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Occupational heat stress in Australian workplaces

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ABSTRACT

The aim of this review was to summarize the current state of knowledge on heat stress risk within typical Australian occupational settings. We assessed identified occupations (mining, agriculture, construction, emergency services) for heat production and heat loss potential, and resultant levels of physiological heat strain. A total of 29 reports were identified that assessed in-situ work settings in Northern Territory, South Australia, Western Australia, Queensland, New South Wales and Victoria, that measured physiological responses and characterized the thermal environment. Despite workers across all industries being regularly exposed to high ambient temperatures (32–42°C) often coupled with high absolute humidity (max: 33 hPa), physiological strain is generally low in terms of core temperature (<38°C) and dehydration (<1 % reduction in mass) by virtue of the low energy demands of many tasks, and self-regulated pacing of work possible in most jobs. Heat stress risk is higher in specific jobs in agriculture (e.g. sheep shearing), deep underground mining, and emergency services (e.g., search/rescue and bushfire fighting). Heat strain was greatest in military-related activities, particularly externally-paced marching with carried loads which resulted in core temperatures often exceeding 39.5°C despite being carried out in cooler environments. The principal driver of core temperature elevations in most jobs is the rate of metabolic heat production. A standardized approach to evaluating the risk of occupational heat strain in Australian workplaces is recommended defining the individual parameters that alter human heat balance. Future research should also more closely examine female workers and occupational activities within the forestry and agriculture/horticulture sector.

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Introduction

Australia, the great "sunburnt country" immortalised by Dorothea Mackellar's iconic poem *My Country*,[1] is an island continent stretching from its most northerly point in the tropics (Cape York, Queensland: 10 41S) to its most southerly point in the Southern Ocean (South East Cape, Tasmania: 43 39S). It embraces a wide range of climates, from the hot humid tropics in the northern parts of Queensland and Western Australia as well as the *Top End* of the Northern Territory, through the hot and arid/semi-arid central deserts of the *Outback*, to the temperate coastal fringes of Western Australia, South Australia, Victoria, New South Wales and Tasmania (Fig. 1). While the majority (66% in 2015) of the Australian population resides in major cities located in these latter regions (e.g. Sydney, Melbourne, Adelaide, Perth, Hobart) they can be dramatically affected by sudden changes in wind direction leading to heat wave conditions that can last for a week or longer.[2] For example, the *Angry Summer* of 2012–13 led to record or near-record temperatures in Sydney (45.8°C), Adelaide (45.0°C), Canberra (42.0°C) and Hobart (41.8°C).[2]

While the service sector dominates the Australian economy and is primarily based in the major cities, more than one-quarter of Australia's gross domestic product is represented by the mining, agriculture and construction industries whose activities principally take place in the hotter (and sometimes more humid) regions of the country. As high levels of physical exertion are also often required to perform jobs in these industries, the insidious effects of heat stress on

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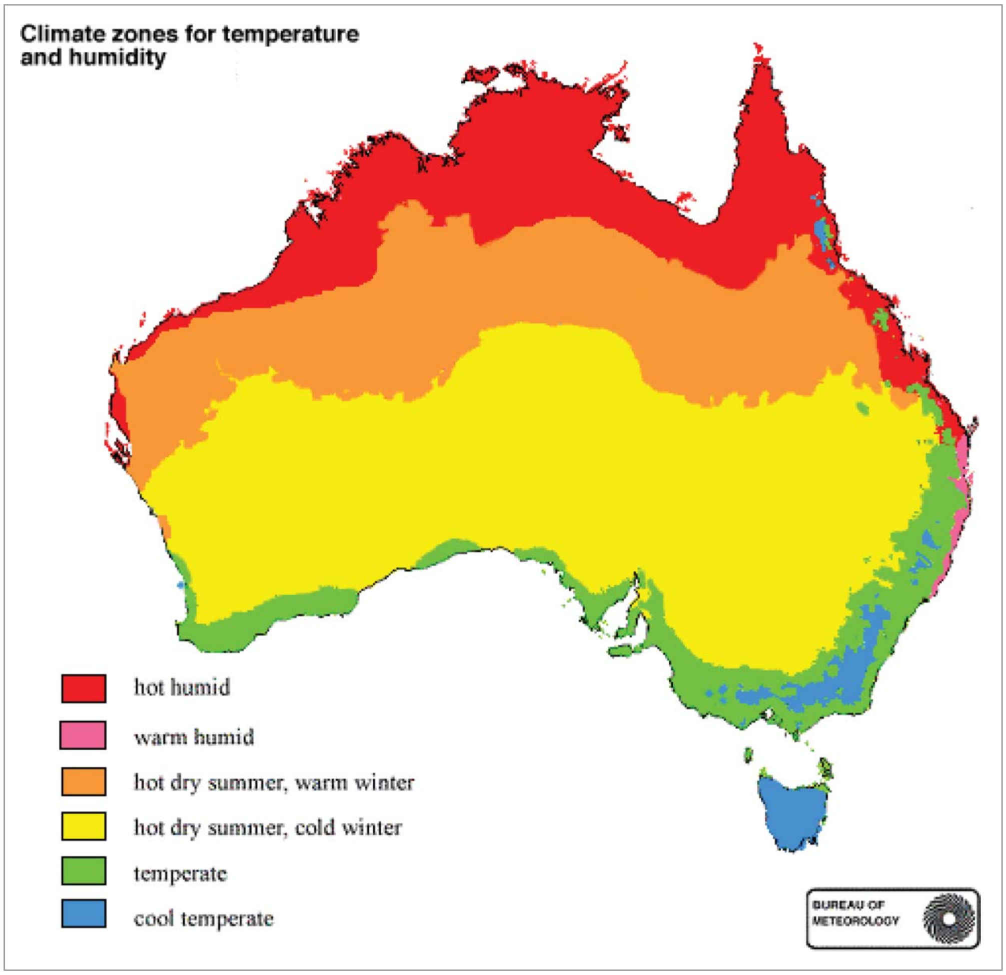

Figure 1. Climate zones of Australia. Courtesy of Australian Bureau of Meteorology.

worker health is a persistent concern.[3,4] Other Australian occupations that lead to potentially excessive levels of heat stress include those in the military and emergency services (e.g., firefighters), who must tolerate both exogenous and endogenous sources of heat when performing high intensity physical tasks while wearing protective clothing – often coupled with exposure to high ambient temperatures.[5,6] However the extent to which heat stress risk differs across these Australian occupations that employ about 1.7 million people, and therefore how worker health should be managed, is presently unclear.

