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The impact of protective helmets on physiological strain and cognitive function during horseback mustering

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Abstract

Equestrian helmets have recently been introduced into the cattle industry. Anecdotal evidence indicates that such helmets may increase the probability of stockmen developing heat illness or experiencing reduced workplace performance. To evaluate this possibility, three phases of field and laboratory testing were completed. In Phase One, the working environment of northern Australian cattle stations was evaluated, and found to thermally uncompensable during mustering season. Physiological strain associated with mustering cattle under such conditions was also quantified, revealing that stockmen were able to modulate work rates to prevent the progressive rise in core temperature. From bench-top, heat-penetrations trials were performed on a range of equestrian helmets and a felt hat. On overall performance, the Aussie 21 helmet was deemed to be superior. The third Phase of this project involved laboratory-based trials under precisely-controlled, and reproducible environmental conditions, in which the physiological impact of the Aussie 21 helmet was compared with the standard felt hat, during a simulated working and thermal exposure. This helmet did not adversely affect any of the physiological, psychophysical or cognitive functions that were evaluated.

Executive summary

Equestrian helmets have recently been introduced into the cattle industry, and some pastoral companies require stockmen to wear protective helmets during horseback mustering. Anecdotal evidence indicates that such helmets, particularly those with poor ventilation, may increase the probability of stockmen developing heat illness or experiencing reduced workplace performance. The ***Human Performance Laboratories*** (University of Wollongong) were engaged by **Meat and Livestock Australia (MLA)** to evaluate this possibility under field and laboratory conditions, and **Three Phases** of testing have been completed.

From field measurements (**Phase One**), it is abundantly clear that the working environment on northern Australian cattle stations is, on average, **thermally uncompensable** during the mustering season. That is, the interactions among the body, clothing and the environment are such that the body is likely to eventually enter a state of hyperthermia, due either to heat production (work) or heat exposure. This uncompensable state was found to obtain, on average, after 1200 hours in September, 1000 hours in October and at 0900 in November, and did not retreat to more compensable conditions until after the sun had set. A detailed appreciation of the physiological strain associated with mustering cattle under such conditions, whilst wearing an equestrian helmet, has now been achieved. From the observations of heart rate, and the projected metabolic heat production, it is evident that horseback mustering is a relatively low-intensity activity, interspersed with short periods of high-intensity work. This activity level was also reflected within core temperature measures, which rarely climbed above values associated with light-moderate physical activity. Thus, whilst the working conditions were uncompensable for most of the working day, stockmen were able to modulate work rates such that the progressive rise in core temperature was kept below levels that might lead to heat illness. From sensors located within the helmet and clothing, it was observed that the helmet, though unpleasant to wear, did not appear to behave in a manner that would disadvantage the physiological well being of stockmen (Taylor and Caldwell, 2007).

In **Phase Two**, bench-top trials were performed on a range of equestrian helmets and a felt hat (Akubra Arena). It was concluded that, of the helmets provided for testing, the Aussie 21 had superior physical characteristics, while, from a heat penetration perspective, the Derby and Aussie 21 appeared to provide very similar thermal protection. On overall performance, the Aussie 21 helmet was deemed to be superior (Caldwell and Taylor, 2007), and this helmet was used in the final phase of testing (laboratory-based trials) to compare the physiological and cognitive affects of headwear on exercising and thermally-stressed individuals.

The aim of **Phase Three** experimentation was to undertake laboratory-based trials under precisely-controlled, and reproducible environmental conditions, in which the equestrian helmet that performed best during bench-top trials was compared with the standard felt hat, during a simulated working and thermal exposure. Eight male subjects completed two trials in a hot-dry environment (38^{o}C, 30% relative humidity). In one trial, subjects wore a felt hat (Akubra Arena), and in the other, they wore the equestrian helmet (Aussie 21) These conditions represented the average maximal air temperature and the average relative humidity for Victoria River Downs during November, for the 15-year period 1991-2006.
In addition, three, 500-W radiant heat lamps were positioned about 1 m overhead to simulate solar loading, and two fans were positioned in front of the subject and set to provide an airflow of 5.16 km.h^{-1}, the average riding speed observed in the field (Taylor and Caldwell, 2007).

A critical part of this experimental Phase was the ability to reproduce conditions and work levels observed in the field, and also to ensure that between-trial conditions and the physiological

status of the experimental subjects were standardised. To this end, the subjects acted as their own controls, and presented for each of the two trials with an average urine specific gravity less than 1.017, well within the normal range for adequately-hydrated individuals. From field trials, we determined a mean working heart rate of 101.2 beats.min^{-1} for the male stockmen. The current exercise and thermal loading protocol elicited heart rate averages of 102.8 and 101.9 beats.min^{-1} for these trials, verifying the validity of the work simulation. It was observed that, for about 66% of each field trial, core temperatures were within the range 37.3-37.7^{o}C. In the current experiment, core temperatures remained within this range by design, but were slowly driven upwards over time. In the field, the mean skin temperatures followed a linear elevation over time, and typically commenced at about 32^{o}C, and terminated near to 36^{o}C, and this pattern was successfully reproduced, with the mean terminal skin temperatures averaging 36.0-36.1^{o}C for each experimental condition. Taken collectively, these observations allow one to reasonably conclude that the climate chamber simulations were faithful, laboratory-based replications of the stresses encountered by working stockmen from northern Australia (during November) that may impact upon their physiological status and cognitive function.

With these experimental conditions established and replicated for every trial, and with the trial sequence balanced across subjects, it was evident that the Aussie 21 equestrian helmet did not adversely affect any of the physiological, psychophysical or cognitive functions that were evaluated. These observations are summarised in the following Table, which contains data collected over the last 5 min of each condition, where physiological strain was greatest.

Summary Table: Physiological, psychophysical and cognitive function observations. Data are means for the last 5 min of each trial (core and skin temperatures and heart rate), the overall mass change, and for the last sampling point (psychophysical state and cognitive function).

Variable	Akubra	Aussie 21
Core temperature (^{o}C)	37.4	37.7
Skin temperature (^{o}C)	36.0	36.1
Heart rate (beats.min^{-1})	117.2	118.0
Mass change (kg)	2.1	2.2
Perceived exertion (6-20)	12.0	13.8
Thermal sensation (1-13)	10.1	10.0
Thermal discomfort (1-5)	2.4	2.5
Skin wetness sensation (1-13)	10.1	10.5
Skin wetness discomfort (1-5)	2.6	2.5
Vigilance (number correct)	87.5	86.3
Reasoning (number correct)	7.1	7.5
Verbal working memory (number correct)	44.4	45.3
Perceptual reaction time (number correct)	38.5	38.8

Laboratory-based assessment of physiological and cognitive strain:
The Aussie 21 equestrian helmet did not adversely affect any of the physiological, psychophysical or cognitive functions that were evaluated.

Recommendations:
It is recommended that the Aussie 21 equestrian helmet be adopted for use in the field.

Physiological specifications:

Given the superiority of the Aussie 21 helmet (Phase Two) and the above outcome, there is no need to recommend the re-design of equestrian helmets, providing this helmet is used in the field.

Contents

1 Background

Humans can successfully live within a broad range of thermal environments by adopting both physiological (sweating, skin blood flow, shivering) and behavioural strategies (*e.g*. clothing, work:rest schedules, air conditioning) to regulate body temperature. However, individuals working in hot environments will invariably experience an increase in body core temperature due to the combined influences of metabolic heat production and external heat sources. This temperature elevation can be restricted to a safe and manageable level if physiological heat loss mechanisms can be sustained, allowing for the dissipation of heat to the external environment.

Unfortunately, the use of thermal clothing and other personal protective equipment impedes heat dissipation (Taylor, 2006b). One such protective device is the helmet, which is known to increase physiological strain within hot climates (John and Dawson, 1989; Nunneley, 1989; Armstrong *et al*., 2002; Caldwell *et al*., 2005; Fogarty *et al*., 2005), though this outcome has not been unequivocally supported (Gisolfi *et al*., 1988; Sheffield-Moore *et al*., 1997). Many industries and sports use protective helmets, and, in recent years, helmets have been introduced into the cattle industry, following the lead of equestrian sports (AS/NZS 3838:2006), as part of the increasing Occupational Health and Safety responsibilities of pastoral companies. Some companies require stockmen to wear protective helmets during horseback mustering. Anecdotal evidence points to the possibility that protective helmets, particularly those with poor ventilation, may increase the probability of workers developing heat illness or experiencing reduced workplace performance.

The ***Human Performance Laboratories*** (University of Wollongong) were engaged by **Meat and Livestock Australia** to evaluate this possibility, under field and laboratory conditions. This was undertaken as a three-Phase project involving field trials (**Phase One**), the bench-top assessment of heat penetration through helmets (**Phase Two**) and laboratory-based trials to evaluate the physiological impact of wearing an equestrian helmet (**Phase Three**).

2 Project objectives

This project had six objectives:

1. Quantification of the physiological demand of horseback mustering (Phase One).
2. Bench-top evaluation of heat penetration through equestrian helmets and the traditional felt hat (Phase Two).
3. Laboratory-based physiological trials comparing changes in physiological strain and cognitive function of people wearing helmets or felt hats during a work simulation (Phase Three).
4. Development of recommendations concerning the likely impact of helmet use during horseback mustering in hot climates on physiological and cognitive performance, and as assessment of the risk of exertional heat illness to these workers.
5. Review current practices for the minimisation and prevention of exertional heat illness, and provide supplementary procedural recommendations.
6. Provide physiological specifications (if warranted) for the re-design of helmets for use by stockmen.

3 Introduction and literature review

Workers in some trades are frequently exposed to extremely stressful climatic conditions, and the concurrent physiological challenges are met through both physiological and behavioural strategies designed to support thermal and cardiovascular regulation. Whilst such environments are anticipated within many industrial, military and emergency service trades, one does not normally expect farm workers to encounter such climatic extremes. However, northern Australian cattle stations are often exceptions to this expectation.

Notwithstanding these thermal problems, and the empirical data indicating the possibility of increased thermal strain when clothed individuals wear helmets, the Australia and New Zealand Standard (AS/NZS 3838:2006) that covers equestrian helmets does not include any consideration for helmet ventilation or heat dissipation.

3.1 Factors that predispose to heat illness

In epidemiological analyses, one can identify factors that directly lead to, or cause, a clinical condition. These factors are called agents, and they are largely dictated by the conditions of the working environment. 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, and these are often most readily able to be modified to reduce the risk of heat illness. The agents and host factors associated with hyperthermia, and its accompanying heat illnesses, are summarised in Figure 1 (Goldman, 2001), with the former being of primary interest.

Air temperature heavily impacts upon some special populations, such as sedentary elderly individuals and people working in very hazardous occupations. Accordingly, it is almost universally accepted that air temperature is the dominant cause of heat illness. However, this is generally not correct for most athletic, industrial, military (excluding armoured vehicle operations) or most emergency service scenarios. Air temperature is very important[1], for we rarely see heat illness during the winter months. However, air temperature is only one of six heat illness agents, and it is frequently not the most important factor (Goldman, 2001), particularly when relatively small increments in air temperature occur, such as may be expected during the normal daily summer fluctuations. The next three agents (air movement, humidity and radiant heat) can collectively or separately magnify or ameliorate the impact of air temperature. However, it is the metabolic heat production, and the impact of clothing that can precipitate heat illness in workers and athletes, even in cool conditions, and these agents are of principal interest in this project.

When working or exercising, humans convert stored chemical potential energy (carbohydrates and lipids) 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. Consequently, even at rest, humans produce heat at a rate of about 1.5 Watts per kilogram of body mass.
An average sized person therefore emits about the same amount of heat as a domestic, 100-Watt light bulb. If we consider a 70-kg person (an average mass for males and females) performing 200 Watts of external work (*e.g.* cycling, running, working), this person would experience a metabolic energy conversion at the rate of ~1000 $J.s^{-1}$, with approximately 800 $J.s^{-1}$ (800 Watts) being converted into thermal energy. Unless this heat is dissipated, then heat

[1] When air temperature is the primary causal agent of hyperthermia, then the associated illness is classified as ***classical*** or ***non-exertional heat illness***.

storage at this rate will cause the average tissue temperature of the body to rise ~1°C in just over 5 min. While such a rapid rise can occur in some states, such a change in body temperature is not generally observed. For instance, if a person is immersed in temperate water, heat loss can easily keep up with metabolic (endogenous) heat production. However, when faced with this heat load in hot water (40°C), the body heat content will rise rapidly, and approach dangerous levels very quickly. This adiabatic state can also occur in people wearing heavy personal protective ensembles when working in the heat. This is why one need not be in the heat to suffer a heat illness. That is, one can cook from the inside to the outside, and this is known as ***exertional heat illness***.

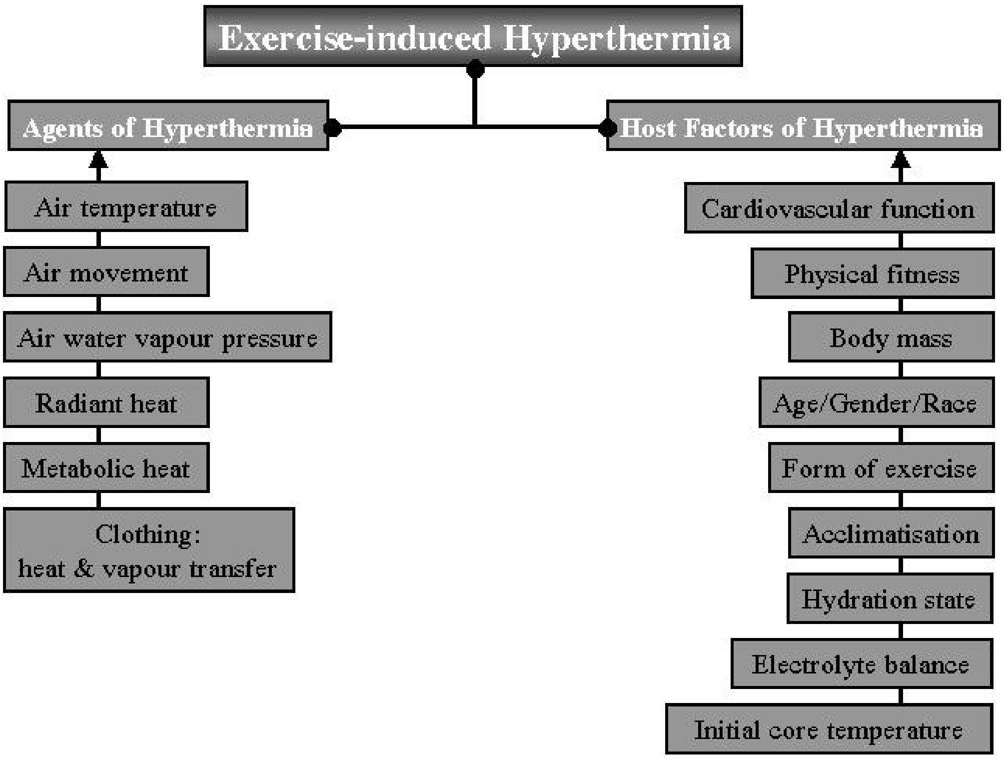


Figure 1: The agents and host factors of heat illness (Taylor, 2006b).

When clothing and helmets are worn, a microclimate[1] is created close to the skin surface. The air trapped within this space is warmer, it contains more water vapour and its movement across the skin surface is limited.
Thus, such protective clothing will markedly affect heat and water vapour transfer, and the stockman working in the northern Australian summer faces three thermal problems:

- extremes of environmental heat
- intermittent and occasionally high metabolic heat production
- the problem of facilitating the escape of metabolically-produced heat

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 (Ramsey and Morrissey, 1995; Caldwell

[1] The air trapped between the outer surface of the garment and the skin surface.

et al., 2006). Furthermore, the risk of exertional heat illness[2] is heightened with increments in body core temperature (Wyndham and Heyns, 1973), and the World Health Organisation has recommended an upper core temperature limit of 38°C for workers, thus implicitly limiting total metabolic heat production to approximately 325 W or less (World Health Organisation, 1969).

For a resting, unclothed person, the average skin temperature in comfortable conditions is 30-33°C. When the air temperature is greater than skin temperature, heat will be gained from the environment. Exercise and clothing act to lower the (critical) air temperature at which this occurs. However, clothing impedes both heat gained from, and heat lost to the environment. When wearing the clothing typically worn by stockmen (collared shirt with long sleeves and long trousers: insulation 0.29 $m^2K.W^{-1}$), and working at a light-moderate exercise intensity, the critical air temperature can be as much as 10°C lower than for an unclothed, resting person.

Using first-principles biophysical equations, we have modelled a wide range of work intensities and air temperatures for people wearing this standard clothing ensemble, but without head wear. A three-dimensional surface was created from these data (Figure 2) to facilitate the prediction of scenarios in which heat storage would occur. From this modelling, two generalisations are evident:

- When exercising at an external work rate of 120 Watts or above (~30-40% of maximal intensity), only unclothed people in cool conditions (15°C) can avoid a nett heat gain.
- When working at 70 Watts (~20-30% of maximal intensity), a nett heat loss is only possible in cooler air temperatures (<20°C).

The latter scenario represents the predicted mean work rate of male stockmen during mustering, based on heart rate analyses. The former is about 10% greater than the predicted maximal average work rate of stockmen during mustering. Therefore, even without head wear, one may reasonably expect stockmen to gain some heat.

[2] The probability of heat stroke in hot-humid environments at various core temperatures: 38.2°C 1:500 chance; 38.0°C 1:1,000 chance; 37.8°C 1:10,000 chance; 37.6°C 1:500,000 chance (Wyndham and Heyns, 1973).

3.2 The head and heat dissipation

The head has a mass of 4-5 kg (~7% of body mass; Vital and Senegas, 1986), and contributes about 7% of the total body surface area (Hardy and DuBois, 1938). Thus, it has a surface area to mass ratio 1.6 times that of torso, favouring rapid heat loss. In addition, the cutaneous vasculature of the head provides an impressive means for heat dissipation (Zenker and Kubik, 1996). The vasomotor activity of the head is relatively stable, resulting in the tissue insulation of the head remaining fairly constant across a wide range of air temperatures (~0.059 $m^2K.W^{-1}$; Froese and Burton, 1957). As a consequence, for an adult resting in temperate conditions (23^oC), the head loses heat at a rate that is more than eight times that of the rest of the body, when expressed in relative units ($W.m^{-2}$: Froese and Burton 1957; Clark and Toy, 1975; Rasch *et al.*, 1991). In absolute terms, due to its much smaller surface area, its contribution (45 W) is reduced, but is still very impressive, averaging ~60% of the total body heat loss (75 W). During exercise (150 W at 25^oC), heat loss from the head can increase about threefold (130 W: Rasch *et al.*, 1991).

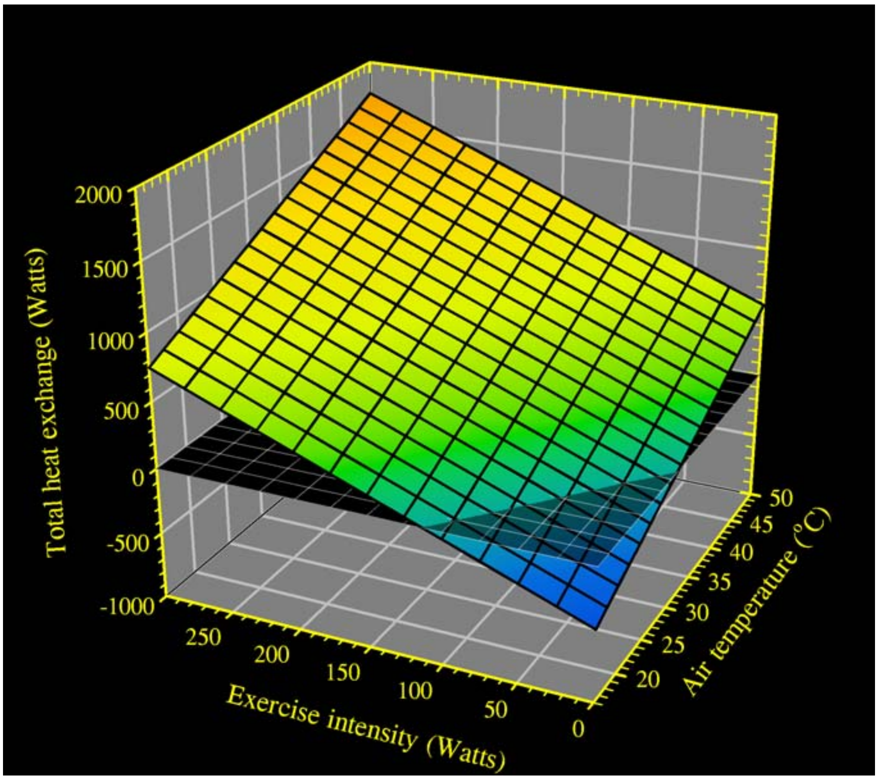


Figure 2: Three-dimensional surface for heat exchange across ranges of external work rates and air temperatures (50% relative humidity, 0 $m.s^{-1}$ wind velocity), when wearing the clothing typically used by stockmen (insulation 0.29 $m^2K.W^{-1}$), but without a hat.

With the head playing such a significant role in heat dissipation, the use of protective helmets may adversely affect thermal homeostasis, particularly in individuals who already have 80-85% of the total body surface covered with clothing, as is the case with stockmen. For instance, Liu and Holmer (1995) found that helmets can reduce evaporative cooling by 25-40%, depending upon the ease with which air flows through the helmet, and several groups have explored the impact of forced convection on heat loss (Reischl, 1986; Ellis *et al.*, 2000; Bruhwiler *et al.*, 2006). The thermodynamics of helmet design becomes more significant in hot climates (Patel and

Mohan, 1993), and research has shown that physiological strain can be significantly elevated within hot climates in fully-clothed individuals (John and Dawson, 1989; Nunneley, 1989; Fogarty *et al*., 2005).

However, others have reported minimal impact of helmets on heat loss (Gisolfi *et al*., 1988; Sheffield-Moore *et al*., 1997). Although in these studies, subjects were not fully-clothed, but wore shorts and cycling clothing, leaving only 50-60% of the body surface clothed. In this state, the impact of the helmet would be much less pronounced. Notwithstanding this, exposure of the unprotected head to radiant heat can have a significant and adverse impact upon thermal sensation, comfort and physiological strain (Buyan *et al*., 2006; Nunneley *et al*., 1971; Williams and Shitzer, 1974), and even baseball caps have been shown to provide a significant reduction in heat transfer (Bogerd *et al*., 2007).

4 Methods

4.1 Phase One: Field trials

4.1.1 Quantification of the working environment

Four cattle stations participated in this project (Table 1), with each being part of Heytesbury Beef Pty. Ltd. The average size of each station was 3,514 km^2. Stations bordered one another, and were positioned approximately 320-590 km to the south of Katherine (Figure 3), in the Northern Territory (Australia). This placed all stations approximately 6-7^o above the Tropic of Capricorn, and within a tropical climate.

Table 1: Cattle stations from which data were collected.

Station	Pastoral company	Location
Moolooloo	Heytesbury Beef	16^o 24 S, 131^o 5 E
Mount Sanford	Heytesbury Beef	16^o 98 S, 130^o 60 E
Pigeon Hole	Heytesbury Beef	16^o 86 S, 131^o 15 E
Victoria River Downs	Heytesbury Beef	16^o 36 S, 131^o 03 E

Climatic data for this region were obtained from the Australian Bureau of Meteorology[1], with the most detailed data being available for the Victoria River Downs Station[2]. Thus, these data were used to characterise the climate for each of the four stations. For the purpose of this report, data for the three months September, October and November were of greatest relevance, since these were both the hottest months and those in which horseback cattle mustering generally took place. Since the Bureau holds a database of historical climatic information, hourly data for September-November 2006, and monthly data from the years 1991 to 2006 were purchased and analysed.

[1] http://www.bom.gov.au/

[2] http://www.bom.gov.au/climate/averages/tables/cw_014825.shtml

4.1.2 Metabolic heat production during mustering

Twenty-four different stockmen (16 males and 8 females; Table 2) participated in these trials, following the provision of written, informed consent. Stockmen were aged between 15-50 years, and had a mean age of 22.8 years. Subjects 1-6 were involved in both laboratory- and field-based testing, while the remaining subjects only participated the latter trials.
The average daily air temperatures for the field trials, obtained over the 8-hour working period (0800-1600 hours), was 35.6^{o}C. Some subjects provided more than one data set from the field, with such data being obtained on different days, and a total of 38 heart rate data sets contributing to this stage of testing. The mean data collection period was 3 hours 52 minutes 48 seconds (range: 1.44-9.04 hours). All procedures were approved by the Human Research Ethics Committee (University of Wollongong: HE06/250).

To quantify the metabolic demands of physical activity, one should measure oxygen uptake and the respiratory exchange ratio during work. However, since the sensitive and expensive gas analysis equipment necessary to take these measures would not tolerate the physical demands of mustering, it was not possible for this equipment to be carried by the stockmen in the field. Therefore, metabolic heat production was approximated from heart rate data. This required a two-stage experimental protocol. The first stage involved recording the heart rates of stockmen during horseback activities, whilst wearing standard clothing (collared, long-sleeved shirt, long trousers, boots: insulation 0.29 $m^2K.W^{-1}$) and a protective helmet. The helmet chosen for these trials was that which the stockmen deemed to be the most stressful (New Derby Classic, Equine Science Marketing Pty. Ltd, Tullamarine, Australia), since it was considered that this helmet would provide an adequate opportunity to witness heat strain in stockmen, if it was likely to occur. The second stage of testing required the calibration of heart rate data against simultaneously measured oxygen uptake and the respiratory exchange ratio data.

Table 2: Experimental subjects and field trial details.

Subject	Gender	Age (y)	Test date	Air temperature (^{o}C)	Activity
1A	F	21	27-10-06	34.6	Walking cattle
1B	F	21	30-10-06	34.0	Walking cattle
1C	F	21	31-10-06	33.4	Mustering cattle
1D	F	21	06-11-06	34.8	Mustering cattle
1E	F	21	09-11-06	37.0	Mustering cattle
2A	M	19	27-10-06	34.6	Walking cattle
2B	M	19	31-10-06	33.4	Walking cattle
2C	M	19	09-11-06	37.0	Mustering cattle
2D	M	19	10-11-06	38.4	Mustering cattle
3A	F	19	27-10-06	34.6	Walking cattle
3B	F	19	31-10-06	33.4	Walking cattle
4A	M	26	27-10-06	34.6	Walking cattle
4B	M	26	31-10-06	33.4	Mustering cattle
4C	M	26	10-11-06	38.4	Mustering cattle
5A	M	19	27-10-06	34.6	Walking cattle
5B	M	19	30-10-06	34.0	Walking cattle
5C	M	19	06-11-06	34.8	Mustering cattle
6A	F	23	31-10-06	33.4	Mustering cattle
6B	F	23	10-11-06	38.4	Mustering cattle
7	M	17	02-11-06	34.2	Mustering cattle

Subject	Gender	Age (y)	Test date	Air temperature (^oC)	Activity
8	M	17	03-11-06	33.1	Mustering cattle
9	M	19	03-11-06	33.1	Mustering cattle
10A	M	28	09-11-06	37.0	Mustering cattle
10B	M	28	10-11-06	38.4	Mustering cattle
11	M	17	12-11-06	37.2	Walking cattle
12	M	15	12-11-06	37.2	Walking cattle
13	M	19	13-11-06	35.2	Walking cattle
14	F	21	13-11-06	35.2	Walking cattle
15	F	26	14-11-06	36.3	Breaking in horses and walking cattle
16A	M	24	13-11-06	35.2	Walking cattle
16B	M	24	15-11-06	38.6	Mustering cattle
17	F	29	03-11-06	33.1	Mustering cattle
18	M	20	03-11-06	33.1	Mustering cattle
19	M	24	06-11-06	34.8	Mustering cattle
20	F	50	06-11-06	34.8	Mustering cattle
21	M	27	12-11-06	37.2	Walking cattle
22	M	25	15-11-06	38.6	Mustering cattle
23	F	23	15-11-06	38.6	Mustering cattle
24	F	19	15-11-06	38.6	Mustering cattle

Notes: Subjects are coded by number, with letters signifying multiple sampling of the same subject. Air temperatures are means recorded over the duration of work for each day of testing (0800-1600 hours), with data sampling for any one subject occurring either before or after the lunch break.

Stockmen wore portable heart rate monitors during a series of routine mustering and horseback duties (Table 2; Figure 3). To ensure data were collected from the broadest possible range of working conditions, stockmen were asked to ride at several different intensities. Following data collection, core temperature measurements were taken to track thermal status, since core temperature increments will displace the heart rate upwards for a given metabolic demand, particularly at lighter work rates.

Figure 3: Field recording of heart rates and core temperatures.

Following data collection, heart rate, oxygen uptake and carbon dioxide production were simultaneously measured during cycle ergometry (Figure 4), to elicit heart rates similar to those observed in the field. These trials were performed outside, but under shade, so that ambient conditions (34.9°C, 41.5% relative humidity) could be used to elevate core temperature. This process enabled the calibration of heart rate and oxygen uptake for each stockman. From this calibration, subsequent heart rates obtained within field trials would allow the investigators to approximate the metabolic heat production associated with mustering duties. Five different work intensity levels (steps) were used, each lasting about 10 min, and each was determined from the heart rate observations obtained during routine mustering and horseback duties. The heart rates used in this stage of testing were determined directly from those collected for that subject in the field. Data were collected at rest and at four exercise intensities relative to the median heart rate (Table 3).

Table 3: Determining target work rates from heart rate data.

Level	Classification	Heart rate (b.min^{-1})
1	rest	60
2	lower quartile	85
3	median	110
4	upper quartile	135
5	median plus 3 standard deviations	160

Prior to starting the exercise protocol, an exercise-induced thermal load was applied to ensure the core temperature reached the mean core temperature observed in the field, at the end of the initial horseback data collection. Table 4 shows the time line for these tests.

Figure 4: Calibration of individual heart rates to oxygen uptakes.

Table 4: Heart rate calibration: experimental time line.

Time (min)	Activity summary
0	Subject arrival
0-35	Subject preparation, 500 ml water consumed
35-40	Thermoneutral baseline data collection
40-70	30-min warm-up to target core temperature
70-80	First stage of step protocol
80-90	Second stage of step protocol
90-100	Third stage of step protocol
100-110	Fourth stage of step protocol
110-120	Fifth stage of step protocol
120-130	Terminate data collection

Heart rate was monitored from ventricular depolarisation throughout each trial (5-sec intervals) using a portable data logger (Polar Electro Sports Tester, Finland). Data were subsequently downloaded to a portable computer.

Core temperatures were approximated using infrared tympanic thermometry (FirstTemp Genius, Model 3000A, Sherwood IMS Inc., CA, U.S.A.). Data were collected at the conclusion of each field trial. These data were used only to determine the appropriate experimental core temperature for each subject during the calibration trials.

Expiratory gases were analysed for oxygen (zirconium oxide analyser), carbon dioxide content (infrared analyser) and flow (triple-V digital) using a Metamax portable gas analysis system (Metamax I, CORTEX Biophysik, Leipzig, Germany). These data, sampled at 10-sec intervals, were used to derive oxygen uptake, carbon dioxide production and respiratory gas exchange ratio data online. Calibration gases were obtained from the Northern Territory Institute of Sport (Darwin) and taken into the field.

4.1.3 Physiological and cognitive strain

Sixteen male and female stockmen (Table 5) participated in this activity, with three being studied twice. All procedures were approved by the Human Research Ethics Committee (University of Wollongong: HE06/250), with subjects providing written, informed consent.

Stockmen were monitored whilst performing routine horseback duties and mustering whilst wearing standard clothing (collared, long-sleeved shirt, long trousers, boots: insulation 0.29 $m^2K.W^{-1}$) and an equestrian helmet (Figures 5 and 6). The helmet chosen for these trials was that which the stockmen deemed to be the most stressful (New Derby Classic, Equine Science Marketing Pty. Ltd, Tullamarine, Australia), since it was considered that this helmet would provide an adequate opportunity to witness heat strain in stockmen, if it was likely to occur. Trials were of varying durations, during which physiological data were recorded continuously (portable data logging equipment) and cognitive function testing was performed before and after each. Subjects voluntarily rehydrated throughout each trial, as per their normal practice. The average daily air temperatures for these trials, obtained over the 8-hour working period (0800-1600 hours), was 35.7^oC.

The timing of these field tests was designed to maximise the external thermal strain. The ambient conditions are summarised in Table 5.

Table 5: Subject characteristics and details for field tests.

Subject	Gender	Age (y)	Height (m)	Mass (kg)	Sum of skinfolds (cm)	Test date	Air temperature (^oC)	Activity
1A	F	21	177.0	69.5	90.5	30-10-06	34.0	Walking cattle
1B	F	21	177.0	69.5	90.5	06-11-06	34.8	Mustering cattle
2	M	19	182.5	74.5	68.0	31-10-06	33.4	Mustering cattle
4A	M	26	181.4	82.0	78.5	31-10-06	33.4	Mustering cattle
4B	M	26	181.4	82.0	78.5	09-11-06	37.0	Mustering cattle
5	M	19	184.1	73.0	65.0	30-10-06	34.0	Walking cattle
6	F	23	171.1	65.0	94.0	10-11-06	38.4	Mustering cattle
7	M	17	183.5	75.0	57.0	02-11-06	34.2	Mustering cattle
8	M	17	182.0	76.5	44.0	03-11-06	33.1	Mustering cattle
9	M	19	181.0	78.0	65.0	03-11-06	33.1	Mustering cattle

Subject	Gender	Age (y)	Height (m)	Mass (kg)	Sum of skinfolds (cm)	Test date	Air temperature (^oC)	Activity
10A	M	28	181.4	89.0	64.5	10-11-06	38.4	Mustering cattle
10B	M	28	181.4	89.0	64.5	10-11-06	38.4	Mustering cattle
11	M	17	177.0	67.0	60.5	12-11-06	37.2	Walking cattle
12	M	15	165.0	63.5	49.5	12-11-06	37.2	Walking cattle
13	M	20	179.0	76.0	79.0	13-11-06	35.3	Walking cattle
14	F	21	168.5	62.5	101.0	13-11-06	35.3	Walking cattle
15	F	26	169.3	71.0	102.5	14-11-06	36.3	Breaking in horses and walking cattle
16	M	24	175.1	70.0	50.0	15-11-06	38.6	Mustering cattle

Notes: Subjects are coded by number, with letters signifying multiple sampling of the same subject. Air temperatures are means recorded over the duration of work for each day of testing (0800-1600 hours), with data sampling for any one subject occurring either before or after the lunch break.

