, and requires the subject to focus upon two different (unrelated) stimuli. ***The task:*** Subjects were presented with four geometric shapes (circle, triangle, square, star) that appear in four shades (white, grey, dark grey, black). The two recognition criteria are therefore shape and shade. The subject must identify either of two states (ignoring all other information): circles or white shapes, or triangles and black shapes. ***Test duration:*** 40 trials were administered, with 10 s allowed for responding: duration 2-3 min.

Perceptual reaction time

The purpose of this test is to evaluate whether or not changes in reaction time are a function of altered cognitive or physical (motor control) states. ***The task:*** Subjects were given a stimulus (small oval) that appeared over one of four keys. The subject then responded by pressing that key as quickly as possible. ***Test duration:*** 40 trials were administered, with a 5 s inter-trial interval.

3.2.5 Statistical analyses

This project was based upon a repeated-measures experimental design, with subjects acting as their own controls, participating in all trials, and wearing each of the clothing ensembles. Between-ensemble differences were analysed using two-way, repeated measures analyses of variance, with Tukey's *HSD post hoc* procedure used to identify sources of significant differences. Paired *t*-tests were also performed. *Alpha* was set at the 0.05 level for all statistical comparisons.

3.3 Results

3.3.1 Core temperature

Statistical analysis on core temperature (calculated as the mean of T_{au} and T_{re}) data revealed no significant main effect of uniform configuration, however significant time by uniform interactions were revealed between the control and body armour trials (F=10.93, df=11/88, P<0.001), control and armour and helmet trials (F=10.93, df=11/88, P<0.001), and the armour and armour and helmet trials (F=4.64, df=11/88, P<0.001). That is, as time progressed, core temperature deviated significantly between each of these trials. These data are presented in Figure 3.1 (inset shows overall mean).

3.3.2 Skin temperatures

A significant main effect for skin temperature, between control with both uniformed trials (Figure 3.2; F=5.92, df=11/77, P<0.001) was revealed, however no significant difference between the two armoured uniforms (combat body armour with and without helmet) was found. The skin temperature response curves also revealed significant time by uniform interactions: control versus armour (F=2.09, df=11/88, P=0.0288), and control versus armour and helmet (F=6.54, df=11/88, P<0.001).

Analysis of the scapula skin temperature revealed a significant main effect of uniform at 90, 105, 120, 135 and 150 min (F=64.43, df=1/8, P<0.001). Furthermore, significant time by uniform interactions existed between the control and armour trials (F=7.95, df=11/77, P<0.001), and the control and armour with helmet trials (F=18.08, df=11/88, P<0.001). Chest skin temperature (Figure 3.3) comparisons only revealed significant interactions: control verus armour (F=5.44, df=11/88, P<0.001), control versus armour and helmet (F=20.52, df=11/88, P<0.001). Data for the arm (Figure 3.3) demonstrated less separation among the conditions, with a significant interaction for time and uniform only evident for the control and helmet trials (F=2.86, df=11/88, P=0.0030).

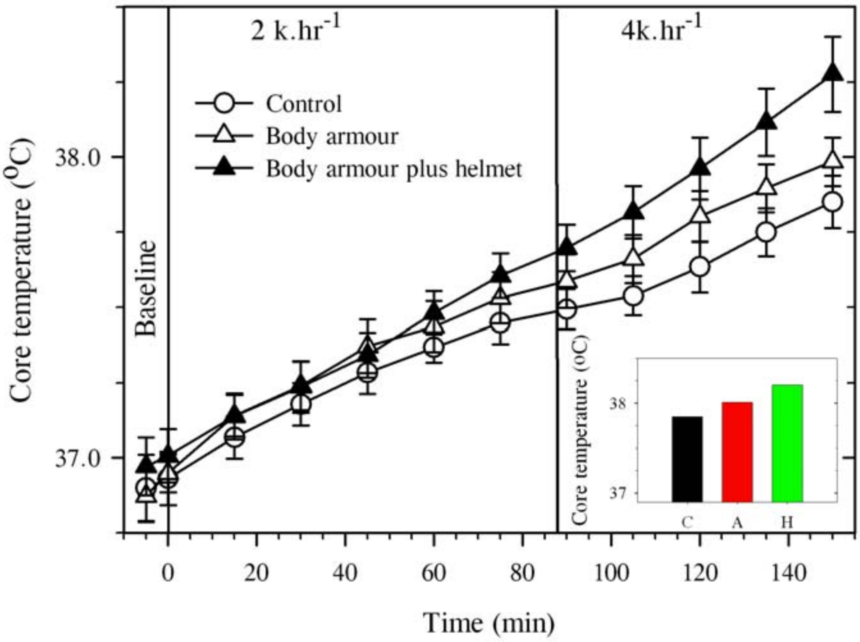

Figure 3.1: Core (auditory canal) temperature changes during steady-state walking at two speeds in a hot-humid environment (36°C, 60% relative humidity, radiant heat ~750 W.m^{-2}) with three clothing configurations: camouflage uniform (control), camouflage uniform with body armour, and camouflage uniform with armour and helmet.

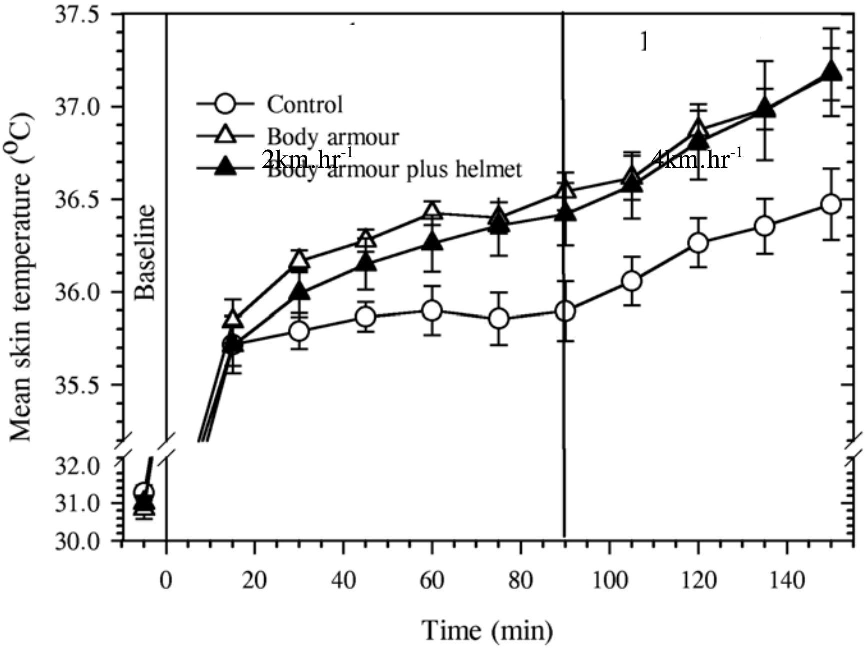

Figure 3.2: Mean skin temperatures during steady-state walking (two speeds) in a hot-humid environment (36°C, 60% relative humidity, radiant heat ~750 W.m^{-2}) with three clothing configurations: camouflage uniform (control), camouflage uniform with body armour, and camouflage uniform with armour and helmet.

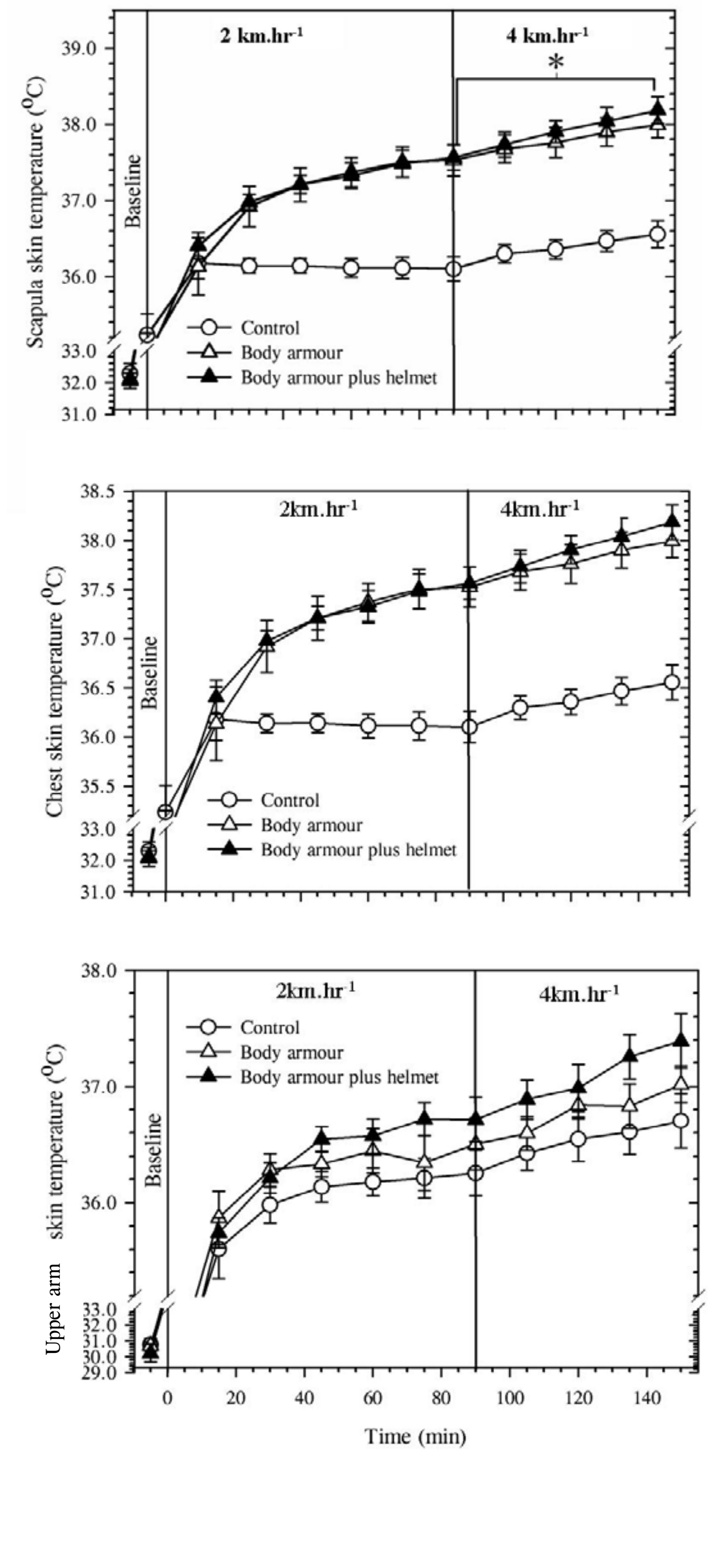

Figure 3.3: Scapular, chest and arm skin temperatures during steady-state walking at two speeds in a hot-humid environment (36°C, 60% relative humidity, radiant heat ~750 $W.m^{-2}$) with three clothing configurations: camouflage uniform (control), camouflage uniform with body armour, and camouflage uniform with armour and helmet.

3.3.3 Cardiac frequency

Analyses revealed that no significant main effect of uniform was evident for any of the uniform configurations ($P>0.05$. Figure 3.4), with the mean trial heart rates being: 100.0 $\pm$2.2 b.min^{-1} (control); 105.3 $\pm$3.6 b.min^{-1} (armour); 110.7 $\pm$2.4 b.min^{-1} (armour plus helmet). However, time by uniform interactions were again significant: control versus body armour ($F=4.27$, $df=11/88$, $P<0.001$), and control versus armour plus helmet ($F=5.24$, $df=11/88$, $P=0.0000$). That is, as time progressed each of the armoured trials differed significantly from the control trial.

3.3.4 Whole body sweat and evaporation

Subjects lost significantly more sweat during each of the two armoured states, relative to the control state (armour: $F=5.87$, $df=1/8$, $P=0.0417$; armour plus helmet: $F=6.91$, $df=1/88$, $P=0.0302$), with significant uniform affects also apparent for evaporation (armour: $F=62.99$, $df=1/8$, $P<0.001$; armour plus helmet: $F=170.84$, $df=1/8$, $P<0.001$). Differences between the two armoured states were not significant ($P>0.05$). These changes are illustrated in Table 3.3 and Figure 3.5. In each of the two armoured trials, significantly more sweat was retained within the clothing relative to the control state ($F=11.20$, $df=1/8$, $P=0.0101$), and evaporation was also less (Table 3.3).

3.3.5 Psycholphysical indices

Effort sense showed a significant main effect of uniform was present for the comparison of the control and armour with helmet trials at 120, 135, and 150 min ($F=8.59$, $df=1/8$, $P=0.0190$, Figure 3.6); a significant time by uniform interaction was also apparent between these trials ($F=2.58$, $df=9/72$, $P=0.0123$). Thermal sensation, thermal discomfort, perceived skin wetness and skin wetness discomfort data are presented in Figure 3.7. While the response curves from the armour with helmet condition invariably fell above those for the other trials, indicating stronger sensation and discomfort, the between-trial differences were generally not significant ($P>0.05$). A time by uniform interactions was evident for the comparison between the control and armour and helmet states for thermal sensation ($F=2.57$, $df=10/88$, $P=0.0094$).

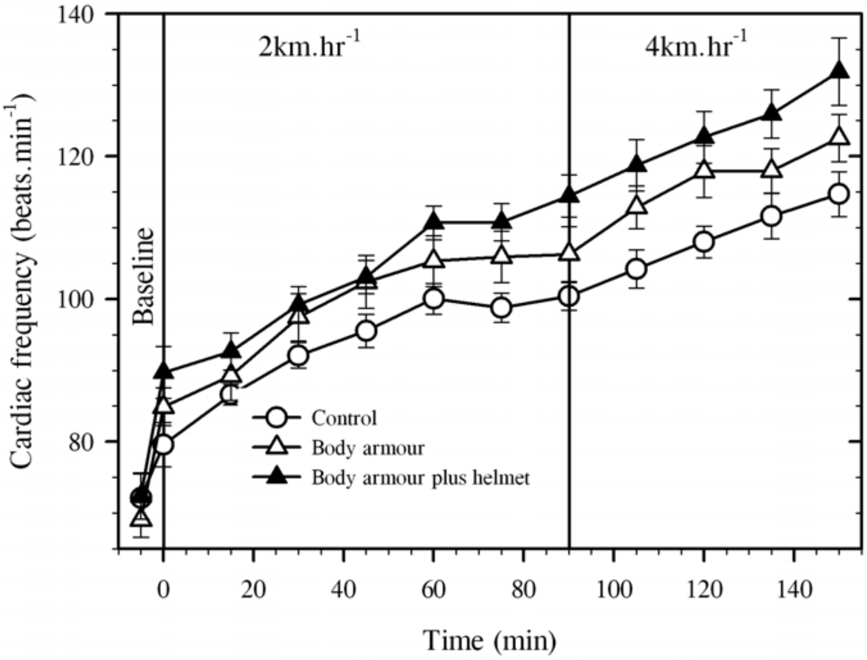

Figure 3.4: Cardiac frequency during steady-state walking (two speeds) in a hot-humid environment (36°C, 60% relative humidity, radiant heat ~750 $W.m^{-2}$) with three clothing configurations: camouflage uniform (control), camouflage uniform with body armour, and camouflage uniform with armour and helmet.

3.3.6 Cognitive function

The cognitive-function data are presented in Figure 3.8. However, none of the function tests revealed either significant main effects (time or uniform) or time by uniform interactions ($P > 0.05$). These data are illustrated (in part) in Figure 3.8.

Table 3.3: Body mass changes during steady-state walking in a hot-humid environment with three clothing configurations: camouflage uniform (control), uniform with body armour, and uniform with armour and helmet. Data show mean mass changes, with relative changes in clothing and armours masses, and mass loss due to evaporation.

	Control	Armour	Helmet
Body mass change (kg)	-1.32	-1.72*	-1.74*
Clothing mass change (%)	21.9%	25.6%*	27.2%*
Armour mass change (%)	0	12.8%	9.5%
Head wear mass change (%)	0	0	1.2%
Fractional evaporation (%)	78.1%	61.6%	62.1%

* Significantly different from the control trial ($P < 0.05$).

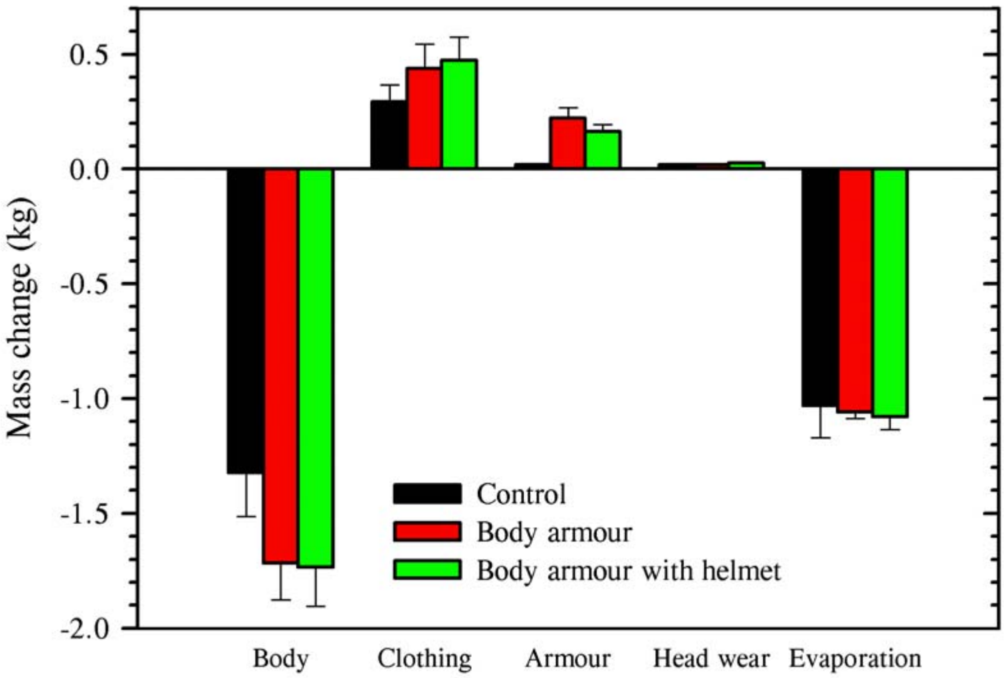

Figure 3.5: Mass changes and evaporation during steady-state walking (two speeds) in a hot-humid environment (36°C, 60% relative humidity, radiant heat ~750 W.m^{-2}) with three clothing configurations: camouflage uniform (control), camouflage uniform with body armour, and camouflage uniform with armour and helmet.

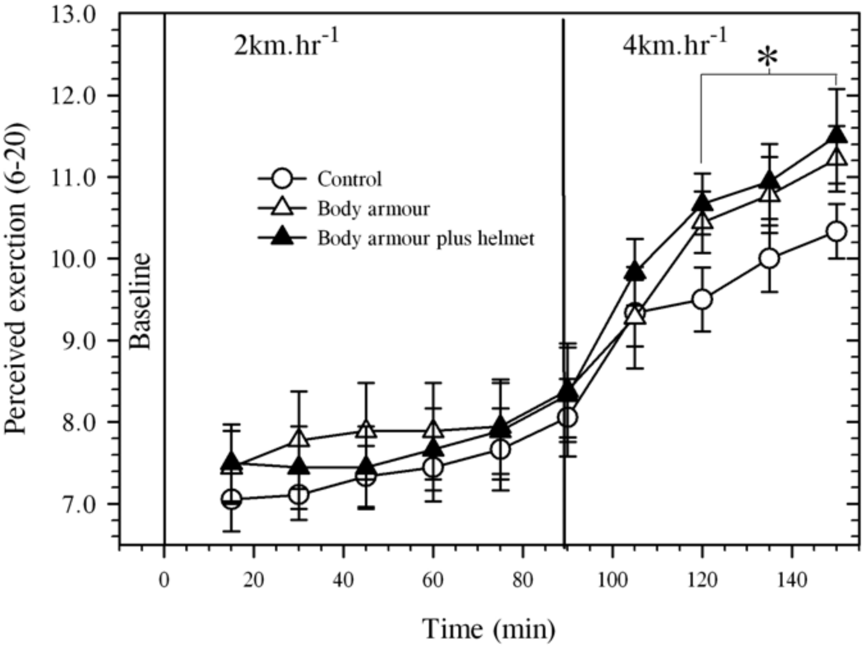

Figure 3.6: Perceived exertion (effort sense) during steady-state walking (two speeds) in a hot-humid environment (36°C, 60% relative humidity, radiant heat ~750 $W.m^{-2}$) with three clothing configurations: camouflage uniform (control), camouflage uniform with body armour, and camouflage uniform with armour and helmet.

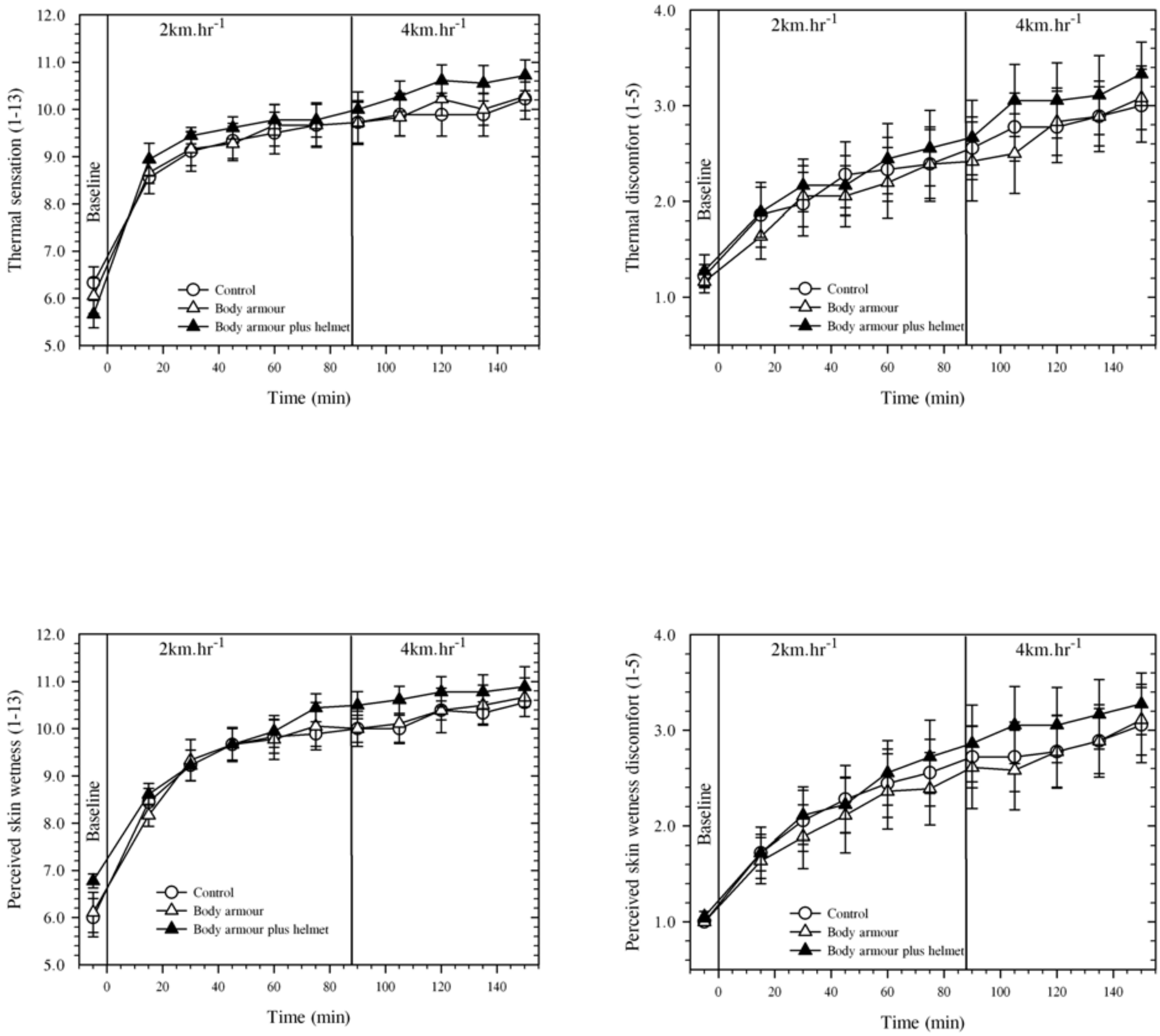

Figure 3.7: Psychophysical responses during steady-state walking (two speeds) in a hot-humid environment (36°C, 60% relative humidity, radiant heat ~750 $W.m^{-2}$) with three clothing configurations: camouflage uniform (control), camouflage uniform with body armour, and camouflage uniform with armour and helmet.