To fully appreciate the level of heat strain and associated likelihood of heat-related illnesses in these occupations, one must first consider the individual parameters that determine the magnitude of core temperature rise within a given worker. Ultimately elevations in internal body temperature occur due to an imbalance between metabolic heat production (H_{prod}) and the rate at which heat can be dissipated from the skin surface to the surrounding environment (H_{loss}).[7] The greater and more prolonged this imbalance for a person, the greater their change in body temperature.[7] H_{prod} is chiefly governed by the rate of oxygen consumption and the mechanical efficiency of the task at hand;[8] whereas H_{loss} for a fixed sweat rate and level of cutaneous vasodilation, is determined by 4 climatic characteristics, namely, air temperature (T_a), mean radiant temperature (T_r), air velocity across the skin (v) and ambient humidity (P_a).[9] For a given skin temperature, the prevailing T_r and T_a define the rate of dry heat exchange via radiation and convection respectively, with the latter augmented by increases in v. Evaporative heat loss, which accounts for nearly all heat dissipation at a T_a and T_r above skin temperature (~35°C),[10] is limited by P_a, and is again modified by v.[11,12] Finally, for a particular H_{prod} under a fixed set of environmental conditions H_{loss} can be profoundly altered by clothing, especially garments that exert a high evaporative resistance.[13]

The aim of this review paper is to summarize the current state of knowledge on heat stress risk within the Australian mining, agriculture and construction industries, as well as military and emergency services. Specifically, we will assess the identified occupations in terms of the primary contributors to H_{prod} and H_{loss}, i.e. activity levels associated with these jobs, environmental conditions of the setting in which these jobs typically take place, and the clothing worn. We will also assess the levels of subjective and physiological heat strain, i.e., core temperature elevation and sweat losses, previously measured in these occupations.

Literature search

The existing published literature (in English) listed in PubMed was assessed using the following search terms: "Australia", "heat stress", "work" or "occupational", and "temperature" or "core temperature" or "sweating". Together these searches yielded 89 published journal articles. In addition, individual enquiries were made with prominent Australian occupational heat stress researchers to identify the existence of commissioned research reports not present in the published literature. To be included in our final analysis, papers had to fulfill the following selection criteria: 1) Studies performed in an in situ Australian work setting; 2) Occupational activities only (sport-related studies excluded); 3) Original research article, peer-reviewed conference paper or commissioned report (review papers excluded); 4) Thermal environment was measured (T_a or Wet Bulb Globe Temperature (WBGT) at a minimum); 5) Core temperature or sweating responses were measured.

Upon completing this assessment a total of 19 published journal articles or conference papers, 5 commissioned research reports, and 1 commissioned research book (containing 5 relevant chapters) were identified with no duplicate studies/data sets identified. Research articles/reports/chapters were stratified according to occupational sector (Agriculture; Construction; Emergency services; Military; Mining; Other) and are summarized in Table 1.

Work, job and subject characteristics

In total 28 separate jobs/tasks were identified: Agriculture (2); Construction (3); Defense (8); Emergency services (4); Maintenance (4); Mining (5); Other (2) (Table 1). The most participants tested was in studies examining defense-related activities (total n = 338). Studies of mining activities have also examined a relatively large number of participants (n = 182), and while only 2 articles/reports were found for agricultural activities, thermal responses in sheep shearers are particularly well characterized (n = 43).[14]

In terms of the Australian State/Region, the greatest number of reports was for studies conducted in the Northern Territory (9), while South Australia (6), Western Australia (5 + 1 "Northwestern Australia," assumed to be WA), and Queensland (5) were also well represented. On the other hand, there was a paucity of data collected in New South Wales (2) and Victoria (1), and no studies have been carried out in the Australian Capital Territory or Tasmania.

Participants in the included studies were almost exclusively male with only 3 studies[5,15,16] including any females: in one study (surface mine blast crew[16]) 1 of 15 participants was female; in another study (medical emergency response team[15]) 4 of 10 participants were female. The majority of participants were in their 20s, 30s or 40s, with mean ages typically ~35 y. The oldest participant in any study was 64 y (carpentry[17]) and the youngest was 18 y (sheep shearing[14]).

Occupational metabolic heat production (H_{prod})

The most precise method for assessing rates of metabolic heat production (H_{prod}) among different occupations is indirect calorimetry whereby rates of oxygen consumption and carbon dioxide production are measured and used alongside caloric equivalents for the oxidation of carbohydrates and fats to estimate energy expenditure.[18] By definition H_{prod} is determined by subtracting any external work done from energy expenditure. Due to the inefficient nature of the human body the proportion of external work done relative to energy expenditure (mechanical efficiency) is very low, ranging from a maximum of ~20–25% to 0%. Indeed, all energy spent when walking or running on a flat surface ultimately appears as heat released in the body[19,20]; as such, for occupations predominantly involving these types of activities, net external work can be considered to be zero. Mechanical efficiency of workers is sometimes estimated to be ~20% however this probably leads to an underestimation of H_{prod} in most cases. In total, estimations of H_{prod} were found for 13 of the 29 studies in the present review

Table 1. Workplace activities and subjects.

Industry/Activity	Ref	State or Region	n	Sex	Age, y	Body mass, kg
Agriculture						
Sheep shearing	14,74	SA, NSW	43	M	(18–59)	75.6 (10.9)
Horse back Mustering	75	NT	14	M	21.5	74.1
Construction						
Carpenters	17	Port Pirie SA	4	M	(21–64)	—
Laying and tying steel reinforcing	76	WA	24	M	—	—
Mine construction	77	Coastal Pilbara WA	12	M	—	—
Defense						
5 km march, load 40 kg	78	Singleton NSW	78	M	26.4 (3.6)	83 (8.2)
10 km, 5.5 kh^{-1}, load 42 kg	66	—	37	M	—	81.2 (9.9)
5 km, load 20 kg, 55 min	79	Townsville QLD	51	M	—	79.8 (10.5)
20 km, load 35 kg, 4.0 h	79	Townsville QLD	18	M	—	79.8 (10.5)
15 km march (August)	5	NT	23	—	—	
15 km march (November)		″	49	—	—	
Patrol & Recon, load 30 kg	21	NT	14	M	22 (3)	76 (11)
Tank crews	80	NT				
Exterior (June)		″	27	—	—	—
Interior (June)		″	″	—	—	—
Exterior (September)		″	9	—	—	—
Interior (September)		″	″	—	—	—
Jungle Patrol	81	Tully N.QLD	32	M	24.8 (5.6)	78.0 (8.6)
No body armour, load 21 kg		″	″	″	″	″
With body armour, load 29 kg		″	″	″	″	″
Emergency services						
Medical emergency resp team	15	Yarrawonga NT	10	4M, 6F	38.4 (8.5)	68.8 (13.4)
Search and Rescue	67	NT				
Heat acclimatised		″	8	M	37.9 (4.7)	86.2 (5.1)
Non-heat acclimatised		″	8	M	41.3 (6.6)	95.7 (11.9)
Prescribed burns	82	SA	10	M	29 (11)	83.8 (15.8)
Day 1		″	″	″	″	″
Day 2		″	″	″	″	″
Bush fire, fireline constr.	22-25	WA, Victoria	27	M	26 (6.8)	71.7 (10.5)
With fire (F)		″	″	″	″	″
Without fire (NF)		″	″	″	″	″
Maintenance						
Power station maintenance	70	NT	9	M	31 (10)	81 (11)
Council workers	83	Tropical N.QLD	15	M	38.5 (10.5)	83.6 (12.2)
Railway track maintenance	30	Nullarbor Plain SA				
Day 1		″	4	M	(19—37)	—
Day 2		″	″	″	″	—
Day 3		″	5	M	—	—
Electrical utility	71	NT North	13	M	34.6 (11.2)	91.4 (15.5)
		NT South	7	M	25.6 (2.4)	76.2 (6.3)
Mining						
Open cut mine processing	84	NW Australia	31	M	34.4 (10.3)	91.8 (13.9)
Shipping/processing port		″	46	M	35.2 (11.5)	82.3 (17.8)
Surface mine. Blast crew	16	Coppabella QLD	15	14M, 1F	36.7 (9.7)	100.9 (14.3)
Deep mine. 1200—1600 m	85	Mt Isa QLD	31	M	35.4 (7.6)	88.8 (14.0)
Machinery operators	77	Coastal Pilbara WA	11	M	—	—
Various		Inland Pilbara WA	10	M	—	—
light manual work A	76	WA	15	M	—	—
light manual work B		″	23	M	—	—
Others						
Zinc cathode strip	26	Port Pirie SA	7	M	(25–45)	—
Lead/zinc process operators	73	Port Pirie SA	5	M	(25–44)	—