For each experimental stage, subjects were asked 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. During preparation, subjects were provided with supplementary water (10 ml.kg^{-1}). At the end of the testing day, subjects were rehydrated, consuming an iso-osmotic drink equivalent to 150% of the body mass change.

Experimental measurements

Body core and skin temperatures, clothing and helmet temperatures and water vapour pressures, heart rate, sweat rate, and hydration status were recorded. In addition, an array of psychophysical and cognitive function variables were quantified.

Figure 5: Subject preparation: in station hut and the field.

Core temperature was approximated from gastrointestinal temperatures, measured continuously using a radio capsule (Jonah; 1.75 g) ingested prior to each trial. Data were sampled at 1-min intervals (VitalSense, Mini Mitter Co. Inc, OR, U.S.A.). This method of measuring core temperature has been validated during routine daily activities (McKenzie and Osgood, 2004), and also during intermittent exercise of varying intensities (Gant *et al*., 2006).

Skin temperatures were measured (30-sec intervals) using thermistors (Temperature sensor T-3, DS18B20, Prospective Concepts AG, Switzerland) taped to eight skin sites, and recorded using an MSR data logger (Prospective Concepts AG, Switzerland). Mean skin temperature (T_{sk}) was derived using standard skin surface area weightings (ISO 9886, 1992; after Hardy and DuBois, 1938).

$$T_{sk}=0.07 \cdot T_{sk-1}+0.175 \cdot T_{sk-2}+0.175 \cdot T_{sk-3}+0.07 \cdot T_{sk-4}+0.07 \cdot T_{sk-5}+0.05 \cdot T_{sk-6}+0.19 \cdot T_{sk-7}+0.2 \cdot T_{sk-8} \quad [^{o}C]$$

where:

T_{sk-1} = forehead [^{o}C]
T_{sk-2} = chest [^{o}C]
T_{sk-3} = scapula [^{o}C]
T_{sk-4} = arm [^{o}C]
T_{sk-5} = forearm [^{o}C]
T_{sk-6} = hand [^{o}C]

T_{sk-7} = thigh [^oC]
T_{sk-8} = calf [^oC].

Figure 6: Stockman wearing data collection equipment.

Combination temperature and relative humidity sensors (sensors DSB18B20 and SHT15, Prospective Concepts AG, Switzerland) were used to measure local air temperatures and relative humidities at three sites (external air, inside the helmet, inside the shirt), with data sampled at 30-sec intervals and recorded using an MSR data logger (Prospective Concepts AG, Switzerland). These data were used to derive local water vapour pressure (P_{H20}) using the following relationship.

$$P_{H20} = RH_{local} * \exp^{(16.6536-4030.183/(T+235)} \quad [kPa]$$

where:
RH_{local} = local relative humidity [%]
T = local temperature [^oC].

Heart rate was monitored from ventricular depolarisation throughout each trial (30-sec intervals; Polar Electro Sports Tester, Finland).

Unclothed body mass was measured before, and immediately following the completion of each trial (standard bathroom scale). From these data, gross body mass changes were used to approximate sweat secretion rates. Urine specific gravities were determined before and after each trial to evaluate hydration state.

Cognitive function

Cognitive function was evaluated immediately before, and immediately after each trial, using the Mini-Cog rapid assessment battery (Shephard and Kosslyn, 2005) administered via a personal digital assistant (PDA, PalmOne, Tungsten C). Four cognitive function tests were administered: vigilance, working memory, problem solving and perceptual reaction time. Previous research within our laboratory has established the learning curves from these tests, and determined the number of trials necessary to obtain a learning plateau (Caldwell *et al*., 2005). Accordingly, each subject performed the cognitive-function test battery on seven occasions prior to commencing the present trials. Test administration was always performed whilst subjects rested in a thermoneutral state.

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.

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).

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.

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.

Psychophysical measures
Subjects were asked prior to, and at the end of each trial, 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 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	

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 was evaluated using another modified scale (Gagge *et al.*, 1967), and in response to the question: "*How comfortable 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 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?*". This scale was developed within the current laboratory (Caldwell, 2007).

13-point skin 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 was evaluated using a modification of the thermal discomfort scale above, and developed within the current laboratory (Caldwell, 2007). Subjects responded to the question: "*How comfortable are you with the wetness of your skin (clothing)?*"

The 5-point skin wetness discomfort scale

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

Design and analysis

These trials were based upon a single-observation experimental design, with the desired outcome being a quantitative description of environmental stress, and the corresponding physiological and cognitive strain. Therefore, data were predominantly analysed to provide standard descriptive parameters (means and standard deviations). However, *t*-tests were performed to compare different horseback activities, and also to compare the results of the psychophysical assessments and cognitive function tests administered before and after each trial. For all comparisons, *alpha* was set at the 0.05 level.

4.2 Phase Two: Bench-top trials

4.2.1 Heat penetration trials

Phase two testing did not involve human subjects, but physical testing on a range of helmets and the standard felt hat worn by stockmen, with heat penetration and other physical characteristics being evaluated under controlled laboratory conditions. These tests were all performed using a head manikin (Figure 7).

Four helmets and one felt hat (Figure 8), each of the same hat size, were exposed a radiant heat load within an air-conditioned laboratory, in which air temperature was regulated at 20.7^{o}C (SD 0.60) across the trials. Radiant heating was applied using three 375-Watt heat lamps, that were set at a fixed distance from the surface of each helmet/hat. This distance was set to prevent heat damage to the helmet/hat, whilst exposing it to an extreme heat source. The resultant mean, maximal outer surface temperature across the helmets/hat was 115.2^{o}C. Heating was applied for 20 min, followed by 20 min of passive cooling, and then 20 min of active cooling using forced ventilation. The ventilation applied was controlled to match the average speed of horses (5.16 km.h^{-1})[1], recorded when stockmen were mustering or undertaking related horseback activities during Phase One of this project (Taylor and Caldwell, 2007). Manikin surface temperatures were allowed to return to baseline conditions prior to commencing the next test, to minimise residual heat bias.

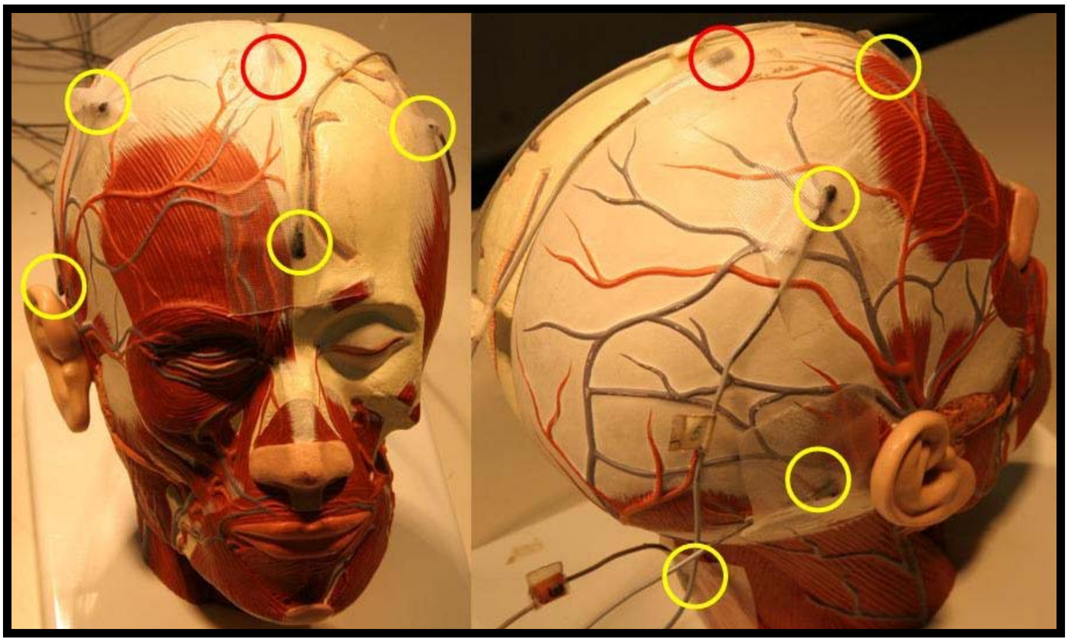


Figure 7: Head manikin showing positioning of skin temperature sensors (circles).

[1] These data were recorded from 51.1 hours of testing, using a global position system mounted on stockmen during routine horseback duties in the field (Taylor and Caldwell, 2007).

Temperature sensors (Type EU thermistors, Yellow Springs Instruments Co. Ltd., Yellow Springs, OH, U.S.A.) were attached to the outer and inner surfaces each helmet/hat (secured with waterproof tape), and also positioned within the air cavity between the top of the head and helmet (Figure 2). Data were collected at 15-sec intervals using a data logger (1206 Series Squirrel, Grant Instruments Pty. Ltd., Cambridge, U.K.).

Manikin surface (skin) temperatures were measured at six sites (Type EU thermistors, Yellow Springs Instruments Co. Ltd., Yellow Springs, OH, U.S.A.): forehead, top of the head, nape of neck, behind the right ear, and two thermistors placed 3 cm to the right and left of the centre thermistor. These sensors will be secured with waterproof tape, and were not moved between trials. These data were also collected at 15-sec intervals (1206 Series Squirrel, Grant Instruments Pty. Ltd., Cambridge, U.K.).

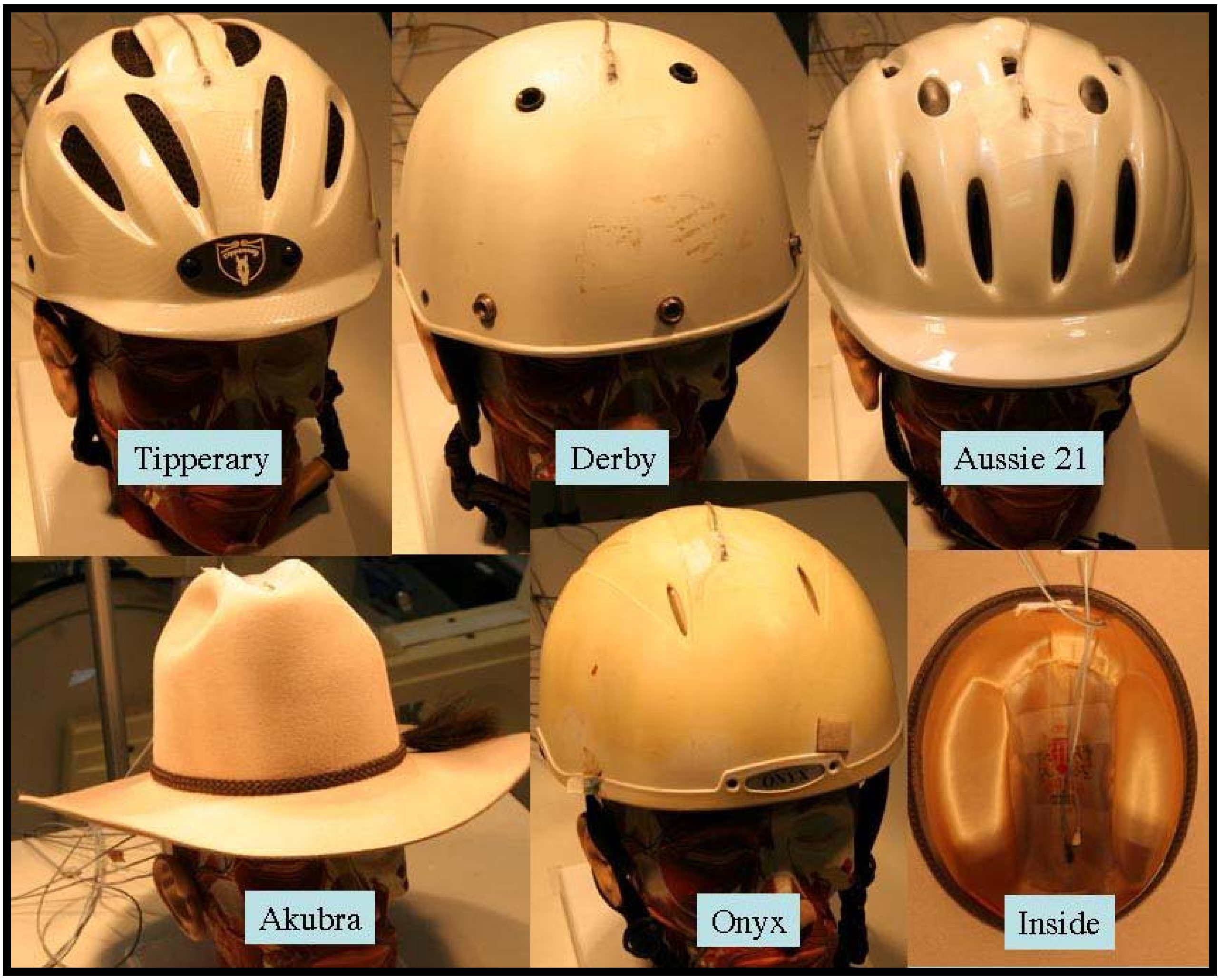


Figure 8: Equestrian helmets and felt hat used in heat penetration trials.

4.2.2 Centre of mass

When viewed laterally, the axis of gravity of the upright human body passes through the external auditory meatus, the sixth cervical vertebra (C6), the ninth thoracic vertebra (T9) and the third sacral segment (Asmussen and Klausen, 1962). In this section, the focus is on the centre of gravity of the head, and the mechanical forces at this point that are induced by wearing a helmet. The term centre of mass is used in preference to centre of gravity, since the head is neither of uniform shape nor density.

Vital and Senegas (1986) suspended isolated cadaver heads (male and female), finding the centre of mass of the head to be most frequently positioned at the centre of the nasion-inion line (Figure 8); just above, and anterior to the external auditory meatus, and very close to the forward, upper junction of the ear (helix) with the scalp. Figure 9 shows the head orientation when one adopts either the attention (Figure 9A) or neutral positions (Figure 9B). The latter is most commonly assumed during conversation, when performing most daily activities, and is the position recommended by ergonomists for maintaining a good working posture. It will therefore be the reference position for head carriage, or cervico-cephalic equilibrium, and corresponds with the gaze directed approximately 15-30^{o} below the horizontal. In this position, the line joining the nasion and the opisthion will be horizontal, and the centre of mass (point 1 on Figure 9B) will be forward of the pivot point of the skull (point 2 on Figure 9B).

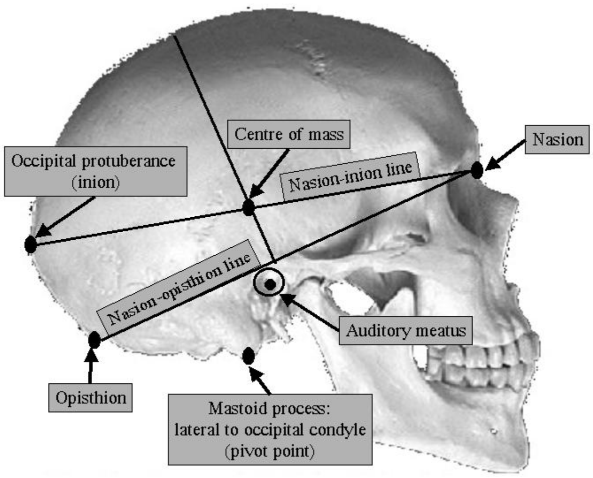


Figure 8: Lateral aspect of the skull showing key anatomical landmarks (the occipital condyles are located behind the mastoid process).

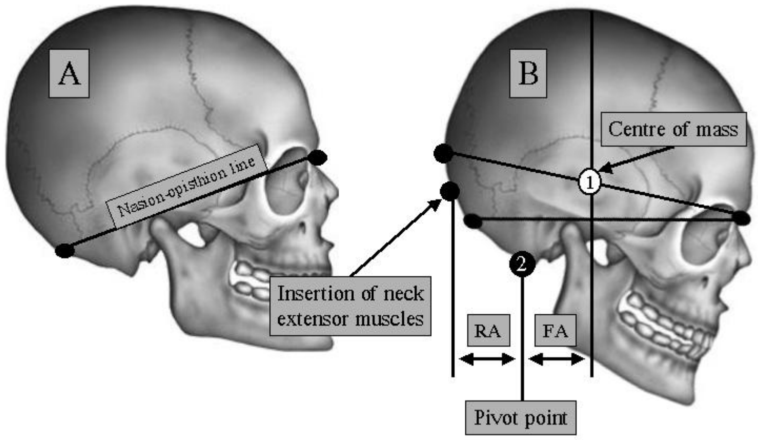


Figure 9: The skull in the attention (**A**) and neutral positions (**B**). The centre of mass (1) is forward of the pivot point (2) of the skull, and the lengths of the load (resistance) arm (FA) and the effort arm (RA) are equal.

If the centre of mass of the head is positioned directly above its axis of rotation, then no muscular activity would be required to hold a constant head position. However, since the centre of mass is forward of the occipital condyles, then a constant tendency exists for the head to rotate forwards into a more flexed position, and the neck extensor muscles (*trapezius*, *erector spinae*, transverse *spinalis*) are constantly activated to hold the neutral position. The tendency of a force (*e.g.* head mass or muscle activation) to cause rotation about a pivot point is known as torque, and it is derived from the product of the force applied and the perpendicular distance from the line of the force (force vector) to the axis of rotation. This distance is called the moment or torque arm.

T = F * MA
where:
T = torque [Newton-metres: N-m]
F = force [Newtons: N]:
F [N] = mass [kg] * acceleration due to gravity [9.807 $m.s^{-2}$]
MA = moment (torque) arm [metre: m].

In Figure 9B, two moment arms are indicated. The first is the horizontal distance from the centre of rotation (pivot point) of the head to the centre of mass of the head. This is the length of the load (resistance) arm, and it is forward of the occipital condyles. It is shown as a forward acting moment arm (FA), and it is due to the mass of the head. The second is the rearward acting moment arm (RA), which is the horizontal distance from the centre of rotation of the head to the average insertion point of the posterior neck muscles. In the neutral (reference) position, the two moment arms are equal, so the force exerted by the muscles must exactly equal the force exerted by the mass of the head to prevent rotation of the head. However, when head wear is used, both the force vectors and the moment (torque) arms are influenced. While load *per se* is very important, it is the difference between the moment arms that dictates muscular activity. For example, lengthening the load (resistance) moment arm by 50% results in a doubling of the muscular force necessary to maintain a constant, neutral head posture.

The reaction-board method was used to determine the mass and centre of mass for each helmet (after: Njus *et al*., 1984 and Taylor *et al*., 2004). This process involved the following steps:
(a) determining the mass of each helmet ($Mass_{Helmet}$; scale: Mettler Toledo)
(b) attaching a rigid beam to two, parallel knife edges, such that one knife edge was mounted in the centre of a scale (Mettler Toledo), and the second was positioned off the scale so that the beam was horizontal
(c) measuring the distance between the knife edges (D)
(d) determining the mass of the above apparatus, as positioned, but without the helmet ($Mass_{Partial}$)
(e) positioning the rear of each helmet at the same fixed position, and at a point immediately above the latter knife edge
(f) weighing the apparatus with the helmet ($Mass_{Total}$); the combined apparatus and helmet masses were measured five times for each helmet/hat.
The centre of mass locus for each helmet was then derived using the following equation:

$$\text{Centre of mass [cm]} = (Mass_{Total} - Mass_{Partial}) * D / Mass_{Helmet}$$

where:
$Mass_{Total}$ = combined mass of helmet and apparatus [kg]
$Mass_{Partial}$ = mass of apparatus without the helmet [kg]
D = distance between the two knife edges [cm]
$Mass_{Helmet}$ = mass of the helmet [kg].

Data analysis
Data were analysed to provide standard descriptive parameters.

4.3 Phase Three: Laboratory trials

Phase Three of this project was aimed at providing an assessment of the physiological and cognitive strain encountered during a standardised exercise-heat stress test, performed under controlled climatic conditions and physical work rates, as determined during Phase One of this project. In addition, differences in the influence of an equestrian helmet and a felt hat on physiological and cognitive function were evaluated.

4.3.1 Experimental procedures

Eight healthy, physically-active adult males participated in this study (Table 6), following the provision of written, informed consent. All procedures were approved by the Human Research Ethics Committee (University of Wollongong). Subjects were recruited to reflect the stature of stockmen evaluated in Phase One of this project, and each was tested on two occasions wearing one of two types of headwear (felt hat and equestrian helmet), with standardised clothing. Subjects acted as their own controls.

Table 6: Subject characteristics.

Subject	Age (y)	Height (m)	Mass (kg)	Surface area (m^2)	Surface area to mass ratio ($m^2.kg^{-1}$)	Sum of skinfolds (mm)
S1	35	170.6	68.96	1.86	0.027	46.2
S2	20	181.6	82.12	2.03	0.025	67.5
S3	21	180.3	79.80	2.00	0.025	47.7
S4	29	167.6	64.62	1.73	0.027	72.1
S5	21	185.4	81.84	2.06	0.025	71.1
S6	22	178.1	86.88	2.05	0.024	77.9

Subject	Age (y)	Height (m)	Mass (kg)	Surface area (m^2)	Surface area to mass ratio ($m^2.kg^{-1}$)	Sum of skinfolds (mm)
S7	20	172.0	81.84	1.95	0.024	70.7
S8	22	180.7	69.28	1.88	0.027	47.6
Mean	23.8	178.0	76.92	1.95	0.025	62.6
S.D.	5.39	5.67	8.07	0.11	0.001	13.1

Subjects completed two trials (Table 7) in a hot-dry environment (38°C, 30% relative humidity). These conditions represented the average maximal air temperature and the average relative humidity (1500 hours; hottest time of day) for Victoria River Downs during November, for the 15-year period 1991-2006 (Taylor and Caldwell, 2007). In addition, three, 500-W radiant heat lamps were positioned about 1 m overhead to simulate solar loading, and two fans were positioned in front of the subject and set to provide an airflow of 5.16 $km.h^{-1}$, the average riding speed observed in the field (Taylor and Caldwell, 2007).

Table 7: Phase 3: Experimental time line.

Time (min)	Activity summary
0-5	Subject arrival, hydration check (urine sample) Body mass measured
5-60	Subject preparation (22°C), consume water:10 $mL.kg^{-1}$ If urine SG >1.029: 500 mL iso-osmotic drink
60-75	Cognitive function tests (baseline)
75-80	Enter climate chamber (38°C, 30%RH)
0	Commence experiment
0-5	Baseline data collection: seated rest in heat
5-30	Exercise level 1: 75 W 20 min: Remove felt hat (only) for 30 sec 20 min: Consume water: 7.5 $mL.kg^{-1}.hr^{-1}$
30-35	Rest Psychophysical questionnaires 35 min: Remove felt hat (only) for 30 sec 35 min: Consume water: 7.5 $mL.kg^{-1}.hr^{-1}$
35-60	Exercise level 1: 75 W 50 min: Remove felt hat (only) for 30 sec 50 min: Consume water: 7.5 $mL.kg^{-1}.hr^{-1}$
60-65	Rest Psychophysical questionnaires 65 min: Remove felt hat (only) for 30 sec 65 min: Consume water: 7.5 $mL.kg^{-1}.hr^{-1}$
65-72.5	Exercise level 2: 90 W
72.5-77	Exercise level 3: 100 W
77-80	Exercise level 4: 110 W 80 min: Remove felt hat (only) for 30 sec 80 min: Consume water: 7.5 $mL.kg^{-1}.hr^{-1}$
80-90	Exercise level 1: 75 W

Time (min)	Activity summary
90-95	Rest Psychophysical questionnaires 95 min: Remove felt hat (only) for 30 sec 95 min: Consume water: 7.5 $mL.kg^{-1}.hr^{-1}$
95-120	Exercise level 1: 75 W 110 min: Remove felt hat (only) for 30 sec 110 min: Consume water: 7.5 $mL.kg^{-1}.hr^{-1}$
120-125	Rest Psychophysical questionnaires 125 min: Remove felt hat (only) for 30 sec 125 min: Consume water: 7.5 $mL.kg^{-1}.hr^{-1}$
125-150	Exercise level 1: 75 W 140 min: Remove felt hat (only) for 30 sec 140 min: Consume water: 7.5 $mL.kg^{-1}.hr^{-1}$
150	Terminate exercise: do not remove hats Psychophysical questionnaires Cognitive function tests in chamber
165	Terminate experiment: supervised recovery Body mass measured Provide post-trial urine sample Post-trial rehydration provided: 150% mass change

Within each trial, subjects wore a long-sleeved, collared shirt, denim trousers and shoes (insulation ~0.29 $m^2K.W^{-1}$). In addition, subjects wore either an equestrian helmet (Aussie 21, Equine Science Marketing Pty. Ltd., Tullamarine, Australia; thermoplastic alloy) or a felt hat (Arena, Akubra Hats Pty. Ltd., Kempsey, Australia; 100% pure felt), with four subjects using the helmet for their first trial (Figure 10). The choice of the Aussie 21 helmet was made on the basis of bench-top testing (Caldwell and Taylor, 2007), which revealed this helmet to be superior to all others tested. It was considered essential that headwear comparisons be performed against the best possible helmet.

Figure 10: Experimental set-up.

Within each trial, subjects performed intermittent work at four different work intensities, on a recumbent cycle ergometer, for 2.5 hours. These intensities were based on those determined in the field: derived from 27 heart rate data sets obtained during horseback mustering (Taylor and Caldwell, 2007).

These heart rates were used to determine external work rate (W) for the current testing Phase (rounded to the nearest 5 W). Durations reflected the time spent at each work intensity in the field:

Level one (135 min including rest periods): mean work rate: 75 W
Level two (7.5 min): mean work rate: 90 W
Level three (4.5 min): mean work rate: 100 W
Level four (3 min): mean highest work rate: 110 W.

Every 15 min, subjects consumed water equilibrated to climate chamber temperature: 7.5 $mL.kg^{-1}.hr^{-1}$ (*i.e*. 140 mL for 75-kg subject). At this time, subjects also removed the felt hat for 30 sec, and wiped the forehead with a cloth. This was to simulate typical behaviour in the field. This did not occur with the helmet. Every 30 min, subjects rested for 5 min. During this time, they were permitted to stand and stretch, but not to leave the chamber.

Subjects were required to refrain from strenuous exercise, and the consumption of alcohol and tobacco during the 12 h prior to each trial. For the night preceding each trial, subjects were instructed to drink 15 $mL.kg^{-1}$ of additional water before retiring, and to eat an evening meal high in carbohydrate and low in fat. Breakfast was also to be high in carbohydrate and low in fat. Subjects refrained from using caffeine for 2 h prior to each trial. On arrival at the laboratory, hydration state was checked (urine specific gravity). During each trial, subjects consumed water at a rate of 7.5 $mL.kg^{-1}.h^{-1}$ (at chamber air temperature) every 30 min (80-kg person: 640 $mL.h^{-1}$).

Subjects provided an immediate urine sample on arrival at the laboratory, for a pre-experimental hydration check (urine specific gravity). Any subject with a urine specific gravity >1.029 was provided with 500 mL of iso-osmotic drink, to be consumed during preparation. 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).

Experimental measurements
Physiological data were sampled continuously, with psychophysical collected every 30 min and cognitive function data collected before and after each trial.

Auditory canal temperature (T_{au}) was measured (Edale Instruments Ltd, U.K.), with data recorded throughout each trial at 60-s intervals 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 (T_{re}) was also measured continuously (60-s intervals), at a depth of 12 cm beyond the anal sphincter (Edale Instruments Ltd, U.K.). This measure was used with auditory canal temperature to derive an average core temperature index.

Skin temperatures were measured (60-s intervals) using thermistors taped to eight skin sites (Type EU, Yellow Springs Instruments Co. Ltd., Yellow Springs, OH, USA). These sites were: forehead, right scapula, right chest, right upper arm, left forearm, left dorsal hand, right anterior thigh and left posterior calf (ISO 9886, 1992). Mean skin temperature (T_{sk}) was derived using standard skin surface area weightings (ISO 9886, 1992; after Hardy and DuBois, 1938):

$T_{sk}=0.07.T_{sk-1}+0.175.T_{sk-2}+0.175.T_{sk-3}+0.07.T_{sk-4}+0.07.T_{sk-5}+0.05.T_{sk-6}+0.19.T_{sk-7}+0.2.T_{sk-8}$ [^{o}C]

where:

T_{sk-1} = forehead
T_{sk-2} = chest
T_{sk-3} = scapula
T_{sk-4} = arm
T_{sk-5} = forearm
T_{sk-6} = hand
T_{sk-7} = thigh
T_{sk-8} = calf.

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 the range 21-46^{o}C, in 5^{o}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^{o}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.

Local air temperatures and relative humidities were measured within the hat and shirt (chest), as recorded during filed trials (Taylor and Caldwell, 2007). Data were recorded throughout each trial at 60-sec intervals using combination temperature and relative humidity sensors (sensors DSB18B20 and SHT15, Prospective Concepts AG, Switzerland), with data recorded using an MSR data logger (Prospective Concepts AG, Switzerland). These data were used to derive local water vapour pressure (P_{H20}) using the following relationship.

$P_{H20} = RH_{local} * \exp^{(16.6536-4030.183/(T+235)}$ [kPa]

where:

RH_{local} = local relative humidity [%]
T = local temperature [^{o}C].

Heart rate was monitored from ventricular depolarisation throughout each trial (60-sec intervals; Polar Electro Sports Tester, Finland).

Unclothed body mass was measured before, and immediately following the completion of each trial, after complete drying of the subject (A&D, Model No. fw-150k, California, U.S.A.). Data were corrected for fluid replacement and urine productio, and used to approximate the whole-body sweat rate.

Psychophysical measures

Subjects were asked, at 30-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 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	

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 was evaluated using another modified scale (Gagge *et al.*, 1967), and in response to the question: "*How comfortable 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 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?*". This scale was developed within the current laboratory (Caldwell, 2006).

13-point skin 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 was evaluated using a modification of the thermal discomfort scale above, and developed within the current laboratory (Caldwell, 2006). Subjects responded 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

Cognitive function

Cognitive function was evaluated immediately before, and immediately after each trial, using the Mini-Cog rapid assessment battery (Shephard and Kosslyn, 2005) administered via a personal digital assistant (PDA, PalmOne, Tungsten C). Four cognitive function tests were administered: vigilance, working memory, problem solving and perceptual reaction time.

Previous research within our laboratory has established the learning curves from these tests, and determined the number of trials necessary to obtain a learning plateau (Caldwell *et al*., 2005). Accordingly, each subject performed the cognitive-function test battery on seven occasions prior to commencing the present trials. Test administration was always performed whilst subjects rested in a thermoneutral state.

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.

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).

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.

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.

Design and analysis

This project was based upon a fully-crossed, repeated-measures experimental design, with each subject participating in all trials, and using one of the two forms of headwear.

Due to anticipated variations among the pre-experimental baseline data, associated with circumstances beyond the control of the investigators, all physiological data were normalised to a common pre-experimental baseline. This point was the observed baseline mean, derived across each of the trials, for the variable of interest. Between-hat 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. *Alpha* was set at the 0.05 level for all statistical comparisons. Data are presented as means with standard errors of the means, unless otherwise stated (standard deviations: S.D.). Data collection commenced within a pre-experimental baseline period, and continued throughout exercise. All graphs are referenced to the commencement of exercise (0 min).

5 Results

5.1 Phase One: Field trials

5.1.1 Quantification of the working environment

Across the three months of interest (September-November: 2006), the mean 24-hour air temperature was 28.5^{o}C, while the relative humidity was 40.5%. The hourly climatic data for these months are summarised in Figures 11-13 and Table 8. These data show the normal reciprocal changes in humidity with air temperature. In a dry climate, where water is predominately added to the air via transpiration from plants, and via evaporation from the soil and exposed water, the total water content of the air remains quite stable. Thus, air temperature largely dictates relative humidity, since it modifies the total number of water molecules that can be held within a given air volume. Since this increases with air temperature, relative humidity swings out of phase with air temperature (Figure 13).

Table 6: Climatic summary for Victoria River Downs Station (2006).

Variable	September	October	November
Mean air temperature (^oC): work	30.3	33.7	35.7
Maximal air temperature (^oC)	33.8	36.4	38.8
Time of maximal temperature	1600	1600	1500
Minimal air temperature (^oC)	15.6	21.7	24.5
Time of minimal temperature	0700	0600	0600
Change: maximal - 0800 hours	13.8	9.7	9.8
Mean humidity (%): work	28.0	29.7	33.4
Maximal humidity (%)	59.7	58.6	62.8
Time of maximal humidity	0700	0700	0600
Minimal humidity (%)	19.8	21.0	22.7
Time of minimal humidity	1500	1700	1500
Change: maximal - minimal	39.9	37.6	40.1
Mean water vapour pressure (kPa)	1.14	1.51	1.85
Maximal vapour pressure (kPa)	1.28	1.81	2.32
Minimal vapour pressure (kPa)	1.03	1.26	1.55

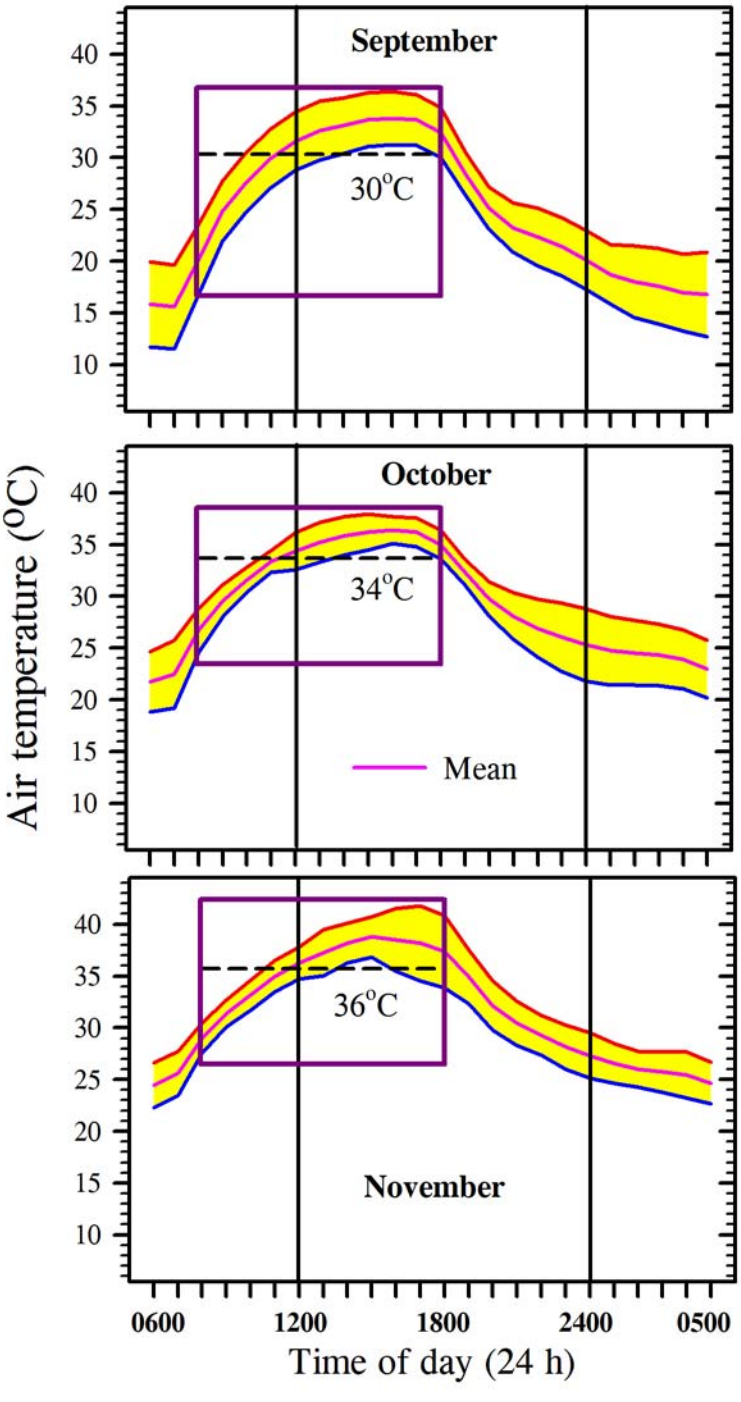


Figure 11: Hourly air temperatures for Victoria River Downs (September-November) for 2006. Data are means, with the yellow shaded zones representing one standard deviation above and below the means. The rectangles define the ten-hour working period, with the dashed lines (and numbers) indicating the means over this time.