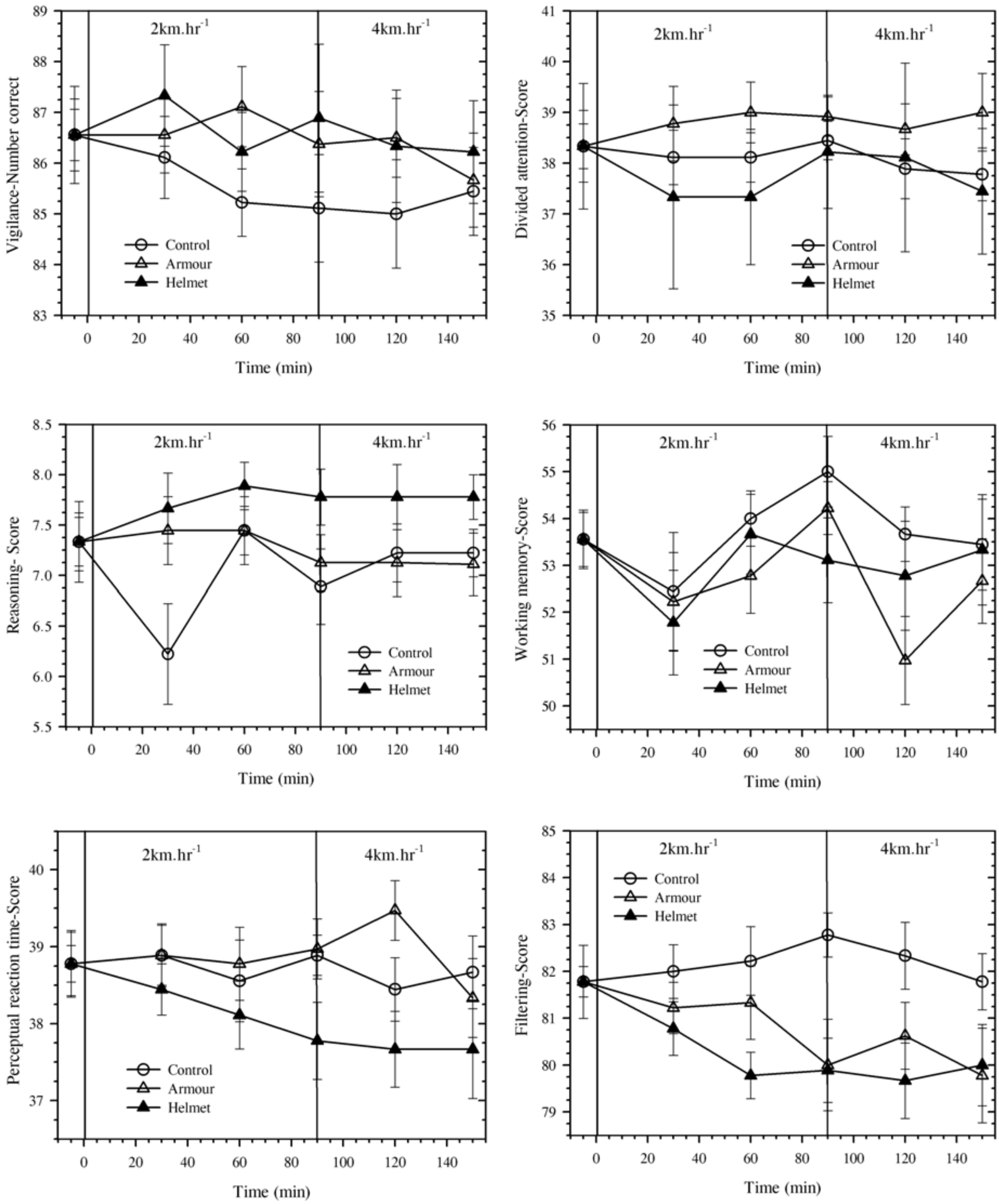

Figure 3.8: Change in cognitive function during steady-state walking (two speeds) in a hot-humid environment (36°C, 60% relative humidity, radiant heat ~750 W.m^{-2}) with three clothing configurations: camouflage uniform (control), camouflage uniform with body armour, and camouflage uniform with armour and helmet.

3.4 Discussion

3.4.1 Core temperature

Since the principal aim of this project was to evaluate the risks of exertional heat illness when wearing combat body armour in tropical environments, we shall first focus upon the impact of body armour on core temperature. It is immediately apparent that core (auditory canal) temperature did not approach levels that may indicate impending exertional heat illness. However, it is also apparent that the response curves for each of the three treatment conditions (uniform configurations) deviated over time.

This was an unexpected observation. First, it confirmed the possibility that, for either a heavier work rate or a longer exposure time, the body armour imposes a greater thermal load upon the wearer than does the standard combat uniform. This was entirely predictable. However, it also clearly demonstrates that adding the combat helmet alone represents a further significant thermal load. Therefore, had the subjects been asked to continue the test for longer, these response curves would have deviated even further.

The addition of an extra 1.3 kg to the head, on its own, is not likely to have such a powerful impact, even though this would be approximately equivalent to carrying 1.7 kg on the back (Soule and Goldman, 1969). Since the body armour dramatically reduces heat loss from the torso, it is more likely that it was the combination of this helmet load and its impact on heat dissipation that produced this result. These effect have been demonstrated (in part) by Goldman (1969), Bishop and Krock (1991) and Majumdar *et al.* (1997).

3.4.2 Skin temperatures

The addition of the body armour and the helmet displaced mean skin temperature upwards about 0.5°C relative to the control condition but differences between the two armoured conditions were not significant ($P > 0.05$). These differences in mean skin temperature are attributable primarily to changes in the skin temperatures of the torso (Figure 4.3), and reflect the impact of the body armour on heat trapping during exercise, as previously reported by Majumdar *et al.* (1997). Thus, from 90-150 min, scapula skin temperature differed significantly between the control and armour with helmet conditions.

3.4.3 Cardiac frequency

A clear separation of the three heart rate curves was apparent (Figure 4), resulting in terminal heart rates of 115 $b.min^{-1}$ (control), 123 $b.min^{-1}$ (armour) and 132 $b.min^{-1}$ (armour plus helmet). However, these differences were only apparent through time by uniform interactions, indicating progressive deviations in physiological strain. This trend very nicely matches that observed for core temperature (Figure 3.1).

The continual rise in heart rate within each condition is due to cardiovascular drift, and is associated with a progressive increase in cutaneous blood flow during prolonged heat exposure (Coyle and Gonzalez-Alonso, 2001). It is not certain whether the progressive increase in heart rate is due to a decline in stroke volume, occurring as a result of increased cutaneous blood flow, or due to some other intervention, such as an increased sympathetic activity accompanying the rise in core temperature (Coyle and Gonzalez-Alonso, 2001).

3.5 Conclusion

The following primary results are highlighted due to the potentially significant impact of combat armour on ADF personnel.

First, significant main effects of combat armour were evident for whole-body sweating, evaporation, skin temperature on the back (scapula) and perceived exertion (effort sense). That is, both of the armoured states elicited significant elevations in skin temperature, effort perception and sweating, with significantly more sweat being retained within the clothing. These observations have implications for ADF through the possibility of premature soldier fatigue, thermal discomfort, the formation of blisters on the feet and dehydration.

Second, significant time by uniform interactions revealed that, over time, each of the armoured states would lead to a significant elevation in physiological strain, relative to the control condition. These interactions were present for core temperature, skin temperature, heart rate and perceived exertion (effort sense). Therefore, as time progressed, physiological strain deviated significantly, and unfavourably, between the armoured and control trials.

Third, in the case of core (auditory canal) temperature, a significant time by uniform interaction revealed that the addition of only the combat helmet to the body armour was enough to elicit a further disadvantageous deviation in physiological strain. Had the current subjects been asked to continue the test for longer, these response curves would have deviated even further, leading to the more rapid development of hyperthermia when wearing the combination of the combat body armour and the helmet. Although physiological strain was elevated when the individual wore the helmet, no detriments in cognitive function were observed. This may have been due to poor sensitivity of the tasks, possibly meaning that slight changes in cognitive function remained undetected.

While it is evident from these observations that the ADF needs to consider the modification of work-rest intervals for personnel wearing combat armour, advice on the appropriate strategies for implementing such changes is not possible from the current investigation. It is therefore recommended to the ADF that additional research be undertaken to further explore these relationships. Finally, while it is outside the brief of this thesis, it is further recommended that the ADF give consideration to adopting a more appropriate index for evaluating environmental stress, since the WBGT index suffers a number of short comings for use in heavily-clothed personnel working under tropical climatic conditions.

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CHAPTER 4: A FIRST-PRINCIPLES EVALUATION OF AUXILIARY COOLING FOR ADF PERSONNEL

4.1 Introduction

4.1.1 Purpose

The thermodynamics of human heat exchange provide a first-principles means through which to evaluate the potential for thermal environments to induce physiological strain in clothed military personnel. The purpose of this chapter is to apply these principles to a theoretical treatment of the situations for which auxiliary (microclimate) cooling may be used to support military personnel in the performance of their routine tasks, across varying climatic conditions, and whilst working over a wide range of intensities. In addition, a first-principles analysis of different auxiliary cooling methods is provided to facilitate the selection of appropriate cooling devices across the military trades.

4.2 Modelling the problem

A first-principles, mathematical model, based upon the heat balance equation (Equation 1, page 4), was developed using the assumptions and operational conditions shown in Table 1. Three clothing states were evaluated: (a) nude, (b) wearing standard Australian Defence Force camouflaged, combat fatigues (ADF), and (c) wearing standard Australian Defence Force NBC clothing, but without wearing the face mask, gloves or boots. A wide range of physical and physiological variables were derived from the model, but, for the purposes of this thesis, only the nett heat exchange will be reported.

4.2.1 Two-dimensional analyses

Nett heat exchanges[1] from the model are reported in both two- and three-dimensional graphs. Figures 4.1-4.4 illustrate the effects of moving from unclothed, resting exposures (Figure 4.1), to exercising exposures (nude: Figure 4.2), to resting exposures in clothed and unclothed states (Figure 4.3), and finally to exercising exposures with clothing.

[1] Heat loss is signified by negative numbers; heat gain (storage) is signified by positive numbers.

Table 4.1: Assumed operational indices for use in mathematical modelling

Variable	Assumed value
Mass	78 kg
Height	1.78 m
Body surface area	1.95 m^2
Core temperature	38°C
Mean skin temperature	35°C
Total insulation (I_{TOT})	0-0.45 $m^2K.W^{-1}$ (nude-NBC uniform)
Moisture permeability (i_m)	0.09 (NBC), 0.4 (ADF), 1.0 (nude)
Ratio: i_m / I_{TOT}	0.13 (NBC), 0.76 (ADF), 4.19 (nude)
Heat loss through clothing	10% (both ensembles)
Thickness of trapped air	0 (nude), 10 mm (ADF) and 20 mm (NBC)
Skin surface area exposed	100-20% (nude-clothed)
Wind	0 $m.s^{-1}$
Air temperature	15-50°C
Relative humidity	40-85%
Radiant temperature	equal to air temperature
Total metabolic heat: rest + work	117 (rest), 397 and 917 Watts

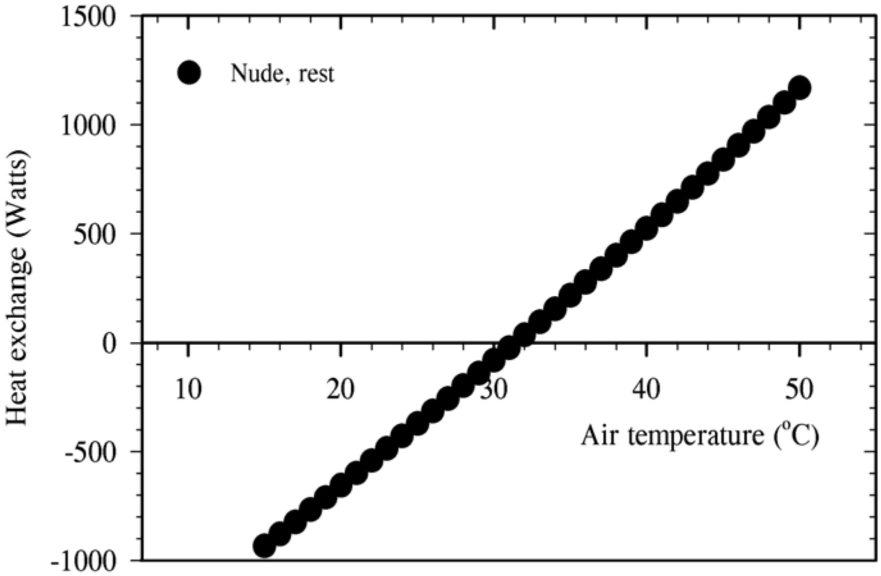

Figure 4.1: Heat exchange during nude, resting exposures.

Figure 4.1 illustrates several principal facts.

- When heat exchange is positive, the body will gain heat from the environment.
- For a resting, unclothed person, the point at which the data line crosses the zero heat exchange axis corresponds to the average skin temperature of a person resting in comfortable conditions (30-33°C), with data to the right of this point corresponding to heat being gained from the environment.
- Thus, when as air temperature rises above 30-33°C, the body will gain increasingly more heat.

Now we can add the stress of exercise (Figure 4.2). The heat exchange line remains parallel to the unclothed line, but is moved upwards. That is, the effect of exercise is to lower the air temperature at which heat gain occurs; this is due to an elevated internal heat production. Indeed, even in cold air, if the heat production is high enough, one may experience heat illness.

Compare now the effect of adding clothing (Figure 4.3): the unclothed versus the clothed states. The heat exchange line is now displaced leftwards (relative to its intersection with the zero heat exchange axis) and rotated clockwise. Two primary effects of clothing become immediately evident.

- Clothing protects (insulates) the wearer from both heat losses to, and heat gains from, the thermal environment (the line is rotated).
- Clothing also lowers the air temperature at which heat gain occurs.

Finally, we see the interaction of clothing and exercise (Figure 4.4). This most closely approximates the scenario of relevance to the ADF. The following points are noted.

- The air temperature at which heat gain occurs is now at its lowest point, and some 10°C lower than in the unclothed, resting person.
- When exercising in clothing, most air temperatures are associated with heat gains.
- The added clothing insulation reduces the ability of the wearer to dissipate metabolically-produce heat, as reflected by the upwards displacement of the heat exchange line.

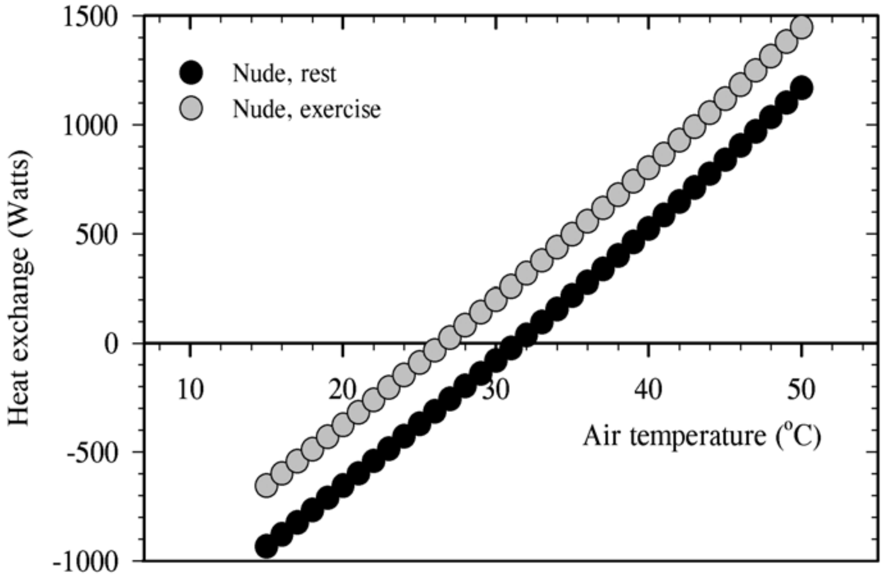

Figure 4.2: Heat exchange during unclothed, resting and exercising exposures.

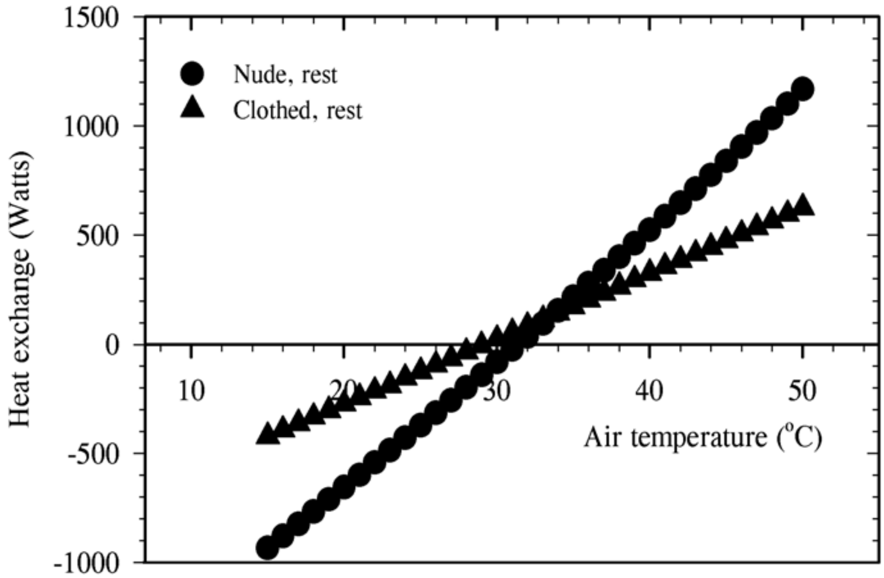

Figure 4.3: The impact of clothing on resting heat exchange.

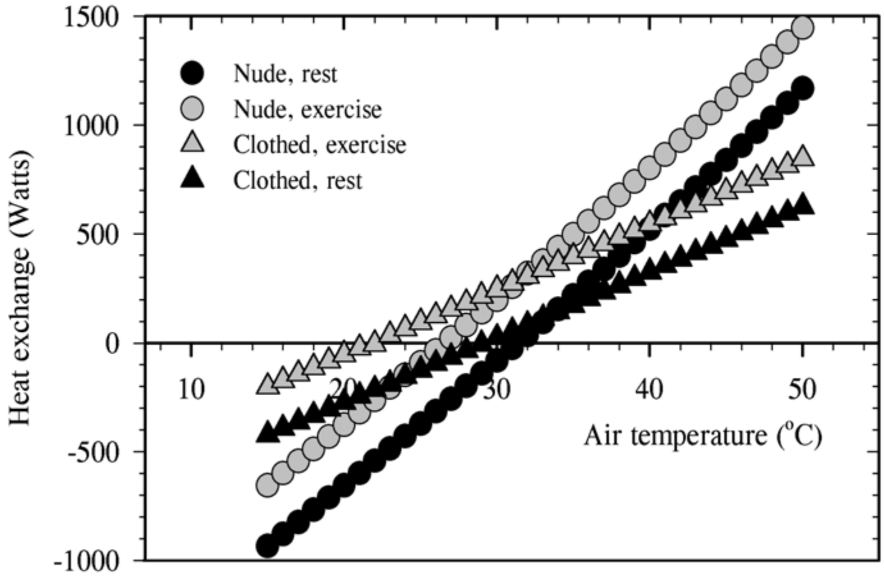

Figure 4.4: The interaction of clothing and exercise on heat exchange.

4.2.2 Three-dimensional analyses

The above analysis can be extended so that a wide range of conditions and clothing configuration can be simultaneously explored. These analyses result in three-dimensional surfaces (plots) that describe total heat exchange for various combinations of air temperature, clothing insulation and metabolic heat production. These are shown for rest (Figure 4.5) and two external work rates: 70 Watts (Figure 4.6; total heat production = 400 Watts); 200 Watts (Figure 4.7; total heat production = 920 Watts). A key feature of these graphs is the zero heat exchange axis; the transparent black surface. Each three-dimensional surface is colour coded with respect to this surface, with graduations along the colour spectrum between blue (maximal heat loss) and orange (maximal heat gain). The closer that any point on the surface falls to the orange end, the greater is the requirement for auxiliary cooling for that combination of air temperature and clothing insulation.

The scenarios of greatest relevance to the ADF are the exercise states, from which the following summary points are important.

- It is apparent that, when exercising at 200 Watts (external work), only near-nude people in cool conditions (15°C) can avoid a nett heat gain (Figure 4.7).
- When working at 70 Watts, the situation is dramatically improved. Heat loss is possible at air temperatures <20°C, even with maximal insulation.
- The zero total heat exchange surface is used as the current reference plane (where heat gain equals heat loss). This reference has considerable practical limitations. Indeed, it is totally impractical in many working situations to attempt to achieve this state. Thus, some arbitrary level of "acceptable positive heat exchange" (an offset reference surface) would need to be adopted for military use.

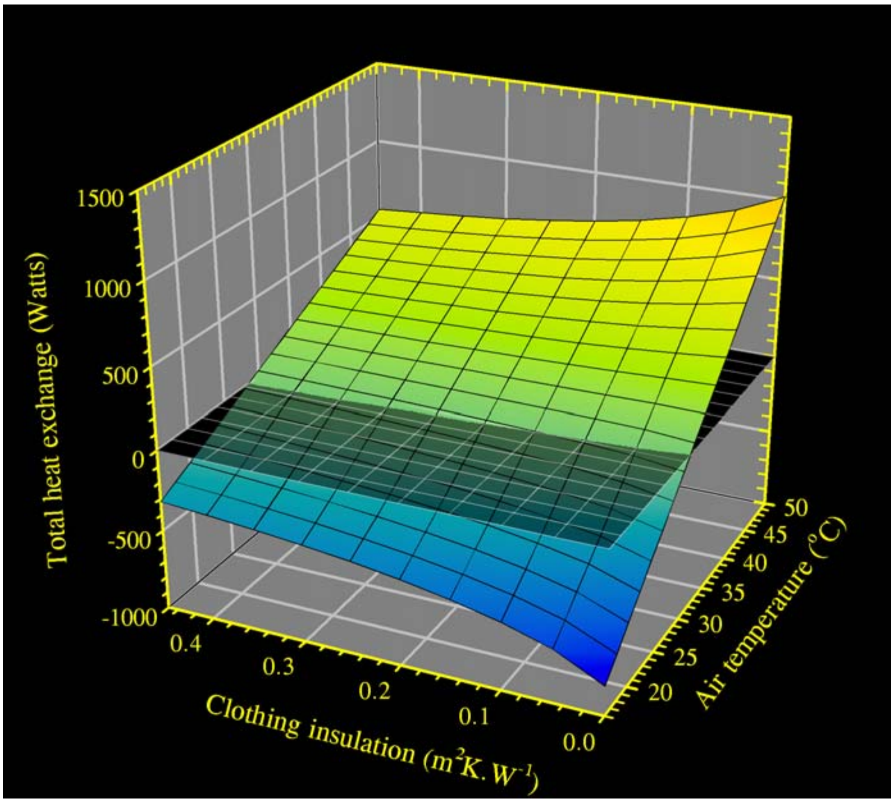

Figure 4.5: The three-dimensional surface for resting exposures to combinations of clothing insulation and air temperature.