In all Tables ″ denotes same as above; - denotes data not available. Data in parentheses are SD (single number) or range (2 numbers).

(Table 2). The occupational sector with most estimated H_{prod} values was the military with 6 of 8 studies. On the other hand, no captured studies in the Australian mining sector reported measured or estimated H_{prod} values.

Of the 6 occupational sectors represented in this review, studies on military-related activities reported the greatest rates of H_{prod}, with peak values as high as 870 W observed.[21] Particularly noteworthy is that heat production of 500–770 W was sustained (intermittently)

Table 2. Work duration and intensity.

Industry/Activity	Duration, min	H_{prod}, W	HR, bpm
Agriculture			
Sheep shearing	600	390–410	—
Horse back Mustering	≈300	363	—
Construction			
Carpenters	420	159–244	93 (78–115)[#]
Laying and tying steel reinforcing	—	—	104 (12)
Mine construction	—	—	—
Defense			
5 km march, load 40 kg	51	760	—
10 km, 5.5 kh^{-1}, load 42 kg	110	600	166 (157–178)
5 km, load 20 kg, 55 min	48 (4.4)	570	—
20 km, load 35 kg, 4.0 h	236	590	—
15 km march (August)	165	600	150 (14)
15 km march (November)	165	600	155 (12)
Patrol & Recon, load 30 kg	600–720	700–870	120–160
Tank crews		—	—
Exterior (June)	3660 (61 h)	—	—
Interior (June)	"	—	—
Exterior (September)	3600	—	<100
Interior (September)	"	—	<100
Jungle Patrol			
No body armour, load 21 kg	300	—	99 (12)
With body armour, load 29 kg	284	—	98 (7)
Emergency services			
Medical emergency resp team	150	—	100–120
Search and Rescue	240	—	
Heat acclimatised	"	—	141 (17)
Non-heat acclimatised	"	—	136 (17)
Prescribed burns	720	—	—
Day 1	"	—	—
Day 2	"	—	—
Bush fire, fireline constr.			
With fire (F)	87 (42)	406–519	157
Without fire (NF)	157 (36)	493–630	149
Maintenance			
Power station maintenance	420	—	96 (14)
Council workers	360	115–595	90 (28)
Railway track maintenance		192–312	
Day 1	570	"	106 (97–121)[#]
Day 2	570	"	96 (84 –117)[#]
Day 3	450	"	97 (89–107)[#]
Electrical utility		—	
(NT North)	480–720	—	104 (14)
(NT South)	480–720	—	104 (14)
Mining			—
Open cut mine processing	720	—	—
Shipping/processing port	720	—	86 (15)
Surface mine. Blast crew	720	—	120 (20)
Deep mine. 1200—1600 m	450–600	—	—
Machinery operators	—	—	—
Various	—	—	
Light manual work A	—	—	88 (7)
Light manual work B	—	—	90 (10)
Others			
Zinc cathode strip	180–360	442	115 (106–122)[#]
Lead/zinc process operators	420	194–269	87 (73–103)[#]

[#]Indicates P60: heart rate measured 60 seconds after pause in activity.

for 5–6 h. Other military activities typically involved high rates of H_{prod} (~600–750 W) sustained for relatively short periods of time (~1–3 h). The lowest value (570 W) in military studies captured in the present analysis was actually greater than the highest H_{prod} values reported in all other occupations, with the exception of bushfire fighting which reported values as high as 630 W.[22-25] Zinc cathode stripping[26] and sheep shearing[12] also elicited moderate H_{prod} values (~400–450 W) for prolonged periods (6–10 h).

For occupations with few studies reporting H_{prod} values (i.e. mining and emergency services), a level of comparison of metabolic rates can be made using heart rate values, particularly if there is no systematic difference in aerobic fitness between participants. While this characteristic is not reported for most of the captured studies, the age range of workers were similar (Table 1) and therefore theoretical maximum HR (age-predicted) should also be similar.

Furthermore, for studies within other sectors that did report both H_{prod} and HR data, we found a good correlation ($r = 0.87$). It follows that a greater H_{prod} was presumably associated with medical response and search and rescue activities (HR: ~120–140 bpm) compared to a surface mine blast crew, deep mining activities, and light mining work (~90–120 bpm). When comparing HR values across all jobs/sectors (including those with parallel indirect calorimetry data) it is clear that military- and emergency services-related activities elicit higher work intensities (and therefore H_{prod}), whereas occupations associated with maintenance, mining, lead refinery, construction, and to a lesser extent agriculture generally resulted in lower work intensities (Table 2).

Potential for heat dissipation (H_{loss})

Physiological responses, such as sweating and alterations in skin blood flow, obviously modulate heat dissipation from the skin surface to the surrounding environment. However for the sake of comparison between occupations in the present review it is assumed that there are no differences in sweating and skin blood flow responses between workers. That is, all workers can attain a fully wet skin and maintain central blood pressure during maximal vasodilation. This assumption may be limited by circumstances where the workforce for a particular occupation is generally older, as age-related decrements in physiological heat loss responses are known to occur as early as 40 y,[27] and are particularly pronounced above the age of 60 y.[28] However, the literature captured in the present review did not report substantially different worker ages between occupations (Table 1). As such, differences in the potential for H_{loss} primarily would be mediated by differences in environmental conditions (i.e., air temperature (T_a), mean radiant

Table 3. Environmental Conditions.