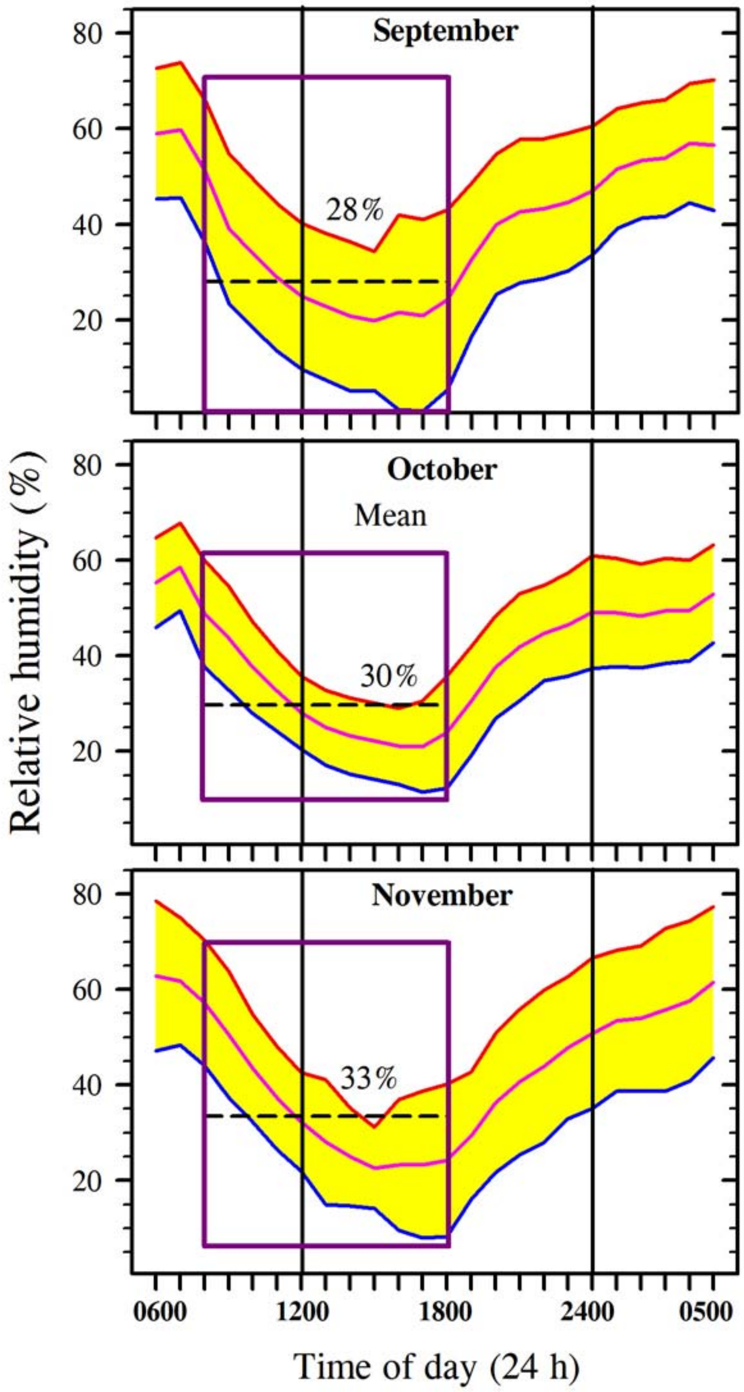


Figure 12: Hourly relative humidity for Victoria River Downs (September-November) for 2006. Data are means, with the yellow shaded zones representing one standard deviation above and below the means. The rectangles define the ten-hour working period, with the dashed lines (and numbers) indicating the means over this time.

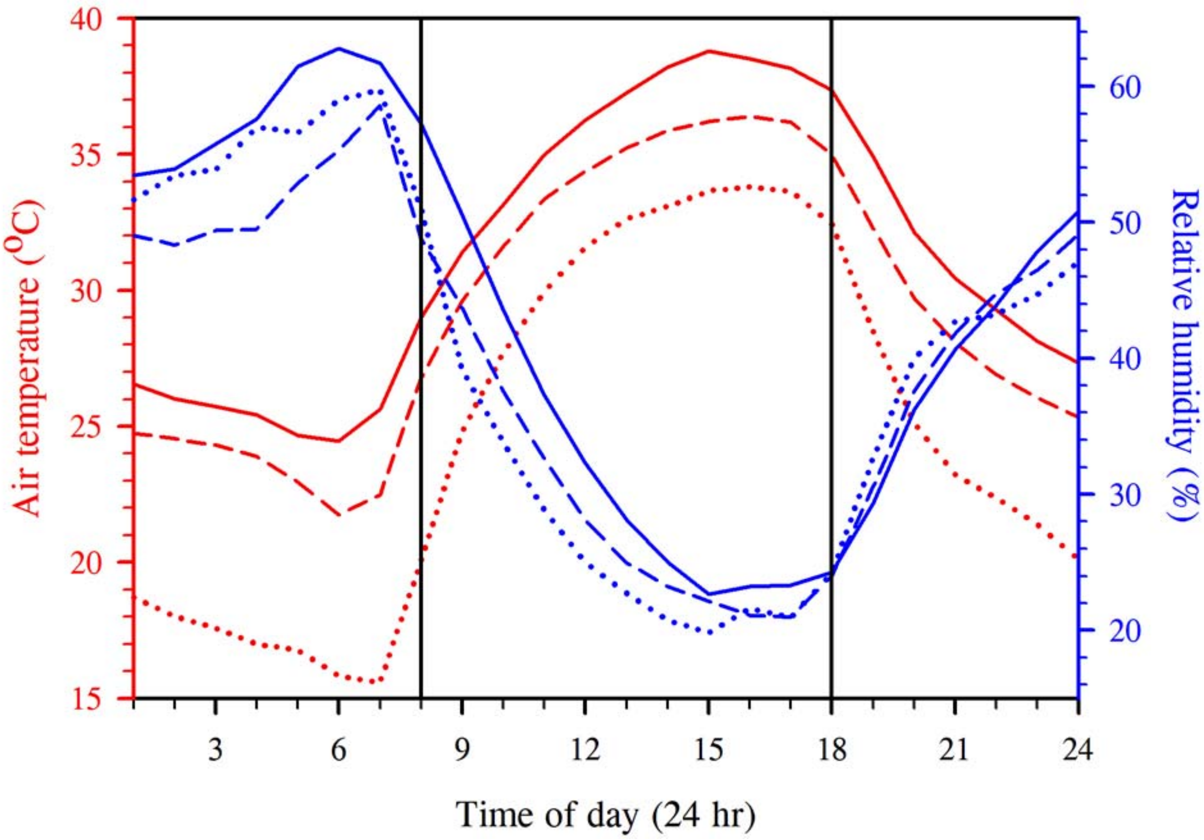


Figure 13: Combined hourly air temperatures (red) and relative humidities (blue) for Victoria River Downs averaged for 2006. Data are means for September (dots), October (dashes) and November (solid lines).

For each month, the peak air temperatures progressively increased, and occurred between 1500-1600 hours (Tables 8, 9A and 9B), with significant cooling only occurring after work ended for the day. Fortunately, at these times, the relative humidity was very low (<25%), enabling the evaporation of sweat to help dissipate body heat. At the coolest times, 0600-0700, the relative humidities were maximal, approaching 60% (Tables 8 and 9). Thus, even during the cooler hours, the environmental conditions can be difficult for some individuals to work with comfort. As a consequence of these minimal and maximal temperatures, stockmen encountered a 10-15^{o}C elevation in air temperature during the course of their working day. These data are reflected in the 16 years of climatic information obtained from the Bureau of Meteorology (Tables 9A and 9B). A very powerful way to quantify the thermal impact of the combined work and environmental conditions is to compute its thermal compensability.

Thermal compensability: background overview

An early thermal stress index was developed by Houghten and Yagloglou (1923): the effective temperature.

The critical feature of this scale was that it aimed at defining thermal comfort limits for people within air-conditioned spaces, by identifying combinations of dry-bulb temperature, air motion and relative humidity that would elicit equivalent thermal comfort. If one assumes that thermal discomforture initiates behavioural responses (Cabanac, 1981; Hensel, 1981), and that the signals driving thermoregulation may be of a different origin (Cabanac, 1975; Hensel, 1981; Jessen, 1990; Rowland, 1996), then the link between the effective temperature scale and assessing physiological risk is perhaps insubstantial. Consider also that these experiments were performed with subjects wearing standard office clothing, and that the resultant scale was designed for use in environments close to the thermal comfort zone. Thus, extrapolation to thermally-stressful environments is also tenuous, particularly when physical work is to be performed, or when people are wearing protective clothing.

Table 9a: Monthly climatic summary data for Victoria River Downs (1991-2006).

Variable	September	October	November
Maximum temperature (^{o}C)	35.5	37.3	38.1
Minimum temperature (^{o}C)	18.6	22.3	24.5
Average temperature (^{o}C)	27.1	29.8	31.3

Table 9b: Monthly climatic summary data for Victoria River Downs (2001-2006).

Variable	September	October	November
Maximum temperature (^{o}C)	35.2	38.4	38.7
Minimum temperature (^{o}C)	18.0	22.0	22.8
Average temperature (^{o}C)	26.6	30.2	31.7
9 AM relative humidity (%)	37.8	41.6	53.6
3 PM relative humidity (%)	21.6	21.4	31.2
Number of days of rainfall	1.6	2.8	7.2
Total monthly rainfall (mm)	3.7	7.9	45.5
Daily solar exposure (MJ.m^{-2})	22.4	25.3	26.9

Nevertheless, a wide variety of effective heat stress indices has arisen directly from this scale and, due to their simplicity, these are the most widely used thermal indices (Belding, 1970). Of these, the most frequently used index for industrial, military and sporting applications is the wet-bulb globe temperature index (WBGT), developed by Yagloglou and Minard (1957) to reduce the incidence of heat illness during military training. Indeed, 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).

A number of researchers have evaluated the physiological efficacy of using the WBGT-index (Ramanathan and Belding, 1973; Azer and Hsu, 1977; Lotens and van Middendorp, 1986; Rastogi *et al*. 1992; Moran and Pandolf, 1999), with the most eloquent studies coming from Wenzel's group (Ilmarinen, 1978; Wenzel, 1978; Wenzel *et al*., 1989). Notwithstanding the almost ubiquitous adoption of the WBGT-index, these studies have identified several significant limitations of this method. 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, it 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). Since hyperthermia can be induced simply by exercise-induced heat production, then metabolic heat production is a critical consideration. Furthermore, Lind (1963a, b) and Wenzel (1978) demonstrated that the physiological influence of air humidity, at a fixed air

temperature, was elevated when metabolic rate was increased. Fourth, Ilmarinen (1978) and Wenzel *et al.* (1989) both 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, the 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 or heart rate. Fifth, the usefulness of the WBGT-index for clothed workers has been found to range from inferior (Lotens and van Middendorp, 1986) to wholly inappropriate when encapsulating ensembles are used (Goldman, 1994).

One can generally attribute these limitations to the fact the WBGT-index is not a rational scale. That is, it is not based upon heat balance and the thermodynamics of heat transfer, but solely upon quantifying the thermal environment; its greatest strength (simplicity) has thus become its greatest limitation. Consequently, investigators have found that different combinations of air temperature, globe temperature and humidity can result in an identical WBGT, but with markedly different physiological strain (Ilmarinen, 1978; Wenzel, 1978; Wenzel *et al*., 1989). In general, one can reliably assume that conditions with a WBGT of 25°C will be less stressful than those with a WBGT of 35°C, as reflected in the standard risk classifications (American College of Sports Medicine, 1996). This is illustrated in Table 10 and Figure 14 where, for the same air temperature, the risk of heat illness is elevated as relative humidity increases. However, we cannot assume that condition of equal WBGT are equally stressful. Indeed, physiological strain will be greater for hot-dry than for hot-humid conditions, even when both states have an equivalent WBGT (Wenzel, 1978). This limitation makes the WBGT index an inferior scientific tool. Notwithstanding these reservations, WBGT data for Victoria River Downs are summarised in Figure 15.

Table 10: The WBGT Index rating of thermal stress.

WBGT Range (°C)	Recommendation
>28°C	Very high risk
23-28°C	High risk
18-23°C	Moderate risk
<18°C	Low risk

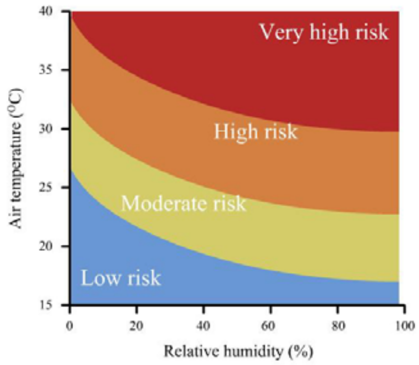


Figure 14: Changes in the risk of developing heat illness for combinations of air temperature and relative humidity (Taylor, 2005c).

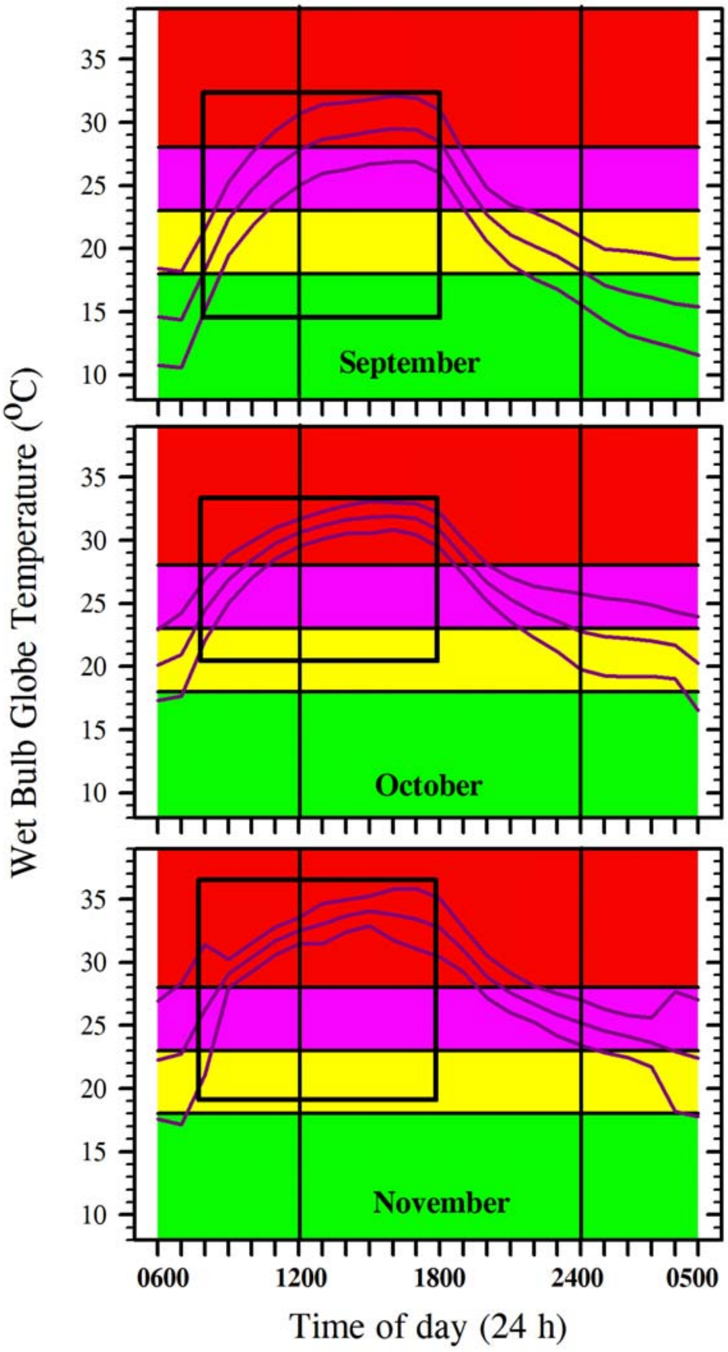


Figure 15: Hourly Wet Bulb Globe Temperatures for Victoria River Downs (September-November) for 2006. Data are means, with standard deviations above and below the means. The rectangles define the ten-hour working period. Coloured regions correspond with very high risk (red), high risk (pink), moderate risk (yellow) and low risk (green).

The climate of northern Australia cattle stations investigated as part of this project, at least for the months September-November, may be classified as a hot-dry environment. It is the opinion of the current authors that, relative to the WBGT index (and other effective scale), rational heat indices provide a superior means by which to identify potentially hazardous environments. Such scales attempt to integrate the quantification of heat exchange with the resultant physiological strain. The first rational index (operative temperature) was that of Winslow *et al.* (1937), with Belding and Hatch (1955) subsequently developing the **Heat Strain Index**, from which several further modifications have arisen. While these indices also have limitations[1], the principles upon which they are based are both sound and balanced. Accordingly, the Heat Strain Index will be used to further quantify the environmental and working conditions.

During work or exercise in the heat, the avenues for non-evaporative (dry) heat dissipation are impeded, and can be reversed, leading to heat gain. For instance, under a full solar load, the body experiences radiative heat gains from the sun and the nearby hot surfaces. These may be minimised through the use of protective clothing and head wear. Similarly, natural convective losses cease when air temperature approximates skin temperature (31-33°C), and this state will occur from 1200-1800 hours during September-November on these cattle stations. Under these conditions, the body becomes heavily, if not totally, reliant upon evaporative cooling for heat dissipation. The capacity of the body to continue its rate of endogenous heat production, without sustaining a progressive elevation in tissue temperature, is now dictated by the compensability of the thermal environment.

Thermal compensability defines the interaction of the body and the environment, such that it defines the conditions under which the body is most likely to enter a state of hyperthermia. For example, in hot environments, where the primary avenue for heat dissipation is the evaporation of sweat, then 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 environmental conditions are uncompensable. This ratio was first suggested by Belding and Hatch (1955) for use as a **Heat Strain Index** (E_{req}/E_{max} ratio) to relate thermal stress to physiological strain, with the derivations of the two variables being summarised in the equations below.

$E_{req} = H - E_{resp} \pm R \pm C$ [W]
where:
E_{req} = required evaporative cooling [W]
H = metabolic energy transformation, or the nett result of resting and exercising metabolism, and external work (*M -(±W)*) [W]
E_{resp} = evaporation accompanying ventilation [W]
R ±C = heat exchanges via radiation and convection [W].
$E_{max} = 6.45 * A_D * i_m / I_{TOT} * 2.2 * (P_{sk} - (RH_a * P_a))$ [W]
where:
E_{max} = maximal attainable evaporative cooling for a given environment and clothing configuration [W]
A_D = body surface area (Du Bois equation) [m^2]
i_m = moisture permeability index (0.45 if unknown) [dimensionless]
I_{TOT} = total insulation, including the trapped boundary layer air and clothing insulation [$m^2K.W^{-1}$]: 1 clo = 0.155 $m^2K.W^{-1}$
RH_a = relative humidity of the air [%]
P_a = water vapour pressure of the air [kPa]

[1] Limitations: (i) it assumes that skin temperature is 35°C regardless of metabolic rate; and (ii) it assumes that all derived values that are equivalent will have the same physiological impact, regardless of whether the E_{req}/E_{max} ratio is 50/100 or 300/600 (Belding, 1970).

P_{sk} = water vapour pressure at the skin surface [kPa]
6.45 and 2.2 = constants.

The above analyses provide us with a first-principles means by which to evaluate the potential for thermal environments to induce physiological (thermal) strain. The required evaporative heat loss (E_{req}) and the maximal evaporative cooling that the environment would permit (E_{max}) were computed for the Victoria River Downs station using data collected from the Bureau of Meteorology and from field observation: clothing insulation (0.29 $m^2K.W^{-1}$), skin surface area coverage (80-85%), average riding velocity (relative wind speed: 1.43 $m.sec^{-1}$), work rates (70-100 W), core temperatures (38.5^oC) and body masses (73.2 kg).

The ratio of the required evaporative heat loss to the maximal evaporative cooling (Heat Strain Index) defines the conditions for which the required heat loss, as determined by the environmental, working and clothing status of the individual, exceeds the capacity of the environment to permit such heat loss. Such conditions are thermally uncompensable, and are associated with a progressive heat gain (core temperature elevation) that ends only when work ceases, the environment cools or when the individual is actively cooled. These data are summarised in Table 11.

From these data, it is evident that the working environment at this station is, on average, **thermally uncompensable**. Certainly, at the coolest times of the day, when there was no requirement for evaporative cooling, the conditions would not place an unbearable load upon stockmen. However, when air temperatures climbed above 30^oC, the thermal load was again uncompensable. This occurred, on average, at 1200 hours in September, 1000 hours in October and at 0900 in November, and did not retreat to more compensable conditions until after work had finished, and the sun had set.

Table 11: Thermal compensability (Heat Strain Index) of the Victoria River Downs station climate. Red cells define uncompensable states, with the intensity of the shading matching the extent to which heat loss demands exceed that which can be supported by the working environment.

Variable	September	October	November
Mean data (0800-1800 hours)			
Required evaporative heat loss (W)	-136	-326	-437
Maximal evaporative heat loss (W)	126	115	103
Thermal compensability (%)	108	283	424
At times of maximal temperatures			
Required evaporative heat loss (W)	-331	-476	-610
Maximal evaporative heat loss (W)	130	124	115
Thermal compensability (%)	253	384	531
At times of minimal temperatures			
Required evaporative heat loss (W)	0	0	0
Maximal evaporative heat loss (W)	130	116	104
Thermal compensability (%)	---	---	---

5.1.2 Metabolic heat production during mustering

The average daily air temperatures for this stage of the field trials, obtained over the 8-hour working period (0800-1600 hours), was 35.6°C. Some subjects provided more than one data set from these field trials. These data were obtained on different days, with a total of 38 heart rate data sets contributing to this stage of testing.

For any increase in exercise or work intensity, more oxygen is required by the muscles, and this must be delivered in the blood by the cardiovascular pump: the heart. Thus, the heart rate will be elevated in direct proportion to the exercise intensity.

The raw heart rate data for each stockman were analysed relative to that person's heart rate reserve, with data being normalised[1] to this value to obtain an assessment of work intensity:

Heart rate reserve = maximal heart rate - resting heart rate [beats.min^{-1}]
where:
resting heart rate was measured
maximal heart rate was derived: 220 [beats.min^{-1}] - age [y].

The heart rate reserve quantifies the operational range of the heart, which varies only between the resting and maximal limits. For the stockmen investigated in this project, the mean heart rate reserve was 129 beats.min^{-1} (Table 12). That is, on average, the heart rate could only increase from its average resting level (69 beats.min^{-1}) through to its average maximal level (197 beats.min^{-1}). Therefore, an increase to 104 beats.min^{-1} (35 beats.min^{-1} above resting) only represents a 26%[2] increase above the heart's resting level, relative to the heart rate reserve. In other words, each additional 13 heart beats represents a 10% increase relative to the heart rate reserve.

Table 12: Summary of heart rate observations during horseback activities. Data were obtained from 24 different stockmen studied over 38 sampling periods: HRR = heart rate reserve.

Variable	Mean	Standard deviation
All horseback activities		
Resting heart rate (beats.min^{-1})	68.9	9.7
Heart rate reserve (beats.min^{-1})	129.1	12.3
Average heart rate (beats.min^{-1})	102.0	14.0
Maximal working heart rate (beats.min^{-1})	162.5	19.5
Proportion of time at <50% HRR (%)	89.1	16.9
Proportion of time at 50-60% HRR (%)	4.7	7.3
Proportion of time at 60-70% HRR (%)	2.1	3.2
Proportion of time at 70-80% HRR (%)	1.2	2.1
Proportion of time at 80-90% HRR (%)	0.6	1.8

[1] Heart rate intensity = (relative intensity [%] * (maximal heart rate - resting heart rate)) + resting heart rate [beats.min^{-1}].

[2] Heart rates are sometimes expressed relative to the maximal heart rate (*i.e.* 104 beats.min^{-1} = 53% of the maximal heart rate). However, this is erroneous, since it incorrectly assumes that the heart rate can drop below its minimal resting value.

Variable	Mean	Standard deviation
Proportion of time at >90% HRR (%)	0.2	0.9
Mustering		
Resting heart rate (beats.min^{-1})	68.5	10.4
Heart rate reserve (beats.min^{-1})	128.7	13.7
Average heart rate (beats.min^{-1})	103.9	14.3
Maximal working heart rate (beats.min^{-1})	167.6	17.9
Proportion of time at <50% HRR (%)	88.3	15.9
Proportion of time at 50-60% HRR (%)	5.9	8.2
Proportion of time at 60-70% HRR (%)	2.7	3.6
Proportion of time at 70-80% HRR (%)	1.6	2.3
Proportion of time at 80-90% HRR (%)	0.8	2.1
Proportion of time at >90% HRR (%)	0.3	1.1

These analyses are illustrated in Figure 16 for stockmen one and two. These data are summarised in Table 12, and have been analysed to isolate the mustering trials (27 trials) from the other horseback activities (11 trials). None of the differences between either the activity durations, or the heart rate responses of these activities, were statistically significant ($P>0.05$).

On the basis of these observations, it may be concluded that horseback mustering, while sometimes being very stressful on the stockman, is not a consistently high-intensity job. Indeed, less than 3% (9 min) of the total time was spent working at intensities greater than 70% of the heart rate reserve, with 1.1% (2.9 min) at work rates greater than 80%. Almost 90% the work time (237.8 min) was spent below 50% of the heart rate reserve.

Oxygen uptake data were collected for stockmen one-six. These data were used to establish the relationship between heart rate and oxygen uptake, with the latter being a surrogate index of metabolic rate. These relationships for the calibration of heart rates are illustrated in Figure 16. It is evident from both the raw data, and the correlations, that a very tight linear relationship existed between these dependent variables within individuals. This is a perfectly normal, and an entirely predictable observation.

The coefficients for these relationships can be used to predict oxygen uptake from heart rates, and therefore derive metabolic heat production. These data are contained in Table 13. It is evident from Figure 17 that steeper positive relationships existed for the females (subjects: 1, 3 and 6). That is, for a given external workload (or oxygen uptake), females had a higher heart rate. This is usually observed, and is explained on the basis of a lower oxygen carrying capacity of the blood of women, due to a smaller haematocrit and haemoglobin concentration, and it is also associated with a small heart size in women of smaller stature. Thus, gender-specific coefficients were used for these derivations.

Table 13: Summary parameters for the linear relationships between heart rate and oxygen uptake during cycle ergometry. Data were obtained from six stockmen (Figure 14), and parameters are presented in the form: X = (Y - slope) / Y intercept (*where:* X = oxygen uptake and Y = heart rate).

Prediction equations	Slope	Y intercept	Correlation
Male stockmen			
X = (Y - 41.90) / 56.72	41.90	56.72	0.947
Female stockmen			
X = (Y - 57.78) / 72.38	57.78	72.38	0.955
All stockmen			
X = (Y - 49.84) / 64.55	49.84	64.55	0.951

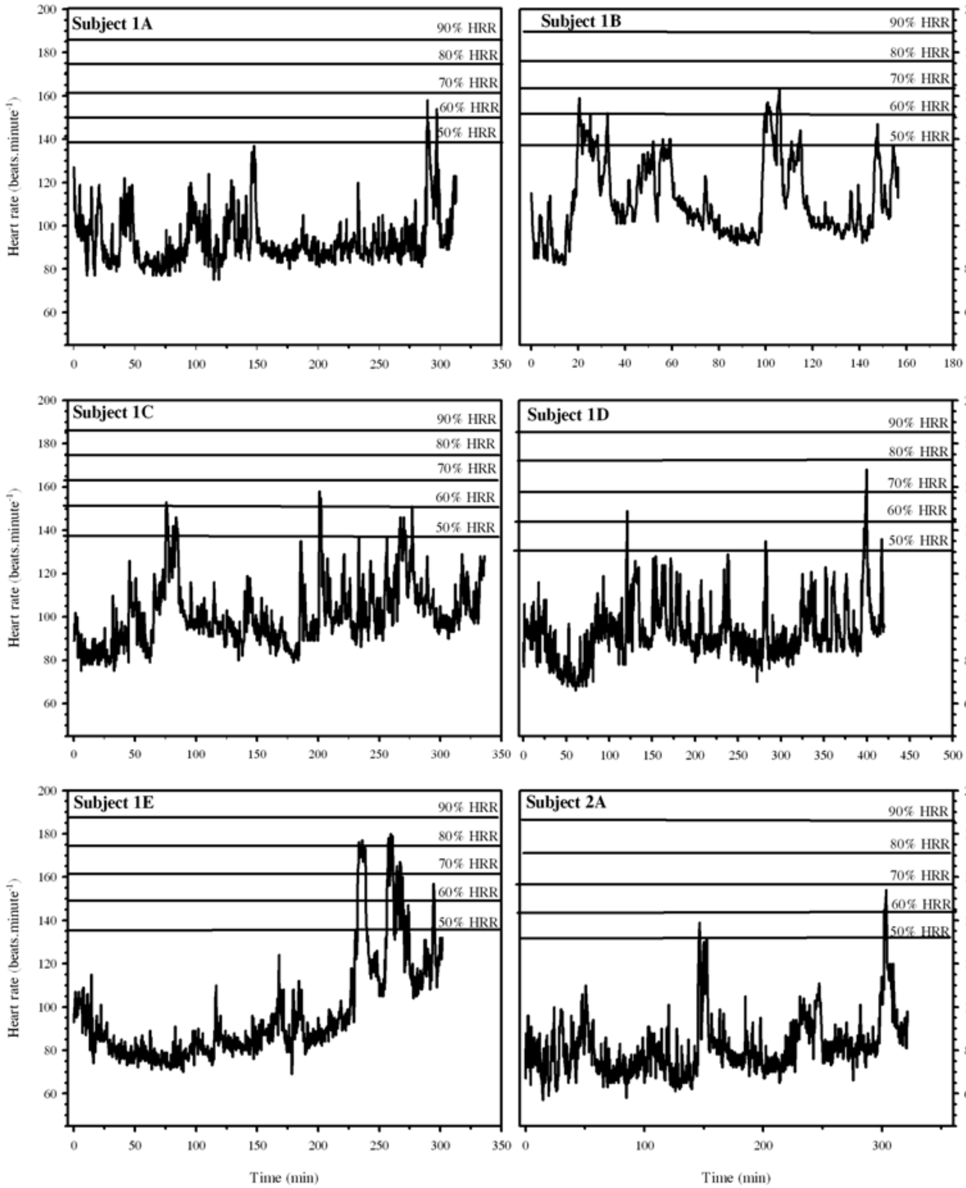


Figure 16: Heart rate data for stockmen one and two (Table 2) when walking and mustering cattle.