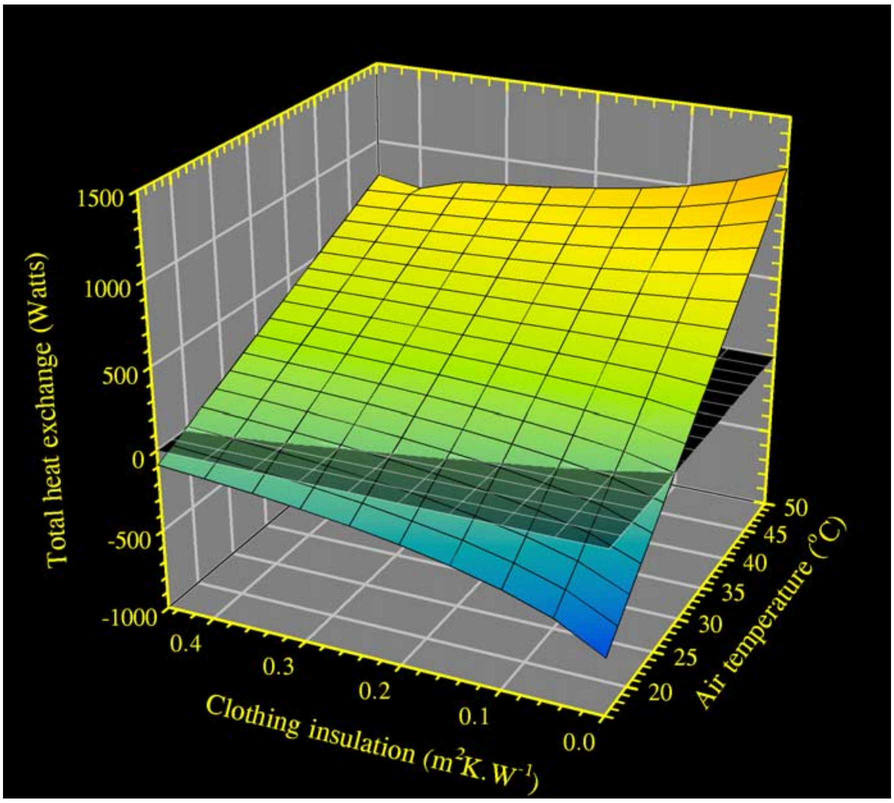

Figure 4.6: The three-dimensional surface (70 Watts of external work) for exposures to combinations of clothing insulation and air temperature.

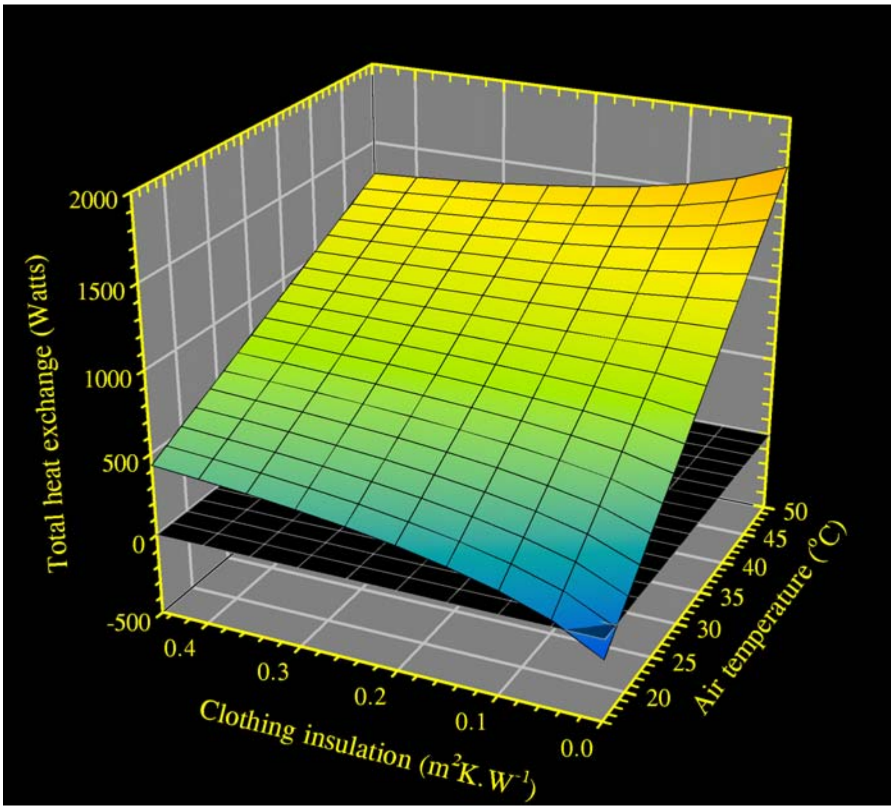

Figure 4.7: Three-dimensional surface (200 Watts): clothing insulation and air temperature.

4.2.2.1 Predicting cooling requirements

The final stage of this modelling was to rearrange the above data into a single graph for generic use by ADF personnel to predict auxiliary cooling requirements. For the purpose of this exercise, a standard ADF ensemble was used: the ADF camouflaged, combat fatigues (insulation 0.29 $m^2K.W^{-1}$). The resulting three-dimensional surface (Figure 4.8) now shows heat exchanges across a wide range of exercise intensities and air temperatures.

4.3 Modelling coolants and cooling system

When individuals are exposed to uncompensable heat stress for long periods, several strategies may be implemented to reduce the risk of exertional heat illness. There are three general ways in which this might be achieved.

- First, one may seek to reduce metabolic (endogenous) heat production.
- Second, one may modify the external heat source.
- Third, one may alter the interface between the individual and the environment.

4.3.1 Modifying the work rate

In most military situations, reducing the work rate of the individual is rarely an option. For instance, many military tasks are performed at set work rates (*e.g.* route marching on patrol), or involve the manual handling of fixed masses. One option might be to modify the duration of tasks, perhaps by including intermittent rest periods. However, Kraning and Gonzalez (1991) compared the physiological effects of intermittent and continuous exercise during both compensable and uncompensable heat stress conditions. During uncompensable conditions, they showed that intermittent work induced greater physiological strain than did continuous exercise, and it also reduced tolerance time by 14 minutes. Although the actual physiological mechanisms of this finding remain unclear, it was suggested it might be attributable to interruptions to the pattern of normal skin blood flow, thereby affecting the heat loss. Similarly, two other studies (Ekblom *et al.*, 1971; Nielsen, 1968), performed under compensable conditions, have shown that little benefit is gained from implementing intermittent exercise. More recently, Aoyagi *et al.* (1996) found a greater rise in T_{core}

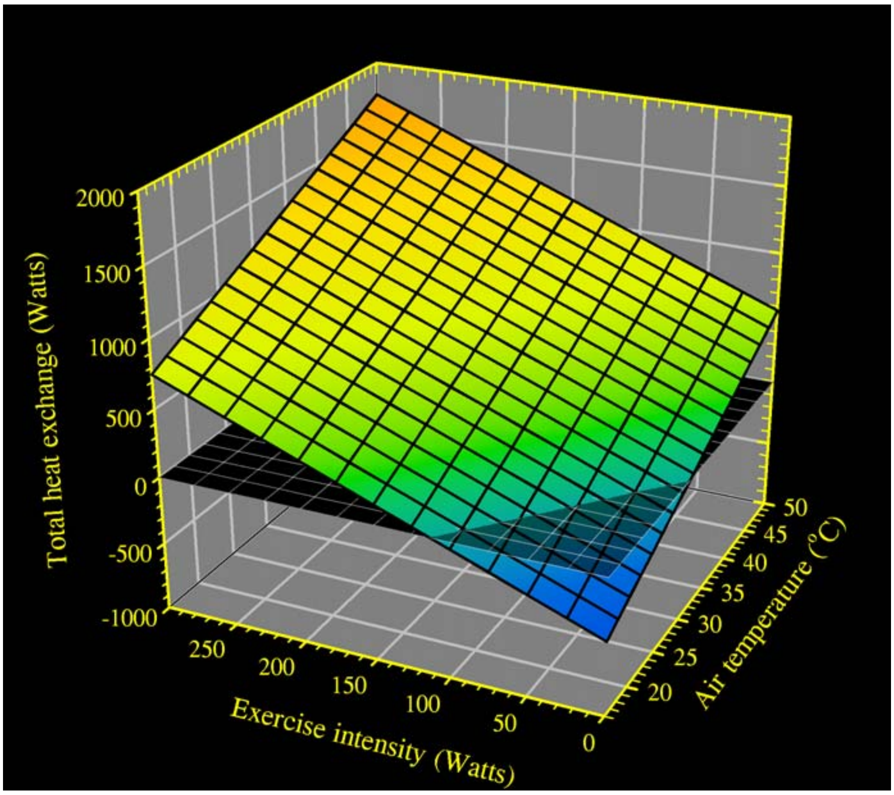

Figure 4.8: Three-dimensional surface for heat exchange across ranges of external work rates and air temperatures, when wearing ADF camouflaged, combat fatigues (insulation 0.29 $m^2K.W^{-1}$).

during an intermittent work protocol.

4.3.2 Modifying clothing

Within enclosed working environments, it is relatively easy to control the external environment. Both air temperature and water vapour pressure of such environments can be modified to increase heat dissipation to, and reduce heat gains from, the external environment. However, this is rarely feasible within the working environments of military personnel.

4.3.3 Modifying the interface between the person and environment

Another method of modifying the influence of the external environment would be to remove all, or part of the personal protective ensemble. This too is often impossible within military situations. For example, one cannot selectively wear components of NBC clothing within a contaminated environment. However, by combining the use of alternating work:rest periods (away from a significant heat source) with partial removal of the clothing (away from the contaminated environment), the possibility of increased heat removal may be achieved. While this may reduce the severity of an uncompensable heat stress condition, it does impact unfavourably upon productivity (capability).

Since it is through the clothing interface that heat passes, then one may, for example, alter the clothing to allow for greater evaporative cooling to occur. One may also modify the microclimate of the individual using auxiliary (microclimate) cooling equipment. This is particularly relevant for individuals wearing thermal and NBC protective clothing. Such systems facilitate heat loss by changes in conductive, convective, radiative and evaporative heat exchange. In this sub-section, we shall briefly overview the key physical principles underpinning the operation of these cooling systems. However, for simplicity, only three general types of systems will be covered: conductive, convective and combined systems. The approach used will be based wholly upon the use of air, water or ice as the primary coolants. The most relevant physical properties of these coolants are summarised in Table 4.2. A first-principles assessment will be provided, using an extension of the above

Table 4.2: Physical properties of standard coolants at the operating temperatures indicated.

Please see print copy for table

Source: Lide (1997).

mathematical model (see Appendix A), of the efficacy of each of these coolants under ideal operating conditions, where matters relating to contact surface area, power supply and flow have been ignored, such that each coolant was given an equal opportunity to remove heat.

The density of each coolant determines its mass, which, in conjunction with its inflow temperature, will dictate the stationary heat capacity and the thermal energy content of the coolant on entry, according to the following relationships:

- heat capacity = specific heat * mass
- thermal energy content = specific heat * mass * inflow temperature.

By performing the latter computation, assuming complete equilibration with skin temperature (zero flow), one can derive the maximal thermal energy content of the coolant at equilibration. The difference between these two thermal energy contents defines the heat capacity of the coolant (stationary), relative to the thermal gradient (*d*T) and contact surface area.

In addition to these physical properties of the coolants, there are three primary design characteristics that must be considered within each cooling system. These are the inflow temperature of the coolant, the contact surface area between the skin and the cooling system, and the flow of the coolant. The impact of these characteristics upon heat extraction is illustrated in Figures 4.9-4.12, using water (15°C, unless stated otherwise) as the coolant.

Two of these relationships (inlet temperature and contact surface area) are linear functions, while the last (coolant flow) is curvilinear. The following design principles are noted:

- Changing the water inflow temperature by 5°C will modify heat removal by about 130 Watts. This relationship is constant across the entire, physiologically-relevant range of inflow temperatures.
    - However, lower coolant temperatures to <21°C has been shown to progressively increase thermal discomfort (Shitzer *et al.*, 1973).
- For a constant inflow temperature, modifying the contact surface area by

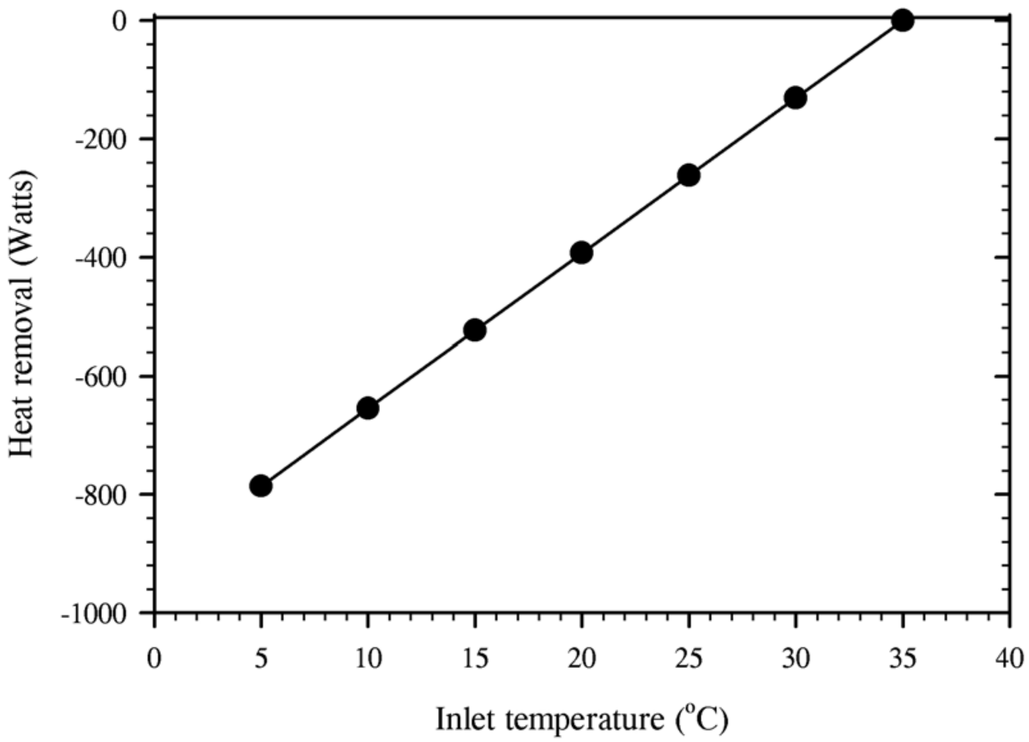

Figure 4.9: The impact of coolant (water) inflow temperature upon heat removal.

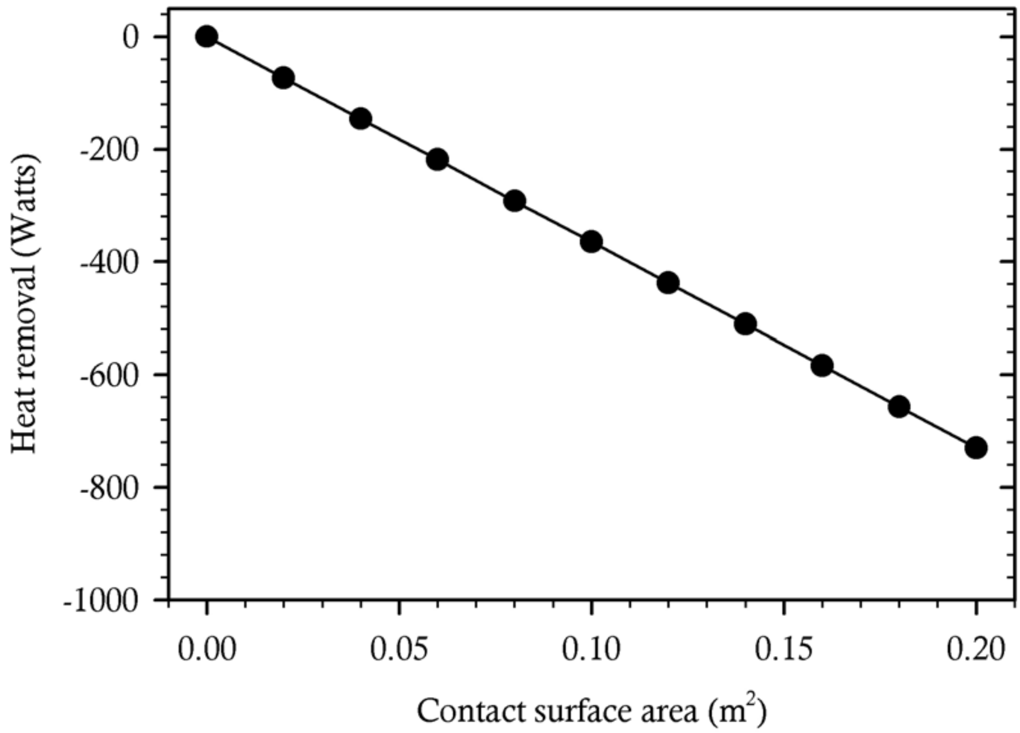

Figure 4.10: The impact of coolant contact surface area (water at 15°C) upon heat removal.

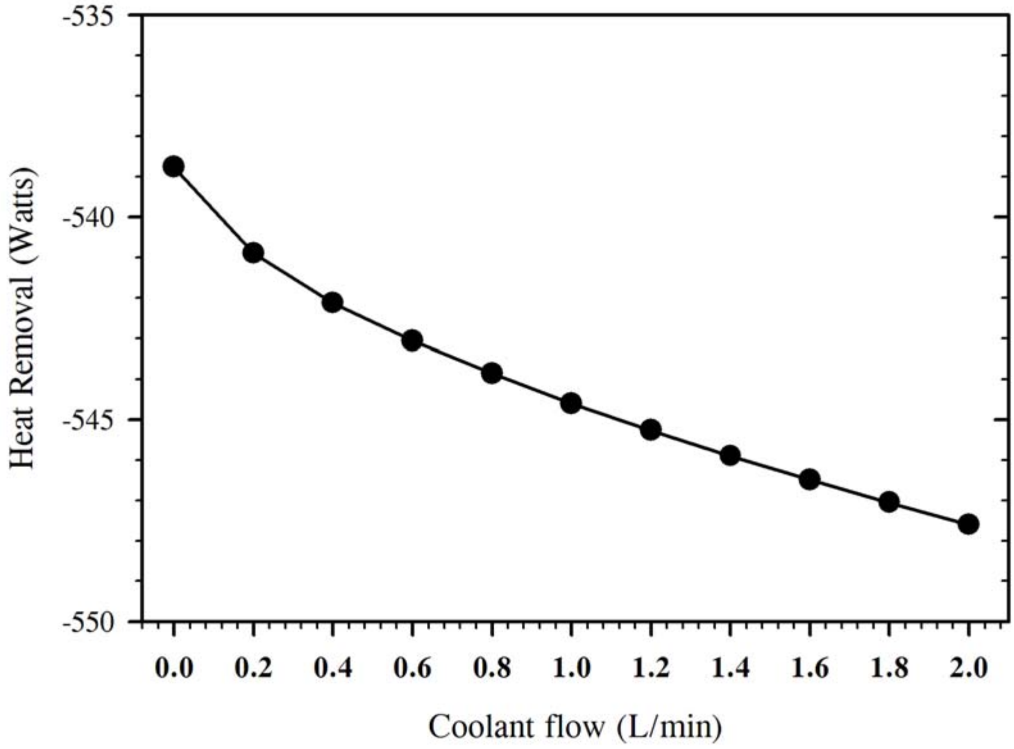

Figure 4.11: The impact of coolant (water at 15°C) flow upon heat removal.

0.05 m^2 (the surface area of the hand or foot), will change heat removal by approximately 220 Watts. Whilst adding a contact surface area the size of the head (0.2 m^2) will increase heat extraction by almost 730 Watts.

- ***Note:*** The sizes of the cooled surface areas reported in the literature range from about 0.13-0.18 m^2.
- Coolant flow rates (at a constant water temperature) have minimal affect upon heat removal. Heat extraction changes about 10 Watts over flows from 0 l.min^{-1} to 2 l.min^{-1}.
- These generic, and quite predictable outcomes provide the following fundamental design specifications:
    - Design modifications that are dedicated to increasing the contact surface area are the most effective manner through which to increase heat extraction:
        - increasing the contact surface area by 0.035 m^2 (less than the size of the hand) is as effective as lowering the inflow water temperature by 5°C;
        - increasing the contact surface area by 0.73 m^2 (the approximate size of the lower limbs) is ten times as effective as lowering the inflow water temperature by 10°C.
    - Design modifications that focus on increasing the flow of the coolant will result in minimal returns to scale.

4.3.3.1 Conductive heat removal

The coolant of choice to optimise conductive heat removal is ice, which will vary in temperature between 0°C and -30°C. This choice is predicated primarily on the basis of its thermal conductivity, which is three times that of water (15°C) and 87 times that of air (15°C). The thermal conductivity of water (15°C) is almost 28 times greater than air at the same temperature (15°C).

4.3.3.2 Convective heat removal

Auxiliary cooling systems that employ this avenue of heat removal are typically the air-cooled systems. These systems rely upon an external energy source to drive air across the skin surface, and to circulate air through open-looped tubes contained within a suit. This air flow cools the individual in two ways: convective cooling and evaporative cooling.

Thus, both the temperature and water vapour pressure of the air, will determine heat extraction. On a simple first-principles basis, one would predict that when the water vapour pressure of the air is low, for a given temperature, then evaporation is facilitated. Similarly, if thermal equilibrium occurs between the skin surface and the air, cooling will be impeded. Low flows across the skin surface act to reduce both the thermal and water vapour pressure gradients. However, at lower air temperatures, fewer water molecules can be held within the air, so an inlet temperature must be sought to optimise both convective and evaporative cooling. This was attempted by Fonseca (1983) who compared heat extraction using three different air-cooled garments and a copper manikin. It was observed that increasing air flow from 170 $l.min^{-1}$ to 283 $l.min^{-1}$, whilst decreasing air inlet temperature to 21°C, increased cooling of the torso, arms and legs for all three garments. Moreover, the use of such high flows will also result in cooling of a larger surface area of the body. That is, even when only the torso was being ventilated, higher flows result in air cooling of both the arms and legs due to a greater circulation of air through the clothing.

More recently, Kaufman (2001) performed a theoretical evaluation of the heat extraction capacity of such systems. The relationships between air temperature, water vapour content and flows were modelled, with the following primary outcomes:

- if water vapour content could be lowered and fixed ($<$40% relative humidity), then complete extraction of metabolic heat (during moderate intensity work) can be achieved at flows $\leq$150 $l.min^{-1}$;
- for flows $<$200 $l.min^{-1}$, inlet air temperatures had to $<$25°C for complete extraction of metabolic heat during moderate intensity work;
- complete extraction of metabolic heat (moderate intensity work) cannot be

achieved when the inlet air temperature is 35°C, even at flows as high as 300 $l.min^{-1}$.

While these data are qualitatively similar to those of Fonseca (1983), there is a need to exercise caution when comparing mathematical data with results obtained from either manikin or physiological testing. A number of factors impact significantly upon the operational efficiency of cooling systems, reducing heat extraction that may be predicted mathematically. These factors include: garment fit, variations in local sweat secretion and skin blood flow, locomotion and the flushing of air between the garment and the body.

4.3.3.3 Combination cooling methods

A liquid-cooled, microclimate cooling system that uses tubes to circulate the coolant, takes advantage of both conductive and convective heat exchanges. These systems typically consist of a cooling unit, battery, pump, water (or a composite coolant) and a tube suit (flexible tubing sewn into a tight-fitting undergarment). Such systems are not readily portable, since they are often tethered to an immobile power source. There are battery-operated, untethered systems, though they have a limited operating time.

4.3.4 Concluding comments

To summarise the heat extraction capabilities of the three standard coolants (air, water and ice), and the performance characteristics of three hypothetical cooling systems were modelled using the following parameters:

- standard person: mass: 78.0 kg, height 1.78 m, surface area 1.95 m^2
- exercising at 70 Watts, with total metabolic heat production of 400 Watts
- environmental conditions: 35°C, 70% relative humidity
- clothing: ADF camouflaged, combat fatigues (insulation 0.29 $m^2K.W^{-1}$)
- contact surface areas: 0.15 m^2 (ice and water systems), 0.78 m^2 (air system)
- inflow temperatures: 15°C (water and air systems), -15°C (ice system)
- coolant flow: 2 $l.min^{-1}$ (water), 280 $l.min^{-1}$ (air), 0 $l.min^{-1}$ (ice).

Heat extraction was computed separately for each of the four primary avenues for thermal energy exchange, and also for total heat removal. These data are presented in Figure 4.12. Two primary assumptions were applied to this modelling. First, it was assumed that the initial (inflow) temperatures were held constant throughout the simulation. Second, heat gains from, and to the external environment were prevented.

From this modelling, three summary statements may be derived:

- First, the ice system dominated conductive and radiative heat exchanges:
    - heat extraction by conduction was only 13% (water) and <1% (air) of that achievable with ice, and
    - heat extraction by radiation was only 58% (water) and <1% (air) of that achievable with ice.
- Second, the air-cooled system dominated thermal exchanges by convection and evaporation, but these were low in comparison to conductive heat losses:
    - heat extraction by convection was only 30% (water) and <1% (ice) of that achievable with air, and
    - heat extraction by evaporation did not occur for either the water or ice systems.
- Third, the ice system dominated total heat extraction, with the water-perfused system attaining only 15% of that achieved by the ice system, while the air-cooled system achieved just 4%.
-

It is again noted that thermal exchanges between these coolants and the external environment was not modelled. Thus, as noted previously (Section 4.3.3.2), mathematical models may not faithfully reflect heat extraction when such systems are worn during typical operational (military) scenarios. Indeed, the above data provide a very optimistic reflection of heat extraction. Nevertheless, they do allow one to draw useful comparisons for ideal operational conditions.