Industry/Activity	T_a, °C	RH, %	P_a, HPa	T_g, °C	T_r, °C	v, ms^{-1}	WBGT, °C	Clothing, clo
Agriculture								
Sheep shearing	33.4 (19.0–41.0)	26*	13.2 (9.2–19.1)	—	37 (20–45)	0.64 (<0.2–1.7)	24.3 (15.9–29.0)	—
Horse back Mustering	36	—	—	Sunny	Sunny	—	—	—
Construction								
Carpenters	32.1 (24.0–38.0)	(17–36)	12	—	(35–58)	(<0.2–1.2)	25 (19–30)	(0.4–0.7)
Laying and tying steel reinforcing	37	55	34	43	—	2.7	32	—
Mine construction	37.7 (37.4–38.0)	50 (48–54)	33 (31–35)	—	—	1.5 (0.9–2.3)	32 (31–32)	—
Defense								
5 km march, load 40 kg	—	—	—	—	—	—	(24–25)	—
10 km, 5.5 k·h^{-1}, load 42 kg	24.2 (1.6)	82	24.8	27.3 (5.4)	—	—	23 (21–26)	1.37
5 km, load 20 kg, 55 min	—	—	—	—	—	—	27.6	—
20 km, load 35 kg, 4.0 h	—	—	—	—	—	—	27.1	—
15 km march (August)	23 (25–16)	—	—	—	—	—	19 (17–21)	—
15 km march (November)	29 (27—31)	75 (59—90)	29 (27—31)	—	—	—	26 (25–28)	—
Patrol & Recon, load 30 kg	32	48	42	(37—44)	—	—	(26–28)	—
Tank crews								
Exterior (June)	31.6 (0.7)	22 (4)	10	—	—	—	28.4 (1.5)	—
Interior (June)	38.3 (1.3)	—	—	—	—	—	29.2 (1.8)	—
Exterior (September)	36.6 (0.5)	26 (1)	16	—	—	—	33.4 (0.8)	—
Interior (September)	40.1 (1.8)	—	—	—	—	—	32.9 (0.8)	—
Jungle Patrol								
No body armour, load 21 kg	27 (21–31)	63 (39–97)	23 (17–24)	—	—	—	—	—
With body armour, load 29 kg	"	"	"	—	—	—	—	—
Emergency services								
Medical emergency resp team	29.3	50	20	Shade	Shade	Breeze	—	—
Search and Rescue								
Heat acclimatized	34.0 (0.7)	48 (2)	25	—	—	—	31.4 (0.5)	PPE
Non-heat acclimatized	"	"	"	—	—	—	"	—
Prescribed burns								
Day 1	31 (4)	—	—	—	—	—	—	—
Day 2	33 (6)	—	—	—	—	—	—	—
Bush fire, fireline constr.								
With fire (F)	29 (19–35)	42*	17 (12–23)	—	66 (33–96)	1.2 (0.7–1.7)	26 (17–34)	—
Without fire (NF)	26 (17–33)	4*	16 (12–20)	—	42 (30–53)	0.8 (0.6–1.0)	22 (15–28)	—
Maintenance								
Power station maintenance	30 (1)	79 (6)	33	—	—	—	28 (26–29)	—
Council workers	30 (27–31)	70 (67–79)	30	—	—	—	26 (25–27)	(0.64–0.74)
Railway track maintenance								
Day 1	34 (22–41)	15 (11–23)	7.9 (6.1–9.9)	—	57 (38–70)	2.0 (0.2–3.7)	24 (15–28)	0.5 (0.2–0.9)
Day 2	Max: 31	78–31	28	—	—	3.4	17–24	"
Day 3	Max: 37	13–25	6	—	—	3.8	13–25	"
Electrical utility								
(NT North)	33.7	54	28.2*	—	—	—	32	—
(NT South)	39.3	9	6.4*	—	—	—	28.7	—
Mining								
Open cut mine processing	35.1	30	17	—	—	—	31 (2)	—
Shipping/processing port	31.5	50	23	—	—	—	31 (4)	—
Surface mine. Blast crew	35.5 (1.3)	24 (6)	16 (14—20)	—	—	—	29.5 (1.9)	—
Deep mine. 1200—1600 m	36.2 (2.6)	56	33	36.3 (2.8)	—	1.1 (1.6)	30.8 (2.0)	—
Machinery operators	33.2 (32.3–33.8)	57 (54–58)	29 (28–30)	—	—	4.5 (4.2–4.9)	29 (28–29)	—
Various	39 (35–42)	21 (15–28)	14 (12–15)	—	—	1.0 (0.7–1.6)	27 (26–28)	—
Light manual work A	35 (2)	59 (6)	33	38.7 (3.6)	—	4.1 (1.8)	30.6 (2.2)	—
Light manual work B	37.6 (3.0)	32 (8)	21	43.5 (5.2)	—	1.8 (1.2)	29 (2)	—
Others								
Zinc cathode strip	33 (25–39)	30	14.5 (12.5–16.9)	—	37 (32–41)	1.5 (0.4–2.4)	25 (22–28)	0.8
Lead/zinc process operators	34 (26–37)	(21–35)	13	—	52 (38—65)	0.4 (0.2–0.7)	(27–30)	(0.8–0.9)

Asterisk * indicates RH derived by present authors from T_a and P_a, or P_a from T_a and RH.

temperature (T_r), ambient humidity (P_a), and air velocity (v)), as well as clothing properties (Table 3).

Convective heat loss from the skin surface to the surrounding environment is determined by the skin temperature-to-air temperature gradient, and air velocity. In a heat stress situation cutaneous vasodilation will typically elevate skin temperature to ~35°C. Therefore as T_a approaches this value convective heat loss will become progressively smaller and eventually eliminated and then reversed to dry heat gain as it exceeds skin temperature. Thus thermoregulation becomes increasingly dependent on sweat evaporation. Studies captured in our review generally examined occupational activities in warm-to-hot (>30°C) environments. Sheep shearing for example took place at air temperatures as high as 41°C, while construction, agriculture, maintenance, and mining work was carried out at T_a values between ~30–38°C. The level of convective heat exchange within this temperature range would be minimal, even with the relatively high air velocities reported in some studies. For example, the T_a of ~38°C reported during mine construction would have resulted in a ~3°C negative gradient between the air and skin, however in terms of convective heat gain this would have equated to only ~30 Wm^{-2} even with an air velocity of 1.5 ms^{-1}. The only occupations that were assessed in relatively cooler (~24–29°C) environments, and therefore conditions under which any meaningful convective heat loss would have occurred, were military- and some emergency-related activities.

Dry heat exchange also arises via radiation and is determined by the temperature differences between the skin and T_r. Indeed, heat gain through this avenue can be substantial in environments containing a significant radiant heat source. Examples captured in the present review include bushfire fighting (T_r: up to 96°C), railway track maintenance during summer in Southern Australia (T_r: up to 70°C) (Fig. 2), and lead/zinc refinery process operators (T_r: up to 65°C). Values for T_r were sparse within the literature however, presumably due to the prevalent use of the Wet Bulb Globe Temperature (WBGT) index, with only 6 of 29 studies reporting values.