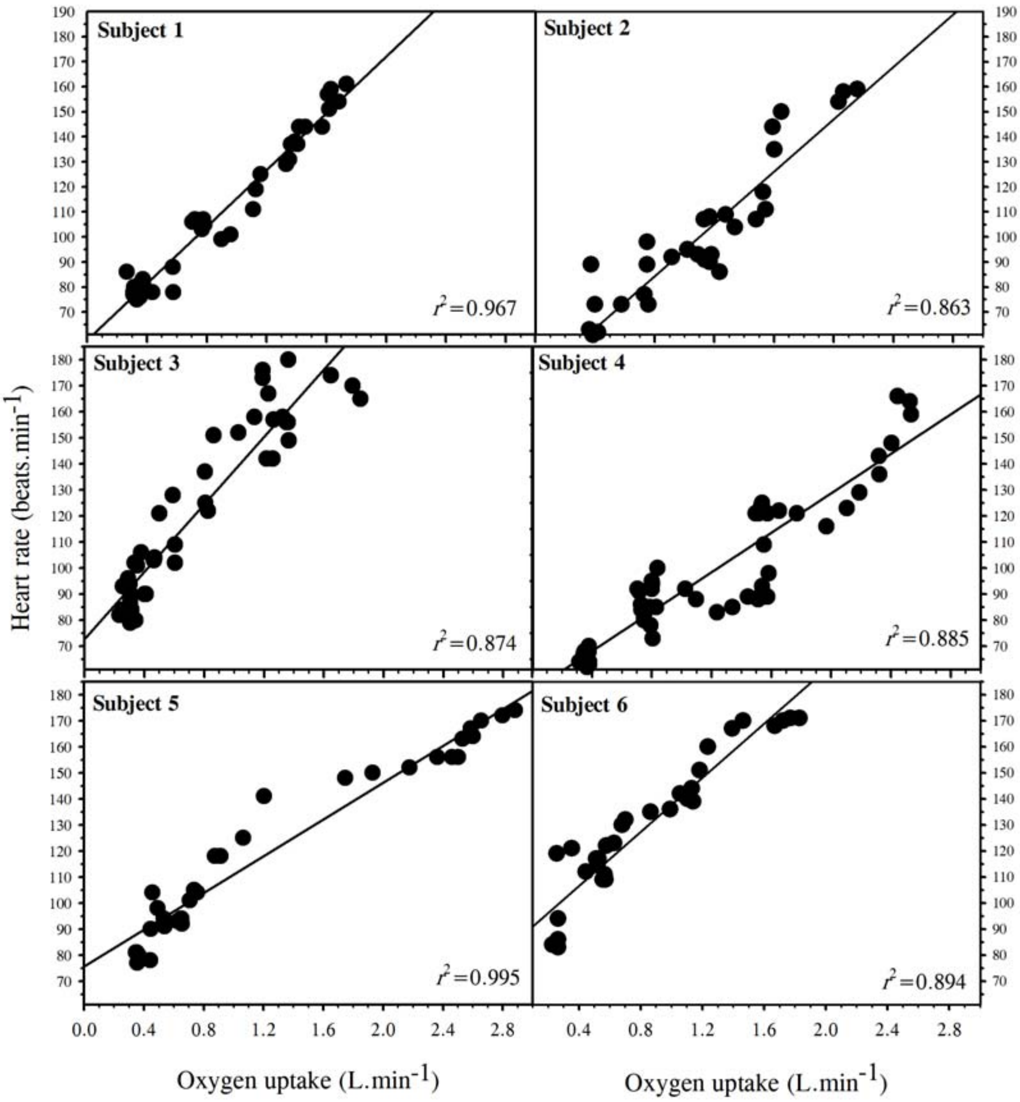


Figure 17: The relationship between oxygen uptake and heart rate for stockmen one to six during cycle ergometer exercise.

Using the gender-specific prediction equations from Table 13, and averaged heart rate data collected from 27 mustering trials, mean oxygen uptakes and metabolic heat production[1] were computed. Three data averages were used for three different analyses. First, all data were averaged to produce grand mean heart rates for male and female stockmen.

[1] Heat production was computed using the gender-specific respiratory exchange ratios observed during oxygen uptake measurements at the corresponding exercise intensities: males: 0.93; females: 0.94. From these data, the corresponding thermal equivalents of oxygen consumed for the non-protein respiratory quotients were used to derive heat production: males: 20.82 kJ.L^{-1}; females: 20.74 kJ.L^{-1}. Thus:

Heat = oxygen uptake [L.min^{-1}] * thermal equivalent [kJ.L^{-1}] [kJ.min^{-1}].

Second, to illustrate the upper and lower limits of these data, the male and female stockmen who had the highest and lowest mean heart rates, across all mustering trials, were isolated for separate analyses. Third, predicted external work rates were calculated, based on the assumption of a 20% metabolic efficiency[2]. These data are summarised in Table 14.

Table 14: Oxygen uptake and metabolic heat production during mustering.

Variables	Male stockmen	Female stockmen
Mean heart rate (beats.min^{-1})	101.2	107.7
Mean oxygen uptake (L.min^{-1})	1.05	0.69
Mean heat production (kJ.min^{-1})	21.8	14.3
Mean heat production (W)	362.7	239
Mean external work rate (W)	72.5	47.7
Highest average heart rate (beats.min^{-1})	130.5	127.5
Highest average oxygen uptake (L.min^{-1})	1.56	0.96
Highest average heat production (kJ.min^{-1})	32.5	20.0
Highest average heat production (W)	541.7	333.2
Highest average external work rate (W)	108.3	66.6
Lowest average heart rate (beats.min^{-1})	76.6	95.0
Lowest average oxygen uptake (L.min^{-1})	0.61	0.51
Lowest average heat production (kJ.min^{-1})	12.7	10.7
Lowest average heat production (W)	212.2	177.9
Lowest average external work rate (W)	42.4	35.6

For healthy adults of average physical fitness, one would assume that the maximal oxygen uptake would equate with approximately 2.5 L.min^{-1} (females) and 3.5 L.min^{-1} (males). This means that, during mustering, such healthy individuals are capable of consuming oxygen, for the purpose of liberating energy to perform useful external work, at rates that represent 25-40% (females: mean to highest average; Table 14) and 30-45% (males) of their maximal capacity. Such light work rates are easily sustainable for 5-8 hours by normal health individuals without rest. Indeed, when one derives the projected external work rates associated with these data (Table 14), these equate with 48 W (female) and 73 W (males), but may range from 36-67 W (females) and 42-108 W (males).

From these derivations, the **metabolic heat production of stockmen during mustering** appears to range between 178-333 W (females) and 212-542 W (males). The latter straddles the implicit 325 W limit specified by the World Health Organisation (1969). It is now possible to better define the operational conditions for stockmen using the first-principles, biophysical model previously illustrated (Figure 2). This three-dimensional surface was created to facilitate the prediction of scenarios in which positive heat storage would occur. When working at 70 Watts, heat gain will be encountered for all air temperatures >23^{o}C (Figure 18). These occur beyond 0900 hours, even in the cooler month of September (Figure 11). As the air temperature increases, the external work rate must decline to remain in a state of neutral heat storage. Therefore, even without head wear, one may reasonably expect stockmen to gain heat in their

[2] Since humans are very inefficient, only about 20% of the chemical energy liberated from stored fats and carbohydrates is able to utilised for external work.

The remaining 80% is lost, and is converted into thermal energy which is stored in the body, at least transiently, causing the body to increase its total heat content.

working environment. However, the rate of this heat gain will be a function of work intensity, which can be modulated by the individual, at during about 90% of the working duration.

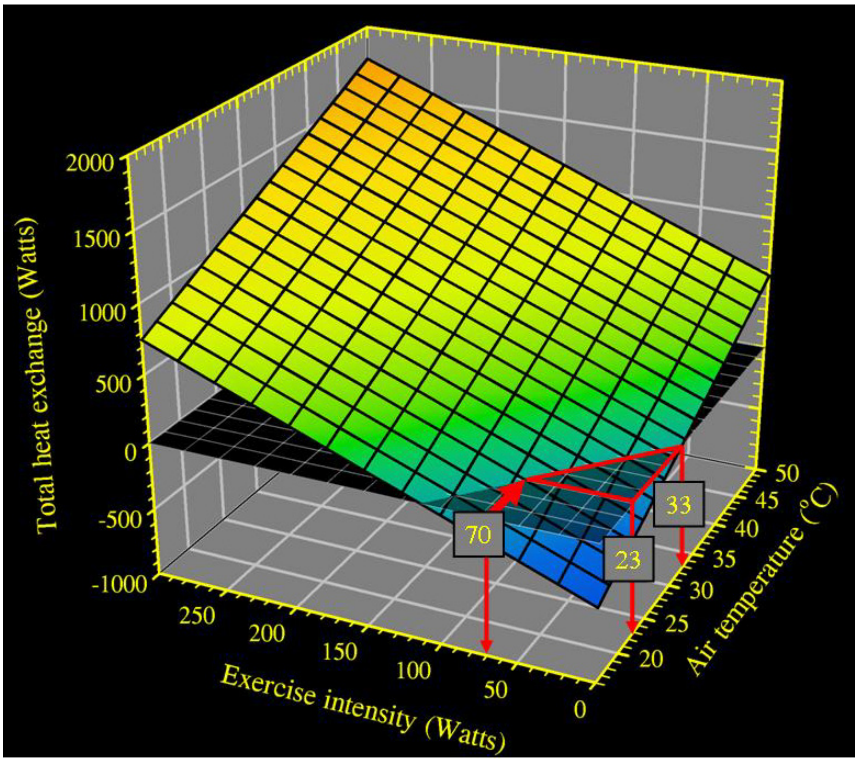


Figure 18: Three-dimensional surface for heat exchange across ranges of external work rates and air temperatures (50% relative humidity, 0 m.s^{-1} wind velocity), when wearing the clothing typically used by stockmen (insulation 0.29 m^{2}K.W^{-1}), but without a hat.

5.1.3 Physiological and cognitive strain

Sixteen stockmen participated in this stage of testing, which involved complete instrumentation. Eighteen separate horseback trials were completed, 11 of which were mustering. These trials varied in duration, but averaged 5 hours 5 minutes 51 seconds. However, this duration represented the complete data logging period, which included travel from the station to the mustering area and meal breaks. Physiological data were recorded continuously, and cognitive function and psychophysical testing were performed before and after each trial. Subjects voluntarily rehydrated throughout, and the average air temperatures, obtained over the work period (0800-1600 hours), was 35.7^{o}C. A portable global positioning system was mounted on each stockman, with output data revealing an average riding velocity of 5.16 km.h^{-1} (SD 1.99)[1], with a mean peak velocity of 22.41 km.h^{-1} (SD 9.17), and an average total riding distance of 16.69 km (SD 8.04).

Stockman were instrumented to record air temperature and relative humidity. In addition, a sensor was positioned within the back pack in which data logging equipment was housed. These data were recorded at 1-min intervals during each field trial (Figure 19).

[1] This is slightly faster than the average walking speed of a person. These data were derived from data collected during 51.1 hours of testing.

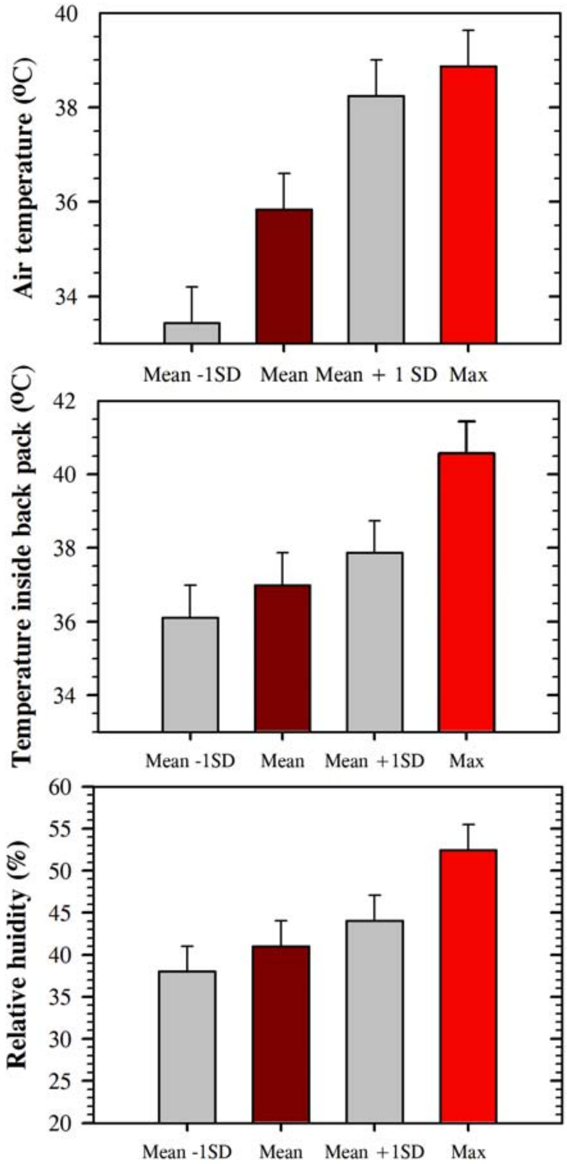


Figure 19: The thermal environment when walking and mustering cattle on horseback. Data are means, one standard deviation above and below the mean, and average maximal observations.

Data for body core temperatures are illustrated in Figure 20 for stockmen one, two, four and five. On each graph are indicated times of water consumption. Since stockmen drank *ad libitum*, and since the core temperature sensors were inside gastrointestinal capsules, drinking water will transiently suppress local temperature, but not core temperature *per se*.

From these data, it was found that only one stockman (subject 9) exceeded a core temperature of 39°C. However, a further four stockmen had core temperature peaks in excess of 38.5°C, but less than 39°C.

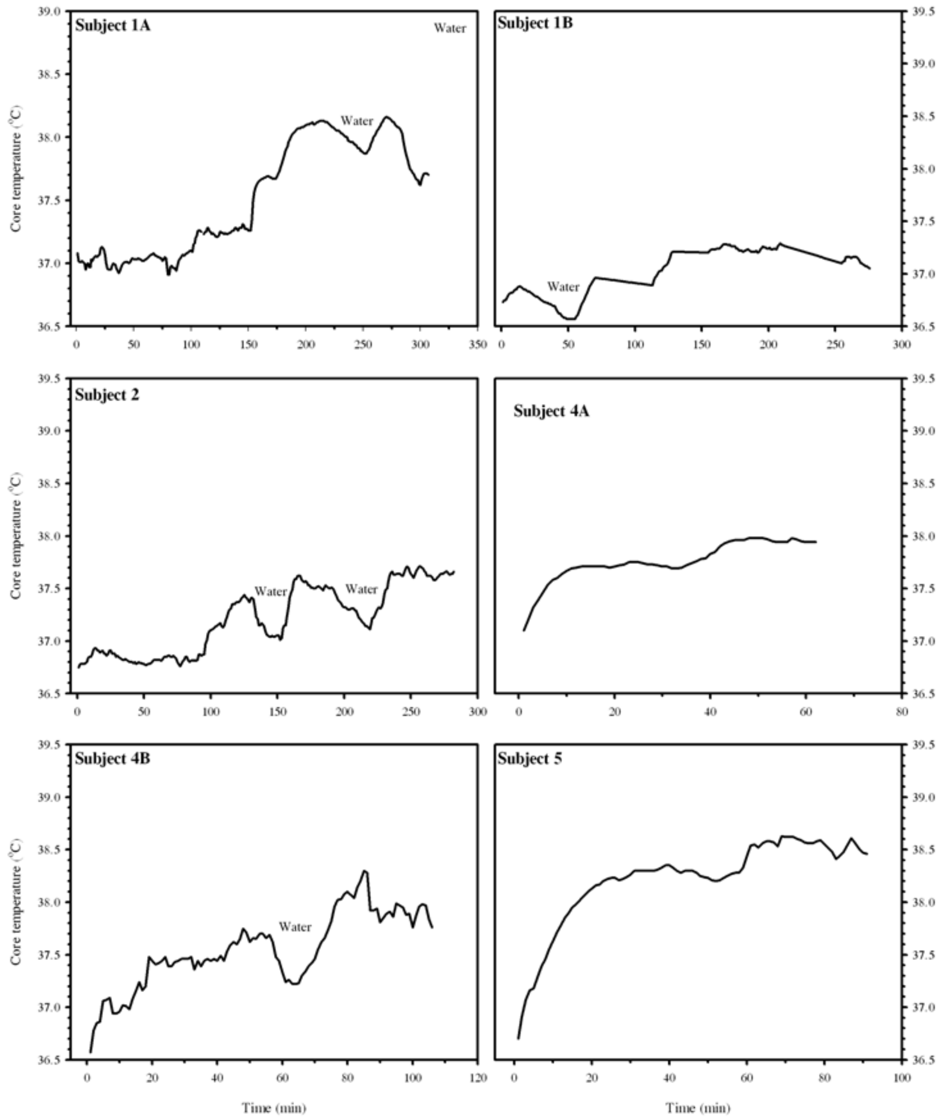


Figure 20: Body core temperatures for stockmen when walking and mustering cattle.

The World Health Organisation has recommended an upper limit for core temperature in workers of 38^{o}C (World Health Organisation, 1969). However, a range of other criteria has also been suggested. For example, work:rest ratios and the cessation of work have been recommended on the basis of heart rate limits (Belding, 1970), average sweat secretion (Adam *et al*., 1955), the convergence of skin and core temperatures (Pandolf and Goldman, 1978), and for several physical heat stress indices (Lind, 1963; Belding, 1970).

Nevertheless, from an occupational health perspective, the primary objective for evaluating the thermal environment is to determine the maximal likelihood that adverse physiological responses may be elicited when working under stressful conditions. It then becomes necessary to interpret these data with respect to the probability of adverse health outcomes. This is a difficult topic due to the lack of empirical evidence, and is therefore beyond the scope of this project. Nevertheless, these interpretations will be propelled by the opposing needs to maintain productivity and worker health. In the emergency services and military situations, interpretation can become very skewed, with the outcome frequently left to the discretion of the individual, and often with health being compromised.

The individual core temperature data were pooled to provide descriptive summary parameters. These are presented in Figure 21. It is clear that, for about 66% of each field trial, core temperatures were within the range 37.3-37.7^{o}C. These temperatures are within the normal daily range, and cannot be considered to be stressful under most circumstances. In fact, one would predict a less than 10% probability of someone with such a core temperature of experiencing heat exhaustion[1] (TBMED507, 2003). Nevertheless, these data are consistent with the outcome predicted from the biophysical model (Figure 18), and also with the relatively low working heart rates (Table 14). That is, the low work intensity within an uncompensable environment, has resulted in a gradually climbing core temperature.

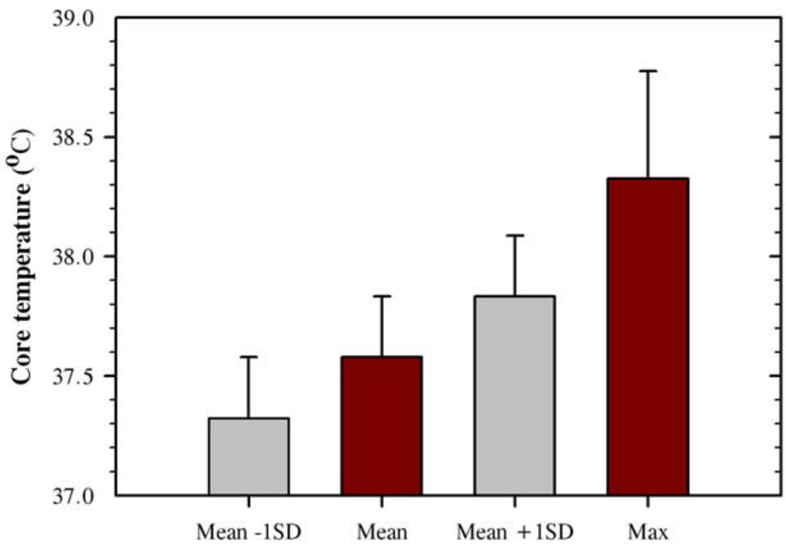


Figure 21: Summary core temperatures. Data are means (plus one standard deviation above and below), with ranges indices, obtained from individual averages. The maximal column shows the mean maximal core temperatures, with standard deviations.

However, if one looks at the averages from the maximal core temperatures (Figure 21: far right bar), a slightly more stressful situation is revealed. Sixty-six percent of the peak core temperatures, observed across all subjects, fell within the range 37.6-38.8^{o}C. The upper 33% of these temperatures exceed the recommended upper core temperature limit for workers (World Health Organisation, 1969). One would now anticipate approximately 25% of such individual may experience heat exhaustion (TBMED507, 2003).

Mean skin temperatures for all subjects, followed linear increases over time (Appendix Three), and these data are summarised in Figure 22. Typically, these temperatures commenced at about

[1] Heat exhaustion is not heat stroke. It is simply a form of fatigue, but that which is associated with the additional physiological strain accompanying protracted work in the heat (American College of Sports Medicine, 1996). The individual is unable to continue working at the same intensity.

32°C, and terminated near to 36°C, with stockmen one, 13 and 15 approximating 38°C at the end of their trials. In all instances, mean skin temperatures were less than core temperature. Since heat flows down a thermal gradient[1] (from warmer to cooler regions), a positive gradient is absolutely essential during extended heat exposure, since it is the only way that the core heat can be transferred to the subcutaneous tissues. However, desert and 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.

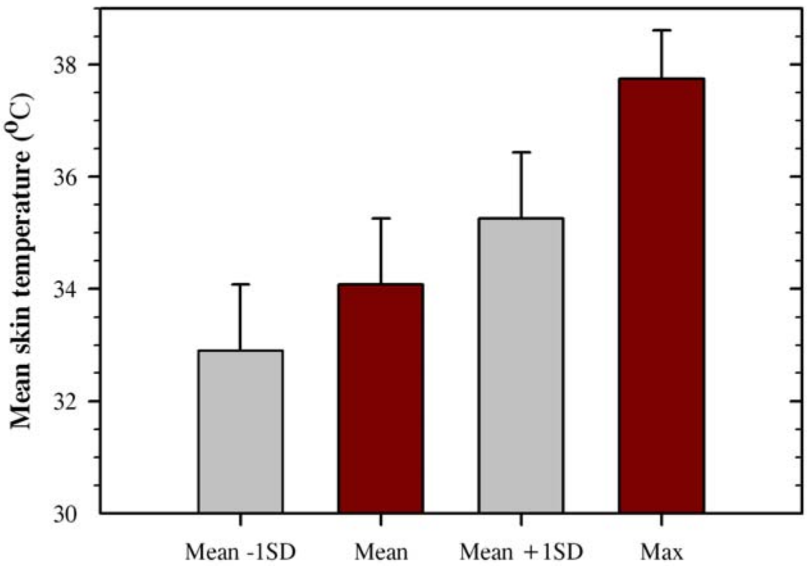


Figure 22: Summary mean skin temperatures. Data are means (plus one standard deviation above and below), with ranges indices, obtained from individual averages. The maximal column shows the mean maximal skin temperatures, with standard deviations.

It is well recognised that human tissues vary markedly in temperature (Bazett and McGlone, 1927; Eichna *et al.*, 1951), with this being most evident at the skin surface (Werner and Reents, 1980), particularly when people are cool. Without such a heterothermic state there will be no heat flow. At the skin surface, under states where environmental temperature approximates skin temperature, and where cutaneous tissue metabolism is relatively stable, cutaneous blood flow delivers central heat (including that which is produced by exercising muscles) to the skin for dissipation. When exposed to air temperatures greater than skin temperature, as is currently the case (Figures 8 and 19), peripheral heterothermy is replaced by more uniform skin temperatures, reflecting a generalised cutaneous vasodilation. This rise in skin temperature reduces heat gain from the environment, and it also increases the water vapour pressure at the skin surface, and thereby increasing evaporation. However, an increasing skin temperature gradually reduces heat flow from the core. These skin temperature affects can be modelled mathematically, revealing that, in a resting person (air temperature 35°C, 70% relative humidity), a 1°C elevation in skin temperature (33-34°C) could reduce the required evaporative heat loss by as much as 35% (Taylor, 2006a). This skin temperature is therefore an important physiological defence mechanism.

[1] A gradient is the difference between two measures of the same variable, made at different sites.

It was anticipated, based upon anecdotal feedback from stockmen, that helmet temperatures would be high when worn continuously during mustering on hot, sunny days. Accordingly, temperature and relative humidity sensors were positioned inside the helmet, and within the shirt. Sensors were also used to monitor these variables in the surrounding air. Water vapour pressure was computed from these variables. Thus, since skin temperatures were measured, and sweating skin is 100% saturated, it was possible to use these sensors to quantify both the thermal and water vapour pressure gradients acting across the helmet and shirt. The water vapour pressure gradient is particularly important, since the evaporation of sweat is dependent upon the gradient between the skin and the external environment, and can be heavily influenced by the presence of physical barriers to evaporation. One impediment to evaporation is created by clothing, regardless of its moisture permeability (Taylor, 2005b, 2006).

The temperature data for air trapped within the helmet and shirt are summarised in Figure 23. Both regions were remarkably uniform. Indeed, trapped air temperatures did not differ significantly (P>0.05). That is, both the shirt and helmet behaved similarly with respect to heat transfer, with each appearing to allow equivalent heat dissipation from the body, and heat gain from the surrounding air and via solar radiation. This was not an altogether novel observation, for both ensembles trapped air, and air is an extremely powerful insulator. However, the mean relative humidity within the shirt (68.7% (SD 20.5)) significantly exceeded that under the helmet (63.0% (SD 19.3); P<0.05). Since the trapped water vapour pressures were derived from equivalent temperatures, but different relative humidities, then these also differed significantly (3.7 kPa (SD 1.1) versus 3.4 kPa (SD 1.1); P<0.05). These outcomes were probably associated with a greater sweat secretion from the torso, although they could also be related to superior ventilation of the helmet, though, from its design characteristics, this would seem to be unlikely.

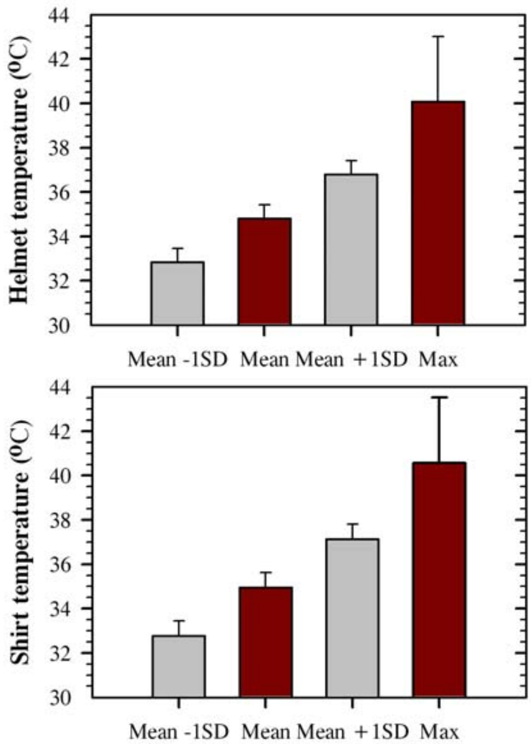


Figure 23: Summary of helmet and shirt temperatures and relative humidities. Data are means (plus one standard deviation above and below), with ranges indices, obtained

from individual averages. The maximal column shows the mean maximal temperatures, with standard deviations.

From these data, the respective gradients were derived (Table 15), and these were again conspicuously similar. Positive gradients indicate continuous heat loss, or evaporation, from the body and trapped air cavities, with negative gradients reflecting heat gain[1]. The thermal gradients were positive from the skin to the trapped air, but negative from the trapped air to the surrounding air. Thus, these air cavities gained heat from both the body and external environment, presumably via solar radiation. In the case of the water vapour pressure gradients, both the shirt and helmet retained trapped air that had a water vapour pressure conducive to the evaporation of sweat, and also to the loss of that moisture to the surrounding air. These observations are particularly important, since the helmet was perceived by stockmen to retain heat. It may therefore be concluded from these observations that the helmet, at least within the current field trials, did not appear to behave in a manner that would disadvantage the stockmen, at least from a thermodynamics perspective, more than would any other garment worn on the head.

Table 15: Thermal and water vapour pressure gradients.

Site	Gradient	Skin to trapped air	Trapped air to external air
Helmet	Thermal	0.64^{o}C	-0.27^{o}C
Shirt	Thermal	0.71^{o}C	-0.34^{o}C
Helmet	Water vapour	2.23 kPa	1.06 kPa
Shirt	Water vapour	2.00 kPa	1.29 kPa

Heart rate data are reported above, and from these observations, it was concluded that horseback mustering, while sometimes being very stressful on the stockman, is not a consistently high-intensity job. Less than 3% of the total time was spent working at intensities greater than 70% of the heart rate reserve, with 1.1% at work rates greater than 80%. Almost 90% the work time was below an intensity of 50% of the heart rate reserve.

Worst case results

To illustrate the worst case of physiological strain that was observed, various tissue and clothing temperatures, along with heart rate data, are presented in Figure 24. In this individual, core temperature peaked at 38.9^{o}C and heart rate reached 197 beats.min^{-1}.

Whole-body sweat rate and hydration state

Stockmen commenced these field trials with an average urine specific gravity of 1.027. This value is towards the upper end of the normal range[1] for adequately hydrated (euhydrated) people

[1] A negative water vapour pressure gradient occurs only during condensation. This is seen when one's wife takes a beer from the fridge, and delivers it to her couch-ridden husband. It will also occur when one enters a steam bath. However, the current authors do not recommend drinking beer in a steam bath, as the negative thermal gradient that is similarly encountered, results in very unpleasant beer.

[1] Hydration classifications based upon urine specific gravity: (a) well hydrated: <1.013; (b) euhydrated: 1.013-1.029; and (c) hypohydrated: >1.029 (Armstrong *et al.*, 1994).

(Armstrong *et al.*, 1994). Thus, it may be assumed that the stockmen investigated in this project either followed suitable hydration practices, or that they at least adhered to the researchers' requests to commence each trial in a euhydrated state.

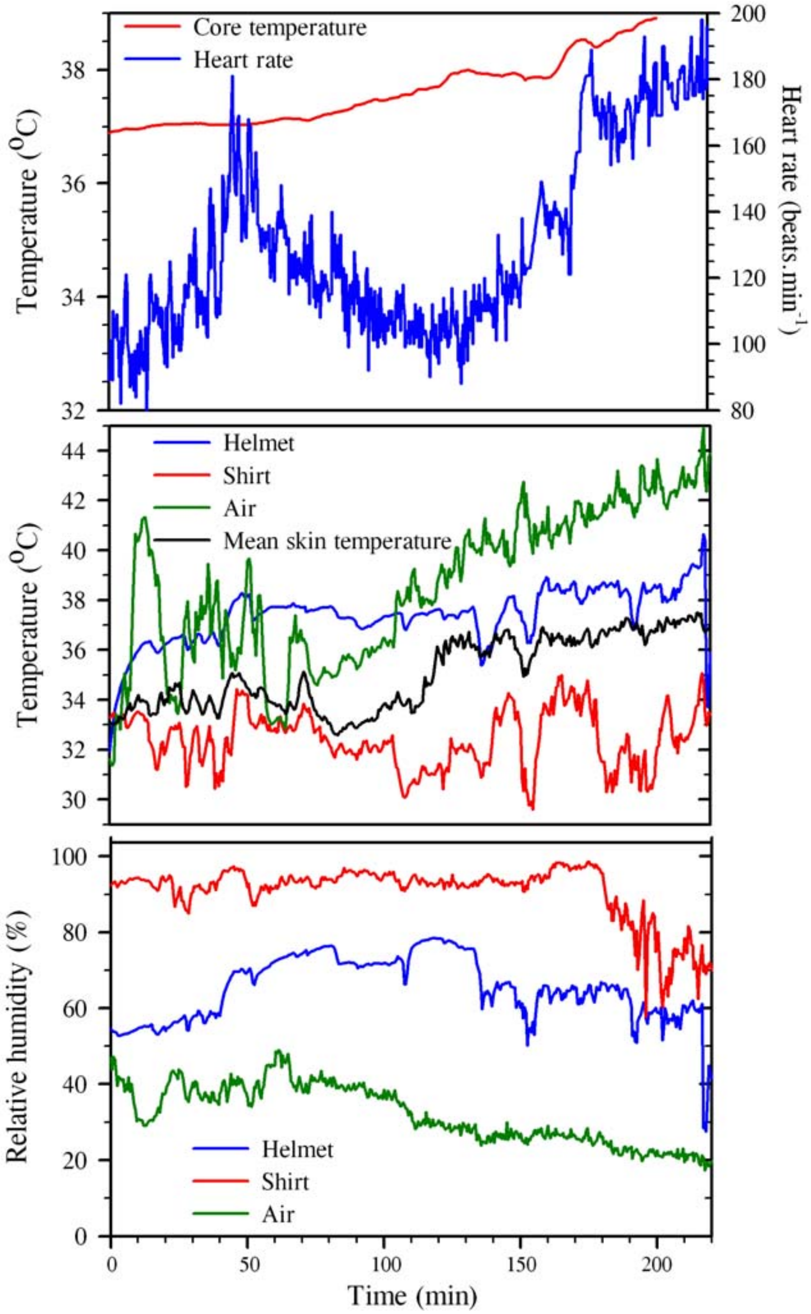


Figure 24: Sample data from the stockmen demonstrating the greatest physiological strain during mustering.

During the course of each field trial, stockmen were instructed to drink *ad libitum*, and not to modify their normal behaviour during experimentation. As a consequence, a 1.8% dehydration was observed over these trials, as reflected by a change in body mass (Figure 25).

This represents a 1.8 litre water deficit, and was mirrored within the urine specific gravity changes (Figure 26). Both of these differences were statistically significant (*P*<0.05). However, while this is a discernible dehydration, and should be prevented, such a mild dehydration is well tolerated, and is unlikely to have a significant physiological impact.

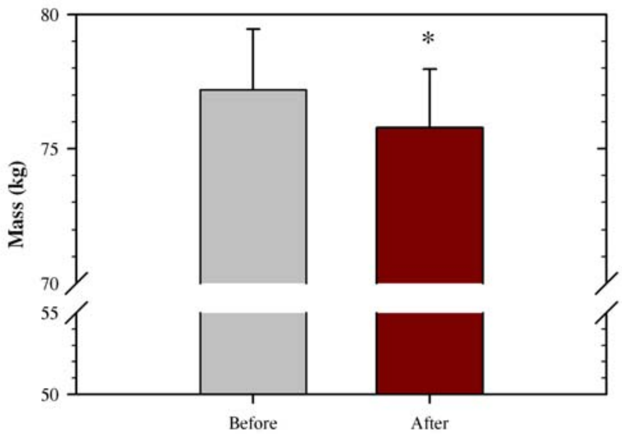


Figure 25: Change in body mass (before versus after horseback mustering): * = statistically significant difference (*P*<0.05).

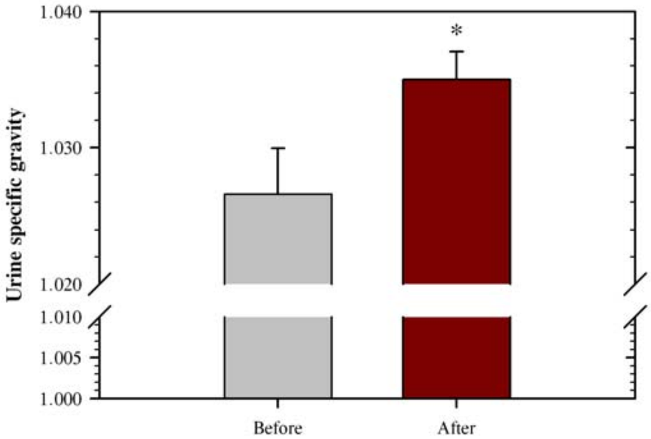


Figure 26: Change in urine specific gravity (before versus after horseback mustering): * = statistically significant difference (*P*<0.05).