Although these three types of cooling systems have been shown to effectively alleviate heat strain for individuals exposed to hot environmental conditions, not all systems are equally effective, and there exists a need to evaluate these systems according to the requirements of the user and the characteristics of each system. In the past, liquid-cooled systems have been considered preferable to convective cooling systems (Nunneley, 1970). However, while

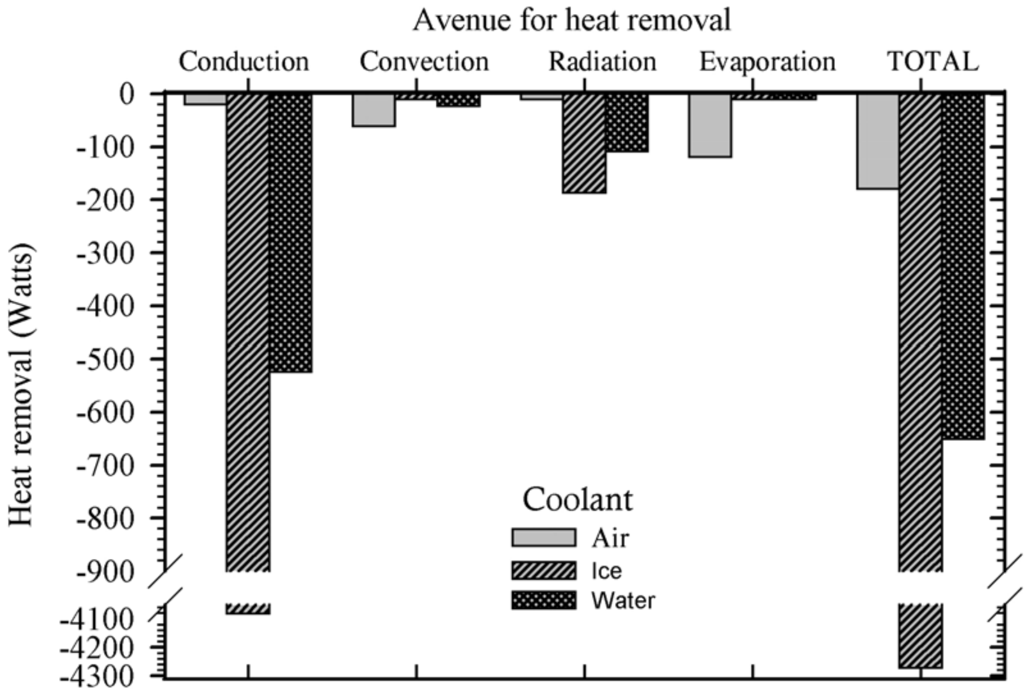

Figure 4.12: Heat removal capabilities of three hypothetical cooling systems.

heat extraction is critical, one must also consider the mass and power requirements of each system. This is necessary because some systems will be used to cool individuals within vehicles, while others will need to be portable, and will be used to cool people whilst they are performing physically-demanding work, and without a supplementary power supply.

4.4 Physiological considerations

4.4.1 Regional versus whole-body cooling

The current, commercially-available cooling garments largely consist of whole-body cooling suits, cooling vests and cooling caps. Most systems incorporate torso cooling, however, whole-body cooling is not always necessary to prevent adverse heat storage. In addition to simplifying system designs, a system that cools a smaller surface area will impose less upon its wearer, and should be more cost effective.

A number of groups have considered the possibility of facilitating heat extraction and thermal comfort by only cooling selected skin regions, rather than most of the body surface (Nunneley and Maldonado, 1983; Young and Sawka, 1987; Frim, 1989; Pandolf *et al.*, 1995; Tipton *et al.*, 1995; Cotter and Taylor, 2005). Most recently, Cotter and Taylor (2005) have found that, while facial cooling provided the greatest impact on thermal comfort, it appreciably reduced general sweating, possibly exacerbating heat storage. Conversely, cooling the distal limb surfaces had minimal impact upon sweating, and could possibly be well suited for heat extraction. In this regard, the hands have three attributes: (i) high surface area to volume ratio; (ii) large reserves for skin blood flow and sweating; and (iii) lower thermosensitivity. Not surprisingly, hand (House *et al.*, 1997; Livingstone *et al.*, 1989) and feet cooling (House, 1998; Livingstone *et al.*, 1995) effectively alleviates heat storage. Thus, facial cooling reduces thermal discomfort, but may exacerbate the actual heat load, whereas cooling the hands and feet impacts only slightly upon comfort and sweating, but more effectively reduces the actual thermal load (Cotter and Taylor, 2005).
For any skin region to be considered suitable for selective cooling, it should ideally possess each the following characteristics:

- it should have a good blood supply, and its vessels should display a limited vasoconstrictor response to local cooling (Tipton *et al.*, 1995);

- it should have a surface area to volume ratio that enables rapid tissue cooling;
- it should exert minimal negative (thermoafferent) feedback upon whole-body sweating and comfort (Cotter and Taylor, 2005).

The first two of these attributes were evaluated, at least in part, using readily available anatomical data. The body was broken into ten segments for this purpose (Figure 4.13), and two level of analysis were performed:

- a determination of segmental surface area to mass ratios (Table 4.3), and
- an evaluation of segmental blood supply.
- This data indicates that the **hands** and **feet** have the most favourable surface area to mass ratio, followed by that of the **upper leg** (thigh). The thigh also has the second highest relative surface area and the third highest mass, and it contains muscles that are very active (heat sources) in most military activities.

Of these body segments, five contain significant blood vessels close (<3 cm) to the skin surface (Table 4.4). However, the most advantageous segments in this regard are the **hand** and **lower leg**.

The **head** is also an efficient site for heat exchange as it is highly perfused by a rich vascular network, yet its major blood vessels are less superficial. As perfusion of the brain is constant, even during hyperthermia, and the blood vessels supplying the scalp are relatively insensitive to cold-induced vasoconstriction (see below), head cooling could be very effective for heat extraction. Indeed, the head has been shown to have an extremely high heat flux (Nunneley *et al.*, 1971).

Gender	Male
Height (m)	1.78
Weight (kg)	78
Surface area (m^2)	1.95

Region	Body part
1	head
2	neck
3	upper torso
4	lower torso
5	upper arm
6	forearm
7	hand
8	upper leg
9	lower leg
10	foot

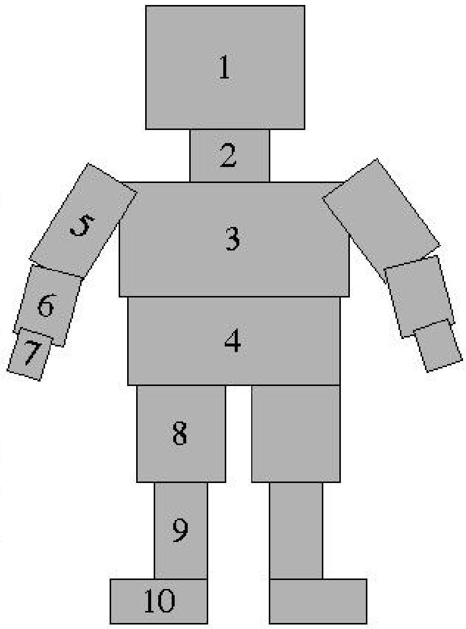

Figure 4.13: Body segments and stature of the model.

Table 4.3: Morphometric data for ten body segments.

Please see print copy for table

Sources: Werner and Buse (1988), and Lotens and Havenith (1991).

Table 4.4: Major blood vessels within 3 cm to the skin surface.

Please see print copy for table

Sources: Werner and Buse (1988), and Lotens and Havenith (1991).

Another possible area for heat removal is from the **skeletal muscles** used for work (Young *et al.*, 1987). Young *et al.* (1987) investigated the effects of cooling different surfaces of lower than observed with cooling to the torso alone. This improvement was most likely to be associated with the increase in active muscle being cooled, and also demonstrate that increasing the surface area exposed to the cooling system increases heat removal (Figure 4.10); a most predictable outcome. Although this study did not investigate torso and leg cooling compared with torso cooling alone during lower-body exercise, it was assumed that arm cooling had very little effect on the reduction in thermal strain during lower-body exercise. The advantage of regional cooling, as opposed to whole-body cooling, is that a great reduction in the power requirements of the system can be achieved. In reducing the surface area of the body in contact with the cooling system, and the power of the system, compensable working conditions can still be achieved.

4.4.1.1 Concluding comments

From the above analyses, five skin regions appear to have advantages when selectively cooled: hands, feet, thigh, lower leg and head. Not all of these regions would be suited for cooling during work due to obvious affects upon manual dexterity and locomotion. However, these factors will not be considered at this time. Of these five regions, we would exclude the following sites:

- feet: inadequate blood supply close to the skin surface, and
- head: low surface area to mass ratio and powerful negative feedback role with sweating.

It would, therefore, seem prudent to recommend that selected regional cooling be focussed on the **hands, thigh and lower leg**.

4.4.2 Cutaneous vasoconstriction and heat extraction

Blood flow is the primary avenue for heat removal from the core to the periphery (mass flow: convection). While more heat may theoretically be extracted from the skin surface when the thermal gradient is maximised, the application of a strong cooling stimulus may result in physiological changes that nullify this possibility, since the optimisation of heat extraction requires adequate cutaneous blood flow. The principal physiological change is a local reduction in skin blood flow, with vasoconstriction in some areas occurring at a skin temperature between 32-33°C (Veicsteinas *et al.*, 1982).

Vasomotor function of the skin is controlled by the hypothalamus via a negative (thermoafferent) feedback loop involving cutaneous thermoreceptors. There are two types of efferent flow to the cutaneous blood vessels: passive adrenergic vasoconstrictor and active vasodilator flow. The acral skin regions (hands, feet, ears, nose, lips) receive only adrenergic vasoconstrictor input. These regions are generally in a vasoconstricted state, with low local blood flow when thermoneutral. Indeed, local cooling will induce maximal vasoconstrictor tone. Vasoconstrictor tone is only released when T_{core} is elevated. Thus, the cooling of such regions may result in local vasoconstriction. This is less likely to occur in the heated person, but will certainly occur in thermoneutral conditions. Indeed, Ducharme *et al.* (1999) have shown that finger blood flow can be well maintained in subjects exposed to air at -25°C without gloves, when torso heating was used.

The skin blood flow to the non-acral skin regions is controlled by both adrenergic vasoconstrictor non-adrenergic vasodilator flow. Constrictor tone to these regions is minimal when individuals are in a thermoneutral state. Vasodilation is driven by sympathetic activation of the active vasodilatory pathway.

The highly-perfused blood vessels of the **scalp** are relatively insensitive to cold-induced vasoconstriction. It is only when powerful cooling (<7°C) is applied that vasoconstriction of the scalp occurs (Nunneley *et al.*, 1971). In contrast, skin blood vessels of the limbs will constrict at a skin temperature <32-33°C (Veicsteinas *et al.*, 1982). Thus, the head may seem to be a good target for auxiliary cooling, when considered from the perspective of changes in vasomotor tone. In fact, head cooling has been shown to remove large amounts of heat, relative to equal surface areas from other body regions, enhancing the potential to successfully alleviate heat stress in uncompensable environments (Nunneley and

Maldonado, 1983; Katsuura *et al.*, 1996). Indeed, cooling the frontal portion of the head has been shown to provide significant reductions in thermal strain (Katsuura *et al.*, 1996).

However, due to its low absolute surface area (7-9% of the body's surface area) and its moderate surface area to mass ratio (Table 3), heat extraction from the head, on its own, whilst being very efficient, is limited in absolute terms (Nunneley *et al.*, 1983). Indeed, while Frim (1989) found a greater reduction in T_{core} from combined head and torso cooling (0.3°C) than from torso cooling alone, the difference was not much greater than could be accounted for on the basis of diurnal variations. It was concluded that head cooling offered minimal physiological benefit, and there was also no sign of improved performance when head cooling was applied. Thus, whilst it was desirable to cool the head, it should not be considered to be an essential region for the application of local cooling.

4.4.2.1 Concluding comments

It is concluded that, while the head shows the potential to be a very effective surface through which to remove heat, it appears not to achieve this potential, possibly due to its limited absolute surface area. Instead, one must look to other skin regions. Since blood flow to the hands can be optimised when the body core is heated, it appears that hand cooling may be very effective for heat extraction.

4.4.3 Intermittent versus continuous cooling

Since cutaneous blood flow is so important for heat dissipation, and since it is the T_{skin} that dictates the onset of cutaneous vasoconstriction (Veicsteinas *et al.*, 1982), then it would seem sensible to endeavour to minimise vasoconstriction by reducing the fall in T_{skin} during auxiliary cooling. This can be achieved in two ways.

First, one could use coolants at higher temperatures. Since very low inflow temperatures are uncomfortable (Shitzer *et al.*, 1973), and result in reduced skin blood flow and heat extraction (Pergola *et al*, 1994), one may consider an approach that has been employed in whole-body, pre-cooling research. For example, one group has developed a technique where the temperature of the immersion bath was reduced from 29°C to 24°C over 45 min (Booth *et al.*, 1997), to minimise both the thermogenic and vasoconstrictor responses. However, changing the inflow temperature by 5°C will modify heat removal by 130 Watts, and this relationship is constant across the physiologically-relevant range of inflow temperatures (Figure 4.9). If we take 30°C as the critical T_{skin} for vasoconstriction, then, relative to a coolant delivered at 15°C, a coolant at this temperature will extract 650 Watts less heat. This design option, however, is not recommended.

Second, one could use an intermittent cooling protocol to attenuate the fall in skin temperature, whilst simultaneously maximising heat extraction (Cheuvront *et al.*, 2003). We suggest that this is a superior approach. The premise of this method is based upon the observation of Constable *et al.* (1994), that heat extraction is maximal during the first minutes of auxiliary cooling.

Cheuvront *et al.* (2003) compared intermittent and continuous cooling methods in heat-adapted subjects during treadmill walks (30°C, 30% relative humidity) whilst wearing chemical protective clothing. Water inlet temperatures were always kept at 21°C. They used four different intermittent cooling protocols, and found these to be equally effective in heat extraction. These intermittent protocols, which were applied to smaller skin surface areas, had much greater heat extraction efficiencies (164-215%) relative to continuous cooling of 72% of the body surface. The authors concluded intermittent cooling to be both physiologically and pragmatically superior, enabling an extension of the cooling capacity life of portable systems. Indeed, the authors also suggested that the next generation of intermittent cooling device may be fitted with feedback loops, whereby skin cooling is reduced when T_{skin} falls below the threshold of optimal heat extraction.

Xu *et al.* (2004) have developed a mathematical model to evaluate the efficacy of intermittent regional cooling. While such models cannot replace the need for manikin and physiological testing, they do have the potential to contribute to the developmental process, when new cooling systems are being designed.

4.4.3.1 Concluding comments

It is recommended that an intermittent cooling protocol be used to attenuate the fall in skin temperature. Since the nature of the intermittent cooling does not appear to affect heat extraction (Cheuvront *et al.*, 2003), it is further recommended that alternating, symmetrical, square-wave cooling cycles be used, using either 2- or 4-min, symmetrical cooling periods.

4.5 Cooling systems

4.5.1 A general overview of cooling systems

The operating principles and efficacy of auxiliary cooling methods will now be discussed.

4.5.1.1 Ice cooling systems

This type of cooling system usually takes the form of a vest with pockets for ice, where the torso is the only surface from which significant heat exchanges can occur. Torso cooling is sometimes supplemented using a cooling hood. Such systems have been evaluated by several groups including: Banta and Braun, 1992; Bennett *et al.*, 1995; Muir *et al.*, 1999; Nishihara *et al.*, 2002). The vest is worn underneath the personal protective ensemble, and a t-shirt is usually worn underneath the ice vest to reduce discomfort caused by close contact between the skin and ice.

The main differences among ice-vest systems include: the fabric from which the primary garment is made, the cooling agent (Nishihara *et al.*, 2002; van Rensberg *et al.*, 1972), and the number of ice packs used (Bennett *et al.*, 1995). The traditional coolant is ice, typically made from water or carbon dioxide (dry ice). However, the physical properties of ice (Table 2) can be modified to enhance heat extraction. This is achieved by adding agents to the water that modify the thermal conductivity, specific heat or melting point of the resultant ice. One such substance is ethylene glycol (1,2-dihydroxyethane, anti-freeze: $C_2H_6O_2$), which has a melting point of -13°C, a boiling point of 196-198°C and a specific gravity of 1.113.

An ice-cooled system is by far the simplest to design, as it works passively to cool the individual. It does not require an external power source, it is ideal for use in portable, field-based systems, and it is a good alternative for short-duration exposures. These systems are generally less bulky and easier to carry, with the potential duration of cooling usually 2-4 hours, depending on the number of ice packs used, the size of the ice packs, the metabolic rate of the individual and the insulation from the external environment (Speckman *et al.*, 1988). Critical considerations include the mass of ice and the contact surface area, both of which impact upon the time taken for the ice to melt. For a given ice mass, one may increase the contact surface area, and therefore the potential for heat extraction, by using smaller ice blocks. However, this also increases the speed of melting, since melt time is a function of the surface area to mass ratio of each ice block.

Although this form of cooling has proven to successfully reduce thermal strain, and hence increase work tolerance time (van Rensberg *et al.*, 1972), it has one major disadvantage. The duration of cooling is limited to the time it takes for the melted ice to equilibrate with T_{skin}. When this phase transition occurs, heat extraction ceases. This is problematic for individuals wearing protective clothing, as they need to remove part of the ensemble to get access to the ice vest, to remove and replace ice packs. As a consequence, the individual must stop work, and in cases of contamination exposure, the worker will need to leave the hazardous environment.

4.5.1.2 Water-perfusion systems

These systems typically consist of a cooling unit, battery, pump, water (or a composite coolant) and a tube suit (flexible tubing sewn into a tight-fitting undergarment). The prototype of this system was developed in 1962 for the protection of aircraft crewmen in hot environments (Kaufman and Pittman, 1966). However, over the years, liquid-cooled systems have advanced, allowing for precise control of coolant temperature and its flow (Hexamer and Werner, 1995). Such systems are not readily portable, since they are often tethered to an immobile power source. Battery-operated, untethered systems do exist, though they have a limited operating time. The inflow temperature of these systems is quite variable, depending on its design and application (Nag *et al.*, 1998; Nyberg *et al.*, 2001;

Xu *et al.*, 1999).

4.5.1.3 Air cooling systems

Although the specific heat capacity of air is considerably lower than that of water or ice, air cooled systems have been shown to be effective in lowering thermal discomfort during high-intensity workloads in moderately hot environments (Bishop *et al.*, 1991). However, the greatest advantage of the air-cooled method comes from the fact that relatively drier air (lower water vapour pressure than the skin) is passed over the skin surface, enhancing evaporative cooling. This form of cooling is likely to be more comfortable than either ice- or liquid-cooled systems, as it can potentially keep the user much drier. However, the water vapour pressure gradient between the skin and the ventilating air is a critical determinant of evaporative heat extraction, and lowering the vapour pressure of the air is heavily reliant upon airflow. It has been found that flows <300 $l.min^{-1}$ are quite ineffective in air cooling systems (Fonseca, 1983). Also see Kaufman (2001) for a more detailed analysis of the interaction of flow, air temperature and water vapour content on heat removal.

Clearly, the best way to ensure both the dryness and the quality of the ventilating air is to use compressed and filtered air. This is an expensive option. Ventilating with gases other than air is also possible. For instance, the very high thermal conductivity, greater specific heat and very low density of helium make it an ideal ventilating gas, but this is a very expensive option.

Vallerand *et al.* (1991) found that, due to an increase in the evaporative cooling efficiency of an air-cooled vest, this type of system increased tolerance time, and reduced rectal temperature significantly, when compared to a liquid-cooled system. The results also showed reduced heart rate, reduced evaporative efficiency index, and increased thermal comfort during an exercising, heat exposure (150 min; total metabolic rate: 240 Watts; 37°C, 50% relative humidity). Bishop *et al.* (1991) found air cooling to sufficiently lower skin temperature(total metabolic rate: 430 Watts) for a short duration (45 min) exposure in a temperate environment (25°C). Therefore, for an individual working at low-moderate work rates, and exposed to hot-humid conditions, or working at high work rates in a temperate environment, the air-cooled system has sufficient cooling power to change a set of potentially uncompensable working conditions into a more compensable state (Bishop *et al.*, 1991; Shapiro *et al.*, 1982).

4.5.1.4 Phase-change cooling systems

Phase-change materials (PCM) are used to control microclimates across a wide range of applications, including refrigerated transport, building construction, vehicle upholstery, clothing (Wittmers *et al.*, 1999; Shim and McCullough, 2000; Mekjavic *et al.*, 2005), and electronic and medical applications. Many substances absorb and release thermal energy when changing from one state to another (phase transition). For example, the melting of ice (solid into liquid) and the evaporation of sweat at the skin surface (liquid into vapour) represent phase transitions during which heat is absorbed, but without an elevation in the temperature of the water. During subsequent condensation into water droplets, this heat is released, again without a change in temperature. Some substances are particularly efficient in absorbing, retaining and releasing thermal energy, and these have become know as phase-change materials. For most applications, phase-change materials are used in solid forms, turning to liquid once they have absorbed a critical (transitional) amount of thermal energy. This thermal energy is released when the phase change is reversed. Thus, the removal or release of thermal energy only occurs during the phase transition.

For applications in clothing, phase-change materials come under a wide variety of trade names (*e.g.* Greiz, Microtek, Outlast, Sympatex). Almost invariably, these materials are in the form of an paraffin-wax substance, encased in capsules of inert, and very stable polymers or plastics (Figure 4.14). However, two primary limitations of phase-change materials are evident. First, since a phase change within stable, *albeit* stressful, environments occurs only once, then their usefulness approximates to that of a single-use item. Second, since the quantity of heat that can be absorbed, or released, by these materials is a function of mass, then the material mass that can be used becomes self limiting. Once the entire mass has changed from solid to liquid, the material ceases to

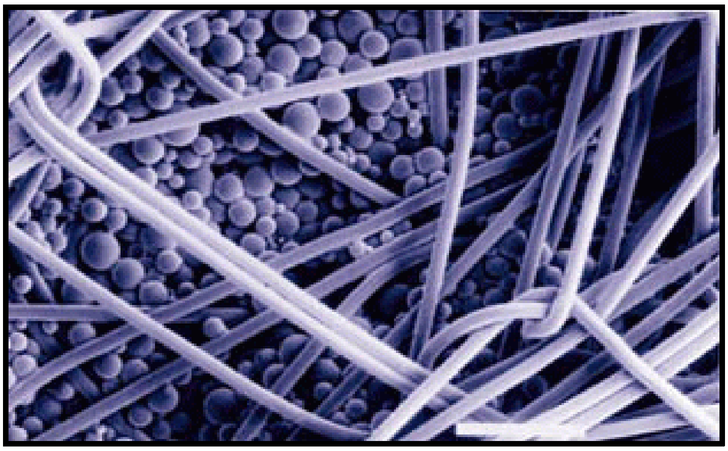

Figure 4.14: An electron micrograph of phase-change material within a fabric.

remove heat. For example, within a building, the mass of such phase-change materials is of minimal consequence to the overall design and strength of the building. However, when used within protective clothing ensembles (*e.g.* SWEDE Cooling Vest) and footwear, where this mass must be carried by the user, then it may become a critical limitation. Both of these limitations, at least with the current generation of phase-change materials (Shim and McCullough, 2000), represent very real weaknesses for use within the military for microclimate cooling of individuals in the field.

Another form of this technology uses the phase conversion of water into vapour, which is absorbed into a silicate, to dissipate heat. Zeolites are crystalline, porous aluminium-silicates having pores through which water may pass. Whist not strictly being a phase-change material, zeolites have the effect of first evaporating, and then condensing water. When water vapour is absorbed into the zeolite, thermal energy is released. However, since this water must first leave a surface, the transition of water into vapour removes heat from that surface; this is the phase transition. When used in an air-free, semi-vacuum, this process can be very rapid and will result in the freezing of water. Thus, zeolites may be used to rapidly cool (and even freeze) water that is subsequently used to directly cool a person, or to refrigerate a coolant that is then supplied to a person. Such systems typically have a limited working capacity (about 2 hours), which is again due to the mass of the material that can be used within the cooling system.