The prevailing environmental conditions in most of the occupational environments assessed would have resulted in little to no dry heat loss, and in some cases substantial dry heat gain via radiation. As such, the evaporation of sweat would have essentially been the only avenue for heat dissipation in nearly all cases. Despite relative humidity being reported most often in the literature, evaporation from the skin is determined by the absolute humidity gradient between skin (altered by the secretion of sweat) and the ambient environment. In a fully vasodilated state in heat stress conditions, skin temperature can be assumed to be ~35°C, and therefore saturated water vapor pressure would be ~56 hPa. In comparison, the highest absolute humidities reported in the studies captured in our review were during patrol and reconnaissance military activities (42 hPa), mine construction (31–35 hPa) and mining machine operation (28–30 hPa). However the extent to which evaporative heat loss would have been compromised by this high humidity would have been limited on account of the high ambient air velocities (1.5–4.5 ms^{-1}) concurrently reported which would have accentuated the convective component of evaporation.[29]

Wet Bulb Globe Temperature (WBGT) – a weighted mean of air temperature, black globe temperature and natural wet bulb temperature - typically measured using a single self-contained unit, was the most commonly reported (25 of 27 studies) environmental measurement. The highest WBGT values were reported for military tank activities in September in the Northern Territory (33.4°C) and mine construction activities (32°C) in coastal Western Australia. Whereas the lowest WBGT values reported were outdoor military activities in winter (August) in the Northern Territory (17–21°C) and inside a sheep-shearing shed in NSW during the early morning (15.9°C).

Other than some military activities, the majority of jobs examined take place across a typical working day constituting of 9.5 to 12 hours. Naturally environmental conditions and therefore the potential for heat loss fluctuate greatly throughout the workday. An example of how the within-day variation of environmental conditions can be different even in the same State (South Australia) is illustrated in Figure 2 for outdoor railway maintenance work and inside a sheep-shearing shed.[14,30] Predictably ambient temperature increases as the working day progresses with peak values attained between 14:00 and 16:00 in all examples. On the other hand, radiant temperature reaches a peak closer to 12:00; however these peak values are markedly different depending on whether the work activity takes place indoors (shearing shed: ~45°C) or

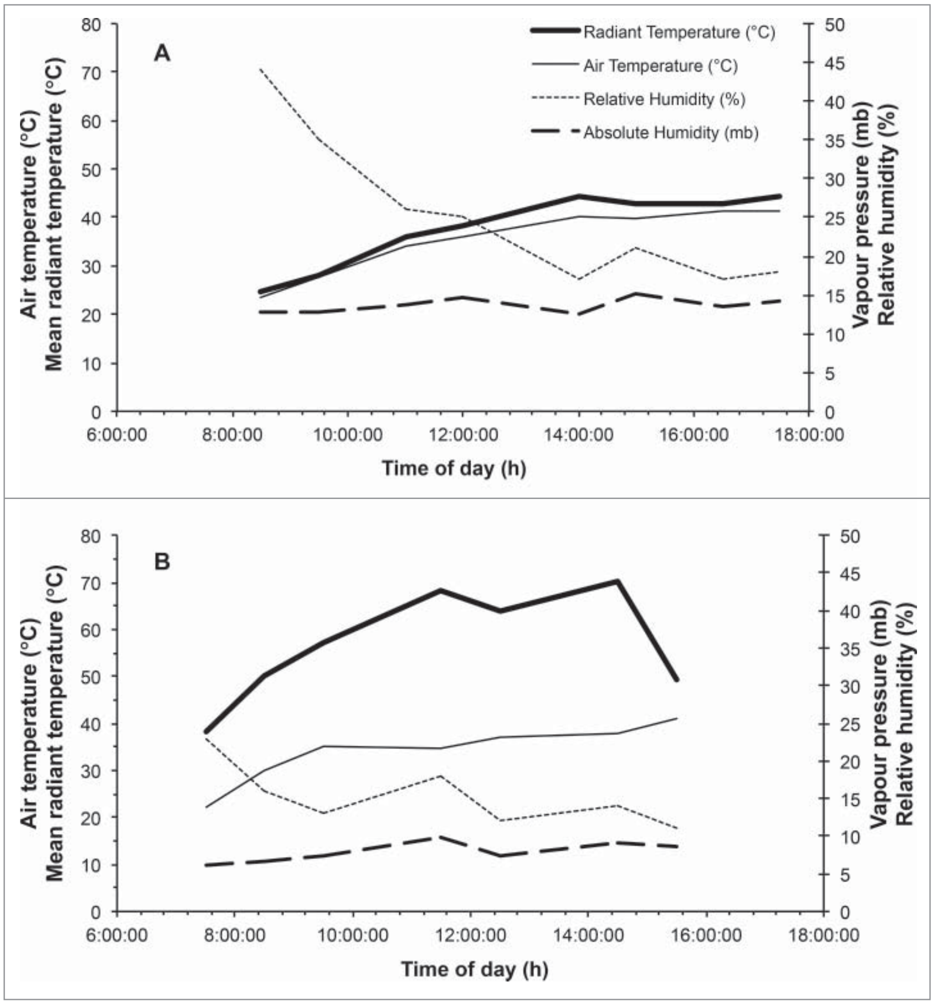

Figure 2. Variation in the thermal environment across working days in summer for a sheep shearing shed in South Australia,[12] (Panel A), and for railway track work on the Nullarbor Plain in South Australia (Panel B).[27]

outdoors (railway maintenance: ~70°C). Such observations demonstrate the importance of accounting for radiant heat sources when evaluating the potential risk of heat strain in a given work environment, as typically meteorological data report ambient air temperature in the shade only. From an evaporative heat loss perspective, it is also essential to recognize that absolute (and not relative) humidity principally determines the evaporative capacity of an environment. Relative humidity typically declines throughout a working day, as it is inversely proportional to ambient temperature. Yet, absolute humidity (and therefore the evaporative drive) often remains near constant.

Physiological heat strain

Physiological strain in the heat can be expressed in terms of the magnitude of core temperature elevation, the volume of sweat lost (and the subsequent degree of dehydration if fluids are not fully replaced), and to a lesser extent the elevation in mean skin temperature. From a work productivity perspective, the subjective assessment of the environment through perceptions of thermal comfort or sensation is also important.