A resting human will lose body fluid at the rate of about 38 mL.kg^{-1} of body mass per day. Thus, a 70-kg person will lose approximately 2.8 litres of fluid each day, even when laying in bed. If we assume an average sweat loss of 1 L.h^{-1} for a 70-kg person, then performing 10 hours of work in the heat, and resting for 10 hours, will result in the 24-hour water loss for this person being approximately 13 litres (Table 16). These fluid losses vary slightly between men and women, due primarily to the lower sweat rates of women. The failure to take in an adequate amount of fluid results in progressive dehydration, which can have significant implications for physical performance and cognitive function.

Table 16: Projected daily fluid losses (litres) based on the typical work/rest patterns of stockmen.

Mass (kg)	Rest (10 h)	Work (10 h)	Other (4 h)	Total (24 h)
50	0.8	7.9	0.9	9.6
60	1.0	9.5	1.1	11.6
70	1.1	11.1	1.2	13.4
80	1.3	12.7	1.4	15.4
90	1.4	14.3	1.6	17.3

Heavy exercise and work in the heat can easily elicit a 7-10% dehydration (5-7 kg of mass loss for a 70-kg person), and such changes are seen in elite marathon runners at the completion of a race. The reason for this is that extended sweating results in the loss of fluid at the rate of about 12-22 $mL.kg^{-1}$ (female-male values) for each hour of exercise. This can be doubled in well-trained and heat-adapted people.

Relative dehydration can be gauged from short-term fluctuations in body mass. Without fluid replacement, one might expect to lose about 7% of one's body mass in 24 hours. Physical performance can be noticeably impaired at the 3-4% dehydration level, and this is associated with a impairment in both physiological and mental functions. These performance changes can approach a 20% reduction, but this level of dehydration is well tolerated, and the performance decrement is mostly of limited short-term consequence. It is generally considered that only when dehydration reaches 15% (10.5 kg for a 70-kg person) does it pose a significant health risk. Guidelines for maintaining adequate hydration in the workplace are contained within Appendix Four.

Psychophysical indices

Each of the psychophysical indices increased significantly from the start to the end of each field trial (P<0.05). Thus, stockmen perceived that they were working harder, and they felt hotter wetter, and less comfortable with each of these sensations (Figures 27 and 28). This outcome was absolutely predictable. These stockmen were working hard in very oppressive conditions. It would, however, have been surprising if these trends were not observed.

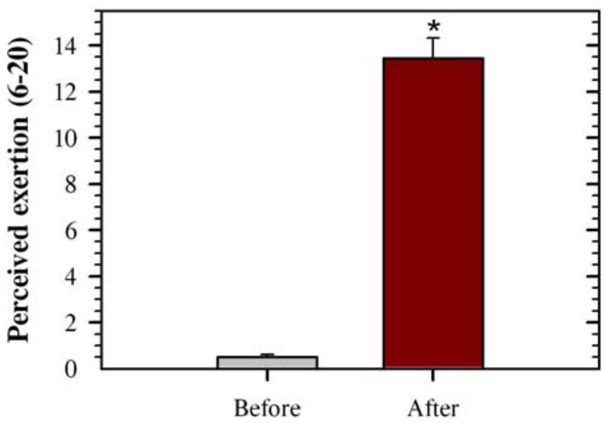


Figure 27: Change in perceived exertion (before versus after horseback mustering). * = statistically significant difference (P<0.05).

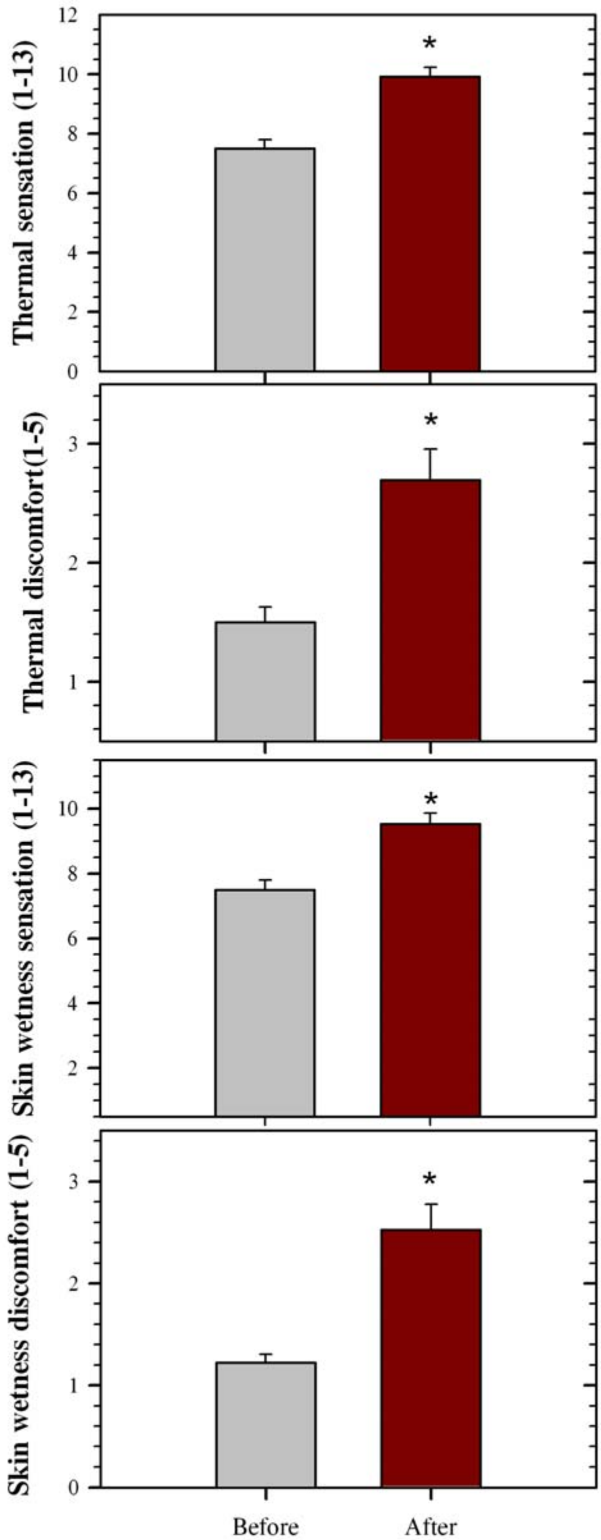


Figure 28: Change in psychophysical sensations (before versus after horseback mustering): * = statistically significant difference (*P*<0.05).

Cognitive function
The cognitive function testing was undertaken primarily as pilot testing for the subsequent laboratory trials (Phase Three), since one would not expect to achieve ideal situations in the field for administering these tests. However, significant pre- versus post-trial performance decrements were observed for both vigilance and problem solving (Figure 28; three-term reasoning; $P<0.05$). This is an interesting phenomenon, which is consistent with a degradation of cognitive function. Nevertheless, this trend could be artefactual, and requires replication under controlled laboratory conditions.

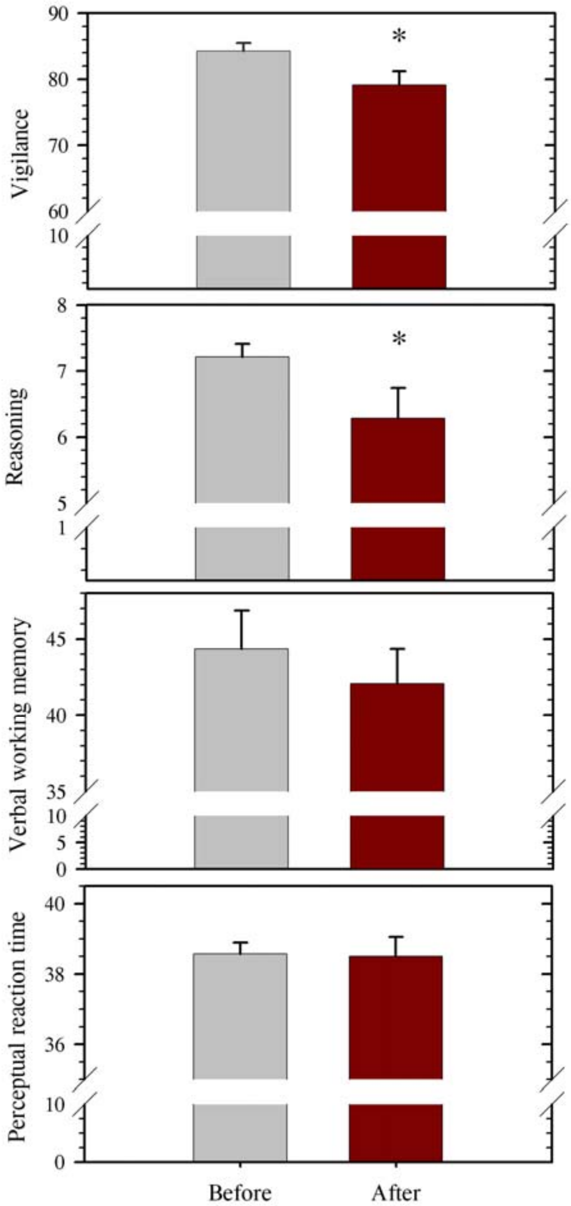


Figure 28: Change in cognitive function test performance (before versus after horseback mustering). Data are the number of correct responses: * = statistically significant difference ($P<0.05$).

5.2 Phase Two: Bench-top trials

5.2.1 Physical descriptions of helmets

Table 17 contains a summary of the physical characteristics of each piece of head wear tested during this Phase of experimentation.

Table 17: Summary of helmet and hat characteristics.

	Helmet 1	Helmet 2	Helmet 3	Helmet 4	Felt hat
Model	Tipperary	Onyx	Derby	Aussie 21	Arena
Manufacturer	Phoenix performance products	Dublin	Equine science marketing pty ltd.	Equine science marketing pty ltd	Akubra
Cost	$129.95	$99.95	$179.95	$130	$145
Outer shell		Acrylonitrile butadiene styrene plastic	Thermoplastic alloy	Thermoplastic alloy	100% pure fur felt
Mass (kg)	0.380	0.470	0.480	0.320	0.204
Centre of mass (cm)	11.85	12.59	11.79	12.06	9.46
Ventilation	11 slots: 2-4.5 cm long	6 slots: 3.5-4 cm long	4 circular holes: 1 cm diameter	11 slots: 2.5-3.5 cm long	nil
Solar protection	inadequate	inadequate	inadequate	inadequate	excellent

The maximal difference in helmet/hat mass was 0.276 g (Derby helmet to the felt hat; Table 1). However, this represented a 135% load increase. The mass of the head is typically 7% of body mass (Vital and Senegas, 1986). Thus, for the stockmen tested in Phase One of this project, who had an average mass of 73.2 kg (Taylor and Caldwell, 2007), the projected head mass would be approximately 5.12 kg. Wearing the helmets described in this report would result in the following total head masses:

(a) Derby helmet: 5.60 kg: a 9.4% increase: **heaviest**
(b) Onxy helmet: 5.59 kg: a 9.2% increase
(c) Tipperary helmet: 5.50 kg: a 7.4% increase
(d) Aussie 21 helmet: 5.44 kg: a 6.3% increase
(e) felt hat: 5.33 kg: a 4.0% increase: **lightest**.

Supporting the mass of the head contributes to the total metabolic rate of the body, and therefore metabolic heat production. However, cervico-cephalic mechanics are such that head motion and support are metabolically less efficient than other body movements, and head loads have a 30% greater physiological (metabolic) impact than do loads carried on the back (Soule and Goldman, 1969). Thus, total head mass changes of the above magnitude will have only a slight impact upon head loading. With an average helmet mass of 0.413 kg, the elevation in head loading will be 8.1%, but this will result in a 10.5% increase in the fraction of the total metabolic load (and heat production) that is associated with head carriage and postural activities.

The centres of mass for the helmets ranged from 11.8 to 12.6 cm forward of the rear helmet edge (Table 1). On average, this represented a potential forward displacement of the head of approximately 2.6 cm, relative to that associated with wearing the felt hat. However, with the helmets, on average, only representing a mean head load elevation of 209 g (4% of the projected head mass), it is assumed that any physiological impact of the change in head centre of mass associated with wearing the helmets would be negligible.

The ventilation holes of the helmets tested varied markedly (Table 17), and these are known to have a marked affect on both dry and evaporative heat loss (Liu and Holmer, 1995). In the case of the felt hat, there were no ventilation holes.

However, this hat can easily be removed at any time, and this is indeed the practice employed by stockmen who use this hat. The best ventilation was provided by the Aussie 21 helmet, in which the forward and rearward facing ventilation shafts are aligned horizontally. While the Tipperary helmet appeared to provide very good ventilation, on closer inspection, the actual hole sizes were up to 50% smaller than was apparent from the outer surface. The forward facing ventilation paths are aligned obliquely.

The Onyx helmet, which had six ventilation slots, suffered due to the orientation of the ventilation paths. These are all vertically aligned, thereby dramatically affecting air flow during locomotion. This is a critical design weakness of this helmet, with its impact being revealed during the forced cooling phase of the heat penetration trials.

5.2.2 Heat penetration

The application of infra-red heating for 20 min elevated the external surface of each helmet to >100^{o}C. Indeed, the mean, maximal outer surface temperature was 115.2^{o}C (SD 1.2), representing temperatures far in excess of those that may reasonably be expected to be encountered in the field. To evaluate heat penetration, one must create a suitably large thermal gradient across the helmet being tested. This was achieved by using these very high external temperatures with an air-conditioned laboratory, with air temperature regulated at 20.7^{o}C (SD 0.60) across the trials. In addition, manikin surface temperatures equilibrated with air temperature between trials. This was successfully achieved, with the mean manikin surface temperature ranging between 20.8-21.7^{o}C (Table 18).

Table 18: Summary of results obtained during a 20-minute radiant heat exposure of a head manikin wearing different head wear.

	Tipperary	**Onyx**	**Derby**	**Aussie 21**	**Akubra**
Initial manikin head temperatures prior to heating (℃)					
Mean	21.7	21.1	20.8	20.4	21.4
Standard deviation	0.2	0.2	0.3	0.2	0.4
Average temperatures during heating (℃)					
Inner helmet surface	47.8	27.3	29.6	25.9	38.8
Air cavity	34.2	27.4	25.4	26.0	33.2
Skin (under helmet)	27.0	24.3	24.2	24.6	26.7
Skin (outside helmet)	24.9	23.1	23.1	23.5	25.3
Increase in temperatures during heating (℃: peak temperature minus initial temperature)					
Skin: forehead	11.5	7.0	7.6	9.6	11.3
Skin: centre of head	15.7	10.9	12.7	13.0	12.1
Skin: nape of neck	3.5	3.4	4.0	3.4	2.1
Skin: right ear	7.4	6.8	6.5	8.6	6.6
Skin: left of centre	6.9	5.7	5.3	5.9	7.8
Skin: right of centre	11.9	8.9	9.0	9.7	11.3

	Tipperary	Onyx	Derby	Aussie 21	Akubra
Inner helmet surface	49.5	19.0	19.0	15.6	26.8
Air cavity	21.8	17.9	11.1	14.9	17.7
Time to reach local peak temperatures during heating (min)					
Skin: forehead	24.3	28.0	26.5	24.0	20.8
Skin: centre of head	21.8	27.5	24.3	26.3	20.8
Skin: nape of neck	19.8	19.5	20.0	20.8	20.0
Skin: right ear	20.0	20.0	20.0	20.8	20.0
Skin: left of centre	25.0	27.8	26.0	25.3	20.8
Skin: right of centre	23.0	25.0	24.0	23.5	20.5
Inner helmet surface	21.5	26.8	23.3	25.8	20.3
Air cavity	21.3	25.5	23.3	25.8	20.3

The first feature of heat penetration is the ease with which thermal energy can pass trough the outer shell of the helmet. This is reflected by the inner surface temperature of each piece of head wear. When averaged over the 20-min heating phase, the inner surface temperature of the Tipperary was 1.8 times higher than the Aussie 21, 1.7 times greater than that of the Onyx, 1.6 times greater than the Derby, and 1.2 times greater than observed for the felt hat (Table 18). On the basis of these observations, the following helmet ranking was obtained (best-worst). Temperatures indicate the peak inner surface temperatures recorded during heating, and are considered to be of slightly less importance than the average temperatures, since the latter reflect the entire thermal load:

Aussie 21:	35.3°C
Onyx:	40.2°C
Derby:	32.1°C
Akubra:	39.1°C
Tipperary:	69.1°C.

Thermal energy is transmitted from the inner surface of each helmet to the air cavity within the helmet. This was quantified using a sensor positioned in the middle of this cavity (Figure 2: lower right). Of all components within any piece of thermal protective clothing, including helmets, the single most powerful insulating material is the air trapped between the clothing/helmet surface and the skin. Thus, the larger the volume of trapped air, the better is the thermal insulation provided by each helmet/hat. The largest trapped air volume was provided by the felt hat. However, its poor thermal insulation resulted in the air within this cavity rising to be just one 1°C less than that trapped under the Tipperary helmet (Table 18). The following helmet ranking was obtained (best-worst), based upon mean air cavity temperatures:

Derby, Aussie 21, Onyx (negligible difference)
Akubra, Tipperary (negligible difference).

Eventually, the external thermal energy will reach the scalp tissues. This is illustrated by the average temperature of the manikin skin surfaces located under each hat (Table 18). Ideally, for a clothed individual working in the heat, thermal energy will pass from the head to the external environment. Head covering restricts this heat loss, and this is the focus of Phase Three testing for this project. In the current experiments, radiant heating ensured that heat always penetrated the helmet and trapped air, such that manikin skin temperatures increased (Table 18).

On the basis of the mean temperatures observed for skin regions located below the hat during heating, the following helmet ranking was obtained (best-worst):

Derby, Onyx, Aussie 21 (negligible difference)
Akubra, Tipperary (negligible difference).

However, the greatest elevation in the skin temperature at the central top position of the head was seen when testing the Tipperary helmet (Table 18).

Two skin regions were tested that did not fall within the dome of the helmet/hat: the forehead and nape of the neck. For these sites, the smallest change in forehead temperature was observed during testing of the Onxy helmet (then: Derby, Aussie 21, Akubra, Tipperary).
This was not anticipated as it does not posses a forward-facing brim. It is therefore assumed to have resulted from the trapping of a greater air volume over the forehead.
The felt hat was associated with the smallest increase in the temperature at the nape of the neck, with all helmets having temperatures with 1^{o}C of each other. In this case, the large brim, with its far superior solar protection in the field, led to this outcome.

During the radiant heating (20 min), the external helmet/hat temperatures increased exponentially to peaks averaging 115.2^{o}C (SD 1.2; Figure 29: outer). However, the Onyx helmet, and to a lesser extent the Derby, did not reach a steady-state peak temperature. All head wear displayed a very clear bi-phasic cooling profile of the external surface (passive and active cooling), with the felt hat more rapidly taking up and losing thermal energy. Nevertheless, temperature differences among the helmets has little physiological impact, since these temperatures are not seen by the head.

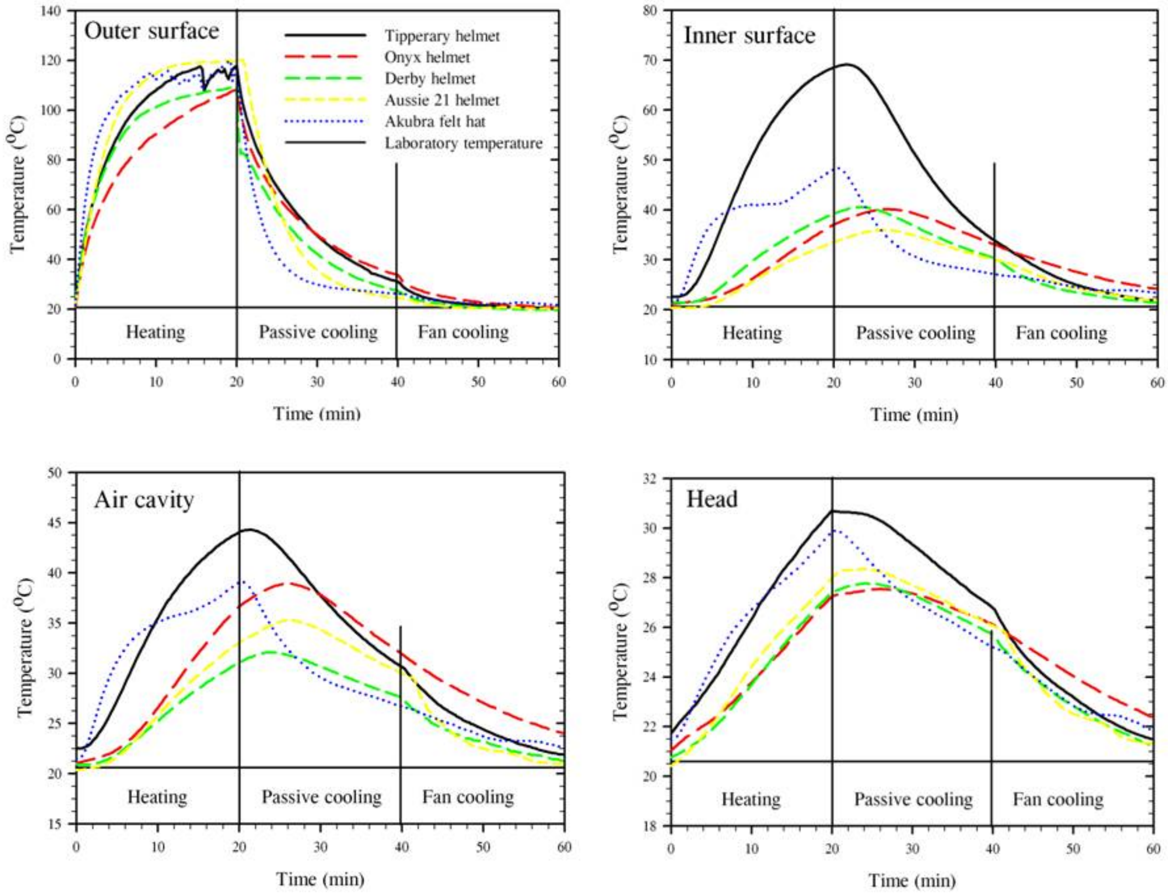


Figure 29: Comparative thermal dynamics across the four helmets and the felt hat.

Very marked deviations between the helmets were observed for the inner surface temperatures (Figure 29: inner). The Tipperary helmet had the highest peak internal temperature, which exceeded that observed for all other helmets by more than 20°C. That is, this helmet permitted the greatest heat penetration. The lower temperature of the Aussie 21 helmet reflects its greater insulative capacity, a feature that also resulted in a significantly greater phase delay between the time for the outer and inner surfaces to attain their respective temperature peaks.
The felt hat again showed a different response, and one that was not evident from the simple analysis of peak temperatures. This hat reached a higher peak temperature than the Onyx, Derby or Aussie 21 helmets, however, it cooled much faster during the passive cooling stage.

The temperatures of the cavity air (Figure 29) are a function of two variables. The internal surface temperature of each hat, and the volume of air trapped between the scalp and the helmet. Larger air volumes take longer to heat. The dynamics of these thermal changes revealed clear separation among the helmets, and it is the air cavity temperature that the head experiences. On the basis of these response curves, the Tipperary helmet would be most stressful during heat exposure, but the Onyx had such a poor cooling profile, that it was more stressful when the heat source was removed.

Active, or ventilation-induced cooling was most effective for the Aussies 21 helmet. However, across the three stages of these bench-top experiments, the Derby helmet performed best for this characteristic.

Manikin surface (head skin) temperature changes (Figure 29) were entirely a function of external heat loading, as influenced by the thermal resistance of each piece of head wear. The lack of differentiation between three of the helmets (Onyx, Derby, Aussie 21) serves to emphasise the insulative power of the microclimate. Thus, regardless of the internal surface and air cavity temperatures, these helmets performed equivalently well, with the Onyx being somewhat inferior during active cooling. This is believed to be due to the vertical orientation of the ventilation paths. The head temperatures under the felt hat returned to track the other temperatures once cooling was initiated. During active cooling, even the Tipperary helmet performed well.

Figure 30 shows each of these local dynamic temperatures responses, but now within each helmet/hat. The vertical distances between each of these curves quantifies the thermal gradients active within each hat, and these data are the focus of the next section.

Three thermal gradients were computed for each hat (Figure 31). These represent the temperature difference between the four regions described in the previous section. A positive gradient is associated with heat influx, with the size of these gradients reflecting the insulative power of the intervening material and air space. Thus, higher thermal gradients provide greater thermal resistance (protection) for the wearer.

Of the three thermal gradients, the one most relevant is that which quantifies the thermal resistance provided by the outer shell of each hat; the outer-to-inner surface gradient (Figure 31; top graph). The lowest thermal gradient across the helmet shell was observed for the Tipperary. This is consistent with this helmet providing the least effective insulation for the air cavity above the head. On this criterion, the hats can be ranked as follows, according to their insulative protection against an external heat source:

Aussie 21 (best)
Onyx, Derby, Akubra (equivalent)
Tipperary (worst).

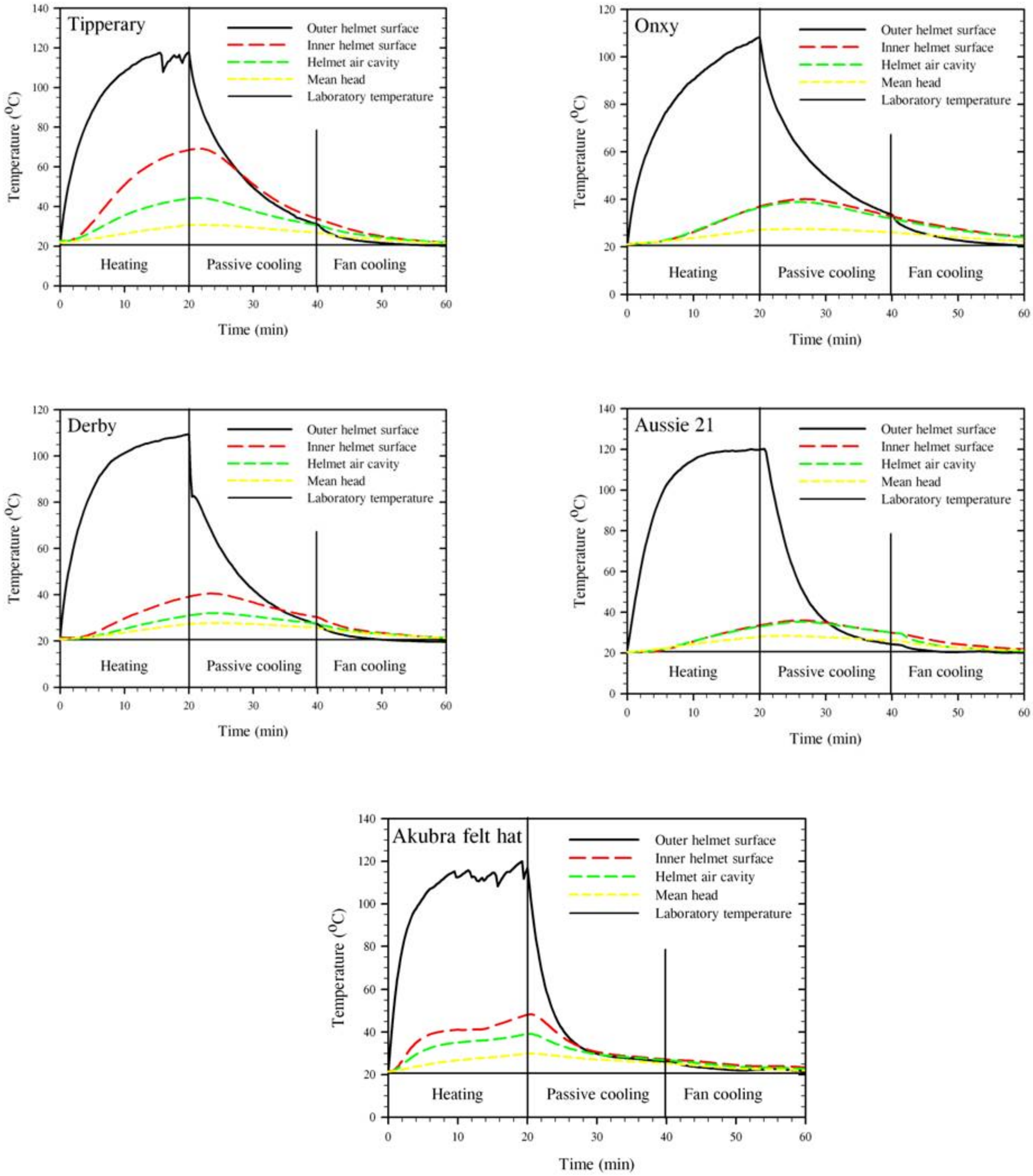


Figure 30 The thermal dynamics of heat penetration through the each the four helmets and the felt hat tested during this Phase of experimentation.

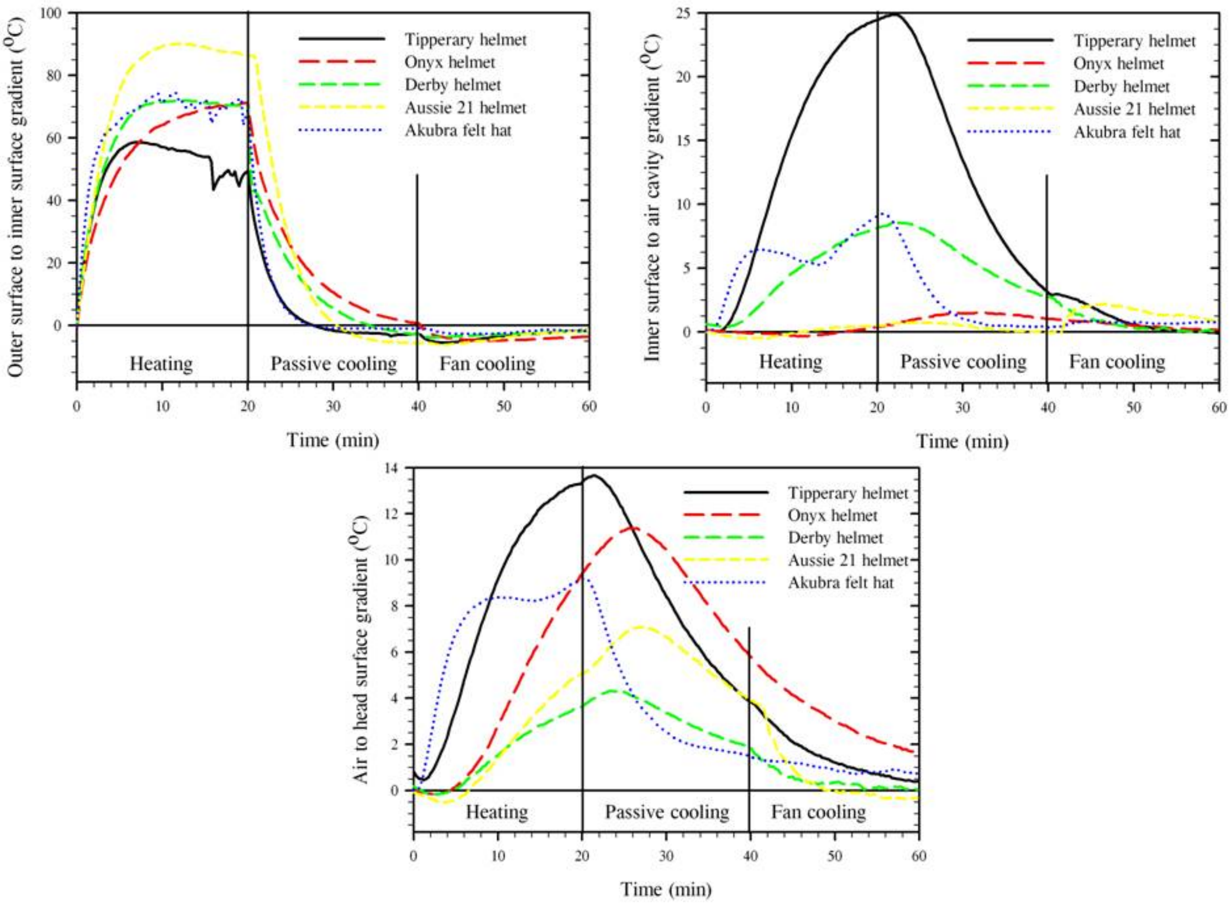


Figure 31 Thermal gradients across the four helmets and felt hat.

5.3 Phase Three: Laboratory trials

5.3.1 Physiological strain

Time series data for body core temperatures are illustrated in Figure 32. Rest periods occurred between the closely-spaced vertical lines, and this format is used for all subsequent graphs presented in this manner. The sensitivity of the auditory canal core temperature index is immediately evident, showing a clear sensitivity to changes in work rate. In the first Phase of this project, gastrointestinal capsules were used to track core temperature, since these provided the necessary mobility required for field research. However, these capsules lack sensitivity, due to the thermal inertia of the abdominal viscera, are not always appropriate for laboratory-based research. In such conditions, the current laboratory uses oesophageal, auditory canal and rectal temperatures. The last index also shows delayed response characteristics, while the first two indices are very well correlated in environments that closely approximate core temperature (Cotter *et al*., 1995).

The overlapping nature of these data, which was created by using the same subject sample under two identical sets of experimental conditions (with the sole exception of the headwear), resulted in there being no statistically-significant differences between the trials (P>0.05). That is, when using the helmet recommended from Phase Two of this project, there was no difference in whole-body thermal strain relative to that experienced when wearing the felt hat, even though it was removed every 15 min for 30 sec, and the forehead wiped with a cloth to simulate typical behaviour in the field. The equivalence of these core temperature responses is illustrated in Figure 33.