4.6 Recommendations

The principal means for the biological transfer of heat within the body, and ultimately to the environment, is via the blood. When this heat reaches the skin surface, it is the thermal and water vapour pressure gradients between the skin and the immediate environment (the microclimate) that dictate heat loss, through their respective impacts upon conduction, convection and radiation, and the evaporation of sweat. Auxiliary (microclimate) cooling systems should therefore be designed to optimise these gradients without compromising biological heat transfer.

4.6.1 General recommendations for the selection of cooling systems

4.6.1.1 Selecting the appropriate coolant

When different coolants were evaluated for application to the same total contact surface area, when very rapid cooling is required following heat exposure, or when cooling is needed only for a short duration (<2 h), it is recommended that ice be selected as the coolant since its thermal conductivity is three times that of water at 15°C, and 87 times that of air at 15°C. The thermal conductivity of water is almost 28 times greater than air at the same temperature (15°C).

Since the contact surface area for cooling with ice is generally much less than is possible with water cooling, then the comparison for equal contact surface areas is rarely valid. For water-perfused garments comprised of tubes, the contact surface area between the skin and tubing at any given point can be very small, and will probably not exceed that of an arc on the outer tube surface equal to the size of the radius of that tube. This assumption will provide a contact surface area equal to approximately 15% of the tube circumference. For a tube having a radius of 0.3 cm (typical of that found in such garments), and a length of 1 m, the total contact surface area will only be about 14 cm^2. Table 4.5 provides a simple comparison of the contact surface areas for ice-vest and water-perfused systems.

To achieve the same contact surface area in a water-perfused garment (tube radius 0.3 cm), as that obtained from six ice packs (10 * 15 cm), 64 m of tubing is required. Given that the thermal conductivity of ice is three times that of water, then, based solely on these contact surface areas, one would require approximately 130 m of tubing perfused with water at 15°C to achieve equal heat extraction.

However, one must be cautious not to assume that the contact and cooling surface areas are identical, or that they are comparable between water-perfused and ice-vest systems. For each form of cooling, the cooled surface area exceeds that of the contact area, since both vertical (transcutaneous) and longitudinal (surface) thermal gradients are established. The magnitude and extent of the latter will dictate the size of the cooled surface area.

Table 4.5: Contact surface areas for water-perfused tubes and ice packs.

Variable	Ice packs	Water-perfused garment
Number of packs	6	
Length (cm)	15	
Width (cm)	10	
External radius (cm)		0.15
Fractional contact (%)		15%
Total tube length (cm)		6400
Contact area (cm^2)	900	905

Furthermore, when two heat sinks are placed in close proximity, the size of the cooled surface area is further enlarged. This is the situation that exists for water-perfused systems. We have found that the skin is effectively cooled for a distance up 7 mm away from a tube (external radius 0.15 cm) when that tube is perfused with temperate water (25°C) following its perfusion with hot water (48°C; Cotter, 1998). One can assume this also applies to ice-vest cooling systems, and perhaps extending a greater distance, due to the temperature difference between the two coolants. However, in the case of water-perfused systems, one may expect to see overlap in the longitudinal thermal gradients if the tubes are adequately spaced. In this case, the cooled surface area will be many times greater than the contact surface area.

Since the extent of this overlap is currently unknown for most water-perfused systems, it is not possible to fully consider the interaction of the contact and cooling surface areas on heat extraction. Nevertheless, water-perfused systems are recommended when mobility is not a concern, and if there is a sufficient extension of the longitudinal thermal gradient to ensure an adequately large cooled surface area.

Air has a very low thermal conductivity, but it can be used to simultaneously elevate evaporative cooling. Its much lower density reduces the power requirements for pumping. Unfortunately, its lower specific heat (about 25% that of water and ice) means that thermal equilibrium is approached more rapidly. This necessitates the use of flows approaching 300 $l.min^{-1}$ (Fonseca, 1983) that can negate the benefit of its lower density. Furthermore, in contaminated environments, the use of environmental air is no longer possible, necessitating the use of filters or the provision of gas from pressurised cylinders.

4.6.1.2 Selecting the surface area to be cooled

Design modifications that are dedicated to increasing the contact surface area are the most effective manner through which to increase heat extraction, since heat extraction varies as a linear function of the cooled surface area (Figure 11). With the size of the cooled surface area typically ranging from about 0.13 m^2 to 0.18 m^2, adding a contact surface area the size of the head (0.2 m^2), for water-cooled ensemble being provided with water at 15°C, will increase heat extraction by almost 730 Watts.

- Increasing the contact surface area by 0.035 m^2 (less than the size of the hand) is as effective as lowering the inflow water temperature by 5°C.
- Increasing the contact surface area by 0.73 m^2 (the approximate size of the lower limbs) is ten times as effective as lowering the inflow water temperature by 10°C.

One can change both the size of the cooled surface area and the location of that area. Five skin regions were more closely investigated in Section 4: hands, feet, thigh, lower leg and head. Two regions were subsequently excluded from further consideration: the feet (due to an inadequate blood supply close to the skin surface), and the head (due to its low surface area to mass ratio and its powerful negative feedback role with sweating). It is recommended that selected regional cooling be focussed on the **hands, thigh and lower leg**.

4.6.1.3 Selecting the optimal coolant temperature

Changing the inflow temperature by 5°C will modify heat removal by about 130 Watts. This relationship is constant across the entire, physiologically-relevant range of inflow temperatures. However, since the onset of vasoconstriction occurs at a T_{skin} between 32-33°C (Veicsteinas *et al.*, 1982), very low inflow temperatures result in reduced skin blood flow and heat extraction (Pergola *et al*, 1994), and are also quite uncomfortable.

This problem can been addressed in two ways. First, one could elevate the temperature of the coolant (water and air only). Second, one could use an intermittent cooling protocol (see below). It is recommended that both of these solutions be adopted, with the coolant temperatures being about 20°C.

4.6.1.4 Selecting the desired coolant flow

Since increasing the flow of liquid coolants will result in only very small increases in heat extraction (Figure 12), it is recommended that coolant flow be regarded as a low design priority, unless the coolant is air, which requires flows >300 l.min^{-1}. However, it is recommended that an intermittent liquid cooling protocol be used to attenuate the fall in skin temperature. Since the nature of the intermittent cooling does not appear to affect heat extraction (Cheuvront *et al.*, 2003), it is recommended that alternating, square-wave cooling cycles be used, using either 2- or 4-min, symmetrical cooling periods.

4.6.1.5 The selection of cooling systems

Decisions relating to the selection of cooling systems are largely dictated by the operational requirements of personnel, and the environment in which they are required to work. Nevertheless, several critical questions must be answered by those making the decision to use, or not to use, auxiliary cooling systems. These may be grouped under three general classifications: environmental; operational and system considerations.

4.6.1.6 Environmental considerations

The working environment encompasses factors such as **air temperature**, **clothing configuration** and the **intensity of work** (exercise). It is incorrect to assume that work in a cold environment will never require auxiliary cooling, since the interaction of work intensity, which dictates heat production, and clothing, which modifies heat loss, will determine the compensability of the working environment and the thermal load placed upon the worker (Figure 9). These interactions are complex. A simplified approach to this, using air temperature, clothing and work intensity, has been summarised within Tables 6 and 7.

Three broad classifications of environmental temperature are dealt with: cold, temperate and hot. Three clothing configurations are also addressed: minimal clothing (the ADF camouflaged, combat fatigues), multiple layers of clothing (*e.g.* clothing worn pilots) and encapsulating clothing (*e.g.* NBC clothing). Finally, three operational work intensities are used: rest, moderate exercise and heavy exercise. Table 6 presents situations for which auxiliary cooling will not usually be required.

Table 4.7 deals with situations where auxiliary cooling may be needed. Of course, there are some situations which, and personnel who, fall along the boundaries of these environmental conditions. These scenarios require closer and individualised assessment.

4.6.1.7 Operational considerations

A wide range of operational factors can impact upon the selection of an auxiliary cooling system. These include:

- **The mobility requirements of personnel**: important versus unimportant operational consideration
- **The mass of the cooling system**: important versus unimportant
- **The duration for which cooling is required**: <2 hours versus >2 hours
- **The power source of the cooling system**: portable versus unlimited.

These operational factors, whilst separated here, are often tightly related. For example, the requirement for a portable system may restrict the options available for system mass, cooling duration and its power source.

Once the decision has been taken to implement auxiliary cooling, Figure 4.15 is designed to lead the decision-making process such that, through answering each question, the decision maker is led to the recommended cooling system (Table 4.8).

Table 4.6: Environmental conditions for which auxiliary cooling is not required.

Factor	Classification	Environmental state									
Environmental temperature	Cold	X	X	X	X	X	■	■	■	■	■
	Temperate	■	■	■	■	■	X	X	X	X	■
	Hot	■	■	■	■	■	■	■	■	■	X
Clothing insulation	Standard ADF	X	■	■	X	■	X	■	■	■	X
	Heavy ADF	■	X	■	■	X	■	X	■	X	■
	Encapsulating	■	■	X	■	■	■	■	X	■	■
Work intensity	Rest	X	X	X	■	■	X	X	X	■	X
	Moderate	■	■	■	X	X	■	■	■	X	■
	Heavy	■	■	■	■	■	■	■	■	■	■

Notes for using this Table: For each environmental state, select one option (classification) from each of the three broad categories (factors: temperature, clothing, work) that best represents the most relevant set of operational conditions. Black cells correspond to conditions that may require auxiliary cooling, whilst cells containing crosses indicate combinations of factors for which cooling may not be necessary. Within the “temperature” category, find the first classification containing a cross, move vertically to the “clothing insulation” category to your selected cell. If your target cell is black, move to the right to the next column within that temperature, then move vertically to the cell for “work intensity”. If you find that all three cells contain crosses, then the auxiliary cooling may not be required.

Table 4.7: Environmental conditions for which auxiliary (microclimate) cooling may be required.

Factor	Classification	Environmental state																	
Environmental temperature	Cold	X	X	X	X	■	■	■	■	■	■	■	■	■	■	■	■	■	■
	Temperate	■	■	■	■	X	X	X	X	X	X	■	■	■	■	■	■	■	■
	Hot	■	■	■	■	■	■	■	■	■	■	X	X	X	X	X	X	X	X
Clothing insulation	Standard ADF	X	■	■	■	X	X	■	■	■	■	X	X	■	■	■	■	■	■
	Heavy ADF	■	X	■	■	■	■	X	X	■	■	■	■	X	X	X	■	■	■
	Encapsulating	■	■	X	X	■	■	■	■	X	X	■	■	■	■	■	X	X	X
Work intensity	Rest	■	■	■	■	■	■	■	■	■	■	■	■	X	■	■	X	■	■
	Moderate	■	■	X	■	X	■	X	■	X	■	X	■	■	X	■	■	X	■
	Heavy	X	X	■	X	■	X	■	X	■	X	■	X	■	■	X	■	■	X

Notes for using this Tables: For each environmental state, select one option (classification) from each of the three broad categories (factors: temperature, clothing, work) that best represents the most relevant set of operational conditions. Black cells correspond to conditions that may not require auxiliary cooling, whilst cells containing crosses indicate combinations of factors for which cooling may be necessary. Within the "temperature" category, find the first classification containing a cross, move vertically to the "clothing insulation" category to your selected cell. If your target cell is black, move to the right to the next column within that temperature, then move vertically to the cell for "work intensity". If you find that all three cells contain crosses, then the auxiliary cooling may be required.

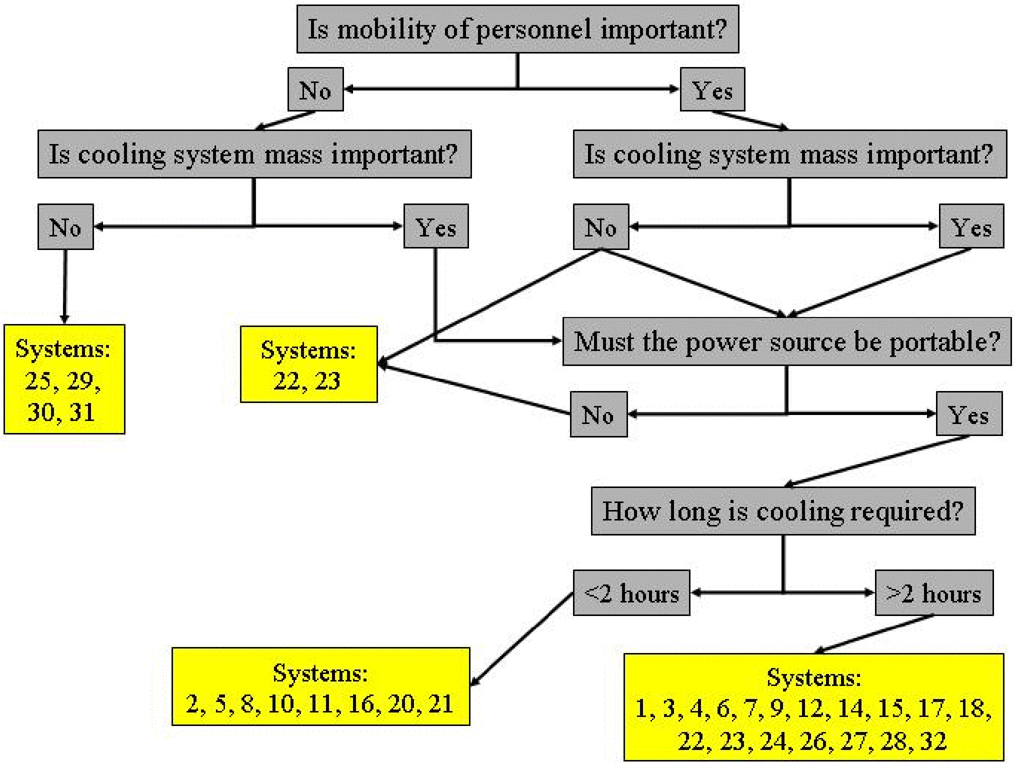

Figure 4.15: Flowchart to guide the selection of auxiliary (microclimate) cooling systems (see Table 4.8 for details of cooling systems).

4.6.1.8 Cooling system considerations

The current generation of auxiliary cooling systems have not kept pace with advances within the literature. Thus, the capacity to use either localised cooling or intermittent cooling is generally not currently available. When such systems do become available, it will be necessary to address several additional system attributes:

- **Does the cooling system allow for variations in the cooled surface area?**
    - whole-body cooling
    - torso only cooling
    - limbs only cooling
- **Does the cooling system allow for discontinuous cooling?**
    - continuous cooling only
    - intermittent cooling is possible
- **Will discontinuous systems allow for modification of the cooling duty cycle?**
    - yes
    - no.

4.6.1.9 An auxiliary cooling system matrix

Table 4.8: Auxiliary cooling systems.

Code	Name	Manufacturer	Description	Mass (kg)	Duration (h)	Power (W)	Inlet temp. (°C)
1	Coolvest classic	Coolsports	Phase-change material technology	2.18	2.0-2.5	†	18
2	Coolvest lite		Concealable light weight cooling.	1.73	1.5-2.0	†	18
3	Coolvest deluxe		Largest and heaviest; hotter environments	3.95	>2.5	†	18
4	Motorsport coolvest		Designed specifically for motor sport	2.18	2.0-2.5	†	18
5	Arctic Blast PCS	Mistymate	Battery operated motor powers a high velocity fan that delivers wind speeds over 25 mph; spray nozzle emits 45-50 $ml.min^{-1}$		1.0-2.0	†	water/ice
6	Pump 24 oz			1.36	4	†	water/ice
7	Pump 16 oz			0.91	2.5-3.0	†	water/ice
8	Pump 10 oz			0.45	<1.0	†	water/ice

Code	Name	Manufacturer	Description	Mass (kg)	Duration (h)	Power (W)	Inlet temp. (°C)
9	Rotary compressors	Aspen Systems	Miniature refrigeration unit chills heat transfer liquid (usually water), which is then circulated to a tube-lined garment	4.1	-	300	12.2-24
10	Kold Vest	Dura Kold	10 ice mats included	†	2	†	ice
11	Kold Kollar		2 ice mats included	†	2	†	ice
12	Gel-ice cooling	SteeleVest	Heat is absorbed by frozen gel (Thermo-Strips) inserted into the vest	3-4.5	4	89.2	12.8-18.3
13	Phase-change material		Paraffin materials that melt when absorbing heat, and solidify when releasing heat	3-4.5	4	59.5	12.8oC-18.3
14	Evaporative material		3-layer composite fabric designed to evaporate water; not effective under protective clothing	1.82-3.18	2.5	~20	-
15	Cool Jacket	Glacier Tek	Cool packs made of phase-change material	2.5	2.5	400	15
16	Economy Cool Vest		Packs rechargeable in ice-water (~20 min)	2.5	2	400	15
17	Classic Cool Vest		Heavy-duty nylon mesh outer shell	2.5	2.5	400	15

Code	Name	Manufacturer	Description	Mass (kg)	Duration (h)	Power (W)	Inlet temp. (°C)
18	Concealable Cool Vest		Lightest of the Glacier Tek cool vests	<2.5	2.5	400	15
19	Vortex personal air conditioner	Innovative Compressed Air Technology	Uses compressed air to separate cool and hot air, and can generate temperatures ~37°C below inlet air temperature	†	-	†	15.5
20	SWEDE Cooling Vest	First Line Technology	21 phase-change material elements; no batteries, ice or pumps required	2	0.75-2.0	†	<27
21	Personal Cooling System	Sharper Image	Motor driven fan that sprays cool water on face	†	2.0-4.0	†	†
22	Cardio-cool Vest	Med-Eng *suit*	Snug fit to upper body gives a full range of motion.	†	-	-	11
23	Cool Tubesuit		The COOL Tubesuit is engineered for maximum, yet controllable, full body cooling in extreme heat environments.	~1.5	-	-	11

Code	Name	Manufacturer	Description	Mass (kg)	Duration (h)	Power (W)	Inlet temp. (°C)
0.458	PC201R	*chiller*	Ice-based personal chiller designed specifically for use with todays wide range of personal protective equipment.	2.9	2.5	290	11
23b	DC230		Uses vapour compression to provide continuous active cooling in a portable system for 2 people.	14	2.5	500	11
23c	DC210		A portable ice based chiller which proveds cooling for up to two individuals.	9.3-13	2.5	1000	11
24	Stay Cool Vest	Coamfashions	Cool packs draw heat away from the body, giving a similar feeling to jumping into a swimming pool	2.5	8	†	15
25	Core-control Systems	Mine Safety Appliances Company	Pumps ice water through plastic tubes sewn in undergarment: shirt, pants, hood.	†	†	†	ice
26	Enhanced personal cooling garment	Mustang Survival Corporation	Vest provides thin layer of water close to skin surface	0.4	-	†	~15

Code	Name	Manufacturer	Description	Mass (kg)	Duration (h)	Power (W)	Inlet temp. (°C)
27	Air cooling vest MSF833			†	†	†	†
28	Zeolite vacuum adsorption technology		Absorbs water which, when released, can rapidly cool and freeze water	<6	>2.5	50	-
29	Air Warrior Microclimate Cooler	Foster Miller	Hardware developed for UH-60, CH-47D, and OH-58D aircraft	5.9	-	324	-
30	AH-64D Apache Microclimate Cooling Subsystem		Uses cool air from vapour compression systems of aircraft to cool both pilots	3.86 (per pilot)	-	360	†
31	F-15 and F-16 Aircrew Personal Environmental Control System		Uses cool air from environmental control system to cool aircrew	†	-	300	†

Code	Name	Manufacturer	Description	Mass (kg)	Duration (h)	Power (W)	Inlet temp. (°C)
32	Advanced lightweight microclimate cooling system	USARIEM	Electrically driven vapour cycle cooler that circulates a chilled fluid through a garment lined with tubing	~5	~3	230	~18-21

Notes: † = information unavailable; * = phase-change material: cooling effect ceases once the solid form of the material is completely transformed into its liquid phase.

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CHAPTER 5: THE PHYSIOLOGICAL AND COGNITIVE CONSEQUENCES OF WEARING NUCLEAR, BIOLOGICAL AND CHEMICAL PROTECTIVE CLOTHING WITH AND WITHOUT AUXILIARY COOLING.

5.1 Introduction

Individuals exposed to extreme environmental conditions are at risk of developing heat strain, which may lead to detriments in physiological and cognitive function and possibly heat illness. This risk is further increased when an individual is required to perform work wearing encapsulating protective clothing that will impede the normal physiological mechanisms for dissipating heat (Chapter 1). Some occupations require an individual to operate at peak cognitive performance, where a slight decrement in performance can result in devastating consequences. For example, Froom *et al.* (1993) found environmental heat stress elevated pilot error, whilst in Chapter 2 we have described impaired helicopter flight simulator performance during progressive hyperthermia. Such changes can reflect reduced cognitive function, and Faerevik and Reinertsen (2003) have shown that heat stress can contribute to deficits in both vigilance and multi-choice reaction time. Presumably, the use of biological and chemical (BC) protective clothing will exacerbate this state.

Elevations in core temperature (T_c) may lead to a detriments in cognitive function. However, the current literature does not provide a consensus concerning the interaction of heat strain and cognitive function. These limitations may be due to experimental design, including quantification of, and control over the thermal environment and the resultant thermal strain, which are often poorly addressed. In this regard, one could consider both static and dynamic thermal states, since thermoreceptor feedback relays such information to the brain. In the former case, and to the best of our knowledge, the impact of elevated and clamped (static) core and shell temperatures on cognitive function has rarely been considered as discussed in Chapter 1. This is important since, only when thermal strain is controlled, can one be certain that it is the thermal energy content *per se*, and not thermal transients that affect cognition. Furthermore, one must choose suitably sensitive cognitive-function indices, so that the affects of various thermal treatments can be determined.

Unless the external environment and physical work requirements can be controlled within certain limits, detriments in cognitive function are quite likely to occur. Therefore, it is important to determine a means with which these detriments can be avoided, or at least reduced. As discussed in Chapter 4, the use of a micro-climate cooling garment will potentially alleviate decreases in physiological and cognitive function. Several studies have investigated the use of a micro-climate cooling system whilst performing work in extreme environmental conditions, but there is little information available in the literature pertaining to the combined influences of heat upon physiological and cognitive function, and the result of using an auxiliary cooling device whilst exposed hot environmental conditions.

5.1.1 Aims of the study

This study was designed to investigate the physiological and cognitive responses when an individual is required to perform exercise while wearing a personal protective ensemble in an uncompensable heat stress environment. Further to this aim, the use of a current, commercially-available liquid-cooling garment was used to evaluate its effectiveness in cooling the individual. This study was designed to replicate the field-based observations (Chapter 2) achieved during the extreme environmental heat exposure for a target mean skin temperature of 39°C).

5.2 Methods

5.2.1 Subjects

Eight healthy, physically-active males (age 27.1 ±6.2 y; mass 80.0 ±8.4 kg; height 179.2 ±6.4 cm) volunteered to participated in this research. The subjects' characteristics are listed in Table 2.1. Females were excluded due to hormonal influences on core temperature and the need to delay testing to allow for the standardisation of these effects (Tenaglia *et al.*, 1999). Before subjects commenced trials, they were required to attend the thermal laboratory for a familiarisation session, lasting approximately 2 hours. During this session, subjects completed 7-10 repetitions of each of the cognitive function tests measured. This was necessary to ensure task learning had been achieved (Chapter 3). Following familiarisation, subjects completed each of three trials, acting as their own control, but only after providing a signed, written, informed consent. All procedures were approved by the Human Research Ethics Committee, University of Wollongong.

5.2.2 Experimental conditions

5.2.2.1 Determination of water temperature for liquid-cooling garment

Prior to the commencement of these experimental procedures, a theoretical evaluation of the current literature on auxiliary cooling devices (Chapter 4), as well as a mathematical prediction of the heat loss capabilities of the chosen liquid-cooling garment were conducted. The purpose of this evaluation was to obtain a first approximation of the water temperature for the perfusion garment that would successfully reduce the thermal strain of an individual required to exercise in a hot-dry environment (48°C, 20%RH). As a result of this evaluation, a water bath temperature of 20°C was chosen. Four pilot tests were then conducted to evaluate the effectiveness of cooling an individual using a water bath temperature of 20°C.

Two subjects participated in the pilot testing phase, where both were required on two separate occasions to perform 60 minutes of low-intensity exercise (approximately 30 watts on the cycle ergometer) while wearing the full ADF biological and chemical protective ensemble. The two trials differed in the environmental conditions to which each subject was exposed. These were a temperate environment (20°C, 40%RH) and a hot-dry environment (48°C, 20%RH).