Core temperature

Elevations in core temperature during work in the heat are ultimately a consequence of the cumulative imbalance between internal heat production and heat dissipation to the environment. Apart from Gun's investigations[14,17,26,30,73] and Project Aquarius 24 in which rectal temperature was measured in other reports T_{core} was measured using temperature sensitive radio pills. For the studies captured in the present review the highest peak core temperatures were observed in i) military-related activities, especially fixed speed marching with additional carrying loads (39.5–41.2°C) in Far North Queensland, NSW and NT; ii) heat acclimatized search and rescue workers (39.6°C) in NT; iii) bush fire fighters (39.6°C); and iv) deep underground miners in Queensland (39.5°C). Strikingly, the highest levels of physiological thermal strain (military activities and bush fire fighters) were observed despite the coolest reported ambient conditions (all <30°C), but alongside the highest reported rates of metabolic heat production. No published metabolic heat production data were available for deep underground miners or search and rescue workers however these activities were performed under hotter and more humid conditions, and in the case of search and rescue workers with substantial barriers to evaporation due to the protective clothing worn. On the other hand, no other occupations yielded a peak core temperature of greater than 38.5°C – with the exception of zinc refinery workers (Table 4). Indeed, despite high ambient and radiant temperatures in the mining, agricultural and construction sectors, in most cases core temperatures remained below 38.0°C, whereby the risk of any heat-related illness or injury is essentially zero in healthy adults.[31] Taken together these observations as illustrated in Figure 3 demonstrate the importance of internal heat production in determining the core temperature response of a worker, somewhat independently of the ambient environment. For example, electrical utility work in the Northern Territory under hot/humid (33.7°C, 54%RH) and hot/dry (39.3°C, 9%RH) conditions, and railway track maintenance in South Australia at air temperature as high as 41°C yielded mean core temperatures of 37.5°C, 37.5°C, and 37.7°C respectively. Similarly, in shearers and bushfire fighters mean core temperatures of 37.7°C and 38.2°C respectively were largely independent of the thermal environment in air temperatures ranging ~19°C to ~35°C.[12,32,74] Whereas, a 15 km military training march at an air temperature of ~23°C led to a mean core temperature 38.3°C. While heat production was only estimated in the latter study, presumably it must have been much lower for activities resulting in lower core temperatures despite far hotter environments.

Ultimately, 3 main factors influence occupational metabolic heat production: the nature of the activity, behavior, and external pacing. In the first case in jobs that are performed sitting or standing with light upper body work, such as in maintenance and some construction jobs, H_{prod} is limited to easily tolerated levels not exceeding 300 W.[9] Other jobs such as sheep shearing require slightly higher H_{prod} values (~400 W) however these are also limited by the majority of work being performed by one arm.[14] In the second case in jobs that involve free ranging self-paced repetitive work such as in laboring with large hand tools, the H_{prod} is determined by the worker, which typically prevents excessive level of heat strain occurring as the worker slows down the rate of work as they become (or rather feel) warmer.[32] However there can be an interaction between the mechanical work required and the worker's preferred cadence with a particular tool-type, which can result in surprisingly high H_{prod} and associated thermal strain despite self-pacing. Such a phenomenon is demonstrated in the present review by first attack bush fire fighters constructing firelines with rake hoes at their own pace who preferred to work at cadences that resulted in H_{prod} values in the order of 700 W[22] despite the resulting high levels of heat strain (T_{core} values as high 39.6°C). Finally, H_{prod} may be enforced by external pacing. The classic example of external pacing is 'sergeant major's pace' – forced marching in the defense forces as present in some of the military-related activities captured in this review. The impact of external pacing is seen in the 10 km march carrying 42 kg with time limit 109 minutes (5.5 kph). Of thirty-seven soldiers twenty-three completed the march in time with T_{core} ~38°C; nine withdrew after 71.6 ± 10.1 min suffering symptoms of heat exhaustion (T_{core} ~38.3°C); and five were removed for body core temperature >39.0°C after 58.4 ± 4.5 min.[66]

In addition to heat production, recent work has demonstrated the biophysical importance of worker body mass on the change in core temperature during physical activity, i.e. for the same absolute heat production (e.g. in W) a smaller individual will exhibit a greater elevation in core temperature owing to their smaller heat sink.[33,34] It follows that a worker's heat production per unit of total body mass (i.e., in W/kg) is the strongest determinant of the rise in core temperature.[35,36] Of the 29 studies captured in the present review, 7 reported metabolic heat production, total body mass and the core temperature response. The derived relationship between the calculated heat production in W/kg and the estimated change in core temperature (assuming a resting value of 37.0°C) is illustrated in Figure 3. While this retrospective analysis is clearly limited by the paucity of

Table 4. Workers' physiological and subjective responses.

Industry/Activity	T_{core}, °C	*Max T_{core}, °C	T_{sk}, °C	Sweat rate, $L\cdot h^{-1}$	Dehydration (%body mass)	Thermal Sensation/Comfort
Agriculture						
Sheep shearing	37.7 (0.3)	38.4	—	—	—	Warm - too hot
Horse back Mustering	37.6 (0.3)	38.1	34 (32–36)	—	—	—
Construction						
Carpenters	37.7 (37.5–38.1)	38.1	—	0.47 (0.41–0.55)	1.1 (0.4–2.0)	Uncomfortably warm
Laying and tying steel reinforcing	37.2 (0.3)	—	—	—	—	—
Mine construction	—	—	—	1.03 (0.36)	0.0 (1.5)	—
Defense						
5 km march, load 40 kg	39.0 (37.7–41.2)	41.2	—	—	—	—
10 km, 5.5 $k\cdot h^{-1}$, load 42 kg	38.3 (0.4)	39.1 (0.2)	—	—	—	—
5 km, load 20 kg, 55 min	38.4 (37.7–39.1)	39.1	—	—	—	Hot
20 km, load 35 kg, 4.0 h	38.7 (38.5–39.7)	39.7	—	—	—	Very Hot
15 km march (August)	38.3 (0.5)	~39	—	—	—	Warm
15 km march (November)	38.5 (0.5)	39.5	—	—	—	—
Patrol & Recon, load 30 kg	(38.0–38.2)	38.5	36.5	0.84 (0.72–0.97)	0.8	—
Tank crews						
Exterior (June)	—	—	—	—	—	—
Interior (June)	38.3 (38.0–38.9)	38.9	—	—	—	—
Exterior (September)	—	—	—	—	—	—
Interior (September)	38.0 (37.6–38.4)	38.4	—	—	—	—
Jungle Patrol						
No body armour, load 21 kg	37.5 (0.18)	37.9 (0.26)	—	—	—	—
With body armour, load 29 kg	37.5 (0.15)	37.9 (0.23)	—	—	—	—
Emergency services						
Medical emergency resp team	37.8 (0.5)	38.5	(34.0–34.6)	0.54 (0.35–0.76)	0.69 (0.44)	Warm
Search and Rescue						
Heat acclimatized	38.5 (0.5)	39.6	36.2 (1.2)	0.98 (0.31)	0.8 (0.8)	Uncomfortably Hot
Non-heat acclimatized	38.1 (0.3)	—	36.3 (1.1)	0.84 (0.12)	0.5 (1.0)	Uncomfortably Hot
Prescribed burns						
Day 1	37.3 (0.4)	37.5 (0.7)	—	—	—	—
Day 2	36.7 (0.3)	37.7 (0.4)	—	—	—	—
Bush fire, fireline constr.						
With fire (F)	38.2	39.6	35.4	1.37	1.53	Just too warm
Without fire (NF)	38.1	39.6	33.5	0.97	1.84	Just too warm
Maintenance						
Power station maintenance	37.6 (37.2–37.9)	37.9	33 (1)	0.16 (0.11)	—	—
Council workers	37.4 (0.2)	—	33.2 (0.3)	0.3 (0.2)	2.4 (1.5)	—
Railway track maintenance						
Day 1	37.7 (37.4–37.9)	38.5	35	0.56 (0.44–0.64)	2.4 (0.9–3.8)	Uncomfortably warm
Day 2	37.2 (36.8–37.6)	37.9	—	—	—	Uncomfortably warm
Day 3	—	—	—	0.40 (0.24–0.50)	1.0 (0.4–1.6)	—
Electrical utility						
(NT North)	37.5 (0.3)	37.9 (0.3)	—	0.45	−0.4 (0.9)	—
(NT South)	37.5 (0.3)	37.9 (0.3)	—	0.43	0.5 (0.7)	—
Mining						
Open cut mine processing	37.5 (0.4)	38.5	—	0.3	0.33	—
Shipping/processing port	37.5 (0.4)	38.3	—	0.3	0.43	—
Surface mine. Blast crew	37.6 (0.2)	37.8 (0.2)	—	—	—	—
Deep mine. 1200–1600 m	37.6 (37.0–38.9)	39.5	—	—	—	—
Machinery operators	—	—	—	0.38 (0.12)	−0.96 (0.05)	—
Various	—	—	—	0.38 (0.09)	−0.34 (0.67)	—
Light manual work A	36.8 (0.2)	—	—	—	—	—
Light manual work B	37.0 (0.3)	—	—	—	—	—
Others						
Zinc cathode strip	38.3 (37.9–38.8)	39.0	33–36	0.92 (0.58–1.24)	2.8 (0.1–6.3)	Much too warm
Lead/zinc process operators	37.6 (37.0–38.1)	38.9	—	0.59 (0.50–0.65)	0.5 (−0.5–1.2)	—