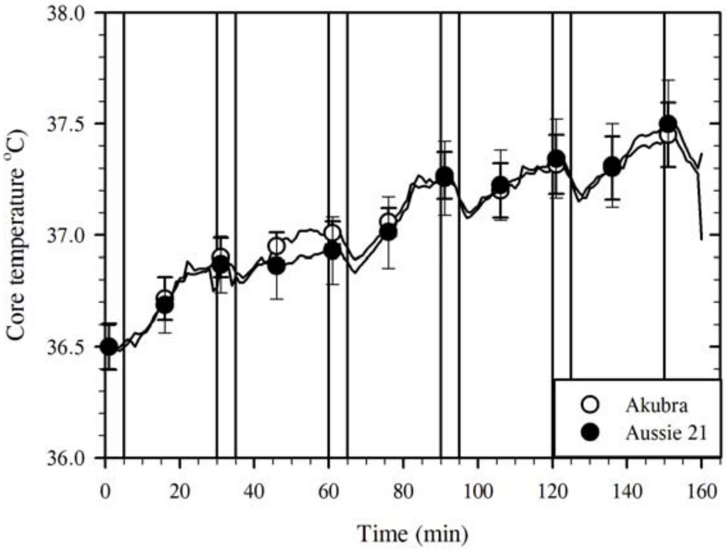


Figure 32: Body core temperatures during an intermittent work and rest protocol in a hot-dry environment (38^{o}C, 30% relative humidity), with subjects wearing either a felt hat (Akubra Arena) or an equestrian helmet (Aussie 21), and work rates set to match those observed in stockmen during mustering. Data are means with standard errors of the means.

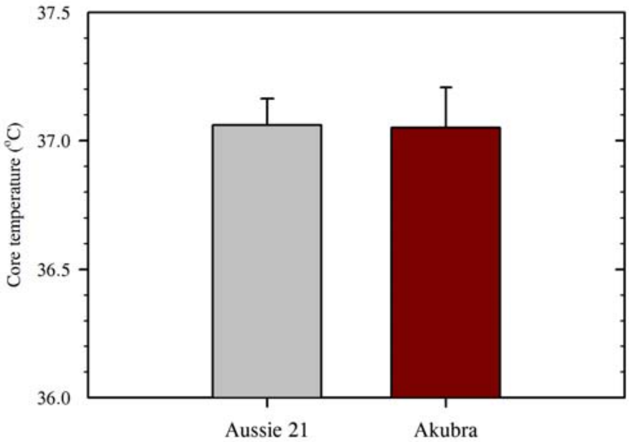


Figure 33: Mean core temperatures, averaged over 150 min, during an intermittent work and rest protocol in a hot-dry environment (38^{o}C, 30% relative humidity), with subjects wearing either a felt hat (Akubra Arena) or an equestrian helmet (Aussie 21), and work rates set to match those observed during mustering. Data are means with standard errors of the means.

From core temperatures measured in the field during mustering (Taylor and Caldwell, 2007), it was observed that for about 66% of each field trial, temperatures were within the range 37.3-37.7^{o}C. In the current experiment, core temperatures remained within this range by design, and were slowly driven upwards (Figure 32). It is well known that, to establish experimental conditions under which subtle changes in clothing may be evaluated for a possible impact upon thermal strain, one must apply a gradually increasing forcing function (Goldman, 1994, 2001), since rapidly increasing work rates invariably result in trial termination due to factors unrelated to the nature of the clothing or garment being evaluated. In the current experiment, this was achieved, and the low work intensity and climatic conditions produced an uncompensable environment, resulting in a gradually climbing core temperature, as observed in the field (Taylor and Caldwell, 2007). However, this experimental design resulted in the peak core temperatures being less than observed in the field, and this was a deliberate consequence of the design, since the aim was not to simulate maximal conditions, but to simulate stressful climatic conditions and typical work rates. The latter intensities were based on those determined in the field from 27 heart rate data sets obtained during horseback mustering (Taylor and Caldwell, 2007).

The only conclusion that can be drawn from these data, as derived within the current experiment, is that the equestrian helmet recommended by Caldwell and Taylor (2007) did not impose a measurable thermal strain upon the experimental subjects, beyond that imposed by wearing a felt hat.

In the field, the mean skin temperatures followed a linear elevation over time, and typically commenced at about 32^{o}C, and terminated near to 36^{o}C, with just three stockmen experiencing higher final skin temperatures (Taylor and Caldwell, 2007). In the current trials, this pattern was reproduced (Figure 34), with the mean terminal skin temperatures averaging 36.0-36.1^{o}C for each experimental condition. Differences between these curves were not statistically significant (P>0.05), although skin temperatures were actually hotter when wearing the felt hat during the first 60 min. This is partially attributable to a higher internal hat temperature, since we have demonstrated that the felt hat does not offer a significant thermal resistance to solar heating (Figure 35; Caldwell and Taylor, 2007), and since 7% of the mean skin temperature derivation comes from forehead temperature, then this non-significant trend is not surprising. Indeed, when averaged over the entire trial, mean skin temperature differed by only 0.1^{o}C (Figure 35).

In all cases, mean skin temperature was cooler than the core temperature, creating a positive thermal gradient for the transfer of heat to the subcutaneous tissues. However, air temperature also exceeded skin temperature, and the negative thermal gradient now resulted in heat gain from the surrounding air. Under such circumstances, the evaporation of sweat becomes the principal avenue for losing heat. As the trials continued, the rise in skin temperature reduced this heat gain, and increased the water vapour pressure at the skin surface, thus enhancing the evaporation of sweat.

Temperature and humidity sensors were located within each helmet, and also within the shirt. These measures were recorded to evaluate the impact of the simulated solar radiation (three, 500-W radiant heat lamps positioned ~1 m overhead) on the thermal stress imposed on these subjects, relative to that encountered in the field (Taylor and Caldwell, 2007). These data are presented in Figure 36.

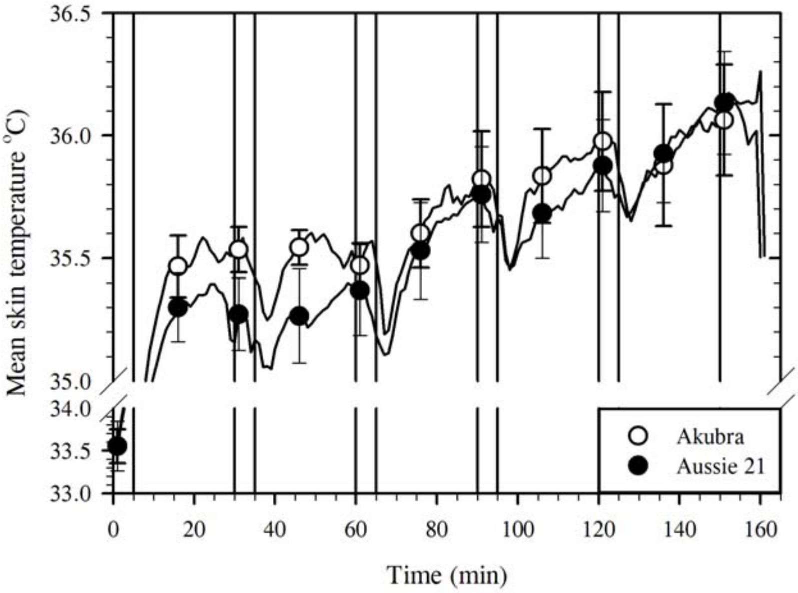


Figure 34: Mean skin temperatures during an intermittent work and rest protocol in a hot-dry environment (38^{o}C, 30% relative humidity), with subjects wearing either a felt hat (Akubra Arena) or an equestrian helmet (Aussie 21), and work rates set to match those observed in stockmen during mustering. Data are means with standard errors of the means.

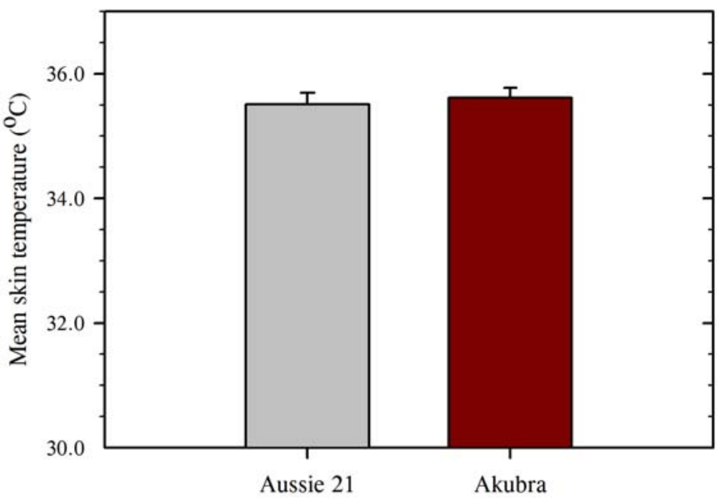
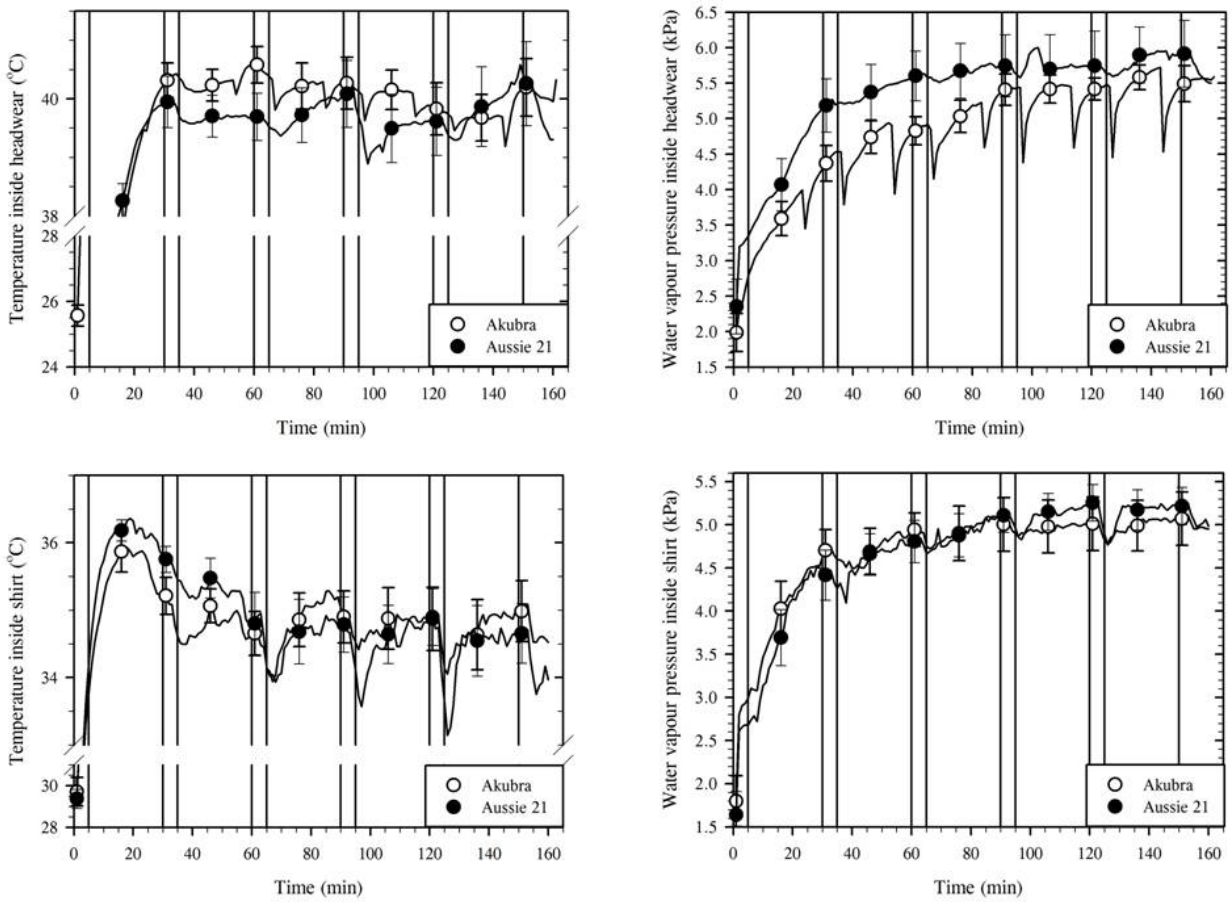


Figure 35: Mean skin temperatures, averaged over 150 min, during an intermittent work and rest protocol in a hot-dry environment (38^{o}C, 30% relative humidity), with subjects wearing either a felt hat (Akubra Arena) or an equestrian helmet (Aussie 21), and work rates set to match those observed during mustering. Data are means with standard errors of the means.



Figures 36-39: Hat (6) and shirt skin temperatures (7) and water vapour pressures (hat: 8; shirt: 9) during an intermittent work and rest protocol in a hot-dry environment (38°C, 30% relative humidity), with subjects wearing either a felt hat (Akubra Arena) or an equestrian helmet (Aussie 21), and work rates set to match those observed in stockmen during mustering. Data are means with standard errors of the means.

The solar simulation was indeed strong, eliciting air cavity temperatures (Figure 36) greater than those obtained during bench-top testing (Figure 35; Caldwell and Taylor, 2007), due to the contribution of metabolically-derived heat being dissipated through the head. Furthermore, these temperatures also exceeded the mean helmet temperatures observed during field trials (Figure 23; Taylor and Caldwell, 2007), but very closely matched the mean maximal helmet temperatures (~40°C), and held this level of thermal stress from 30 min through to 150 min of the current trials. The bulk of these temperatures obtained from within the felt hat exceeded those from within the equestrian helmet, reflecting a lower thermal resistance to heat penetration (Caldwell and Taylor, 2007). However, these differences were not significant (P>0.05).

Temperatures inside the shirt air cavity (Figure 37) faithfully replicated the mean shirt temperatures measured on stockmen engaged in mustering (~35°C; Figure 23, Taylor and Caldwell, 2007). Whilst small between-trial differences are apparent, these were not statistically significant (P>0.05).

From these data, the thermal (and subsequently vapour pressure) gradients were derived (Table 19). Positive gradients indicate continuous heat loss (or evaporation) from the body and air cavities within the clothing, with negative gradients reflecting heat gain. The thermal gradients were positive from the skin to the trapped air within the shirt, but negative from the skin to air trapped within the headwear, with no significant differences being evident between forms of headwear (P>0.05). These thermal gradients were again equivalent, but reversed in sign, when comparing the surrounding air with that trapped inside the hat or shirt.

Table 19: Thermal and water vapour pressure gradients.

		Akubra	Aussie 21	Akubra	Aussie 21
Site	Gradient	Skin to trapped air		Trapped air to external air	
Headwear	Thermal	-3.63^{o}C	-3.40^{o}C	1.33^{o}C	1.30^{o}C
Shirt	Thermal	0.92^{o}C	1.19^{o}C	-3.22^{o}C	-3.19^{o}C
Headwear	Water vapour	1.07 kPa	0.55 kPa	3.17 kPa	3.75 kPa
Shirt	Water vapour	1.16 kPa	1.26 kPa	3.08 kPa	3.07 kPa

Water vapour pressures were also determined for the air cavities within the hat (Figure 38) and shirt (Figure 39). In mustering trials, the average water vapour pressure within the equestrian helmet was 3.4 kPa (SD 1.1), and that of the shirt was 3.7 kPa (SD 1.1). These are lower than were observed in the current trials, which averaged ~5.5 kPa and ~5.0 kPa over the final 60 min of testing. These differences between the field and laboratory trials can attributed to three facts. First, the helmet air temperatures were higher in the laboratory. Second, the variable impact of the shirt could not be controlled in the field. In the laboratory, the shirt remained buttoned (Figure 10). In the field, stockmen were not instructed concerning the use of buttons, and many, particularly the men, used the behavioural approach of keeping the top buttons open. This lowers internal water vapour pressure. Third, the air velocity directed at the experimental subjects was kept constant (two fans positioned in front of the subject), in a simulation of the average riding speed observed in the field: 5.16 km.h^{-1} (Taylor and Caldwell, 2007). During mustering, a riding velocity is constantly changing, and, in combination with button closure differences, will account for a more effective ventilation of the shirt, and a lower water vapour pressure.

In the case of the water vapour pressure gradients (Table 19), the shirt and headwear retained trapped air that had a water vapour pressure conducive to the evaporation of sweat, and the loss of that moisture to the surrounding air, as reported for the field trials (Taylor and Caldwell, 2007). The equivalent of these vapour pressure gradients highlights our field-based conclusion that the helmet did not appear to behave in a manner that would disadvantage the stockmen, at least from a thermodynamics perspective, more than would any other garment worn on the head.

Taken collectively, these observation allow one to reasonably conclude that the climate chamber simulations were faithful, laboratory-based replications of the working environment of stockmen from northern Australia, during November.

However, it is apparent from Figure 38 that the water vapour pressure within the felt hat was consistently lower than within the equestrian helmet. Some of this difference is directly attributable to the lower vapour pressure differences at the start of the trial, which may be explained by differences in the volume of the air cavity within each type of headwear. The felt hat has a larger volume, and takes longer for the water vapour pressure to increase, even at a constant air temperature and evaporation rate.
However, subjects removed the felt hat for 30 sec, and wiped the forehead with a cloth, every 30 min, and the affect of this behavioural simulation is clearly evident on the vapour pressure curve. The precipitous decreases in vapour pressure are evident at 15-min intervals, when water vapour

is lost from the air cavity of the hat, and these depressions are followed by exponential increases to a new steady state. Thus, this cyclical pattern kept the average water vapour pressure lower. In addition, it is possible that water vapour continually passed through the felt, though we have no empirical evidence to support this. It is apparent that, even with the ventilation ports in the equestrian helmet, these influences resulted in a lower mean water vapour pressure within the felt hat (Figure 38). However, when data were initially analysed (two-way *ANOVA* using data at 15-min intervals; as indicated by the symbols on each plot), these differences were not significant (P>0.05), since the data during and following hat removal were not included in these analyses. According, these data were re-analysed (paired t-test) using all points, and revealing a significantly lower water pressure within the felt hat (P=0.047).

From data reported by Taylor and Caldwell (2007; Figure 16, Table 12), it was concluded that horseback mustering, while sometimes being very stressful, was not a consistently high-intensity job. Indeed, <3% of the total working time was spent at intensities >70% of the heart rate reserve[1]The heart rate reserve quantifies the operational range of the heart, which varies only between the resting and maximal limits., with 1.1% at work rates greater than 80%. Almost 90% the work time was spent working below an intensity of 50% of the heart rate reserve. This exercise pattern was incorporated into the current experiment (Table 7), and Table 20 summarises the heart rate data obtained from the resulting trials.

Table 20: Summary of heart rate observations. Data are means with standard errors of the means: HRR = heart rate reserve.

Variable	Akubra	Aussie 21
Resting heart rate (beats.min^{-1})	63.5 (2.5)	62.9 (2.4)
Heart rate reserve (beats.min^{-1})	132.8 (5.5)	133.4 (7.6)
Average heart rate (beats.min^{-1})	101.9 (3.6)	102.8 (2.3)
Maximal working heart rate (beats.min^{-1})	123.0 (5.3)	126.9 (4.6)
Proportion of time at <50% HRR (%)	96.9 (8.8)	95.9 (3.8)
Proportion of time at 50-60% HRR (%)	2.3 (6.4)	3.0 (2.8)
Proportion of time at 60-70% HRR (%)	0.6 (1.8)	0.8 (0.8)

Figure 40 contains the time series heart rate data, which reveal a surprisingly consistent between-trial similarity. Indeed, statistically-significant differences were not apparent between trials (P>0.05). Clearly evident from each plot are the rest periods and the higher intensity work rates between minutes 65-80. At all other times, the work rate was kept constant, yet there was a gradual elevation in the heart rate. This continual rise is known as the cardiovascular drift, and it 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). Nevertheless, it is almost always present during protracted, steady-state exercise in the heat.

[1] Heart rate reserve = maximal heart rate - resting heart rate [beats.min^{-1}]
where:
resting heart rate was measured and maximal heart rate derived: 220 [beats.min^{-1}] - age [y].

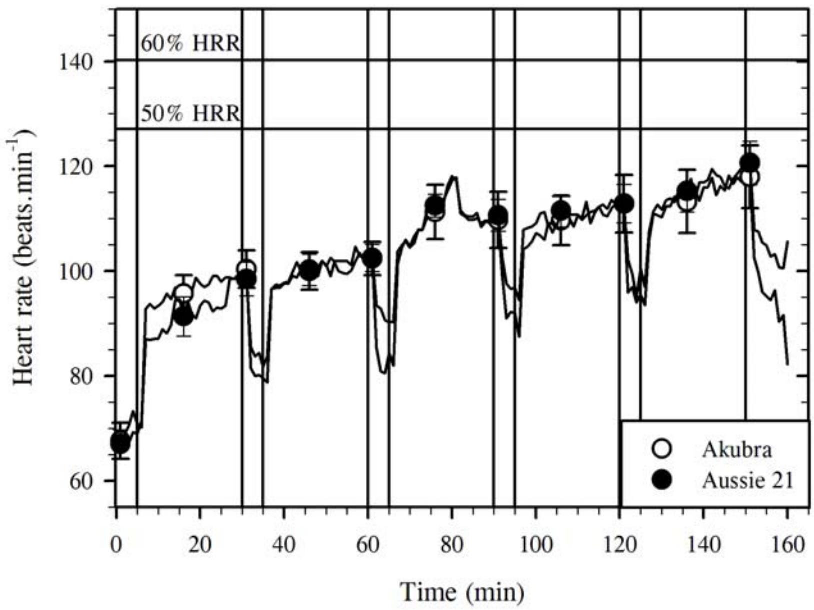


Figure 40: Heart rates during an intermittent work and rest protocol in a hot-dry environment (38°C, 30% relative humidity), with subjects wearing either a felt hat (Akubra Arena) or an equestrian helmet (Aussie 21), and work rates set to match those observed in stockmen during mustering. Data are means with standard errors of the means.

Table 20 summarises the heart rate data from these experiments. Our aim was to simulate both the climatic and work-related stress encountered during mustering. From our field trials, we determined a mean working heart rate of 101.2 beats.min^{-1} for the male stockmen (Table 14; Taylor and Caldwell, 2007). The current averages 102.8 and (101.9 beats.min^{-1}) are remarkably close to this target, verifying the validity of the work simulation.

Before commencing these experiments, subjects presented with an average urine specific gravity[2] less than 1.017 (Figure 41), which is well within the normal range[3] for adequately-hydrated (euhydrated) individuals (Armstrong *et al.*, 1994).
Thus, it may be assumed that subjects satisfied the pre-experimental hydration requirements prior to arrival at the laboratory, and so commenced each trial in a euhydrated state. Indeed, even at the end of the experiment, and due to the forced drinking regimen used during these trials (water consumption at a rate of 7.5 mL.kg^{-1}.h^{-1} every 30 min), subjects completed 150 min of exercise in the heat in a euhydrated state. This drinking rate was designed to match sweat loss during such an experiment, and this was successfully achieved, as indicated by the post-experimental urine specific gravity (Figure 41).

[2] Urine specific gravity quantifies the concentration of urine. The higher the concentration, the more dehydrated is the person producing the specimen. Typically, when out on the turps, one may produce a large volume of dilute urine, signifying the diuretic effect of alcohol. Unfortunately, the next morning, one will produce very concentrated urine, signifying dehydration, the proof of which appears in the form of a rather sore head. Some suggest that this is a negative aspect of alcohol consumption; the authors are currently testing this hypothesis.
[3] Hydration classifications based upon urine specific gravity: (a) well hydrated: <1.013; (b) euhydrated: 1.013-1.029; and (c) hypohydrated: >1.029 (Armstrong *et al.*, 1994).

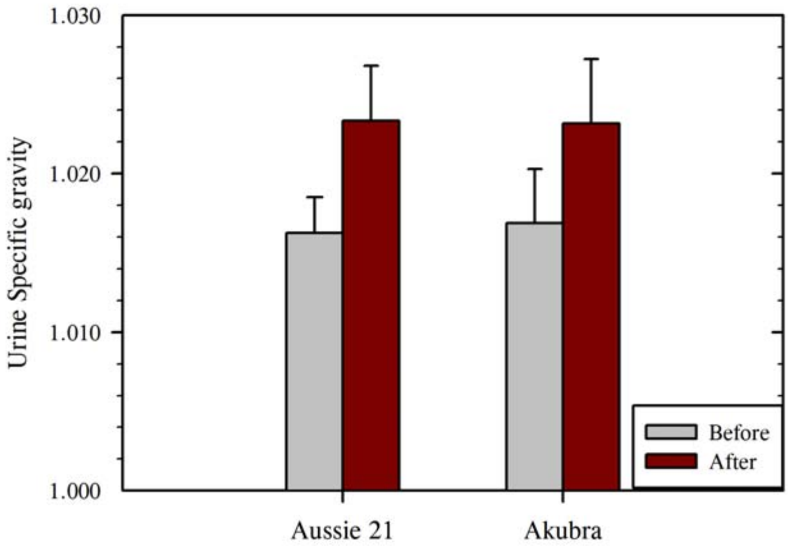


Figure 41: Urine specific gravity before and after 150 min of intermittent work and rest in a hot-dry environment (38^{o}C, 30% relative humidity), with subjects wearing either a felt hat (Akubra Arena) or an equestrian helmet (Aussie 21), and work rates set to match those observed during mustering. Data are means with standard errors of the means.

Not surprisingly, body mass changes were minimal (Figure 42), representing a non-significant (P>0.05) water consumption to sweat rate deficit of 290 mL (Aussie 21) and 150 mL (Akubra). It is therefore concluded that neither form of headwear resulted in a significant deviation in sweat secretion, or greater thermal strain. The differences in the initial body mass of these same subjects between trials (Figure 42; 2.23 kg) was significant (P<0.05). This is just outside the normal daily variation in body mass, and the authors can offer no justifiable reason for its existence, particularly since the trial sequence was balanced across subjects, with 50% commencing the experiment using the felt hat, while the other 50% commenced with the equestrian helmet.

5.3.2 Psychophysical strain

None of the psychophysical indices differed between the trials (Figures 43 and 44; P>0.05). The apparent difference in effort sense (Figure 43) was not significant even when data were re-analysed using the paired *t*-test procedure.

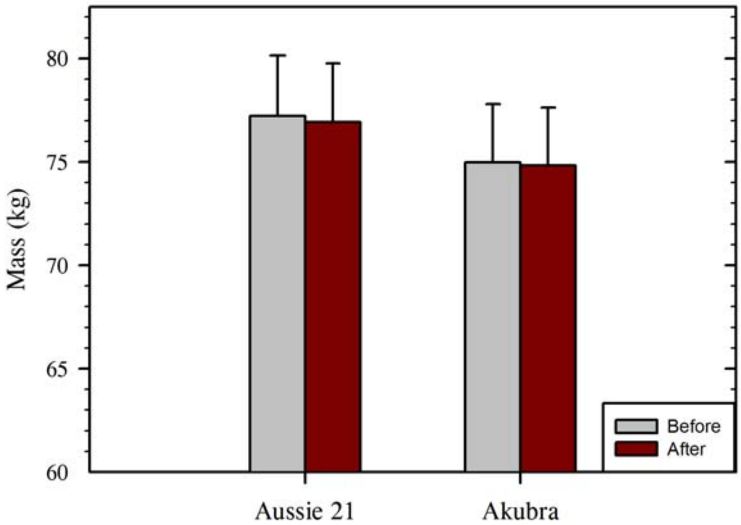


Figure 42: Body mass before and after 150 min of intermittent work and rest in a hot-dry environment (38°C, 30% relative humidity), with subjects wearing either a felt hat (Akubra Arena) or an equestrian helmet (Aussie 21), and work rates set to match those observed during mustering. Data are means with standard errors of the means.

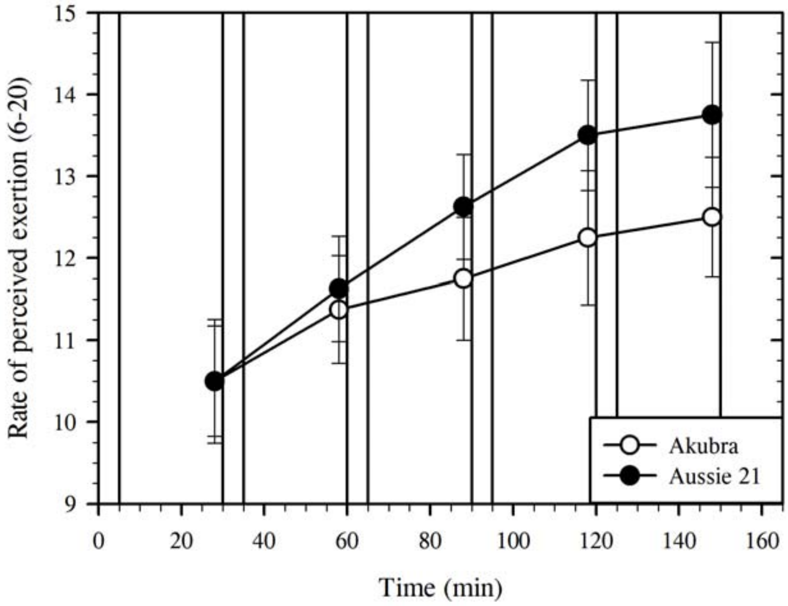


Figure 43: Subjective ratings of physical exertion during an intermittent work and rest protocol in a hot-dry environment (38°C, 30% relative humidity), with subjects wearing either a felt hat (Akubra Arena) or an equestrian helmet (Aussie 21), and work rates set to match those observed in stockmen during mustering. Data are means with standard errors of the means.

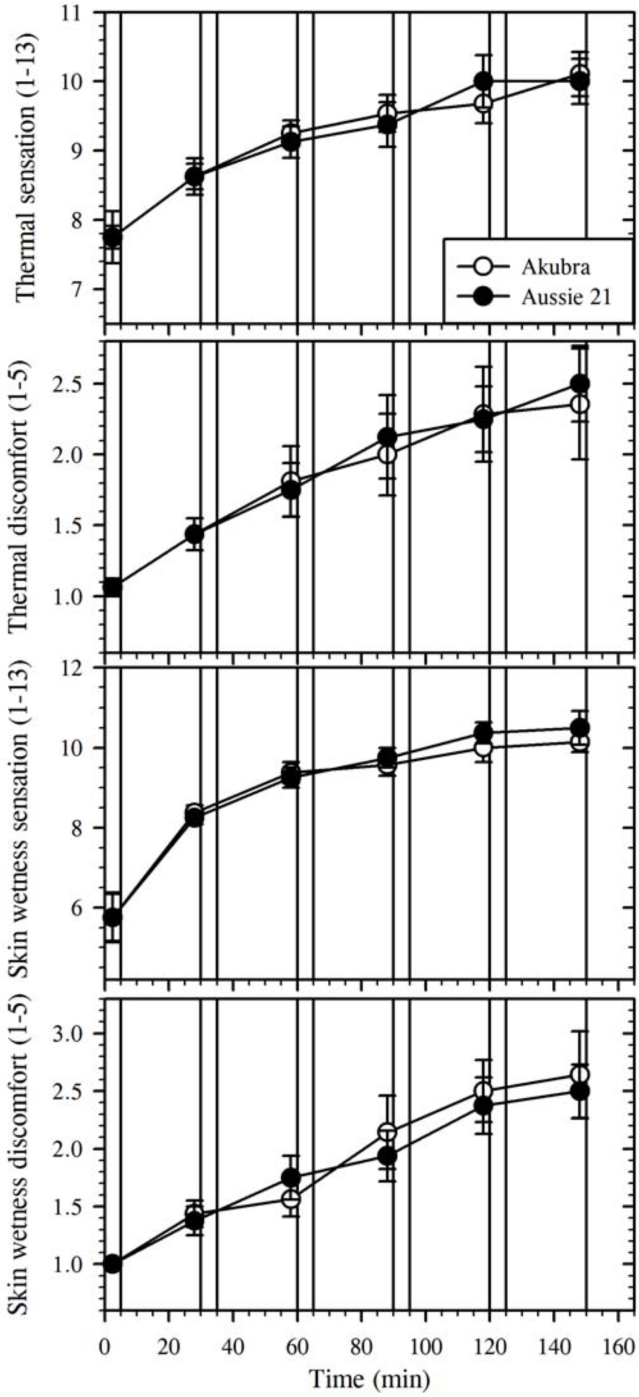


Figure 44: Psychophysical ratings during an intermittent work and rest protocol in a hot-dry environment (38^{o}C, 30% relative humidity), with subjects wearing either a felt hat (Akubra Arena) or an equestrian helmet (Aussie 21), and work rates set to match those observed in stockmen during mustering. Data are means with standard errors of the means.

5.3.3 Cognitive function

There were no significant between-trial differences for any of the cognitive function measures (Figure 45; P>0.05), leading to the conclusion that the equestrian helmet, when used under conditions that faithfully replicated the working conditions of the stockman, but within a precisely-controlled research laboratory, does not adversely affect the cognitive functions investigated.

In our field trials (Taylor and Caldwell, 2007), significant pre- versus post-experimental performance decrements were observed for both vigilance and problem solving (three-term reasoning; P<0.05). These observations were considered to possibly be artefactual, due to the lack of control that could be exerted over the working environment. These tests were repeated within the current experiment, revealing inconsistent and non-significant changes (P>0.05). Thus, under controlled laboratory conditions these cognitive function changes were not able to be replicated, and it is therefore reasonable to conclude that they were indeed the result of measurement artifact.

We have recently undertaken two other projects in which changes in cognitive function was evaluated within thermally-stressful and laboratory-controlled working conditions (Caldwell et al., 2005; Caldwell and Taylor, 2007). In neither of these investigations were we able to elicit reductions in cognitive performance, even though thermal strain clearly and significantly impacted upon physiological performance, with core temperatures of approximately 39oC, skin temperatures >38oC and heart rates in excess of 130 beats.min-1. Whilst it is quite probable that some degree of hyperthermia heightens cognitive function, it is also probable that subjects in these experiments, our previous field trials and the current experiment, were not sufficiently dehydrated in these trials to experience the full effects of the exposure. For instance, 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).

Notwithstanding these observations, within the current trials, a decrement in performance for the perceptual reaction time test was observed, and this was replicated within each of the trials (Figure 45). The average response times for this test changed in the same direction, but just failed to achieve statistical significance (P=0.06 Akubra; P=0.09 Aussie 21). This test evaluates whether or not changes in reaction time are a function of altered cognitive or physical (motor control) states. Since motor control was not altered, then it is assumed that reaction times were impaired due to a change in cognitive function. Furthermore, since this change was replicated under both experimental conditions, then it is reasonable to assume that it was not the result of measurement artefact. Closer inspection of the data from Caldwell et al. (2005) and Caldwell and Taylor (2007) reveals that similar observations were indeed evident. In the former project, a linear decrease in perceptual reaction time was evident in the most stressful condition, and these data have been reproduced in Figure 46.

What is immediately evident, when one compares Figures 45 and 46, is that the inter-subject variability was much lower for the current project. We therefore conclude that, within the project of Caldwell et al. (2005), the high variability, both within and between trials, prevented the reduction in cognitive performance from achieving the required level to be statistically significance. Recently, Neave et al. (2004) reported that the use of a protective cricket helmet caused slower reaction times for some cognitive function tests, following a brief cricket simulation.