Figure 5.1 illustrates the auditory canal and mean skin temperature results of one subject during the pilot study. It shows a clear upward shift for both the auditory canal and mean skin temperature measurements during the hot-dry trial with cooling compared to the control environment, with a mean difference of 0.52°C and 1.68°C for auditory canal and mean skin temperatures respectively between the two conditions. This difference was deemed unacceptable and therefore, 15°C was the chosen water bath temperature for the remainder of the study. However, no further pilot testing took place to evaluate its cooling effectiveness for these working and environmental conditions.

Table 5.1: Physical characteristics of subjects

Subject	**Age (years)**	**Mass (kg)**	**Height (cm)**
S1	21	81.64	184.0
S2	28	68.92	167.2
S3	21	70.98	181.2
S4	28	76.92	173.5
S5	38	81.32	185.1
S6	21	77.26	172.3
S7	27	91.94	184.9
S8	33	91.30	185.7
Mean	27.1	80.04	179.2
S.D.	6.2	8.4	7.2

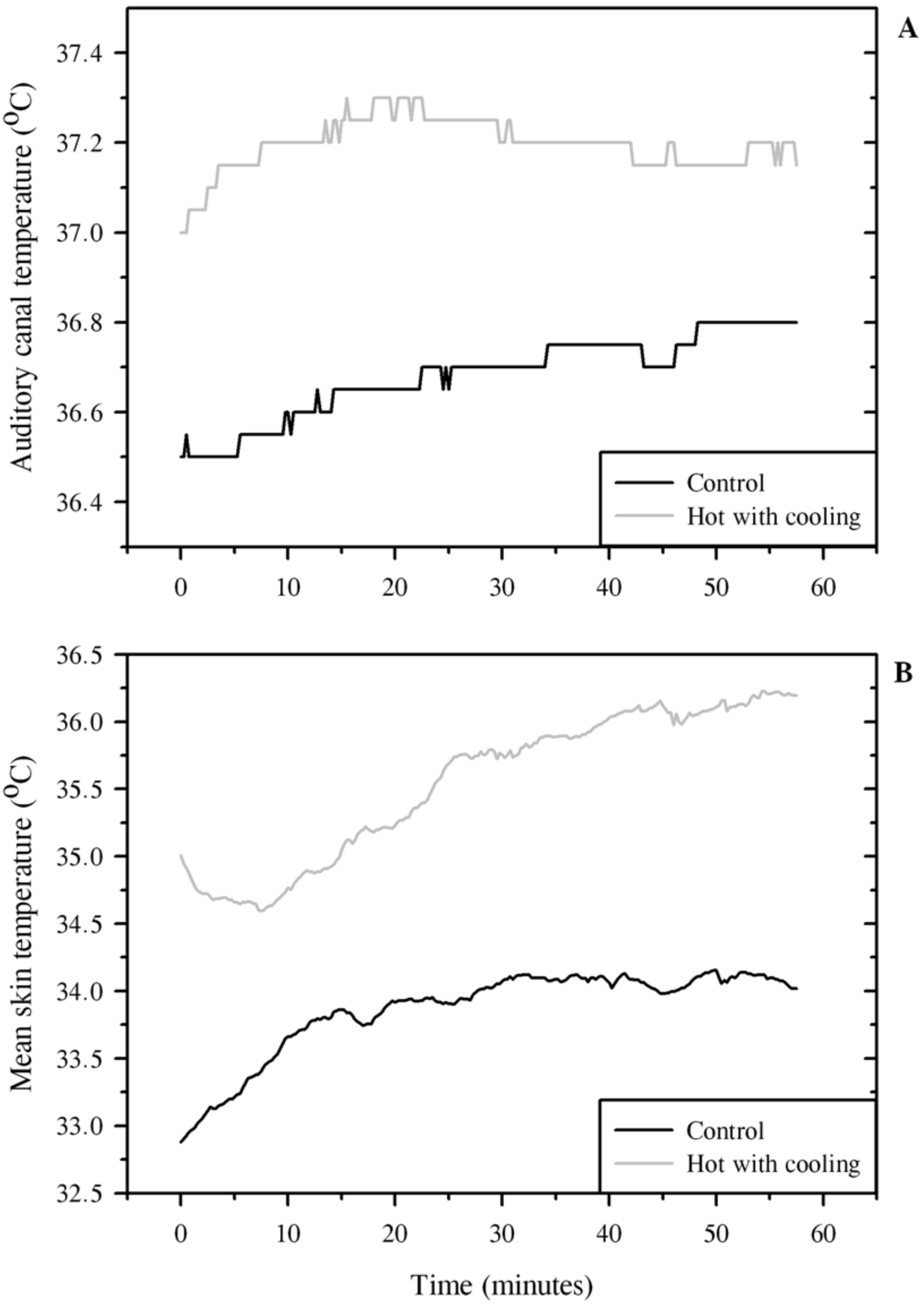

Figure 5.1 Auditory canal temperature (A) and mean skin temperature (B) responses for one subject during pilot testing to determine a suitable temperature for liquid-cooling garment during low intensity exercise (30 watts) on the cycle ergometer.

5.2.2.2 Environmental conditions

Each of the three trials differed in two ways: (i) the environmental condition in which each subject was exposed (temperate and hot-dry) and (ii) the activation state (active or inactive) of a liquid-cooling garment (Cool Tubesuit, Med-Eng, Ottawa, Canada), worn in each trial. However, subjects always wore the cooling garment. One trial was in a temperate environment (control: 20°C, 30% relative humidity) with inactive liquid-cooling. The other two trials were in a hot-dry environment (48°C, 20% relative humidity), with one trial having inactive cooling, and the other using active cooling (15°C). For the hot-dry trials, a substantial radiant heat source (infrared lamps ~750 Watts.m^{-2}) was also applied (to simulate radiant heat emitted from the sun).

5.2.3 Experimental procedures

For each trial, subjects completed low-intensity exercise (total metabolic rate of ~180 Watts) on the cycle ergometer for 2 hours, with 2-min rest periods every 13-min and were required to consume 200 ml of water (at room temperature) during each rest period. They each wore the liquid-cooling garment, the standard combat uniform (disruptive pattern camouflage: insulation 0.29 $m^2K.W^{-1}$), and the complete Australian Defence Force BC protective ensemble (including face mask, over boots and gloves). Physiological data were collected continuously, while psychophysical and cognitive function were collected intermittently (Table 5.2).

5.2.3.1 Experimental standardisation

The night prior to each trial, subjects were instructed to drink 15 ml.kg^{-1} of water and to eat an evening meal and breakfast high in carbohydrate and low in fat. Subjects were also required to refrain from strenuous exercise and the consumption of alcohol and tobacco within the 12-h period, and the use of caffeine for a 2-h period prior to testing. Rehydration was achieved, by subjects consuming an iso-osmotic drink equivalent to 150% of the total body mass change. Trials were at least two days apart to allow the subjects time to fully recover. The order in which these trials were performed was balanced.

Table 5.2: Experimental timeline

Time (min)	Activity summary
0	Subject arrival
0-5	Subject hydration check
5-60	Subject preparation (22°C)
65-70	Baseline data collection
70-85	Enter climate chamber (48°C, 20% RH or 20°C, 30% RH)
85-90	Baseline data collection
90-105	Exercise (180 W total metabolic heat production)
105-110	Rest and drink
110-125	Exercise (180 W total metabolic heat production)
125-130	Rest and drink
130-145	Exercise (180 W total metabolic heat production)
145-150	Rest and drink
150-165	Exercise (180 W total metabolic heat production)
165-170	Rest and drink
170-185	Exercise (180 W total metabolic heat production)
185-190	Rest and drink
190-205	Exercise (180 W total metabolic heat production)
205-210	Rest and drink
210-225	Exercise (180 W total metabolic heat production)
225-230	Rest and drink
230-250	Terminate experiment: supervised recovery

5.2.4 Data collection procedures

5.2.4.1 Physiological measurements

Core temperature and skin temperature were measured, and recorded throughout each trial at 15-second intervals using a portable data logger (Grant instruments Ltd., 1206 Series Squirrel, U.K.). Core temperature was measured at two sites; auditory canal and rectum (Edale Instruments Ltd, U.K.)). Subjects inserted their own rectal thermistor to a depth of 12cm past the anal sphincter. Auditory canal temperature was monitored using an ear-moulded plug with a thermistor protruding from the mould. This probe was positioned in the ear, insulated with cotton wool and held in place with waterproof tape. Skin thermistors (Type EU Yellow Springs Instruments Co. Ltd., Yellow Springs, U. S. A.) were placed carefully and securely using Transpore plastic tape to ensure the sensor was placed in direct contact with the skin surface, thereby reducing the influence of the water perfusion suit on the skin temperature measurement during the hot-dry trial with cooling. These were attached to eight sites (forehead, right scapula, right chest, right upper arm, left forearm, left dorsal hand, right anterior thigh and left posterior calf). All thermistors were calibrated before testing (Chapter 2). Mean skin temperature ($\overline{T}_{sk}$) was calculated using an area-weighted mean (ISO9886, 1992; after Hardy and DuBois, 1938):

$$\overline{T}_{sk} = 0.07 \cdot T_{sk\text{-}1} + 0.175 \cdot T_{sk\text{-}2} + 0.175 \cdot T_{sk\text{-}3} + 0.07 \cdot T_{sk\text{-}4} + 0.07 \cdot T_{sk\text{-}5} + 0.05 \cdot T_{sk\text{-}6} + 0.19 \cdot T_{sk\text{-}7} + 0.2 \cdot T_{sk\text{-}8}$$

where:

$T_{sk\text{-}1}$ = forehead

$T_{sk\text{-}2}$ = chest

$T_{sk\text{-}3}$ = scapula

$T_{sk\text{-}4}$ = arm

$T_{sk\text{-}5}$ = forearm

$T_{sk\text{-}6}$ = hand

$T_{sk\text{-}7}$ = thigh

$T_{sk\text{-}8}$ = calf

Cardiac frequency was monitored from ventricular depolarisation throughout each trial using a Polar heart rate monitor (Polar Electro Sports Tester, Finland) and later downloaded onto a computer. Data were recorded at 0.2 Hz. Gross nude mass changes of each subject for each trial was used to estimate sweat rate. These were recorded at the termination of the trial following complete drying of the subject (A and D electronic balance, Model No. fw-150k, CA, USA) . Evaporative sweat losses were also estimated from changes clothed masses, weighed before and after each trial.

5.2.4.2 Psychophysical indices

Subjects were asked, at 15-min intervals, to rate perceived work effort (exertion), thermal sensation, thermal discomfort, perceived skin wetness, and skin wetness discomfort. Subjects were provided with the relevant subjective scales prior to the start of the trial, with written and oral instruction on how to use each scale.

Thermal sensation

Thermal sensation was monitored using a modified version of the Gagge scale (Gagge *et al.*, 1967). The question was asked, "how does the temperature of your whole body feel?":

13-point thermal sensation scale

1	Unbearably cold
2	Extremely cold
3	Very cold
4	Cold
5	Cool
6	Slightly cool
7	Neutral
8	Slightly warm
9	Warm
10	Hot
11	Very hot
12	Extremely hot
13	Unbearably hot

Thermal discomfort

Thermal discomfort was evaluated using another modified scale (Gagge *et al.*, 1967), and in response to the question: “how does the temperature of your body feel?”.

The 5-point thermal discomfort scale

1.0	Comfortable
1.5	
2.0	Slightly uncomfortable
2.5	
3.0	Uncomfortable
3.5	
4.0	Very uncomfortable
4.5	
5.0	Extremely uncomfortable

Perceived exertion

Perceived exertion was evaluated using the 15 point Borg scale (Borg, 1962), and in response to the question: “How hard are you exercising?”.

The 15-point Borg scale

6	
7	Very, very light
8	
9	Very light
10	
11	Fairly light
12	
13	Somewhat hard
14	
15	Hard
16	
17	Very hard
18	
19	Very, very hard
20	

Perceived skin wetness

Perceived skin wetness was evaluated using another modified scale, and in response to the question: "how wet or moist does your skin (clothing) feel?".

13-point wetness sensation scale

1	Unbearably dry
2	Extremely dry
3	Very dry
4	Dry
5	Slightly dry
6	Very slightly dry
7	Neutral
8	Slightly moist
9	Moist
10	Wet
11	Very wet
12	Extremely wet
13	Totally saturated

Perceived skin wetness discomfort

Perceived skin wetness discomfort was evaluated using another modified scale (Gagge *et al.*, 1967), and in response to the question: "how comfortable are you with the wetness of your skin (clothing)?".

The 5-point skin wetness discomfort scale

1.0	Comfortable
1.5	
2.0	Slightly uncomfortable
2.5	
3.0	Uncomfortable
3.5	
4.0	Very uncomfortable
4.5	

5.0 Extremely uncomfortable

5.2.4.3 Cognitive function measures

Cognitive function was assessed using the MiniCog Rapid Assessment Battery (Shephard and Kosslyn, 2005). The test battery included assessment of attention (vigilance, divided attention, and filtering), perceptual reaction time, verbal working memory and problem solving (three term reasoning) and was administered every 15 minutes, with each battery taking approximately 13 minutes to complete.

Vigilance

Vigilance is the ability to concentrate for a sustained period, whilst waiting for a specific event to occur (Kruegar, 1989; Leproult *et al.*, 2003; Ballard, 2001). A series of geometric shapes (rectangles, parallelograms and trapezoids) was randomly presented (500 ms) to the subjects, followed by an inter-trial interval of 1, 2 or 3 s. The subject responded during this interval. ***The task:*** Subject was required to recognise and identify the correct (and incorrect) shapes as quickly as possible; the shape must be in the same form and orientation as the target shape. ***Test duration:*** For each administration, 90 trials were presented, lasting about 3-4 min.

Three-term reasoning

This is a classical cognitive function test (Yama, 1986) in which three simple statements are made, and the subject was required to answer whether or not the third statement was "true" or "false". ***Test duration:*** Eight trials were presented, with 45 s allotted to each response.

Filtering

This test focusses upon the ability to select relevant (important) information from a range of stimuli, such that attention is only directed to that information which is relevant to the current task. This test is a modification of the classical Stroop test (Stroop, 1935), and appears as a black and white version (numbered Stroop). ***The task:*** Subject was presented with arrays of three numbers (4, 5 or 6). The numbers were always the same within an array, but the number of digits within a presentation varied (either 4, 5 or 6 numbers). The subject had to choose how many numbers were presented by attending to the total number, and not the actual numbers being presented (*e.g.* four 5s: 5555). The subject had 10 s to respond. ***Test duration:*** 84 trials were presented, with each lasting a maximum of 10 s. This test lasted 2-3 min.

Verbal working memory

This test also evaluates the ability to recall and use information held within the working memory (two-back test: Baddeley, 1986; Flowers, 1985): digit recall. ***The task:*** Four numbers were presented to the subject (1, 2, 3, 4), each in the centre of the screen. The subject must recall whether or not the digit is the same as that presented two-back in the sequence. ***Test duration:*** 60 trials were provided, with each stimulus lasting just 1 s. The subject had only 1 s to respond (the inter-trial interval).

Divided attention

This test is part of the vigilance test battery, and requires the subject to focus upon two different (unrelated) stimuli. ***The task:*** Subjects were presented with four geometric shapes (circle, triangle, square, star) that appear in four shades (white, grey, dark grey, black). The two recognition criteria are therefore shape and shade. The subject must identify either of two states (ignoring all other information): circles or white shapes, or triangles and black shapes. ***Test duration:*** 40 trials were administered, with 10 s allowed for responding: duration 2-3 min.

Perceptual reaction time

The purpose of this test is to evaluate whether or not changes in reaction time are a function of altered cognitive or physical (motor control) states. ***The task:*** Subjects were given a stimulus (small oval) that appeared over one of four keys. The subject then responded by pressing that key as quickly as possible. ***Test duration:*** 40 trials were administered, with a 5-s inter-trial interval.

5.2.5 Statistical Analysis

Statistical analyses were performed on all physiological and psychophysical measures using a two-way analysis of variance, with repeated measures. Sources of significant differences were isolated using Tukey's *HSD* statistic. One-way analysis of variance was performed on all cognitive function parameters. *Alpha* was set at 0.05 for all analyses. Variables are reported as means with standard error of the means (±SEM) unless stated otherwise as standard deviation (SD).

5.3 Results

The current research protocol elicited a significant heat stress upon subjects when exposed to the hot-dry environment with inactive cooling. This was evident by a significant increase in all physiological measurements as well as psychophysical indices, when compared to the control and hot-dry trials with active cooling. However, all subjects started the three trials from a common, resting physiological baseline where no significant differences were apparent ($P>0.05$).

Due to the variability of subject tolerance to the heat, not all subjects were able to complete all three trials. While each of the eight subjects completed the control and the hot-dry with active cooling trials (120 min), the duration of the hot-dry trial without cooling, was significantly lower ($P<0.05$) with an average duration of only 98.7 min (±4.2). Only one subject completed the hot-dry trial with inactive cooling, two subjects terminated due to their rectal temperature reaching 39.5°C, with the remaining five subjects ending due to volitional fatigue.

5.3.1 Core temperature

Core temperature increased from baseline for all trials. However, the average increase in core temperature for the hot-dry trial with inactive cooling was 1.95°C (±0.12). This increase was significantly greater than the control, 0.16°C (±0.05) ($F=84.31$; $df=1,7$; $P<0.05$) and the hot-dry environment with an activated cooling system, 0.45°C (±0.06) ($F=98.62$; $df=1,7$; $P<0.05$, Figure 5.2). Although the increase in core temperature for the hot-dry environmental exposures were due to the combined effect of metabolic work and the hot environment, it was only the effect of metabolic work that caused the slight rise in core temperature for the control trial.

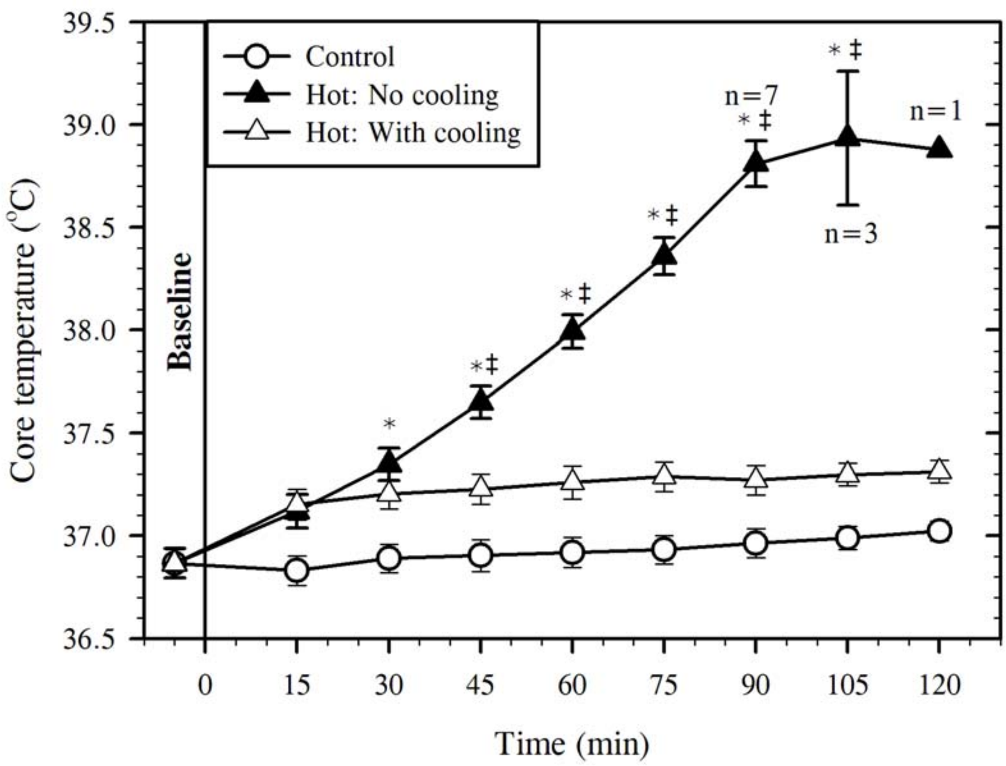

Figure 5.2 Core temperatures (mean of auditory canal and rectal temperatures) during an exercise protocol when exposed to a temperate environment (control), hot-dry inactive cooling or hot-dry with an activated cooling system. Values are means with standard error of the means. * Significantly different from control. ‡Significantly different from hot-dry trial with active cooling. Subject is specified, to illustrate the number of subjects still exercising at that point.

From approximately 30 min of heat exposure, the core temperature data for the hot-dry trial without active cooling increased at a significantly faster rate than for both the other trials ($P<0.05$). In fact, there were no significant main effects ($F=7.89$; $df=1,7$; $P>0.05$) or time by uniform interactions ($F=12.94$; $df=6, 42$; $P>0.05$) between the control trial and the hot-dry trial with an activated cooling system. Further to this, the maximum core temperature measured for the control trial was 37.0°C (±0.04), and for the hot-dry trial with active cooling was 37.3°C (±0.06), whereas for the hot-dry trial without an activated cooling system, the maximum recorded core temperature was 38.9°C (±0.14). One could therefore say that the cooling garment successfully restored core temperature to close to that of the control trials.

5.3.2 Skin temperature

A similar response was evident for mean skin temperature ($\overline{T}_{sk}$), however statistical analysis revealed a significantly higher $\overline{T}_{sk}$ after only 15 min (Figure 5.3) of exercise for the hot-dry trial with inactive cooling when compared to both the control ($F=179.51$; $df=1,7$; $P<0.05$) and hot-dry trial with active cooling ($F=21.52$; $df=1,7$; $P<0.05$). This sudden increase in mean skin temperature was due to the immediate exposure to the hot-dry environment while wearing a personal protective ensemble, without the addition of an auxiliary cooling device. Therefore, in this instance, heat was trapped within the garment causing an immediate and continual rise in $\overline{T}_{sk}$, where the resultant maximum $\overline{T}_{sk}$ for the hot-dry trial with inactive cooling was 38.6°C (±0.18).

Although, $\overline{T}_{sk}$ did not continue to increase over time for the control and hot-dry trial with active cooling, $\overline{T}_{sk}$ did increase from baseline within the first 15 minutes of exercise for all three trials. This observed increase accounted for approximately 79.5%, 77.4% and 84.5% of the total change in $\overline{T}_{sk}$ for the control, hot-dry with active cooling and hot-dry trial without active cooling respectively. That is, just by donning the clothing and starting exercise in the heat or temperate environment, a substantial increase in $\overline{T}_{sk}$ occurred. However, the following 105 minutes of exercise resulted in an increase in $\overline{T}_{sk}$ of only 0.7°C (±0.3) and 0.5°C (±0.2) for the control and hot-dry trial with active cooling, which was significantly ($P<0.05$) lower than that of the hot-dry trial without cooling of 1.2°C (±0.3).

Further to these observations, statistical analysis revealed no significant main effect (F=0.10; df=1,7; P>0.05) or time by environmental interactions (F=0.95; df=6,42; P>0.05) between the hot-dry trial with an activated cooling device when compared to the control condition. This observation occurred because of the careful selection of water bath temperature and hence effective heat removal from within the garment. That is, $\overline{T}_{sk}$ remained less than 33°C throughout the trial with the liquid cooling garment active, but reached levels between 37.5°C and 39.5°C during the hot-dry trial without cooling. One can therefore conclude that, on the basis of these data, the decision to choose a lower perfusion temperature (Section 5.2.2.1) was justified. Indeed, the water temperature resulted in a very close match of $\overline{T}_{sk}$ for both the control and active cooling trials.

5.3.3 Cardiac frequency

As occurred for the body temperature measurements, between-condition differences (P<0.05) were also found for cardiac frequency (f_c) responses. A sharp elevation at the start of exercise occurred for all trials with a mean increase of 15.7 (±3.6), 17.7 (±2.7) and 23.2 (±2.9) beats.min^{-1} (P>0.05) within the first 15 min of exposure for the control, hot-dry trial with cooling and hot-dry trial without cooling, respectively. This level of f_c was maintained for the remainder of the control and hot-dry trial with active cooling where a further increase of only 4.0 (±4.5) and 0.1 (±1.4) beats.min^{-1} occurred (Figure 5.4). This was statistically lower (P<0.05) than the hot-dry trial without cooling of 35.5 beats.min^{-1} (±4.6). Therefore, the resultant mean maximum f_c of 133.2 beats.min^{-1}, was also significantly higher (P<0.05) than the control (92.4 ±6.6) and the hot-dry trial with cooling (87.2 ±3.4) and subjects were working at approximately 48% (±3.2), 45% (±1.7) and 69% (±2.0) of their age predicted maximal heart rate, for the control, hot-dry trial with cooling and hot-dry trial without cooling respectively. This indicates that as time progressed, the effects of the hot-dry trial without cooling on f_c were more powerful than the other two conditions. Thus, for this trial, the longer the duration of the heat exposure the greater the cardiovascular strain.