*Max T_{core} denotes the highest observed individual T_{core}.

studies reporting all 3 variables, there appears to be a strong positive association (r = 0.94) with a greater heat production per unit mass alongside a greater rise in internal body temperature. This association may partly explain the wide range of core temperatures in forced marches. The requirement to carry the same load regardless of body size would result in a greater heat production per unit mass and thus

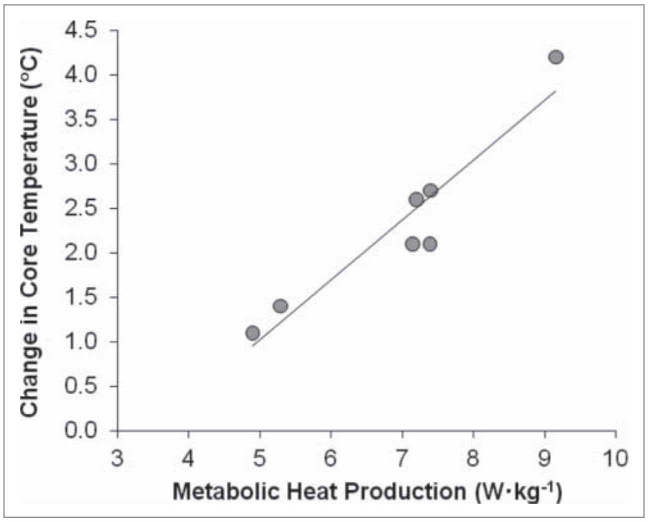

Figure 3. Association between change in average observed core temperature and average observed metabolic heat production normalized for total body mass (i.e. in Wkg^{-1}). Resting core temperature assumed to be 37.0°C across all studies. Data extracted from refs. 14, 22–25, 66, 74, 75, 78, 79.

greater rise in core temperature in smaller compared to larger soldiers.

Sweat losses

It is well established[36,37] that rates of whole-body sweat losses (in $Lmin^{-1}$) during physical activity in a hot environment are determined by the evaporative requirement (E_{req}) for heat balance (i.e. heat production minus sum of non-evaporative heat losses) and the evaporative efficiency of sweat. The effective goal of the human thermoregulatory system is to attain a steady-state core temperature, and in order for this to occur a balance must be struck between the rates of heat production and net heat loss.[38] For a given heat production, the amount of sweating required to achieve E_{req} will therefore change with ambient air temperature as non-evaporative heat losses (i.e., convection and radiation) become progressively smaller as the environment gets hotter and the temperature gradient between skin and air decreases and is eventually reversed.[39] Moreover, for a fixed heat production and ambient temperature, the evaporative efficiency of sweat will be reduced with increasing absolute humidity and decreasing air flow[40] and by clothing[41] as a progressively greater proportion of secreted sweat does not contribute to evaporative cooling from the skin and drips off the body or is taken up by the clothing. Under such a scenario greater sweat rates are required to achieve a given E_{req}. Of all the studies captured in the present review, only 2 reported whole-body sweat losses and all the parameters needed to estimate E_{req} and evaporative efficiency (i.e. T_a, T_r, T_{sk}, H_{prod} and P_a).[14,23,25] Predicted sweat rates from equations based on measured sweat rates and ambient air temperatures from a study on sheep shearers in South Australia[14] and bush fire fighters[25]

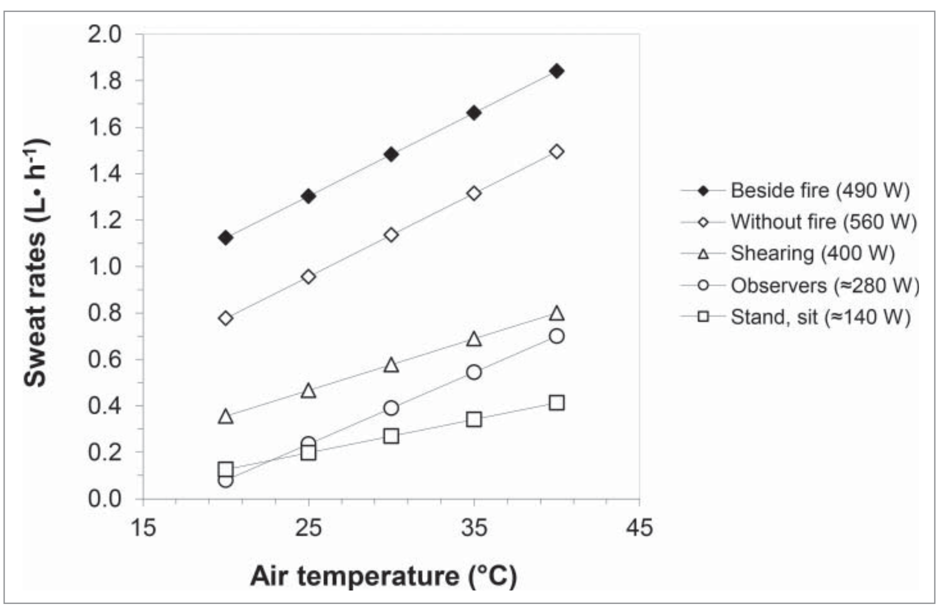

Figure 4. Absolute sweat rates (in Lh^{-1}) estimated for different ambient temperatures for various occupational activities. Numbers in parentheses indicate corresponding absolute metabolic heat production (in W). Sweat rates estimated using equations from Hendrie et al.[25] and Gunn et al.[14]