While these data are consistent with the present observations, the current researchers have reservations concerning the quality of control achieved within this experiment, and the extent to which it reproducibly stressed the experimental subjects. Nevertheless, the cognitive function assessments were most rigorous. Indeed, one often finds within the literature an imbalance of scientific merit when experiments combine two or more disciplines.

For instance, psychologists often fail to fully appreciate physiological strain, and physiologists frequently fail to ensure that cognitive function tests are adequately administered and analysed.

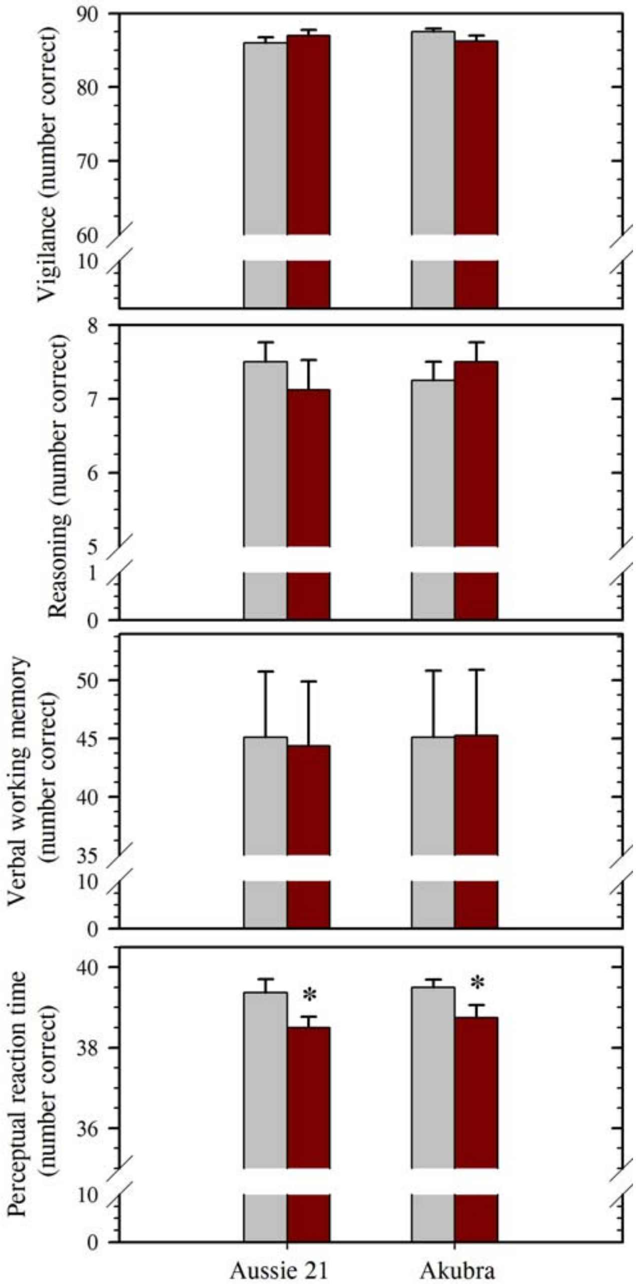


Figure 45: Cognitive function before and after 150 min of intermittent work and rest in a hot-dry environment (38^{o}C, 30% relative humidity), with subjects wearing either a felt hat (Akubra Arena) or an equestrian helmet (Aussie 21), and work rates set to match those observed in stockmen during mustering. Data are means with standard errors of the means.

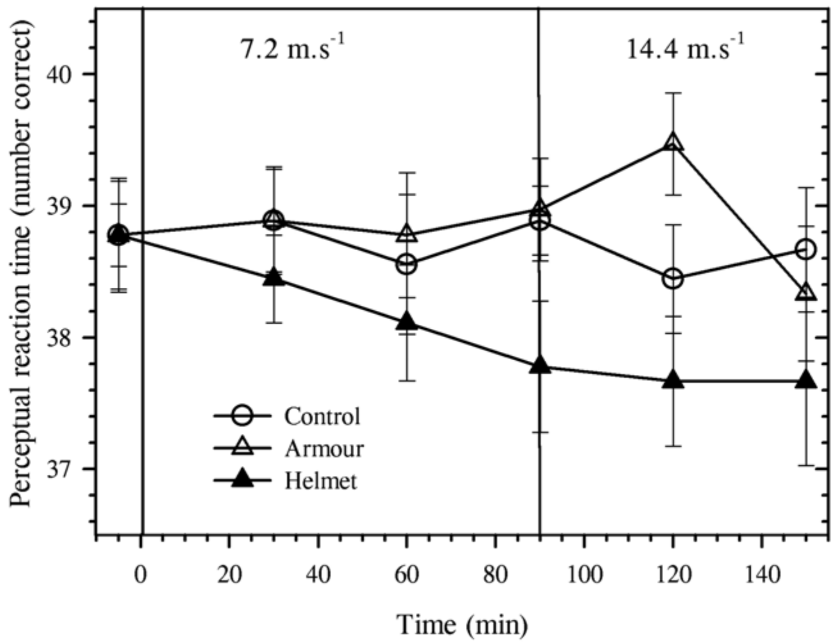


Figure 46: Changes in perceptual reaction time during steady-state walking (two speeds) in a hot-humid environment (36^{o}C, 60% relative humidity, radiant heat ~750 W.m^{-2}) with three clothing configurations: camouflage uniform (control), camouflage uniform with body armour, and camouflage uniform with armour and helmet (reproduced from: Caldwell *et al*., 2005).

The literature contains a wide variety of research in which the interaction of thermal strain upon cognitive function has been evaluated. For the reasons just described, much of this evidence is confusing and difficult to interpret. Handcock and Vasmatzidis (2003) have provided the most recent attempt to assimilate and unify these observations, yet even they fall short of a clear appreciation of the need to control physiological strain when making either their own experimental observations, or interpreting the literature. Nevertheless, they very correctly highlight inconsistencies among experiments, with most studies reporting decreased cognitive performance in the heat, while some report no change, and other improved performance. The current and previous experiments from our laboratory are more consistent with the last two trends within the literature.

Several reasons have been offered by Handcock and Vasmatzidis (2003) for these equivocal outcomes. First, the complexity of the tasks being evaluated is important, since more complex tasks, which presumably require greater concentration, are more susceptible to interference from environmental factors. In the current project, more simple cognitive tests were used. This was deemed appropriate since the cognitive tasks of stockmen are rarely complex, while other occupations may place much higher demands upon cognition (*e.g*. helicopter flight; Caldwell *et al*., 2006). Second, the level of task skill will modify the impact of external influences, with the performance of highly skilled individuals being less susceptible to heat strain.
This was addressed, *albeit* incompletely, in the current project by training subjects in the tests to minimise learning effect, with each test being performed on seven occasions prior to commencing the present trials, and thereby obtaining a learning plateau (Caldwell *et al*., 2005). Third, exposure duration is important. Short exposures, such as that used by Neave *et al*. (2004), are unlikely to elicit the required thermal strain, thereby preventing changes in cognitive function

to be assigned to the stimulus that was applied, regardless of how the researchers themselves may interpret their own observations. In the current experiment, the exposure duration was 2.5 hours.

While each of these reasons are valid, arousal theory has also been used to account for these variations in cognitive performance following heat exposure. This theory is based on the Yerkes-Dobson law, which is illustrated in Figure 17, and implies that arousal state, and cognitive functions that are affected by this state, is increased as the body core temperature rises. Eventually, an optimal arousal and performance state is obtained, with elevations in core temperature beyond that point resulting in decreased arousal and performance (Provins, 1966). More complex tasks were believed to be affected at lower core temperatures. Whilst the validity of this theory has been questioned (Handcock and Vasmatzidis, 2003), it is entirely consistent with the observations within the literature relating to cognitive function changes and increased thermal strain. That is, during mild thermal states, some cognitive functions appear to be enhanced, with moderate strain often being found to have no affect, and some highly-stressful states resulting in impaired function. From the current trials, it would seem that our subjects fell close to the zone of optimal arousal (Figure 47), but perceptual reaction time seems to have been adversely affected. One could explain this observation on the basis of arousal theory, and suggest that, for this cognitive function, optimal performance occurred at a lower core temperature, and the core temperatures at the end of these trials resulted in slightly, but significantly reduced test performance.

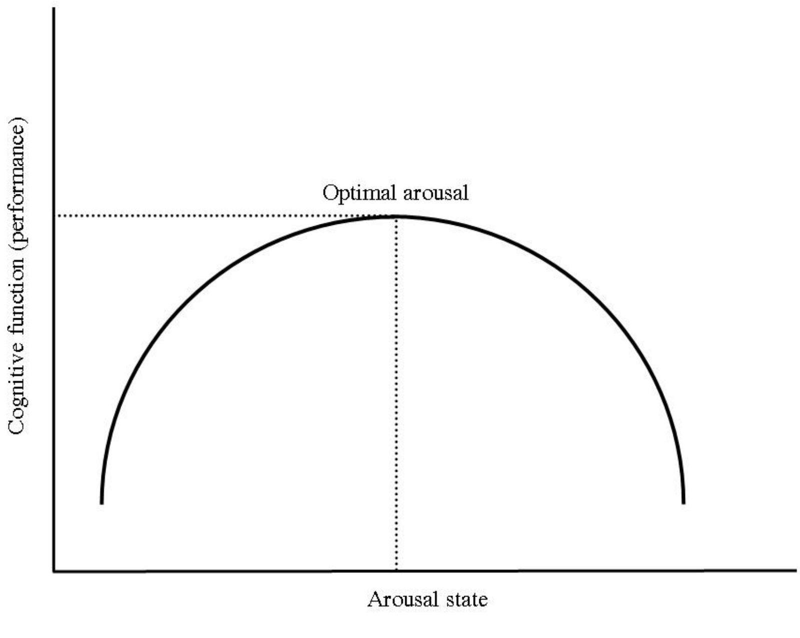


Figure 47: A schematic representation of the Yerkes-Dobson law of arousal theory, applying the interaction of core temperature on arousal, as first hypothesised by Provins (1966).

6 Conclusions

6.1 Phase One: Field trials

This investigation was the first part of a three-Phase project aimed at evaluating the possibility that equestrian protective helmets may predispose stockmen to an increased risk of heat illness, and reduced work performance. One aim of this Phase was to describe the working (thermal) environment of northern Australian cattle stations. However, the principal aim was to quantify of the metabolic demands (heat production) of horseback mustering, as well as providing field-based assessments of the physiological and cognitive strain encountered during mustering. These data were collected across a broad range of climatic and working conditions, using 24 stockmen from four cattle stations.

The working environment
Data for climatic conditions and the working environment (clothing insulation, skin surface area coverage, average velocity, work rates, core temperatures, body masses) were collected from the Bureau of Meteorology (Victoria River Downs station: 1991-2006) and from field observations.

Across the three months of interest (September-November: 2006), the mean 24-hour air temperature was 28.5^{o}C, while the relative humidity was 40.5%. The hourly climatic data showed the normal reciprocal changes in humidity with air temperature. For each month, the peak air temperatures progressively increased, and occurred between 1500-1600 hours, with significant cooling only occurring after work ended for the day. From the data collected over the years 1991-2006, the following average monthly maxima were derived: September: 35.5^{o}C; October: 37.3^{o}C; November: 38.1^{o}C. Fortunately, at these times, the relative humidity was very low (<25%), enabling the evaporation of sweat to help dissipate body heat. However, stockmen encountered a 10-15^{o}C elevation in air temperature during the course of their working day.

The Heat Strain Index was used to quantify the thermal impact of the combined work and environmental conditions. This index enabled the identification of conditions for which the required heat loss, as determined by the environmental, working and clothing status of the individual, exceeded the capacity of the environment to permit such heat loss. Such conditions are thermally uncompensable, and are associated with a progressive heat gain.

It was evident that the working environment at the Victoria River Downs station is, on average, **thermally uncompensable**. Certainly, at the coolest times of the day, when there was no requirement for evaporative cooling, the conditions would not place an unbearable load upon stockmen. However, when air temperatures climbed above 30^{o}C, the thermal load was again uncompensable. This occurred, on average, at 1200 hours in September, 1000 hours in October and at 0900 in November, and did not retreat to compensable conditions until after the sun had set.

Metabolic heat production during mustering
The average daily air temperatures for these field trials, obtained over the 8-hour working period (0800-1600 hours), was 35.6^{o}C. Thirty-eight heart rate data sets were obtained, including 27 mustering trials. Using heart rate calibration coefficients obtained during the simultaneous measurement of heart rate and oxygen uptake on six stockmen, the projected oxygen uptake and metabolic heat production of mustering cattle on horseback were derived.

The mean heart rate across the mustering trials was 104 beats.min^{-1} (both genders); only 35 beats.min^{-1} above the resting heart rate. This represents a 26% increase above the heart's resting level, relative to the heart rate reserve. It was concluded that horseback mustering, while sometimes being very stressful on the stockman, is not a consistently high-intensity job. Indeed, less than 3% (9 min) of the total time was spent working at intensities greater than 70% of the heart rate reserve, with 1.1% (2.9 min) at work rates greater than 80%. Almost 90% the work time (237.8 min) occurs below an intensity of 50% of the heart rate reserve.

With the gender-specific prediction equations, the averaged heart rate data from the mustering trials were used to derive mean oxygen uptakes and the metabolic heat production of mustering. For healthy adults of average physical fitness, the projected oxygen uptakes represented only 25-40% (females) and 30-45% (males) of their maximal capacity. Such light work rates are easily sustainable for 5-8 hours by normal healthy individuals without rest. Indeed, when one derives the projected external work rates associated with these data, these equate with 48 W (females) and 73 W (males), but may range from 36-67 W (females) and 42-108 W (males).

From these derivations, the metabolic heat production of stockmen during mustering appears to range between 178-333 W (females) and 212-542 W (males). From first-principles, biophysical modelling, it was predicted that positive heat storage would occur for all air temperatures >23^{o}C, when working at 70 Watts (Figure 18). These temperatures occur beyond 0900 hours, even in the cooler month of September. Therefore, even without head wear, one may reasonably expect stockmen to gain heat in their working environment.

Physiological and cognitive strain

Sixteen stockmen participated in this stage of testing, which involved eleven mustering trials. The average air temperature, obtained over the work period (0800-1600 hours), was 35.7^{o}C. The average riding velocity was 5.16 km.h^{-1}.

About 66% of the core temperatures were within the range 37.3-37.7^{o}C. These are within the normal daily range, and cannot be considered to be stressful. In fact, one would predict a less than 10% probability of someone with such a core temperature of experiencing heat exhaustion. However, from an analysis of the maximal core temperatures, a slightly more stressful situation was revealed. Sixty-six percent of the peak temperatures fell within the range 37.6-38.8^{o}C. The upper 33% of these temperatures exceed the recommended upper core temperature limit for steady-state work: 38^{o}C (World Health Organisation, 1969). One would anticipate that approximately 25% of such individuals may experience heat exhaustion. Only one stockman exceeded a core temperature of 39^{o}C, while four others had peaks in excess of 38.5^{o}C, but less than 39^{o}C.

Data for air trapped within the helmet and shirt revealed that these air temperatures did not differ significantly. That is, both the shirt and helmet behaved similarly with respect to heat transfer, with each appearing to allow equivalent heat dissipation from the body, and heat gain from the surrounding air and via solar radiation. It may therefore be concluded that the helmet, at least within the current trials, did not appear to behave in a manner that would disadvantage the stockmen, at least from a thermodynamics perspective, more than would any other garment worn on the head.

Stockmen commenced these field trials in an adequately hydrated state. However, during the course of these experiments, a 1.8% dehydration (water deficit) was observed. While this was a discernible dehydration, and should be prevented, such a mild dehydration is well tolerated, and is unlikely to have a significant physiological impact.

On average, stockmen reported significantly greater psychophysical strain following each mustering trial, relative to their pre-trial perceptions. This was entirely predictable. However, two significant cognitive performance decrements were also observed (vigilance and reasoning). Whilst these may be artefactual, due to the nature of the working environment, and the constraints that it places upon such testing, laboratory-based trials conducted within Phase Three of this project, were used to test the veracity of these observations.

Conclusion

This Phase of testing has enabled a clear identification of the working environment for stockmen based on northern Australian cattle stations. It is abundantly clear that this environment is, on average, **thermally uncompensable** during the mustering season. This state obtained, on average, after 1200 hours in September, 1000 hours in October and at 0900 in November, and did not retreat to more compensable conditions until after the sun had set.

In addition, a detailed appreciation of the physiological strain associated with mustering cattle under such conditions, whilst wearing an equestrian helmet, has been achieved. From the observations of heart rate, and the projected metabolic heat production, it is evident that horseback mustering is a relatively low-intensity activity, interspersed with short periods of high-intensity work. This activity level was also reflected within core temperature measures, which rarely climbed above values associated with light-moderate physical activity. Thus, whilst the climatic state was uncompensable for most of the working day, stockmen were able to modulate work rates such that the progressive rise in core temperature was kept below levels that might lead to heat illness. From sensors located in the helmet and clothing, it was observed that the helmet, though unpleasant to wear, did not appear to behave in a manner that would disadvantage the stockmen.

6.2 Phase Two: Bench-top trials

The aim of this Phase of testing was to undertake bench-top testing to determine the heat penetration characteristics of different head wear, and also compare the physical characteristics of equestrian helmets.

The lightest helmet was the **Aussie 21** (320 g). Its centre of mass was 2.6 cm forward of the felt hat, but with the mass differential being only 116 g, this would be expected to have only a minimal physiological impact. The horizontal orientation of the forward and rear facing ventilation shafts of this helmet made it the most suitable for heat and water vapour loss during horseback activities.

No statistical comparisons were made among the helmets for differences in heat penetration. However, a rank-order scale (1-5) was used for each of twelve heat penetration indices (Table 21). A rank of 1 meant that this helmet/hat was associated with the least thermal stress. These rank scores were then summed to provide a single, numerical comparison among the hats tested. This method is rather coarse, due to the unequal physiological impact of every variable. However, it does provide a useful means by which comparisons can be made. On the basis of this ranking system, the helmet that most consistently showed the most favourable heat penetration characteristics was the **Derby**, although differences relative to the **Aussies 21** were quite minimal. Conversely, the **Tipperary** helmet was almost invariably associated with the greatest heat penetration.

Table 21: Summary ranking (1-5) of the fours helmets and the felt hat on the basis of heat penetration data. ***Colour code:*** Blue shaded cells signify the least thermal stress, and red cells show the most stressful head wear. Shading differences reflect the likely physiological impact. When impact is minimal, rankings were halved (inner temperatures).

Variable	Head wear				
	Tipperary	**Onyx**	**Derby**	**Aussie 21**	**Akubra**
Whole trial (60 min): maximal values: heating phase					
Inner temperature	2.5	1.0	1.5	0.5	2.0
Air cavity temperature	5	3	1	2	4
Mean head temperature	5	1	2	3	4
Passive cooling (20 min): maximal values: passive cooling phase					
Inner temperature	2.5	1.0	1.5	0.5	2.0
Air cavity temperature	5	3	1	2	4
Mean head temperature	5	1	2	3	4
Ventilation cooling (20 min): maximal values: active cooling phase					
Inner temperature	2.5	2.0	1.5	1.0	0.5
Air cavity temperature	4	5	2	3	1
Mean head temperature	5	4	2	3	1
Sum	36.5	21	14.5	18	22.5

Note: 1 = least stressful; 5 = most stressful.

The dynamics of these thermal changes revealed clear separation among the helmets for some indices, with the **Tipperary** helmet having the highest peak internal temperature, exceeding that observed for all other helmets by more than 20^{o}C. That is, this helmet permitted the greatest heat penetration. However, it is the air cavity temperature that the head experiences, and the **Tipperary** helmet would be the most stressful during a high external heat exposure, with the **Derby** helmet performing best for this characteristic.

The lowest thermal gradient across the helmet shell was observed for the **Tipperary**. This is consistent with this helmet providing the least effective insulation for the air cavity above the head. On this criterion, the hats can be ranked according to their insulative capacity against an external heat source as follows: **Aussie 21** (best); Onyx, Derby Akubra (equivalent); and Tipperary (worst).

Manikin surface (head skin) temperatures failed to differentiate between three of the helmets (**Onyx**, **Derby**, **Aussie 21**), so regardless of the internal surface and air cavity temperatures, these helmets performed equivalently well, with the **Onyx** being inferior during active cooling.

On the basis of these observations, it is concluded that the **Aussie 21** has superior physical characteristics, while, from a heat penetration perspective, the **Derby** and **Aussie 21** appear to provide very similar thermal protection. On overall performance, it appears that the **Aussie 21** helmet is superior.

Notwithstanding these observations, it is very important to note that while an evaluation of heat penetration is important when working in conditions with very high radiant heat exposure (*e.g*. fire fighting), it only represents part of the problem with helmets. One must remember that equestrian helmets are primarily designed to minimise head injury, and the reduction of heat penetration is a side benefit. However, it is a double-edged sword, for any helmet that impedes heat penetration will also impede heat loss, while one that more easily permits heat flow may be more advantageous when tested using exercising humans.

6.3 Phase Three: Laboratory trials

This investigation was the final part of a three-Phase project aimed at evaluating the possibility that equestrian helmets may predispose stockmen to an increased risk of heat illness, and reduced work performance. The aim of this Phase of testing was to undertake laboratory-based trials under precisely-controlled, and reproducible environmental conditions, in which the equestrian helmet that performed best during bench-top trials was compared with the standard felt hat, during a simulated working and thermal exposure.

Subjects completed two trials in a hot-dry environment (38^{o}C, 30% relative humidity). In one trial, subjects wore a felt hat (Akubra Arena), and in the other, they wore the equestrian helmet (Aussie 21). These conditions represented the average maximal air temperature and the average relative humidity for Victoria River Downs during November, for the 15-year period 1991-2006. In addition, three, 500-W radiant heat lamps were positioned about 1 m overhead to simulate solar loading, and two fans were positioned in front of the subject and set to provide an airflow of 5.16 km.h^{-1}, the average riding speed observed in the field (Taylor and Caldwell, 2007).

A critical part of this experiment was the ability to reproduce conditions and work levels observed in the field, and also to ensure that between-trial conditions and subject status were standardised. To this end, subjects presented for both trials with an average urine specific gravity less than 1.017, well within the normal range for adequately-hydrated individuals. From field trials, we determined a mean working heart rate of 101.2 beats.min^{-1} for the male stockmen. The current exercise and thermal loading protocol elicited heart rate averages of 102.8 and 101.9 beats.min^{-1} for the two trials, verifying the validity of the work simulation. It was observed that, for about 66% of each field trial, core temperatures were within the range 37.3-37.7^{o}C. In the current experiment, core temperatures remained within this range by design, but were slowly driven upwards over time. In the field, the mean skin temperatures followed a linear elevation over time, and typically commenced at about 32^{o}C, and terminated near to 36^{o}C, and this pattern was successfully reproduced, with the mean terminal skin temperatures averaging 36.0-36.1^{o}C for each experimental condition. Taken collectively, these observations allow one to reasonably conclude that the climate chamber simulations were faithful, laboratory-based replications of the stresses encountered by working stockmen from northern Australia (during November) that may impact upon their thermal status.

With these experimental conditions established and replicated for every trial, and with the trial sequence balanced across subjects, it was observed that the Aussie 21 equestrian helmet did not adversely affect any of the physiological, psychophysical or cognitive functions that were evaluated. These observations are summarised in Table 22, which contains data collected over the last 5 min of each experimental condition, where the physiological strain was greatest.

Table 22: Summary of the physiological, psychophysical and cognitive functions observations. Data are means for the last 5 min of each trial (core and skin temperatures and heart rate), the overall mass change, and for the last sampling point (psychophysical state and cognitive function).

Variable	Akubra	Aussie 21
Core temperature (^oC)	37.4	37.7
Skin temperature (^oC)	36.0	36.1
Heart rate (beats.min^{-1})	117.2	118.0
Mass change (kg)	2.1	2.2
Perceived exertion (6-20)	12.0	13.8
Thermal sensation (1-13)	10.1	10.0
Thermal discomfort (1-5)	2.4	2.5
Skin wetness sensation (1-13)	10.1	10.5
Skin wetness discomfort (1-5)	2.6	2.5
Vigilance (number correct)	87.5	86.3
Reasoning (number correct)	7.1	7.5
Verbal working memory (number correct)	44.4	45.3
Perceptual reaction time (number correct)	38.5	38.8

An observation on evidence-based procedures

Whilst it would appear that the use of an equestrian helmet to minimise the risk of head injuries during mustering does not impact unfavourably upon either physiological or cognitive performance, one may wonder about such an implementation. In the true spirit of occupational health, before any intervention is invoked, one must first evaluate risk (the probability of an event occurring). To do this, one needs to know the prevalence of injuries in stockmen during horseback riding. Clearly, the prevention of just one serious injury should be sought. However, sound intervention practices must be based upon evidence. To illustrate this point, a recent epidemiological study, reported by trauma physicians from a large horse-riding region (Calgary, Canada), revealed that, over the ten-year period from 1995-2005, 151 trauma patients were treated following equestrian injuries. Of these injuries, the chest had the highest representation (occurring in 54% of patients), followed by the head (48%), abdomen (22%) and the limbs (17%). Clearly, some riders suffered injuries to more than one site. However, the point is this. If the use of equestrian helmets has been adopted to prevent head injuries, then why have pastoral companies not implemented the use of kevlar chest plates? Of course such a question is rhetorical, but intervention strategies should be based upon appropriate scientific evidence.

6.4 Concluding statements

Three Phases of testing have now been completed. It is abundantly clear that the working environment on northern Australian cattle stations is, on average, **thermally uncompensable** during the mustering season. This state obtained, on average, after 1200 hours in September, 1000 hours in October and at 0900 in November, and did not retreat to more compensable conditions until after the sun had set. A detailed appreciation of the physiological strain associated with mustering cattle under such conditions, whilst wearing an equestrian helmet, has been achieved. From the observations of heart rate, and the projected metabolic heat production, it is evident that horseback mustering is a relatively low-intensity activity, interspersed with short periods of high-intensity work. This activity level was also reflected within core temperature measures, which rarely climbed above values associated with light-moderate physical activity. Thus, whilst the working conditions were uncompensable for most of the working day, stockmen were able to modulate work rates such that the progressive rise in core temperature was kept below levels that might lead to heat illness (behavioural temperature regulation). From sensors located within the helmet and clothing, it was observed that the helmet, though unpleasant to wear, did not appear to behave in a manner that would disadvantage the stockmen (Taylor and Caldwell, 2007).

From bench-top trials performed on a range of equestrian helmets and a felt hat (Akubra Arena), it was concluded that, of the helmets provided for testing, the Aussie 21 had superior physical characteristics, while, from a heat penetration perspective, the Derby and Aussie 21 appeared to provide very similar thermal protection. On overall performance, the Aussie 21 helmet was deemed to be superior (Caldwell and Taylor, 2007), and this helmet was used in the laboratory-based trials to compare the physiological and cognitive affects of headwear on exercising and thermally-stressed individuals.

Finally, it can be concluded from these rigidly-controlled laboratory trials that, during reproducible work and thermal stress simulations, the Aussie 21 helmet does not adversely affect any of the physiological, psychophysical or cognitive functions that were evaluated, relative to that associated with wearing a felt hat.

7 Success in achieving objectives

All aspects of all milestones were successfully achieved. For each Phase of this project, a complete report was submitted to the project manager.

8 Recommendations

1) It is recommended that the Aussie 21 equestrian helmet be adopted for use in the field.
2) It is also recommended that the MLA (or similar body) provide stockmen with a summary sheet containing the information presented in Appendix 1 concerning the maintenance of the necessary hydration status in the workplace.
3) It is recommended that the Pastoral Companies develop appropriate and informative policies with respect to exertional heat illness and hydration. Summary sheet information is provided in Appendix 2.

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10 Appendices

10.1 Appendix 1: Understanding Hydration

Guidelines for maintaining adequate hydration in the workplace

Understanding fluid losses
A resting human will lose body fluid at the rate of about 38 mL.kg^{-1} of body mass per day. Thus, a 70-kg person will lose just approximately 2.8 litres of fluid each day, even when laying in bed. If we assume an average sweat loss of 1 L.h^{-1} for a 70-kg person, then performing 10 hours of work in the heat, and resting for 10 hours, will result in the 24-hour water loss for this person being approximately 13 litres (Table). These fluid losses vary slightly between men and women, due primarily to the lower sweat rates of women. The failure to take in an adequate amount of fluid results in progressive dehydration, which can have significant implications for physical performance and cognitive function.

Table: Projected daily fluid losses (litres) based on the typical work/rest patterns of stockmen.

Mass (kg)	Rest (10 h)	Work (10 h)	Other (4 h)	Total (24 h)
50	0.8	7.9	0.9	9.6
60	1.0	9.5	1.1	11.6
70	1.1	11.1	1.2	13.4
80	1.3	12.7	1.4	15.4
90	1.4	14.3	1.6	17.3

Heavy exercise and work in the heat can easily elicit a 7-10% dehydration (5-7 kg of mass loss for a 70-kg person), and such changes are seen in elite marathon runners at the completion of a race. The reason for this is that extended sweating results in the loss of fluid at the rate of about 12-22 mL.kg^{-1} (female-male values) for each hour of exercise. This can be doubled in well-trained and heat-adapted people.

Relative dehydration can be gauged from short-term fluctuations in body mass. Without fluid replacement, one might expect to lose about 7% of one's body mass in 24 hours. Physical performance can be noticeably impaired at the 3-4% dehydration level, and this is associated with a impairment in both physiological and mental functions. These performance changes can approach a 20% reduction, but this level of dehydration is well tolerated, and the performance decrement is generally of limited short-term consequence. It is generally considered that only when dehydration reaches 15% (10.5 kg for a 70-kg person) does it pose a significant health risk.

What are the consequences of not drinking enough?
The most obvious consequence of inadequate fluid replacement is dehydration, the physiological consequences of which include:

- reduced blood volume
- reduced blood pressure and cardiac output
- reduced blood flow to muscles:
    - ***result:*** reduced work capacity
- reduced blood flow to the skin:
    - ***result:*** more rapid rise in body temperature
    - ***result:*** increased risk of heat illness
- generalised dehydration results in cellular dehydration:

  - ***result:*** general impairment of cell function; this is perhaps most noticeable in nervous tissue (*e.g*. brain function)
- severe dehydration causes increased blood viscosity.

One should always endeavour to stay in a well-hydrated state, particularly when working in the heat, as this will ensure optimal mental and physical performance. However, we need to keep this principle in perspective, particularly as it relates to recreational and short-term working conditions. Consider this example: Alberto Salazar, in whom was observed the highest reported sweat rate, ran the 1984 Olympic marathon in 2 hours 14 minutes, and lost 8.1% of his body mass, despite drinking almost 2 litres of fluid during the race. His sweat loss was 5.43 litres. Of course he was stressed, but that is the nature of the event, and of course his performance was impaired relative to the start of the race, but he still finished fourth.

An important point to note here is that dehydration will affect performance, and it should generally be avoided, but well-trained people can tolerate a significant level of dehydration without serious consequences.

What should you do to prevent dehydration?
Thirst is not a precise indicator of hydration state, as there is a delay between dehydration onset and the sensation of thirst. It works perfectly well in most situations, but if hydration is of critical importance, then you should rely upon other means to track your hydration status, leaving thirst as a back-up (fail safe) indicator. If you feel thirsty, then you can assume that you have already started to become slightly dehydrated.

The best way to gauge dehydration is via clinical measures of blood and urine status. Since the average person does not have access to these, so we must rely upon the visual inspection of urine, particularly urine colour (Figure) and body mass changes. If you know your typical body mass (*i.e*. record it for 7-15 days and take the average), then daily fluctuations in mass can be assumed to be attributable almost entirely to water losses. Drink enough fluid, but not more, to maintain a stable body mass. Below you will find a urine colour chart that can be used to check hydration state (Armstrong *et al.*, 1994): aim for urine colours in the range of 1-4. The more dehydrated a person is, the more concentrated is the urine, and the darker it becomes. This scale provides an easy means through which one may monitor hydration state.

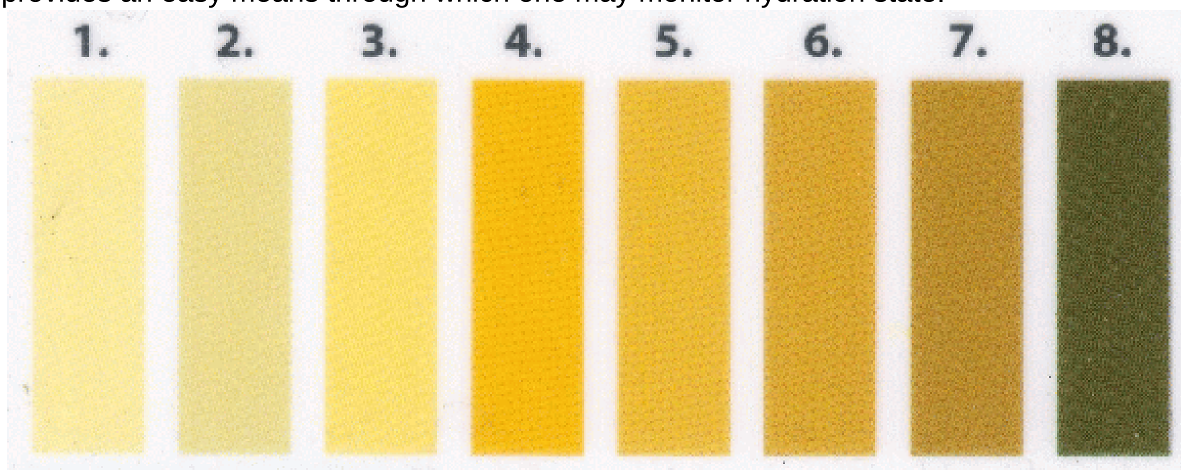

Figure: Urine colour chart: aim for urine to be in the colour range 1-4.

It is recommended that a three-level approach be adopted to the prevent dehydration.

(1) Before starting work:

- hydration strategies should commence the night and morning before work
- use caffeinated drinks and alcohol conservatively
- **guidelines:**
    - achieve normal hydration not over hydration
    - consume about 1.5 litres of fluid each evening:
    - fluid can be consumed in various forms: *e.g*. juice, milk, fresh fruit and vegetables, hot drinks (low caffeine), water
    - drink 0.5 litres of fluid about 2 hours before work.