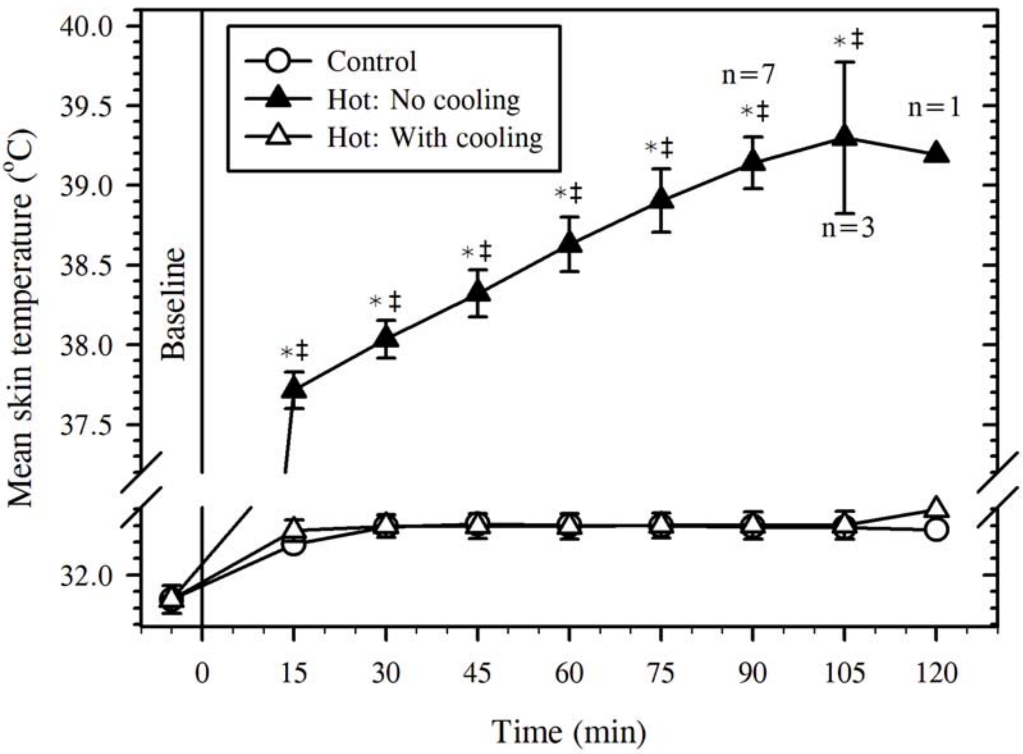

Figure 5.3 Mean skin temperatures during an exercise protocol when exposed to a temperate environment (control), hot-dry, inactive cooling or hot-dry, active cooling trials. Values are means with standard error of the means. *Significant different from control. ‡Significantly different from hot-dry trial with active cooling. Subject is specified, to illustrate the number of subjects still exercising at that point.

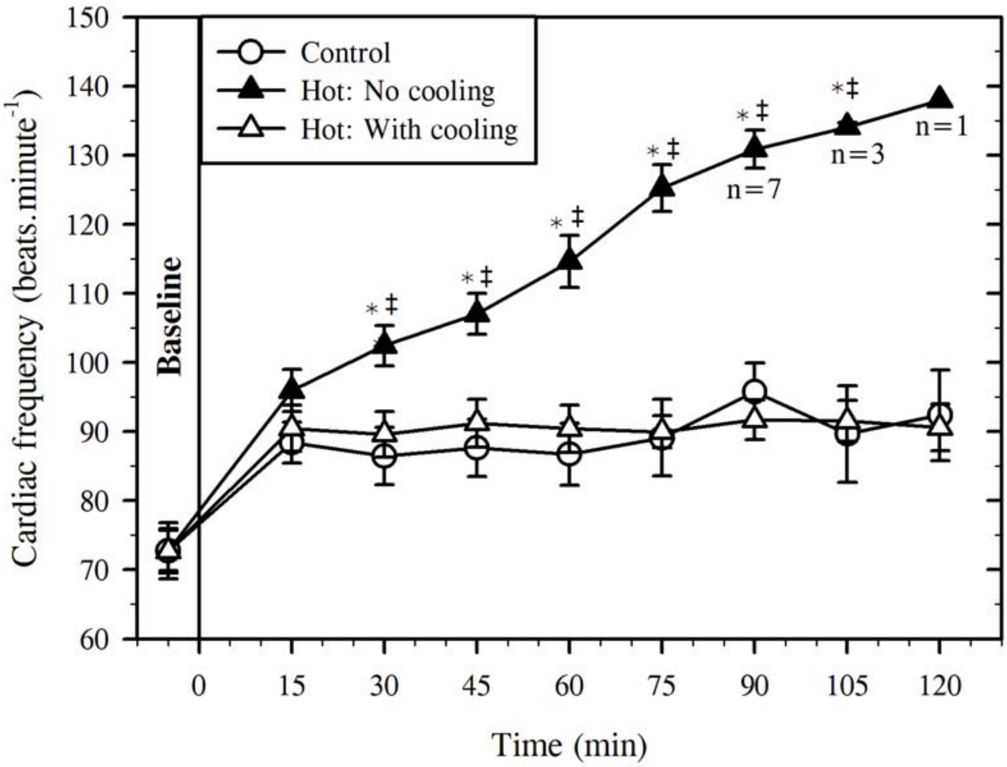

Figure 5.4 Cardiac frequency during an exercise protocol when exposed to a temperate environment (control), hot-dry, inactive cooling or hot-dry, active cooling trials. Values are means with standard error of the means. *Significantly different from control. ‡Significantly different from hot-dry trial with active cooling. Subject is specified, to illustrate the number of subjects still exercising at that point.

5.3.4 Whole body sweat and evaporation

Subjects produced considerably more sweat in the hot-dry trials without cooling when compared to the control and the hot-dry trials with cooling ($P<0.05$,) with losses of 0.85% ($\pm$0.12), 0.89% ($\pm$0.13) and 2.11% ($\pm$0.22) body mass for the control, hot-dry with cooling and hot-dry trials without cooling, respectively (Figure 5.5). No significant differences were found between the control and hot-dry trial with cooling ($P>0.05$), indicating that a significant amount of wasted sweat was trapped within the layers of the biological and protective ensemble during the hot-dry trial without an activated cooling system.

This increase in sweat production for the hot-dry trial without cooling appeared to be slightly advantageous in enhancing evaporative heat losses, where subjects lost 0.49 $kg.hr^{-1}$ ($\pm$0.01). This was significantly higher ($P<0.05$) than evaporative sweat losses for the control trial (0.20 $kg.hr^{-1}$ $\pm$0.02) and for the hot-dry trial with active cooling (0.28 $kg.hr^{-1}$ $\pm$0.04). Although the enhanced evaporative cooling was minimal, and appeared to have no effect on core or skin temperatures, for the hot-dry trial without cooling, the increased evaporation was the direct result of an increased water vapour pressure gradient between the inner layers (increased sweat production) of the clothing and the external environment, where relative humidity was constant (20% RH) for both the hot-dry exposures.

5.3.5 Psychophysical Indices

Ratings of perceived exertion (RPE) were very similar for all three experiential treatment groups. In fact, no significant differences ($P>0.05$) were found between any of the exposures prior to 70 minutes of exercise. After this time, a significant main effect was present for comparison between the hot-dry trial without cooling, and only the control trial ($F=6.36$; $df=1,6$; $P=0.0186$) and at 90 and 105 min. That is, subjects perceived the workload to be the same for all three trials prior to 70 minutes of exercise. Beyond 70 minutes, subjects perceived to be working significantly harder during the hot-dry trial with inactive cooling when compared to the control only (Figure 5.6).

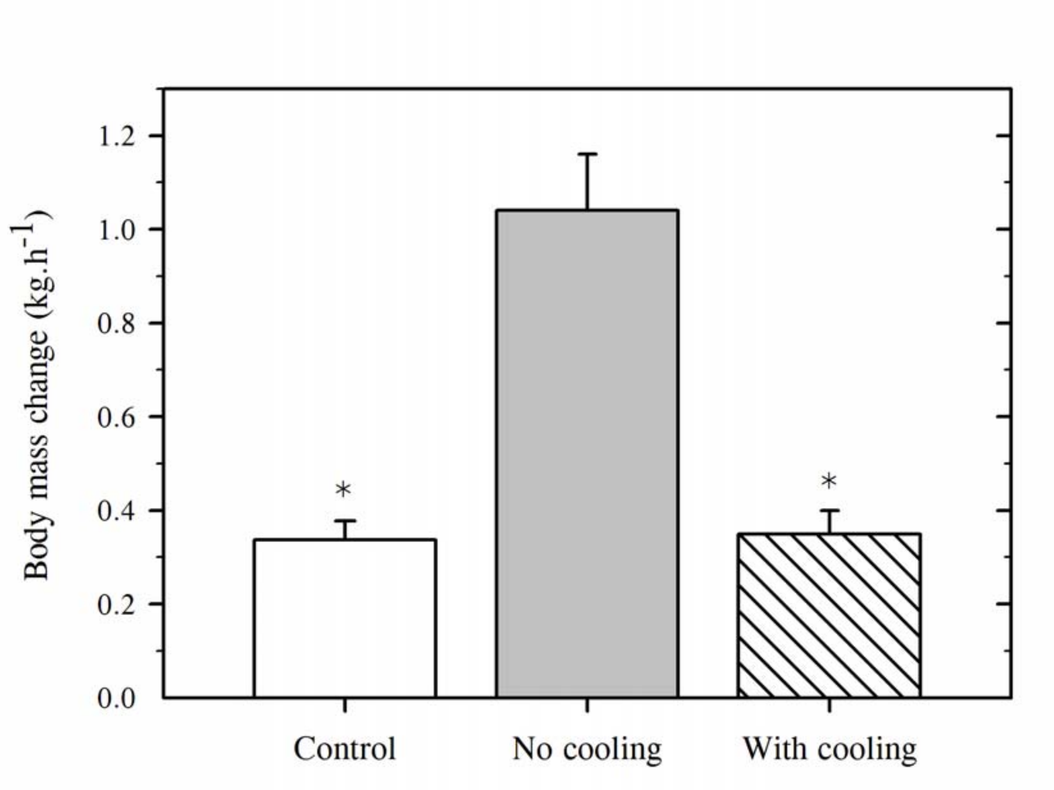

Figure 5.5. Body mass change (kg.h^{-1}) during an exercise protocol when exposed to a temperate environment (control), hot-dry, inactive cooling or hot-dry, active cooling trials. Values are means with standard error of the means. *Significantly different from hot-dry trial with inactive cooling. Subject is specified, to illustrate the number of subjects still exercising at that point.

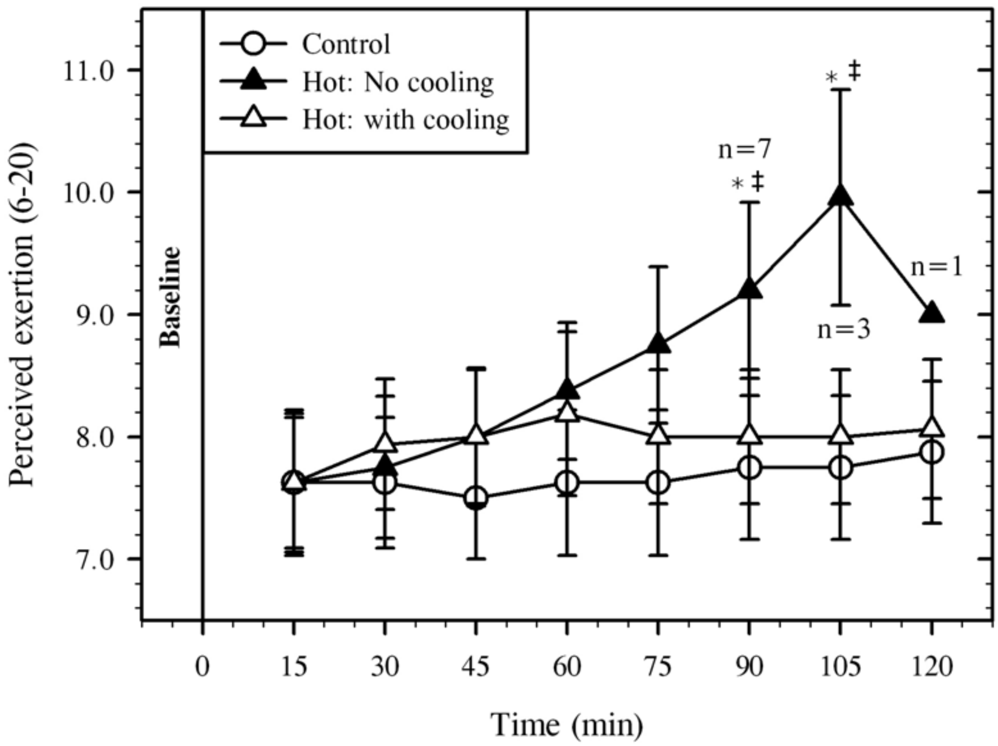

Figure 5.6 Ratings of perceived exertion during an exercise protocol when exposed to a temperate environment (control), hot-dry, inactive cooling or hot-dry, active cooling trials. Values are means with standard error of the means. *Significantly different from control. Subject is specified, to illustrate the number of subjects still exercising at that point.

Thermal sensation, thermal discomfort, perceived skin wetness and skin wetness discomfort data are presented in Figure 5.7, with final responses presented in Table 5.3. Significant differences were evident for thermal sensation, thermal discomfort, perceived skin wetness and skin wetness discomfort from 15 minutes until the completion of exercise for the hot-dry with inactive cooling trials when compared to the control and hot-dry trial with active cooling ($P < 0.05$). No sources of significance were found between the control and hot-dry trial with active cooling trials ($P > 0.05$).

5.3.6 Cognitive function parameters

There were no between-trial differences for any of the cognitive function measures (Figure 5.8, $P > 0.05$) even though the thermal strain clearly and significantly effected physiological performance. However, the final recorded error rate for vigilance, divided attention verbal working memory and three term reasoning were higher for the hot-dry trial without cooling (Table 5.4). These differences were not significant. Therefore, although these scores were of no apparent significance, some subjects were making consistently more errors at the final stage of the hot-dry trial without an activated cooling system.

5.4 Discussion

The current investigation was designed to evaluate (i) the effects of hot-dry environmental conditions on physiological and cognitive function and (ii) to assess the amelioration capabilities of a liquid-cooling garment used during the heat stress exposure. The results indicate that exposure to extreme hot-dry environmental conditions, while performing light work, elicited a significant physiological heat strain within the individual. This comes as no surprise, as there is a vast amount of literature that demonstrates this. Indeed, research into the physiological effects of extreme heat exposure can be found as early as 1775 (Blagden, 1775). However, in this investigation its has been shown that the chosen liquid-cooling garment can successfully ameliorate thermal strain in individuals clothed in biological and chemical protective ensembles and exposed to environmental conditions of 48°C, 20% RH, whilst performing very light work.

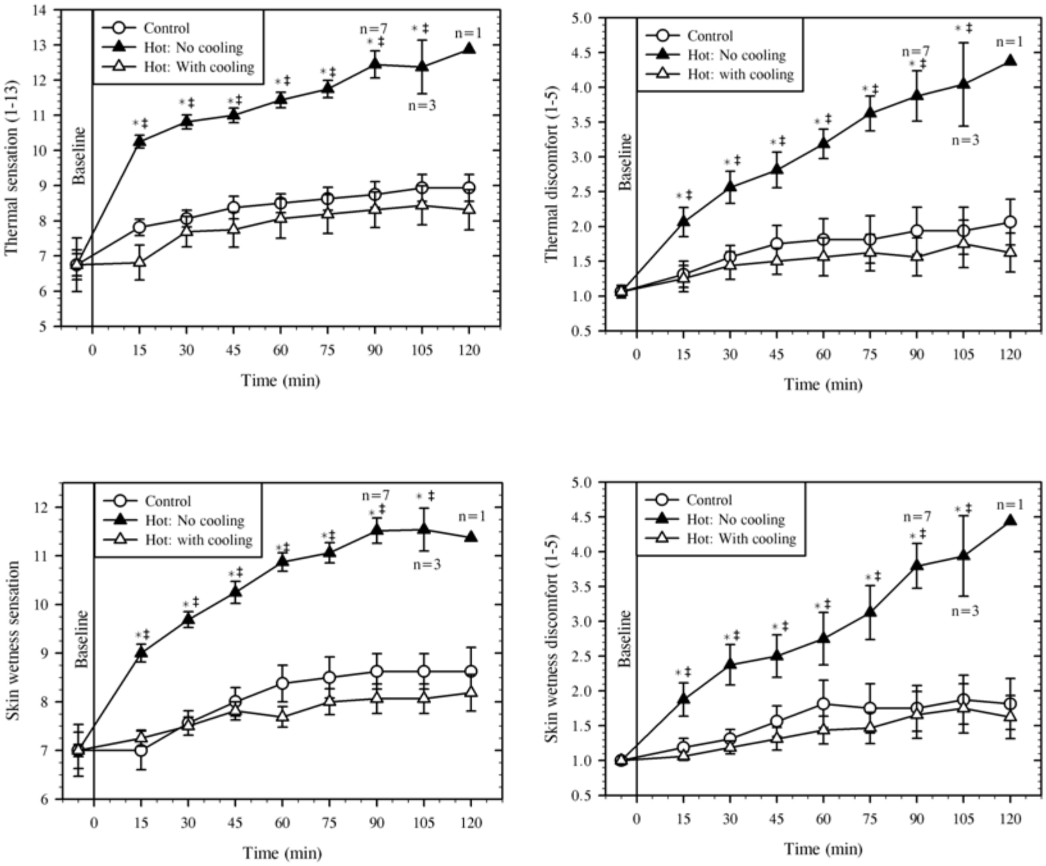

Figure 5.7: Psychophysical responses during an exercise protocol when exposed to a temperate environment (control), hot-dry, inactive cooling or hot-dry, active cooling trials. Values are means with standard error of the means. *Significantly different from control.

Table 5.3: Psychophysical indices for individuals required to perform work during rest and at completion of exercise when exposed to three different heat stress environments.

	Control	**Hot-dry: inactive cooling**	**Hot-dry: active cooling**
Perceived exertion	7.9 (0.6)*	10.1 (0.5)	7.9 (0.6)*
Thermal sensation	8.9 (0.4)*	11.6 (0.3)	7.9 (0.6)*
Thermal discomfort	1.8 (0.3)*	3.9 (0.3)	1.6 (0.3)*
Skin wetness sensation	8.8 (0.5)*	11.2 (0.4)	8.2 (0.4)*
Skin wetness discomfort	1.8 (0.4)*	4.0 (0.6)	1.6 (0.3)*

Values are means to with standard error of the mean (n=8) of the final 5 minutes of testing.

* Significantly different from hot-dry inactive cooling trials.

Table 5.4: Cognitive function measures for individuals required to perform work during rest and at completion of exercise when exposed to three different heat stress environments.

	Control	Hot-dry: inactive cooling	Hot-dry: active cooling
Vigilance	4.3 (0.9)	8.1(2.5)	5.8 (1.4)
Three term reasoning	7.8 (2.3)	17.2 (7.8)	6.3 (3.3)
Filtering	6.1 (1.3)	6.5 (2.9)	6.5 (2.7)
Verbal working memory	9.4 (2.5)	14.5 (2.7)	7.4 (2.3)
Divided attention	6.3 (2.3)	9.1 (2.7)	6.3 (1.8)
Perceptual reaction time	5.3 (2.3)	6.6 (2.8)	8.4 (2.7)

Values are means to with standard error of the mean (n=8) of the final 5 minutes of testing.

* Significantly different from hot-dry inactive cooling trials.

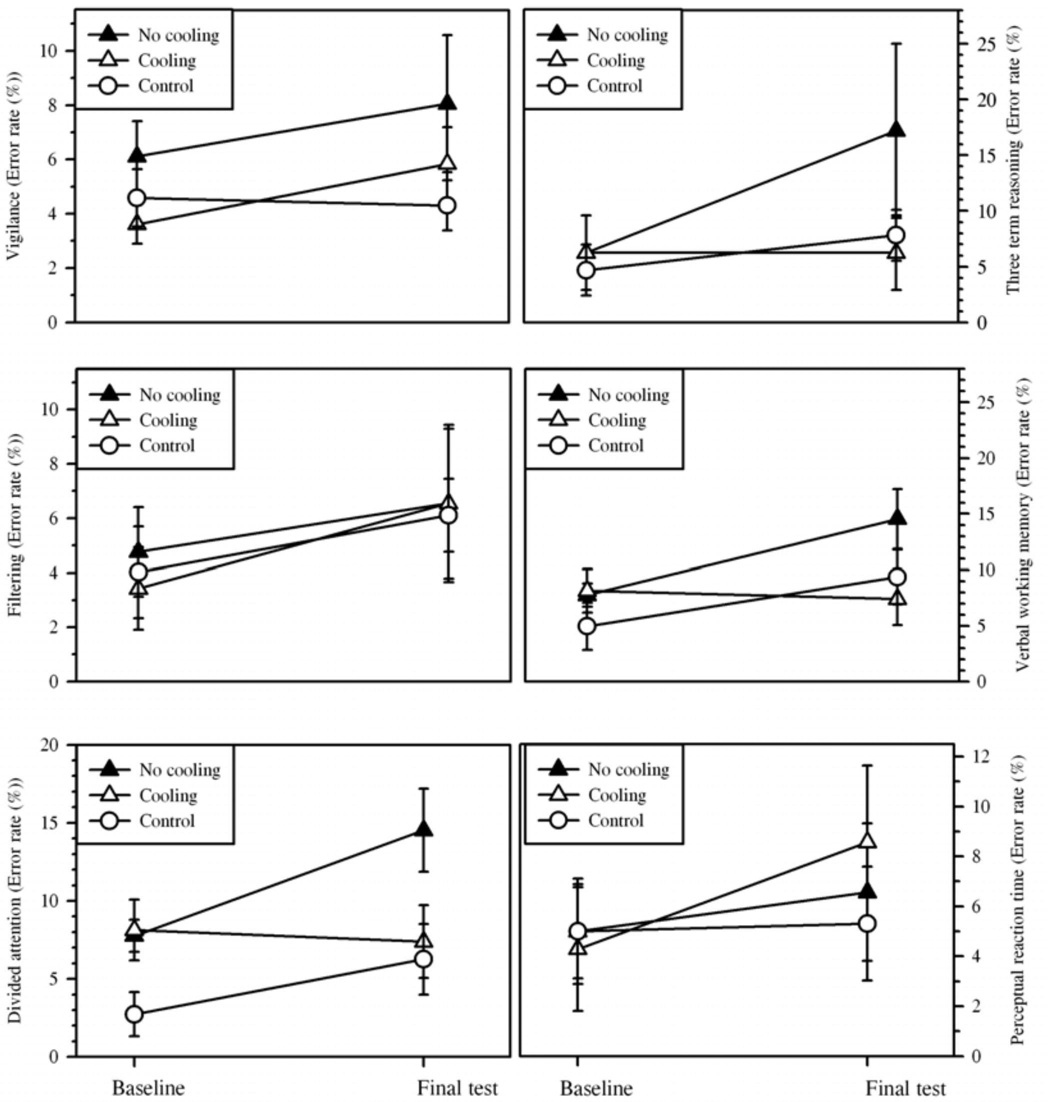

Figure 5.8 Cognitive function: Vigilance, three term reasoning, filtering, verbal working memory, divided attention and perceptual reaction time before and after an exercise protocol when exposed to a temperate environment (control), hot-dry, inactive cooling or hot-dry, active cooling trials. Values are means with standard error of the means. *Significantly different from control.

5.4.1 Core temperature

As indicated by the elevated increases in core temperature, the hot-dry trial with inactive cooling elicited a greater thermal strain than the control and hot-dry with active cooling trial. The low work intensity of this study and the extreme climatic conditions produced an uncompensable environment, therefore resulting in a gradual climb in core temperature. This was not unexpected, and has previously been reported (Goldman, 1994, 2001). Due to the rapid rise in core temperature, during the hot-dry trial without cooling, the duration of these hot trials was markedly shorter than the other two trials and, for two subjects, this duration was limited by the rise in core temperature to 39.5°C.