(2) Hydration during work:

- sweat is more than 99% water
- commercial sports drinks are not required for activities lasting less than 2-3 hours
- it is best to drink small amounts and frequently
- develop a sound habit of regular, and appropriate fluid replacement at work
- **guidelines:**
    - start drinking early at work:
    - fluid can be consumed in various forms: *e.g*. juice, milk, fresh fruit and vegetables, hot drinks (low caffeine), water
    - drink about 0.5 litres of fluid per hour for short work period
    - drink about 1 litre of fluid per hour for longer working periods: modify this to suit your own sweat rate
    - never drink more fluid than you lose via sweating (check you body mass).

(3) Rehydration after work:

- replace about 150% of the body mass that was lost (non-alcoholic fluids):
- fluid can be consumed in various forms: *e.g*. juice, milk, fresh fruit and vegetables, hot drinks (low caffeine), water
- slowly consume this fluid over several hours
- combine fluid replacement with eating food.

After exercise, we need to replace fluid, electrolytes and energy stores. This is typically achieved via the normal healthy diet, and in particular a diet containing fresh fruit and vegetables. We can add to this using water supplementation. This is most effective if fluid replacement coincides with meals. After exercise, fluids need to be much more concentrated (electrolytes) than those used during exercise, particularly when involved in long, heavy and repeated work. The standard commercial sports drinks do not serve this purpose well at all (Maughan, 2003). However, you can add just a bit more table salt to the recipe below.

<u>Simple "sports drink" recipe:</u>

Start with tap water, and to each 1 litre add:

- 40-80 g of raw sugar (adjust to suit taste):
    - ***purpose:*** carbohydrate replacement
    - omit if not required (see below)
- 0.5 g of table salt (adjust to suit taste):
    - ***purpose:*** electrolyte replacement
    - omit if not required (see below)
- flavour to suit taste:

- ***purpose:*** to modify the palatability of the drink.

Serve at room temperature, since cooler drinks often quench the thirst before adequately replacing the fluid that has been lost.

Do not confuse elite athletic or emergency and survival performance with either recreational or occupational scenarios. In the first instance, the outcome is critical, and sustaining adequate hydration is often incidental (in the short term). Indeed, attempting to maintain adequate hydration can be detrimental to some athletic performance, and hydration is often neglected, or deliberately reduced by elite performers in short-term situations (imagine trying to drink 5.43 litres of fluid whilst running a marathon!). In an ideal world, one would always aim to replace precisely that which is lost, when it is being lost, but the working environment is often far from ideal, so hydration during work needs to become a realistically-managed, logistical consideration. Furthermore, most of the fluid consumed during short-term recreational exercise, particularly within gymnasiums, really serves subjective comfort needs, and is not really serving a pressing physiological requirement. However, it is recommended that the habit of drinking regularly during extended work and exercise performance be developed, so that when the physiological need is real, habitual strategies to deal with this need are already in place.

<u>What should I be drinking?</u>
The type of fluid that one should drink is largely determined by three factors:
- the duration of work
- the intensity of work
- the number of repeated work periods.

For short-duration work or exercise (less than 1 hour), dehydration is of minimal physiological consequence, and water will suffice. This can be consumed after exercise. For exercise lasting 2-3 hours, then rehydration is important, and supplementation with electrolytes and carbohydrates should also be considered. Where the need exists to repeatedly perform (*e.g*. working several consecutive days under stressful conditions), then both fluid and electrolyte/carbohydrate supplementation become significant considerations. A sound rehydration strategy should be based upon the following considerations:
- sweat is 99% water: replace sweat with 99% water
- your daily water requirement when working in the heat can be 10-18 litres
- develop and rehearse a sound fluid replacement strategy.

There are many commercial sports drinks available. These are generally developed from sound scientific research, but these are often completely unnecessary when good dietary practices are followed. Furthermore, the electrolyte concentration of these drinks is only about 50% of that which is found in sweat (Maughan, 2003). Indeed, one can quite adequately replace sports drinks with water supplements in the form of diluted fruit and vegetable juices, or homemade sports drinks (as above). These are palatable and inexpensive alternatives.

<u>Electrolyte supplementation:</u>
Sodium is the only electrolyte that needs to be considered for replacement when an adequate diet is maintained (Maughan, 2003). The daily sodium requirement when working in a hot climate is about 11-14 grams per day. Adding sodium to a drink stimulates both glucose and water uptake by the body, but it does make drinks less palatable.

However, the addition of sodium also improves the restoration of body fluid volumes following dehydration, since a smaller volume of urine is produced.

Electrolyte prescription:

- daily sodium requirement when working in a hot climate: 11-14 grams per day
- sodium is the only electrolyte that should be added to drinks
- drinking large fluid volumes, with inadequate sodium content can lead to a sodium deficiency in the blood (hyponatraemia)
- restoration of the blood volume (or the fluid portion of blood (plasma)) is better when glucose_electrolyte solutions are used, since a smaller volume of urine is produced
- to increase water uptake by the body after dehydration, you require a relatively high sodium content in the solution:
- tap water is inadequate, and results in premature suppression of thirst
- commercial sports drinks partially fulfil this role, but they also need additional sodium to optimise their effectiveness.

Carbohydrate supplementation:

Carbohydrate supplementation only needs to be considered if it has been proven that carbohydrate depletion occurs during the activity of interest. This has been established for long-duration, moderately-high intensity exercises, during which food is unable to be consumed. When glucose is added to fluid, it enhances water uptake, and it helps to prevent generalised fatigue whilst aiding recovery (Maughan, 2003).

Carbohydrate prescription:

- 4-8% (4-8 g per 100 ml of fluid)
- it enhances water uptake
- it slows liver glycogen use
- combinations of carbohydrates appear superior to glucose
- dilute solutions (1.6%) appear to be as beneficial as stronger solutions, but concentrated solutions must be avoided
- carbohydrates assist with the post-exercise restoration of muscle glycogen.

Can I drink too much water?

During long-term work/exercise (>4 hours), replacing only water, and not electrolytes, may predispose to a sodium deficiency: hyponatraemia. There are many cases of ultra-distance runners who, when following standard water replacement guidelines, drink too much water and simultaneously fail to replace electrolytes, particularly sodium. This can also occur in the workplace. The outcome is an adequately hydrated person with a sodium deficiency. Indeed, the person may actually gain weight, and this is an early indication of over-drinking. However, the symptoms are hard to distinguish from heat illness: nausea, vomiting and headaches, followed by behavioural changes, and eventually stupor, coma and possibly seizures. The following points are designed to prevent hyponatraemia during both athletic pursuits and work:

- the maintenance of an adequate hydration state is generally desirable
- however, the body can tolerate significant levels of dehydration
- drinking should never exceed weight loss during work or exercise
- when undertaking long-term exercise or work, consider adding sodium to your drinks
- rehydration following exercise or work should occur over several hours, and should be accompanied by the consumption of food.

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10.2 Appendix 2: Understanding Exertional Heat Illness

Notes on exertional heat illness

Factors that predispose to heat illness

In epidemiological analyses, one can identify factors that directly lead to, or cause, a clinical condition. These factors are called agents, and they are largely dictated by the conditions of the working environment. 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, and these are often most readily able to be modified to reduce the risk of heat illness. The agents and host factors associated with hyperthermia, and its accompanying heat illnesses, are summarised in the Figure below, with the former being of primary interest.

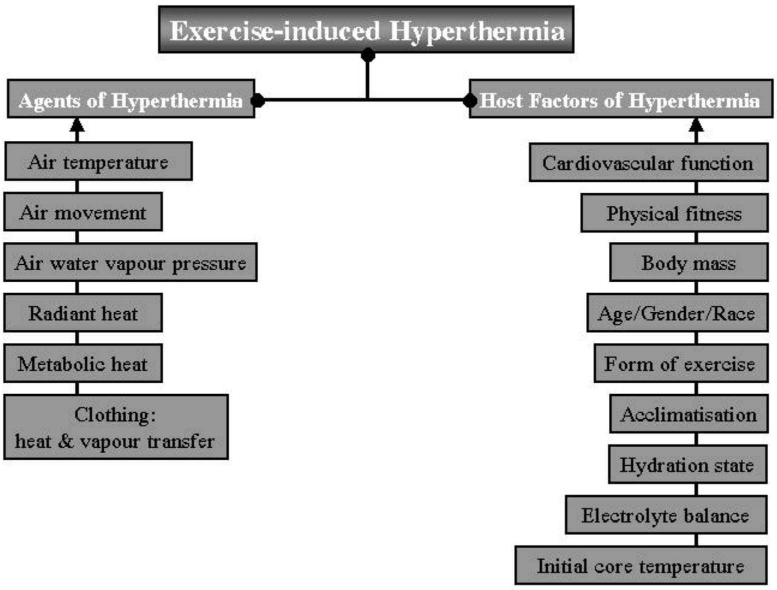

Figure: The agents and host factors of heat illness.

Air temperature heavily impacts upon some special populations, such as sedentary elderly individuals and people working in very hazardous occupations. Accordingly, it is almost universally accepted that air temperature is the dominant cause of heat illness. However, this is generally not correct for most athletic, industrial, military (excluding armoured vehicle operations) or most emergency service scenarios. Air temperature is very important[1], for we rarely see heat illness during the winter months. However, air temperature is only one of six heat illness agents, and it is frequently not the most important factor, particularly when relatively small increments in air temperature occur, such as may be expected during the normal daily summer fluctuations. The next three agents (air movement, humidity and radiant heat) can collectively or separately magnify or ameliorate the impact of air temperature.

[1] When air temperature is the primary causal agent of hyperthermia, then the associated illness is classified as ***classical*** or ***non-exertional heat illness***.

However, it is the metabolic heat production, and the impact of clothing that can precipitate heat illness in workers and athletes, even in cool conditions, and these agents are of principal interest in this project.

When working or exercising, humans convert stored chemical potential energy (carbohydrates and lipids) 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. Consequently, even at rest, humans produce heat at a rate of about 1.5 Watts per kilogram of body mass. An average sized person therefore emits about the same amount of heat as a domestic, 100-Watt light bulb. If we consider a 70-kg person (an average mass for males and females) performing 200 Watts of external work (*e.g.* cycling, running, working), this person would experience a metabolic energy conversion at the rate of ~1000 $J.s^{-1}$, with approximately 800 $J.s^{-1}$ (800 Watts) being converted into thermal energy. Unless this heat is dissipated, then heat storage at this rate will cause the average tissue temperature of the body to rise ~1^{o}C in just over 5 min. While such a rapid rise can occur in some states, such a change in body temperature is not generally observed. For instance, if a person is immersed in temperate water, heat loss can easily keep up with metabolic (endogenous) heat production. However, when faced with this heat load in hot water (40^{o}C), the body heat content will rise rapidly, and approach dangerous levels very quickly. This adiabatic state can also occur in people wearing heavy personal protective ensembles when working in the heat. This is why one need not be in the heat to suffer a heat illness. That is, one can cook from the inside to the outside, and this is known as ***exertional heat illness***.

When clothing and helmets are worn, a microclimate[2] is created close to the skin surface. The air trapped within this space is warmer, it contains more water vapour and its movement across the skin surface is limited. Thus, such protective clothing will markedly affect heat and water vapour transfer, and the stockman working in the northern Australian summer faces three thermal problems:

- extremes of environmental heat,
- intermittent and occasionally high metabolic heat production, and
- the problem of facilitating the escape of metabolically-produced heat.

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. Furthermore, the risk of exertional heat illness[3] is heightened with increments in body core temperature, and the World Health Organisation has recommended an upper core temperature limit of 38^{o}C for workers, thus implicitly limiting total metabolic heat production to approximately 325 W or less (World Health Organisation, 1969).

For a resting, unclothed person, the average skin temperature in comfortable conditions is 30-33^{o}C. When the air temperature is greater than skin temperature, heat will be gained from the environment. Exercise and clothing act to lower the (critical) air temperature at which this occurs. However, clothing impedes both heat gained from, and heat lost to the environment.

[2] The air trapped between the outer surface of the garment and the skin surface.

[3] The probability of heat stroke in hot-humid environments at various core temperatures: 38.2^{o}C 1:500 chance; 38.0^{o}C 1:1,000 chance; 37.8^{o}C 1:10,000 chance; 37.6^{o}C 1:500,000 chance (Wyndham and Heyns, 1973).

When wearing the clothing typically worn by stockmen (collared shirt with long sleeves and long trousers: insulation 0.29 $m^2K.W^{-1}$), and working at a light-moderate exercise intensity, the critical air temperature can be as much as 10°C lower than for an unclothed, resting person.

The possible impact of head wear.
The head has a mass of 4-5 kg, representing approximately 7% of the body mass. Thus, a 70-kg person would have a head mass of approximately 4.9 kg. The head also contributes about 7% of the total body surface area, and it has a surface area to mass ratio 1.6 times that of torso. This ratio favours rapid heat loss, independently of its anatomical and physiological status. However, the anatomical arrangement of the cutaneous vasculature of the head, and of the nasal and paranasal mucous membranes, provides a splendid means through which heat may be transferred from the body core to the surface tissues for dissipation, via either dry or evaporative heat transfer. Indeed, the vasomotor activity of the head is relatively stable, resulting in the tissue insulation of the head remaining fairly constant across a wide range of air temperatures (~0.059 $m^2K.W^{-1}$. As a consequence, for an adult resting in temperate conditions (23°C), the head loses heat at a rate that is more than eight times that of the rest of the body, when expressed in relative units ($W.m^{-2}$). In absolute terms, its contribution (45 W) is much less (~60% that of the rest of the body: 75 W), though nonetheless impressive, due to its much smaller surface area. During exercise (150 W at 25°C), heat loss from the head can increase about threefold (130 W). Helmets will adversely affect this heat loss and evaporation from the head. For instance, the reduction in evaporative cooling can be 25-40%, depending upon the ease with which air flows through the helmet. Thus, covering the head to protect against possible impact injuries, can result in a considerable impediment to the normal heat loss pathways, particularly in individuals who already have 80-85% of the total body surface covered with clothing, as is the case with stockmen. Indeed, for those studies that have reported minimal impact of helmets on heat loss, the subjects were not in a fully-clothed state, but wore shorts and cycling clothing. Thus, the subjects had only 50-60% of the body surface clothed. In this state, the impact of the helmet would be much less pronounced.

Notwithstanding these thermal problems, and the empirical data indicating the possibility of increased thermal strain when clothed individuals wear helmets, the Australia and New Zealand Standard (AS/NZS 3838:2006) that covers equestrian helmets does not include any consideration for helmet ventilation or heat dissipation.

Core temperatures:
From a clinical perspective, if core temperature (T_{core} varies greater than about 2°C either side of 37°C, then one assumes that either thermoregulatory failure, or a regulatory system overload, has occurred. In these states, the regulation of body temperature has been transiently compromised or lost (dysthermia: hypothermia (<35°C), or hyperthermia (>39°C)), with the possibility of death accompanying a reduction of ~10°C, or an elevation of only ~5°C.

Classifications of dysthermia:
Hyperthermia (note: fever and hyperthermia are not interchangeable terms; the former is a deliberate and natural elevation in T_{core} to combat illness, while the latter is an unavoidable consequence of thermal imbalance):

- mild: 37.2-38.5°C
- moderate (heat exhaustion): 38.5-39.5°C
- profound: >39.5°C
- profound clinical (heatstroke): >40°C
- possible death without treatment: >45°C

Hypothermia:

- mild: 36-33°C
- moderate: 33-25°C
- profound: <25°C
- possible death without rewarming: <24°C
- profound clinical: <22°C

The lowest recorded T_{core} for a survivor of accidental hypothermia is 14.4°C, observed in a woman who, while skiing, was trapped and partially submerged under a waterfall. At the other extreme, the highest recorded, survivable T_{core} (46.5°C) occurred in a man cooking inside, where alcohol-induced dehydration and poor ventilation led to hyperthermia.

Clinically-significant core temperatures:

46.5°C	highest recorded survivable core temperature
43°C	tissue damage (brain, liver)
41°C	cessation of sweating
39°C	threshold of clinically-significant hyperthermia
36.8°C	normal core temperature
35°C	threshold of clinically-significant hypothermia
33°C	impaired muscle function, introversion, loss of mental alertness
30°C	cessation of shivering and then unconsciousness
28°C	possible ventricular fibrillation
26°C	bradycardia and bradypnoea
24°C	possible death without rewarming
14.4°C	lowest recorded temperature for a survivor of accidental hypothermia.

Skin temperatures:

Skin temperatures between 39-41°C represent the threshold for transient pain, the threshold for burning pain occurs between 41-43°C, and local skin temperatures >45°C are accompanied by tissue damage. A second-degree burn would be anticipated from a contact exposure to >50°C for >4 min.

Clinically-significant skin temperatures:

>50°C	second-degree burn
>45°C	tissue damage
41-43°C	burning pain
39-41°C	pain
33-39°C	skin warmth through to discomfort (hot)
28-33°C	thermal comfort
25-28°C	cool through to discomfort (cold)
20°C	impaired physical function
15°C	pain
10°C	loss of skin sensation
5°C	non-freezing cold injury (time dependent, and can occur between 17-0.55°C)
<0.55°C	freezing cold injury (frostbite).

Recognising potentially stressful conditions:

*{**Note:** Much of the text in this section is designed for the further education of Instructors and Occupational Health and Safety Officers. An extended critique of the WBGT Index, heavily used within Australian industrial, military and emergency service settings, is also provided. For completeness, an alternative method by which to quantify the thermal environment is provided.}*

The single most important factor associated with heat illness is the elevation in T_{core}, regardless of whether it is precipitated by one, or more, of the agents or the host factors of heat illness. This can occur through exposure to external heat sources, by heavy exercise in either clothed or unclothed states, or by some combination of these two conditions. We shall soon explore heat illnesses in their various forms. Before doing so, it is important, within all occupational settings, to fully understand the hazards and risks associated with work-related tasks. In the current context, these shall be limited only to heat illnesses.

Within the occupational health and safety realm, hazards and risks do not have the same meaning, though they are often used interchangeably within the English language. A hazard represents physical, or situational, sources that pose a potential harm to individuals or work-related tasks. Such hazards may result in anatomical or physiological damage to personnel, impairing physiological function, and resulting in disabled or handicapped task performance.

Hazards may be managed via one of four methods:

- elimination of the hazard
- modification of the equipment and material that caused the hazard
- modification of the procedures that caused the hazard
- use personal protective equipment.

Risk relates to the chance (probability) of an event occurring, and it is only through the correct evaluation of the hazards and associated risks that sound and appropriate practices can be introduced to the workplace. In high-risk situations, significant hazards exist that have a high probability of occurring. The impact of hazards may easily be minimised, or removed, through risk avoidance (risk aversion). However, this leads to inactivity. Consider driving one's car to work. The hazards associated with high-speed motor vehicle accidents are well known and potentially lethal. On a daily basis, millions of Australians accept this hazard because, through safe driving practices and habits, they are able to reduce the risk such that the probability of a fatal vehicular accident is minimised, to the extent that it is deemed to be acceptable.

The hazards of excessive and repeated heat exposures are well established, but our ability to provide a universally-valid means through which to assess the risk of hyperthermia (and heat illness) has proven to be elusive. This problem was perhaps first identified more than 30 year ago, it still exists today, and it is due to the intricate interactions of a wide variety of physical and physiological phenomena that determine the probability heat illness.

Since heat illnesses are frequently caused by environmental extremes, then a number of heat stress indices have been developed in attempts to quantify the thermal environment. Many of these are valuable. However, the principal problem with these indices is that some are inappropriately used to predict physiological outcomes.

Perhaps the first thermal index developed was the effective temperature. The critical feature of this scale was that it aimed at defining thermal comfort limits for people working within air-conditioned spaces, and identifying combinations of dry-bulb temperature, air motion and relative humidity that would elicit equivalent thermal comfort.

If one assumes that thermal discomforture drives behaviour, and that the neural signals driving autonomic thermoregulation may be of a different origin, then the link between the effective temperature scale and assessing physiological risk is questionable. Consider also that these experiments were performed with subjects wearing standard office clothing, and the resultant scale was designed for use in environments close to the thermal comfort zone. Thus, extrapolation of the effective temperature index to thermally-stressful environments is also tenuous, particularly when heavy physical work is to be performed, or when people are wearing thermal protective clothing.

Nevertheless, a wide variety of effective indices have arisen directly from this scale and, due to their simplicity, these are the most widely used thermal indices. Of these, the most frequently used index for industrial, military and sporting applications is the wet-bulb globe temperature index (WBGT), developed to reduce the incidence of heat illness during military training. Indeed, 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).

$$\text{WBGT (outdoors)} = 0.7\ T_{nwb} + 0.2\ T_g + 0.1\ T_a \quad [^\circ\text{C}]$$
$$\text{WBGT (indoors)} = 0.7\ T_{nwb} + 0.3\ T_g \quad [^\circ\text{C}]$$

where:
T_{nwb} = natural wet bulb temperature[1] [°C]
T_g = black globe temperature [°C]
T_a = air temperature [°C].

Notwithstanding the almost ubiquitous adoption of the WBGT-index, these studies have identified several significant limitations of this method. First, it tends to over-emphasise the effects of dry bulb temperature towards at the top end of the scale. Second, it does not adequately consider air velocity under hot-humid conditions, and it is insensitive to this affect once air velocity exceeds 1.5 $m.s^{-1}$, yet this can have a significant impact upon heat dissipation. Third, it lacks the capacity to accommodate different rates of metabolic heat production, or variations in T_{skin} or skin wettedness. The physiological influence of air humidity, at a fixed air temperature, is elevated when metabolic rate was increased. Fourth, body mass loss (gross sweating) is not independent of climatic conditions, and it invariably diverged from the changes in T_{core} and cardiac frequency. 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 T_{core} or cardiac frequency. Fifth, the usefulness of the WBGT-index for clothed workers ranges between inferior to wholly inappropriate (e.g. encapsulation).

One can generally attribute these limitations to the fact the WBGT-index is not a rational scale. That is, it is not based upon heat balance, and the thermodynamics of those heat exchanges, but solely upon quantifying the thermal environment; its greatest strength (simplicity) has thus become its greatest limitation. Consequently, several groups have found that different combinations of air temperature, globe temperature and humidity can result in an identical WBGT, but markedly different physiological strain. In general, while one can reliably assume that conditions with a WBGT of 25°C will be less stressful than those with a WBGT of 35°C, one can also expect that physiological strain may not be equivalent for hot-dry and hot-humid conditions, when both states have an equivalent WBGT.

[1] The wick is cooled by natural, rather than forced convection, eliminating air movement as a variable.

However, since the WBGT is most frequently used to gauge the risk of heat illness, then it is important that workers understand the recommendations for work based upon this index (Table).

Table: The WBGT Index rating of thermal stress (American College of Sports Medicine, 1996).

WBGT Range (°C)	Recommendation
>28°C	Very high risk
23-28°C	High risk
18-23°C	Moderate risk
<18°C	Low risk

It is the opinion of the current author that rational heat indices provide a superior means by which to identify potentially hazardous environments. Such scales attempt to integrate the quantification of heat exchange with the resultant physiological strain. The first rational index (operative temperature) was subsequently developed: the heat strain index. This is ratio of the required evaporation to maximal attainable evaporation (E_{req}/E_{max}). From this index, several further modifications have arisen, and while these indices also have limitations[2], the principles upon which they are based are both sound and balanced.

Deriving the evaporation required:

$E_{req} = H - E_{resp} \pm R \pm C$ [W]

where:

E_{req} = required evaporative cooling [W]

H = metabolic energy transformation, or the nett result of resting and exercising metabolism and external work (*M -(±W)*) [W]

E_{resp} = evaporation accompanying ventilation [W]

R ±C = heat exchanges via radiation and convection [W].

Deriving maximal evaporation:

$E_{max} = 6.45 * A_D * i_m / I_{TOT} * 2.2 * (P_{sk} - (RH_a * P_a))$ [W]

where:

E_{max} = maximal attainable evaporative cooling for a given environment and clothing configuration [W]

A_D = body surface area (Du Bois equation) [m^2]

i_m = moisture permeability index (0.4 if unknown) [dimensionless]

I_{TOT} = total insulation (1 clo = 0.155 $m^2.K.W^{-1}$), including the trapped air boundary layer and clothing insulation [$m^2.K.W^{-1}$]

RH_a = relative humidity of the air [%]

P_a = water vapour pressure of the air [kPa]

P_{sk} = water vapour pressure at the skin surface [kPa]

6.45 and 2.2 = constants.

The risk of developing heat illness:

Very little empirical evidence is available concerning the risks of heat illness for changes in T_{core}, due to the ethical considerations of the experiments that must be performed to obtain those data.

[2] Limitations: (i) assumes T_{skin} is 35°C regardless of metabolic rate; and (ii) assumes that all derived values that are equivalent will have the same physiological impact, regardless of whether the E_{req}/E_{max} ratio is 50/100 or 300/600.

However, some evidence of relevance to workers is available from the South African mining industry, where miners work under extremely arduous conditions, with wall temperatures approaching 70°C. Retrospective analysis of 314 heatstroke cases revealed the probability of death with a T_{core} in the range 39-40°C was small, but this increased to 50% as T_{core} reached 42°C, and to 100% probability at a T_{core} of 45°C. This same group derived the following heatstroke probability statistics based upon T_{core}:

- 38.2 C was associated with 1:500 probability of developing heatstroke
- 38.0 C 1:1000 chance
- 37.8 C 1:10000 chance
- 37.6 C 1:500000 chance.

The World Health Organisation has recommended an upper limit for T_{core} in workers of 38°C (World Health Organisation, 1969).

However, from an occupational health perspective, the primary objective for evaluating the thermal environment is to determine the maximal likely physiological responses that may be elicited when working under certain conditions. It then becomes necessary to interpret these data with respect to the probability of adverse health outcomes. This is a difficult topic due to the lack of empirical evidence, and is therefore beyond the scope of this module. Nevertheless, these interpretations will be propelled by the opposing needs to maintain worker and operational capability. In the emergency services and military situations, interpretation can become very skewed, with the outcome frequently left to the discretion of the individual, and often with health being compromised.

Critical core temperatures:

37.7°C	threshold of cognitive function decrement
37.9°C	reduced manual dexterity
38.2°C	slowed cognitive function
38.5°C	judgement errors increase
38.8°C	tracking skills dramatically impaired
39.2°C	25% probability of heat exhaustion in some workers
39.5°C	50% probability of heat exhaustion in some workers
40.0°C	100% probability of heat exhaustion in some workers
42°C	50% probability of heatstroke
45°C	100% probability of heatstroke

There are two general forms of heat illness, both of which are classified according to the primary causal agent. The first is primarily attributable to an elevation in air temperature, and is known as ***classical*** or ***non-exertional heat illness***. The second is a function of metabolic heat production, which occurs at a rate that exceeds heat dissipation: ***exertional heat illness***.

Of these, the second form of heat illness is most relevant to workers, and may be brought about through one, or more, of the host factors that result in the following physiological, pathophysiological or pharmacological changes:

- very high metabolic rates
- impaired central temperature regulation
- compromised cardiovascular function
- inhibited heat dissipation (sweating or skin blood flow).

Forms of heat illness:

Heat illnesses form a continuum of pathophysiological disorders ranging from mild and transient hypotension through to frank heatstroke, with its associated cellular and tissue damage, and even death.

Heat cramps:

Heat cramps occur only in those who sweat profusely, and occurs (early) before acclimatisation has been achieved. This illness takes the form of limb or abdominal cramping and is usually associated with vigorous physical activity, heat and profuse sweating. However, the exact mechanism of this illness remains uncertain. Heat cramps occur in approximately 1% of all workers. Some clinical examples include: cane-cutter's cramp, fireman's cramp, miner's cramp and stoker's cramp. *{**Note:** These classifications are based purely upon occupation, with the aetiology being similar in all forms.}*

Heat exhaustion:

Heat exhaustion is the most common form of heat illness, and is frequently seen among the elderly. It is simply a form of fatigue, but that which is associated with the additional physiological strain accompanying protracted work in the heat (American College of Sports Medicine, 1996). As with all types of fatigue, the person affected is simply unable to continue working or exercising at the same intensity, and must either cease work (totally or temporarily) or dramatically reduce the work intensity. It may develop over several days, and it is due to an inadequate cardiovascular response to the combined metabolic and thermal loads. That is, the initial increased skin blood flow is not compensated by an increased blood volume, a reciprocal vasoconstriction elsewhere, or an adequately elevated cardiac output. These factors are exacerbated by progressive dehydration. Heat exhausted people still sweat profusely, and will generally have normal mental function, *albeit* slightly degraded.

Symptoms:

- pallor (sense of depression or gloom), headache, vomiting
- postural syncope (faintness), urge to defaecate, giddiness and loss of coordination, fatigue
- hyperventilation, rapid heart rate (tachycardia)
- profuse sweating.

Heatstroke:

The severe elevation in T_{core} (hyperpyrexia) is due to relative or absolute thermoregulatory failure. That is, the person is no longer able to regulate T_{core}, which will continue to rise unless assistance is provided. This illness must be treated as a medical emergency. The length of time for which T_{core} is elevated has a direct bearing upon the prognosis of the patient, so rapid cooling is essential.

Diagnosis:

- T_{core} 39.5-41.0^{o}C or greater
- no sweating (some consider this to be the single most important diagnostic factor, since it signifies thermoregulatory failure)
- increased breathing rate and depth (hyperpnoea)
- varying degrees of consciousness: lethargy, stupor, coma
- convulsions may occur
- elevation in blood urea nitrogen may be present (*e.g*. 20-40 mg.100 ml^{-1} is common).

Pathophysiology:

- denaturation of protein and blood coagulation
- haemorrhages of the skin
- oliguria (decreased ability to form and pass urine)
- gastrointestinal bleeding (in some severe cases)
- possible extensive muscle damage
    - ***Rhabdomyolisis*** (*rhabdos* = rod, *mys* = muscle, *lysein* = loosen): breakdown of muscle tissue, can occur in both hyperpyrexic and mildly hyperthermic people
- muscle and neural necroses (localised tissue death)
- myoglobinuria (myoglobin in urine)
- myocarditis (inflammation of myocardium).

Therapy:

- wet towels or cold bath
- constant skin rubbing to maximised skin blood flow
- oxygen therapy
- avoid excessive intravenous fluid replacement unless clinical dehydration exists: such therapy can produce pulmonary oedema
- antipyretic drugs (*e.g*. aspirin) are not effective: their action requires a functioning heat loss systems and they may also produce intestinal bleeding
- T_{core} may be unstable for several days, and may even show a secondary elevation.

Additional considerations:

Individual variability:

There exists a wide range of variation among individuals for their susceptibility to heat illness and their tolerance of marked T_{core} elevations. For instance, case reports indicate that:

- well-motivated, non-elite distance runners will routinely complete a marathon race with a T_{core} >41-42 C
- the highest recorded, survivable T_{core} is 46.5^{o}C
- deaths have been reported with T_{core} less than 40^{o}C
- cases of gross *rhabdomyolisis* and organ failure, leading to death, have been reported in people running less than 10 km in comfortable climatic conditions.

Identifying most susceptible individuals:

High risk individuals have one, or more, of the following characteristics:

- overweight
- poor physical fitness
- impaired cardiovascular function
- taking medication
- heavy alcohol or drug use
- previous heat illness
- dehydrated
- poorly acclimatised
- fatigued
- elevated T_{core}
- advanced age
- concurrent illness.

Susceptibility to reinjury:
It is generally considered that those who suffer heat illness are more likely to experience subsequent heat illnesses.

Prevention of heat illness

Heat adaptation:
Heat adaptation occurs through the gradual and repeated exposure to thermally stressful environments. This transition is dictated by the combined effects of air temperature and its water vapour pressure, exercise intensity, clothing and its permeability to water vapour, body composition, hydration status, long-term endurance fitness, and initial state of heat adaptation of the individual. During the first week of heat exposure, work and athletic performance is most affected, and the threat of heat illness is the greatest. When air temperature approaches T_{skin}, and when solar loads are high, the possibility for dry heat loss is negated, forcing an almost total reliance upon evaporative cooling. Given time to adjust, the body will undergo a three-phase adaptation process, resulting in superior heat tolerance.

A wide range of heat adaptation (acclimation) techniques are available, and these may be grouped into three general categories:

Passive heat acclimation: External heat is applied to the resting body to elevate and hold a thermal load necessary to induce adaptation (*e.g.* water baths, saunas and climate chambers).
Exercise-induced heat adaptation: Endurance exercise (with or without heat) will elevate deep tissue temperatures and, if performed regularly, heat adaptation will ensue.
Combined exercise and heat stress adaptation: Conventional heat adaptation regimens involve moderate-to-heavy intensity exercise (*e.g.* walking, running, cycling, bench stepping) within a temperature- and humidity-controlled chamber. Such methods may be grouped into three general categories, that differ according to how the exercise load is applied. These are forms of artificial adaptation or heat acclimation.

From the vast body of research evidence on human heat adaptation, the following generalisations appear to be justified. First, passive acclimation is not as effective as methods incorporating exercise stress. Second, exercise-induced heat adaptation without a significant thermal load is inferior to the more traditional heat acclimation methods, it is an inadequate substitute for heat acclimation, and the elevation of cutaneous tissue temperatures appears to be a necessary stimulus for more complete heat adaptation. Nevertheless, exercise under temperate conditions can induce heat adaptation, but this depends upon the capacity to elevate and hold body temperatures for an extended time, and it appears to provide thermal protection for only relatively short-term heat exposures. Third, humid-heat acclimation produces a greater sweating adaptation than does dry-heat acclimation, while adaptation to repeated dry exposures do not provide optimal protection for subsequent humid-heat stress. Fourth, the manner in which the work load is applied during exercise-heat acclimation will dictate the nature of the adaptation produced, and it appears that the controlled-hyperthermia model will induce a more complete and sustained heat adaptation than either the constant or the self-regulated work rate techniques.

Notwithstanding differences in heat adaptation methods, one typically observes an enhancement of sweat gland function, and this boosts our most effective means of heat dissipation in hot environments. Specifically, there is an increased steady state-sweat rate, heightened sweat gland sensitivity to increments in T_{core}, a reduced temperature threshold for sweating onset, and a more effective reabsorption of sodium and chloride within the sweat duct, leading to better conservation of the body's electrolyte content and fluid volume.

Controlling hydration state: prior, during and after exercise:
See Appendix 1.

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