However, these observations were not replicated in the control trial or the hot-dry trial with cooling. For the control trials, the small change in core temperature was a direct result of the much lower external environmental temperature which resulted in greater convective and conductive heat flow away from the body. Similarly, the metabolic heat produced during this low intensity work load was successfully removed by the cooling garment, during a hot-dry exposure, at a rate that prevented a rise in core temperature over the two-hour duration. This was achieved by an alteration in the microclimate between the skin and the inner surface of the clothing, thereby increasing the thermal gradient between these two surfaces. As a result, conductive heat losses from the individual were enhanced, while heat gain from the external environment was prevented, ultimately preserving core temperature during these trials. That is, a potentially uncomensable heat stress environment was avoided and made compensable.

5.4.2 Skin temperature

Mean skin temperatures rose rapidly in the hot-dry trial with inactive cooling. This increase in skin temperature was a result of the exposure to the hot-dry environment, where the temperature of the microclimate between the protective clothing and the skin was increased, due to the insulation provided by the personal protective ensemble. As metabolic rate increased at the onset of exercise, core temperature also rose. Although nervous innervation was not measured in this study, it is likely that the increase in core temperature activated afferent signals to the hypothalamus which were integrated to increase sympathetic activity to reduce total peripheral resistance, allowing for increased cutaneous blood flow and potentially increased heat flux away for the skin surface. In an environment where air temperature is lower than skin temperature, heat is removed from the individual. However, in an environment where air temperature is well above that of skin temperature, as occurred in the hot-dry environment in this study, the thermal gradient is reversed and the individual begins to gain heat from the environment. This was evident in our results by the rapid increase in $\overline{T}_{sk}$ and T_c.

Not withstanding these observations for the hot-dry trial without cooling, no differences between the control and hot-dry trial with active cooling were apparent. Again, this was expected, as the use of the auxiliary cooling device restored the thermal gradient to allow heat removal from the individual. In this instance, the insulative properties of the garment are negligible because an appropriate method of cooling was chosen. The resultant $\overline{T}_{sk}$ was reduced to temperatures between 32-33°C. It has been shown that $\overline{T}_{sk}$ lower than 32°C can cause vasoconstriction (Veicsteinas *et al.*, 1982), thereby reducing skin blood flow and the resultant heat extraction (Pergola *et al.*, 1994). However, in the present study, a water bath temperature of 15°C was employed, resulting in a maximum skin temperature of approximately 33°C, allowing for optimal heat extraction and the successful restoration of the thermal strain evident during the hot-dry trial without cooling.

5.4.3 Cardiac frequency

As observed for core and mean skin temperature measurements, cardiac frequency was also significantly higher for the hot-dry with inactive cooling trials when compared to the control and hot-dry with active cooling trials. This was again not unexpected, as it is well known that even at rest, when an individual is exposed to a heat stress, cardiac frequency is increased by 10-30 beats.min^{-1} (Rowell, 1986). The continual climbing response of cardiac frequency observed for this trial, is known as the cardiovascular drift. This is associated with a progressive increase in cutaneous blood flow due to an elevated core temperature (Coyle and Gonzalez-Alonso, 2001), while work rate is kept constant (as occurred in this study). As a result of increased blood flow to the periphery to enhance heat loss, arterial blood pressure is decreased causing a decrease in baroreceptor impulses transmitted to the cardiac centres in the medulla, leading to increased sympathetic activity to elevate cardiac frequency and myocardial contractile force and ultimately restoring arterial blood pressure.

It is not certain whether the progressive increase in cardiac frequency is solely due to a decline in stroke volume, occurring as a result of increased cutaneous blood flow, or due to some other intervention, such as an increased sympathetic activity accompanying the rise in core temperature (Coyle and Gonzalez-Alonso, 2001). Nevertheless, it is almost always present during protracted, steady-state exercise in the heat. In the present study, the observed increases in f_c were only present in the hot-dry trial without an activated cooling system even though the hot-dry trial with cooling was performed in the heat. This is because the auxiliary cooling device removed heat at a rate that matched metabolic heat production and prevented the individual from gaining heat from the environment. As a result, core and skin temperatures were maintained well below those observed in the hot-dry trials without cooling, which is likely to have altered the afferent signals to the thermoregulatory centre in the hypothalamus. That is, core and skin temperatures were low (<38°C and 33°C respectively), resulting in little vasodilation and ultimately preserving arterial blood pressure without activating sympathetic activity.

Several studies investigating the use of auxiliary cooling devices have reported similar reductions in f_c during a heat stress exposure, at rest (Epstein, 1986) or during exercise (Shapiro, 1982, Banta, 1992) . For example, Nunneley (1983) reported similar observations in f_c when an auxiliary cooling device was used during a simulated low-level helicopter flight performed in a hot environment (black globe temperature 43°C, 45% RH). Cooling was applied to the head and/or torso, and a reduction in rectal and skin temperatures was achieved, resulting in a drop in f_c of 9-26 beats.min^{-1}. Therefore, utilisation of an auxiliary cooling system is necessary, not only to reduce thermal strain but also to reduce cardiovascular strain associated with performing work in the heat.

5.4.4 Psychophysical indices

The psychophyical responses elicited significantly higher differences after 15 minutes of exposure during the hot-dry trial with inactive cooling, but this observation did not occur for the effort sense questionnaires. In fact, the perceived exertion responses were greater after 70 minutes of heat exposure for the hot-dry with inactive cooling trials. This was an unexpected result, as it is well established that the rating of perceived exertion is closely related to changes in cardiac frequency (Borg, 1962), and in the present study, f_c was significantly higher for the hot-dry trial without cooling. However, as presented by Pandolf (1978, 1982), there is debatable evidence indicating that a number of central and local factors may in fact influence an individual's rating of perceived exertion, and he suggests that differential ratings of perceived effort may reveal more information about the experimental condition than reporting an overall exertion related to the task. That is, a large amount of within subject variation is likely to occur when a number of factors (such as local muscle fatigue, increased cardiovascular strain, discomfort due to increased core temperature or sweating) may contribute to the individual's perceived effort. In the present study, the effort sense responses were related to a general or overall exertion, rather than a local or differentiated rating, and this possibly explains why a large amount of subject variation was observed.

Thermal sensation, thermal discomfort, perceived skin wetness and skin wetness sensation responses were significantly higher in the hot-dry with inactive cooling trial, indicating that subjects felt hotter, wetter and more uncomfortable during this trial. Similar responses in thermal sensation have previously been reported where it is widely accepted that thermal sensation and mean skin temperature are closely related (Gagge *et al.*, 1967, Gagge *et al.*, 1969). In this study, similar differences in mean skin temperature were found after only 15 minutes of exercise. However, a similar pattern was also observed for core temperature, so one cannot say whether these observed changes were solely due to mean skin temperature influences (Boutcher *et al,* 1995), core temperature changes, or the combination of both. While it has been reported that coolant temperatures below 21°C can lead to a progressive elevation in thermal discomfort (Shitzer *et al*, 1973), this did not occur during the hot-dry trial with cooling.

5.4.5 Cognitive function

Although thermal strain clearly impacted upon physiological and psychophysical performance, undesirable effects were not observed for the cognitive function indices. This is not surprising as much of the literature reports some improvements, no change or detrimental responses to cognitive function assessment (Amos *et al*, 2000, Cian *et al*, 2001) with increased thermal strain. The improvements in cognitive function with increased thermal strain previously reported appear to be consistent with changes predicted by Yerkes-Dobson law of arousal. That is, as body core temperature rises, arousal state is increased until a point in which optimal performance is achieved. Beyond this point, detriments in cognitive function and performance are likely to occur (Provins, 1966).

Whilst it is quite probable that some degree of hyperthermia heightens cognitive function, it is also probable that subjects in this study were not sufficiently dehydrated to experience the full detrimental effects of the exposure. For instance, subjects only experienced mild dehydration, with an average body mass change of 2.1% at completion of the most stressful condition. Gopinthan *et al.* (1988) have demonstrated that a positive correlation exists between the severity of dehydration and detriments in cognitive function, and Szinnai *et al.* (2005) found that no changes were evident unless individuals experienced moderate dehydration (2-5% body mass loss). The actual mechanism for reduced cognitive function during severe dehydration is not certain, however there are a number of contributory factors. Wilson and Morely (2003) have briefly described these effects as a result of intracellular, extracellular and intravascular changes. These changes may be caused by a reduction in plasma volume, electrolyte imbalance, or an increase in local metabolites, among others.

5.5 Conclusion

The current study has provided an evaluation of the thermal impact upon physiological and cognitive function whilst wearing biological and chemical protective clothing in hot-dry conditions. In addition, the ability of a liquid-cooling garment to ameliorate adverse changes was evaluated. It was found that thermal strain, as measured by T_c, $\overline{T}_{sk}$, f_c and gross sweat production, was greater when individuals were required to perform very light work in a hot-dry environment while wearing the Australian Defence Force biological and chemical protective ensemble. In the latter instance, the use of a liquid-cooling garment (water temperature 15°C), successfully prevented all detriments in physiological function observed during the hot-dry trial without auxiliary cooling.

While it is evident that individuals required to work in hot-dry environmental conditions are at risk of severe hyperthermia, the duration with which they may work in this conditions is reduced. This may have operational implications where rest periods may not be possible. However, no detriments in cognitive function were apparent in the current study, and two reasons could account for this. First, it is a possibility that the cognitive test battery was not sensitive enough to detect slight changes in cognitive function. Second, because subjects only experienced mild dehydration (~2%), it is possible that the total physiological strain was not adequate enough to elicit cognitive function detriments. Nevertheless, auxiliary cooling devices should be utilised for individuals required to perform operational tasks in hot-dry climates. Further research is required to investigate slight changes in cognitive function that, in a practical application, could lead to devastating consequences. and also the effects of severe dehydration (>5%) upon cognitive function.

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CHAPTER 6: CONCLUSION

This project was designed to explore the problems associated with personnel working in uncompensable environmental conditions while wearing ADF protective clothing. This was evaluated by exposing individuals to uncompensable thermal environments in which they would typically be required to operate. Physiological, psychophysical and cognitive function indices were measured during all heat exposures. In addition, a theoretical evaluation of possible solutions to the heat stress problem was included, with a main focus on auxiliary cooling devices as a potential solution to the problem. Finally, a combined evaluation of the changes in thermal strain associated with working in an extreme environment, and the effects of adding an activated cooling system were determined.

It was found that a significant thermal strain, as measured by core temperature, skin temperature, cardiac frequency and sweat production, was significantly elevated in all subjects in the most extreme conditions of these studies. This was most evident in the measurement of core temperature.

- The application of external heat, through a water perfusion garment, elicited significantly greater states of thermal strain for helicopter pilots, with respective terminal core temperatures averaging: 37.4°C, 38.4°C and 38.8°C (Chapter 2).
- Individuals wearing body armour, relative to control trials without armour, although exposed the same environmental temperatures, experienced greater thermal strain. Also, the simple addition of the combat helmet to the body armour was enough to elicit a further disadvantageous deviation in physiological strain (Chapter 3).
- Although the same biological and chemical protective ensemble was worn, thermal strain was significantly higher in the hot-dry trial without cooling, where terminal core temperature for the hot-dry trial without cooling was 1.6°C greater than the control condition (Chapter 5).

Whilst clear, between-trial separations were evident for physiological strain, this trend for cognitive function parameters, as measured with the Minicog Rapid Assessment Battery and the flight simulator performance indices (required effort, perceived performance quality or performance score) was not apparent. Although, for both the hot and moderately-hot trials flying performance differed significantly from the control trial, no other significant detriments in cognitive function were observed for any of the studies. This indicates that, while the Minicog Rapid Assessment Battery is designed to evaluate cognitive function, it was not sensitive enough to detect slight changes in cognition, as occurred for pilots operating an aircraft. Therefore, a more specific evaluation of cognitive function need to be considered to determine the exact causes of a decline in cognitive function.

In addition to the observed changes in thermal strain, the liquid-cooling garment (water temperature 15°C) successfully prevented all detriments in physiological function observed during the hot-dry trial without cooling. Although, the liquid-cooling device reduced thermal strain in this study, liquid-cooling devices are not always the most effective in other environmental conditions. This was discussed in detail in Chapter 4. It was found from the theoretical evaluation of ice, water and air, as possible coolants, that the ice system dominated conductive and radiative heat exchanges and the air system dominated convective heat losses. However, mathematically, conductive heat losses extracted more heat than through convective mechanisms. Overall, the ice system was superior to the air and water-perfused systems for an equivalent contact surface area. Although these three cooling systems have been shown to effectively alleviate heat strain for individuals exposed to hot environmental conditions, not all systems are equally effective, and there exists a need to evaluate these systems according to the requirements of the user, the climatic conditions with which they are exposed and the characteristics of each system.

Taken collectively, these observations lead us to partially accept the working hypotheses:

(i) An increased thermal strain, as measured by core temperature, skin temperature, cardiac frequency and sweat loss, did result in decreased pilot flight performance.

(ii) The addition of combat body armour caused an increase in thermal strain, but no changes in cognitive function were observed. Furthermore, there was a time by uniform interaction with the addition of the combat helmet. This was an unexpected observation because the mass of the helmet was low and the surface area of the head covered by the helmet was minimal.

(iii) Cognitive function detriments were not observed in individuals required to perform very light exercise in an uncompensable environment while wearing the ADF biological and chemical personal protective ensemble.

(iv) The use of a liquid-cooling device (water temperature 15°C) successfully reduced the thermal strain observed during the hot-dry trial. However, no significant differences in cognitive function were observed with the use of the auxiliary cooling device.

It can be concluded from this investigation that, individuals exposed to extreme environmental conditions while wearing protective ensembles, are at risk of developing increased thermal strain that may lead to heat illness. As observed in the helicopter simulator, pilots could not operate the aircraft without making errors when core temperature reached 38°C. In these cases, where pilots are required to direct their attention to many tasks, slight changes in cognitive ability can result in devastating consequences and lead to a catastrophic impact upon personnel, equipment and operational capability. Therefore, maintaining a reduction in thermal strain is critical. As proven in this investigation, a reduction in thermal strain can be achieved with the use of an auxiliary cooling device.

6.3 Recommedations

It is recommended that the Australian Defence Force, utilise auxiliary cooling devices that will reduce thermal strain of personnel required to work in hot environments, while wearing protective clothing. A flow chart for implementing these devices within different operation scenarios has been developed (Figure 4.15). For pilots who are required to operate aircraft in conditions of increased thermal strain, auxiliary cooling devices must be considered. It is also recommended that for each different operation, the ADF evaluate the type of activity and condition to which they are exposed and choose an appropriate cooling device. An intermittent cooling protocol should be used to attenuate the fall in T_{skin} and an alternating, symmetrical, square-wave cooling cycles be used, using either 2- or 4-min, symmetrical cooling periods. Auxiliary (microclimate) cooling systems should therefore be designed to optimise these thermal gradients without compromising biological heat transfer.

6.2 Future research

The current investigation has confirmed that thermal strain is increased not only when environmental conditions and work rate are increased, but also with the addition of personal protective ensembles. In the case of body armour, a further increase in thermal strain was evident, with the addition of the armoured helmet.

In terms of cognitive function assessment, this project failed to determine specifically, which areas of cognitive function were in fact adversely affected (as observed with changes in the helicopter pilots ability to operate a helicopter simulator) during the laboratory based trials and therefore the exact cause of operational failure is still unknown. Although dehydration may play a role in the reduction of cognitive ability, sufficient dehydration was not apparent in this investigation. Therefore, future studies should attempt to quantify small changes in cognitive function (as may occur when operating an aircraft) and induce more severe dehydration ($>5\%$). If dehydration was in fact the main cause for altered cognitive function, further physiological assessment would need to be included to evaluate how dehydration causes changes in cognitive function.

APPENDIX A: EQUATIONS USED FOR MATHEMATICAL MODELLING

The following sources were used to obtain the equations and reference data used in the development of the first-principles mathematical model:

1. Lotens and Havenith (1991)
2. Goldman (1994, 2001)
3. Gonzalez (1986)

Mean radiant temperature (MRT: °C) = $T_g + 2.2 * (V^{0.5}) * (T_g - T_a)$

T_g = globe temperature (°C)

V = wind velocity ($m.s^{-1}$)

T_a = air temperature (°C)

Wet bulb globe temperature (°C) = $T_a * 0.1 + T_{wb} * 0.7 + T_g * 0.2$

T_a = air temperature (°C)

T_{wb} = wet bulb temperature (°C)

T_g = globe temperature (°C)

Surface area (A_D (DuBois): m^2) = $0.202 * m^{0.425} * h^{0.725}$

m = mass (kg)

h = height (m)

Air water vapour pressure (P_{H2O}: kPa) = $Exp^{(16.6536-4030.183/(Ta+235))} * RH$

T_a = air temperature (°C)

RH = relative humidity (%)

Cutaneous water vapour pressure (P_{H2O-sk}: kPa) = $Exp^{(16.6536-4030.183/(Tsk+235))}$

T_{sk} = air temperature (°C)

Clothing (trapped) water vapour pressure ($P_{H2O-clo}$: kPa) = $Exp^{(16.6536-4030.183/(Tsk-1+235))} * 0.98$

T_{sk} = air temperature (°C)

1 = constant: assumed difference between skin temperature an trapped air temperature

0.98 = constant: assumes 98% relative humidity for air trapped in clothing

Surface layer insulation (I_a: $m^2K.W^{-1}$) = 1 / (0.65 + 1.25 * (+$V^{0.5}$) * 0.155

0.65 = constant:

1.25 = constant:

V = wind velocity ($m.s^{-1}$)

0.155 = constant: to convert from clo to SI units of insulation

Clothing insulation (I_c: $m^2K.W^{-1}$): Data derived using programme of Lotens and Havenith (1991)

Total insulation (I_{TOT}: $m^2K.W^{-1}$) = I_a + I_c

I_a = surface layer insulation ($m^2K.W^{-1}$)

I_c = clothing insulation ($m^2K.W^{-1}$)

Moisture permeability of clothing (I_m: non-dimensional) = 0.4

0.4 = constant: unless value for garment is known

Whole-body thermal energy content (W) = 0.965 * m * $\bar{T}_b$

0.965 = constant: specific heat of tissues (3474 $J.kg^{-1}.K^{-1}$)

m = mass (kg)

$\bar{T}_b$ = mean body temperature (°C)

Resting metabolic heat production (M_{rest}: W) = m * 1.5

m = mass (kg)

Exercising metabolic heat production (M_{ex}: W) = WR * 5

WR = work rate (W)

Total heat production (H: W) = M_{rest} + M_{ex} - WR

M_{rest} = resting metabolic heat production (W)

M_{ex} = exercising metabolic heat production (W)

WR = work rate (W)

Conductive heat exchange (K: $W.m^{-2}$) = (k / 100) / (s) * (T_a-T_{sk})

k = thermal conductivity of object ($W.cm^{-1}.°C^{-1}$)

100 = constant: to convert cm to m

s = distance between objects (m)

(T_a-T_{sk}) = thermal gradient: air to skin (°C)

Radiative heat exchange (R: W) = (11 * 1.16) * (MRT - T_{sk}) * 1

11 = constant: heat exchange in $kcal.h^{-1}$

1.16 = constant: converts $kcal.h^{-1}$ to $J.s^{-1}$

(MRT - T_{sk}) = thermal gradient: skin to radiant heat source (°C)

1 = clothing coverage constant: 1=shorts+shoes, 0.6=long shirt & trousers

Convective heat exchange (C: $W.m^{-2}$) = (12 * 1.16) * ($V^{0.6}$) * (MRT - T_{sk}) * 1

12 = constant (density, viscosity, shape): heat exchange in $kcal.h^{-1}$

1.16 = constant: converts $kcal.h^{-1}$ to $J.s^{-1}$

V = wind velocity ($m.s^{-1}$)

(MRT - T_{sk}) = thermal gradient: skin to radiant heat source (°C)

1 = clothing coverage constant: 1=shorts+shoes, 0.6=long shirt & trousers

Convective + Radiative heat exchange (R+C: W) = (5.55/0.86) * A_D * 1/I_a * (T_a-T_{sk})

5.55 = constant: heat exchange in $kcal.h^{-1}$

0.86 = constant: 3600/4186 to convert $kcal.h^{-1}$ to W

A_D = DuBois surface area (m^2)

I_a = surface layer insulation ($m^2K.W^{-1}$)

(T_a-T_{sk}) = thermal gradient: air to skin (°C)

Evaporative heat exchange (E: $W.m^{-2}$) = (23 * 1.16) * ($V^{0.6}$) * (0 - P_{H2O-sk} * 7.5006)

23 = constant: heat exchange in $kcal.h^{-1}$

1.16 = constant: converts $kcal.h^{-1}$ to $J.s^{-1}$

V = wind velocity ($m.s^{-1}$)

P_{H2O-sk} = cutaneous water vapour pressure (kPa)

7.5006 = constant: converts kPa to mmHg

Respiratory evaporative heat loss (E_{resp}: W) = 0 - m * 0.3 * (M_{ex} / M_{rest}) * 2430 / 3600

0 = constant: to ensure heat loss is negative

m = mass (kg)

0.3 = constant:

M_{rest} = resting metabolic heat production (W)

M_{ex} = exercising metabolic heat production (W)

2430 = constant: heat loss via evaporation ($J.ml^{-1}$)

3600 = constant: to convert h to s

Required sweat evaporation (E_{req}: W) = H + E_{resp} + (R+C)

H = total heat production (W)

E_{resp} = respiratory evaporative heat loss (W)

(R+C) = convective + radiative heat exchange (W)

Required sweat rate ($ml.h^{-1}$) = E_{req} * 3600 / 2430

E_{req} = required sweat evaporation (W)

3600 = constant: to convert h to s

2430 = constant: heat loss via evaporation ($J.ml^{-1}$)

Maximal evaporative cooling (E_{max}: W) = (5.55/0.86) * A_D * I_m/I_{TOT} * 2.2 * (P_{H2O-sk}-$P_{H2O-clo}$)

5.55 = constant: heat exchange in $kcal.h^{-1}$

0.86 = constant: 3600/4186 to convert $kcal.h^{-1}$ to W

A_D = DuBois surface area (m^2)

I_m/I_{TOT} = index ratio: moisture permeability of clothing and total insulation (non-dimensional)

2.2 = constant

$(P_{H2O\text{-}sk}\text{-}P_{H2O\text{-}clo})$ = water vapour pressure gradient (skin to trapped air: kPa)

Sweat demand versus capacity (%) = E_{req} / E_{max} * 100

E_{req} = required sweat evaporation (W)

E_{max} = maximal evaporative cooling (W)

Required auxiliary cooling: total heat removal (W) = H + E_{resp}

H = total heat production (W)

E_{resp} = respiratory evaporative heat loss (W)

Required auxiliary cooling: comfort (W) = required auxiliary cooling + E_{max} * 0.2

E_{max} = maximal evaporative cooling: assumes comfort if <20% sweat remains unevaporated

Heat capacity of coolant (kJ.°C^{-1}) = coolant specific heat (kJ.kg^{-1}.°C^{-1}) * coolant mass (kg)

Conductive heat extraction by coolant (W) = k * 100 / s * $(T_{in}\text{-}T_{sk})$ * $A_{Deffect}$

k = thermal conductivity of coolant (W.cm^{-1}.°C^{-1})

100 = constant: to convert cm to m

s = distance between objects (m)

$(T_{in}\text{-}T_{sk})$ = thermal gradient: coolant inflow temperature to skin (°C)

$A_{Deffect}$ = effective or contact skin surface area (m^2)

Radiative heat extraction by coolant (W) = (11 * 1.16) * (MRT - T_{sk}) * $A_{Deffect}$ * 1

11 = constant: heat exchange in kcal.h^{-1}

1.16 = constant: converts kcal.h^{-1} to J.s^{-1}

(MRT - T_{sk}) = thermal gradient: skin to radiant heat source (°C)

$A_{Deffect}$ = effective or contact skin surface area (m^2)

1 = clothing coverage constant: 1=shorts+shoes, 0.6=long shirt & trousers

Convective heat extraction by coolant (W) = $(12 * 1.16) * (V^{0.6}) * (MRT - T_{sk}) * A_{Deffect} * 1$

12 = constant (density, viscosity, shape): heat exchange in $kcal.h^{-1}$

1.16 = constant: converts $kcal.h^{-1}$ to $J.s^{-1}$

V = coolant velocity ($m.s^{-1}$)

$(MRT - T_{sk})$ = thermal gradient: skin to radiant heat source (°C)

$A_{Deffect}$ = effective or contact skin surface area (m^2)

1 = clothing coverage constant: 1=shorts+shoes, 0.6=long shirt & trousers.

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