are given in Figure 4. Graded increases in sweating are observed from "light" to "moderate" to "strenuous" work activities and therefore the amount of internal heat production that must be balanced by evaporation at a given air temperature. Similarly, for a given rate of heat production greater sweat rates are observed with increasing air temperature – as non-evaporative heat losses become smaller and E_{req} becomes greater. Differences in the slope of these lines likely reflect a disparity in air velocity and/or thermal properties of clothing worn. A lower air velocity and a greater clothing insulation would be associated with a shallower slope due to a smaller change in dry heat transfer for a given increase in air temperature. The independent role of radiant heat can also be observed from the comparison of predicted sweat rates for bush fire fighters working at the same work intensity ("strenuous") and air temperatures away from, and beside a fire. An additional ~350 mLh^{-1} of sweating was elicited by the extra radiant heat absorbed by the body, which if all sweat was evaporated, the worker attained heat balance and maximum sweat rate was not reached, can be calculated using the latent heat of vaporization of sweat[42] to be ~235 W – very similar to the 210 W predicted from the measured mean radiant temperature.[23] Further to prediction of sweat rate from air temperature, measured sweat rates in fireline construction away from fire correlated well with E_{req} estimated from H_{prod} and convective and radiative heat exchanges ($b = 1.07$, $r = 0.69$, $p = <0.001$).[25]

Dehydration

Fluid ingestion and the avoidance of dehydration in hot workplaces is the most prominent heat stress risk mitigation strategy advised by many occupational hygienists.[3] Indeed, this notion is echoed by public health organizations during heat waves and many athletic trainers working with sportsmen/women training and competing in the heat.[43,44] While euhydration can be beneficial for maintaining optimal athletic and work performance in the heat,[45] quite substantial dehydration (>3–4% of total body mass) is necessary to compromise thermoregulatory responses, and at lower levels of dehydration elevations in core temperature do not reliably associate with hydration status.[46] Water intake regulated by thirst alone is a poor indicator of hydration status and often results in "involuntary dehydration" during exercise in the heat.[47] However, according to the studies captured in the present review, dehydration does not seem to be a problem among the Australian workforce, which is no doubt a testament to the education given to workers on the importance of hydration.[48] There are even some studies that reported an increase in body mass due to fluid ingestion exceeding sweat losses (e.g., Electrical utility work in NT North; Mining machinery operators in WA). The only occupations that reported any incidents of individuals exceeding a 3% of total body mass reduction over a given workday was railway track maintenance work (max: 3.8%; mean: 2.4%) and zinc cathode strippers (max: 6.3%; mean: 2.8% in ~4 hours work on the fixed quota job) – both in South Australia (Table 4). However neither of these occupations reported the greatest thermal strain among the studies captured in the present review. While not reported in Table 4, some authors assessed workers' hydration status based on urinary specific gravity (USG). Significant numbers of workers in all jobs apparently were hypohydrated (USG >1.025) at the start of work, and usually most, but not all, were hypohydrated at the end of work. By contrast Brake and Bates,[48] based on USG findings, suggested that most miners at Mt Isa QLD were able to maintain adequate hydration over 12 hour shifts despite some sweating in excess of 1 $L h^{-1}$. Gun observed that shearers are able to replace 70% of sweat losses as great as 9 L in a day.[14] Bush fire fighters on average replaced 43% of sweat losses on the fireline resulting in dehydration rate 0.9% (maximum 2.6%) body mass per hour.[25]

In addition to an emphasis on water ingestion, occupational hygienists typically recommend workers drink cold water in order to mitigate thermal strain.[3] While colder water temperatures can be more palatable and therefore encourage drinking, recent research has demonstrated that under certain environmental conditions the notion that cold fluid ingestion physically cools a worker is likely misplaced. Internal heat exchange via conduction is obviously greater with cold-water ingestion by a magnitude that is determined by the volume, temperature and specific heat capacity (4.186 $J \cdot g^{-1}$) of water. However, parallel reductions in sweat output (and subsequently skin surface evaporation) mediated by independent thermoreceptors located in the abdominal region[49] result in similar changes in body heat content and elevations in deep body temperature with 1.5°C water ingestion compared to warmer (e.g. 37°C) water during physical activity in moderate environmental conditions.[50,51] Moreover, ice slurry (a mixture of crushed ice and cold water) ingestion seems to yield greater increases in body heat content during exercise in hot (34°C) and dry (20%RH) conditions compared to thermoneutral fluid.[49] In view of the much greater latent heat of vaporization of water (2430 J·g^{-1}) relative to specific heat capacity, greater cooling may actually be achieved by dampening the skin surface with water (particularly when accompanied by additional air flow).[52] Only if work is carried out in hot/humid conditions whereby cold fluid ingestion will reduce the amount of sweat that drips off the body without impacting skin surface evaporation, may the ingestion of colder water confer a clear thermoregulatory advantage. In most hot occupational environments, workers should therefore consider dampening their skin with water (with a sponge or water spray) in addition to ingesting water at a temperature that is most palatable.[53]

Skin temperature

Skin temperature data among the studies captured by the present review were sparse, however those that did include this measure often reported values of 35°C or greater (Table 4) which is to be expected from the known associations between skin temperature and the thermal environment. While changes in skin temperature have been demonstrated to be a poor correlate of body heat storage,[54] mean skin temperature determines the temperature gradient for skin surface dry heat exchange for a given set of environmental conditions, and is traditionally viewed as the driver for internal heat transfer from deeper body tissues to the body shell.[55] It follows that the drive for both internal and external convective/conductive heat loss would have been compromised in most of the studies reporting skin temperature, with skin surface evaporation responsible for almost all heat dissipation. High skin temperatures have also been shown in the athletic arena to compromise physical performance.[56-58] Such observations are likely only relevant in the present review to activities with high rate of metabolic energy expenditure (i.e., military-related, fire fighting and search and rescue activities).

Thermal comfort/sensation

High skin temperatures also affect thermal sensation and comfort. Very few studies in the present review reported subjective thermal votes of workers in hot Australian workplaces (Table 4). Nonetheless it is reasonable to assume that most workers in the reported conditions would feel warm to hot, and often uncomfortably so. Given the importance of subjective variables on worker performance and health and safety (from a perspective of both decision making and the ability to focus on the task at hand) such a paucity of data is surprising. Studies that did include such measures reported thermal sensations that included discomfort. Search and rescue workers and zinc cathode strippers appeared to experience the greatest levels of thermal discomfort, however the studies that reported the greatest levels of workplace hyperthermia did not measure subjective responses. Modest rises in deep core temperature can compromise the performance of cognitive tasks,[59] however studies examining the relationship between environmental heat stress and cognitive functioning have been far from conclusive. In some cases heat stress was detrimental[60,61] while others have reported enhanced arousal/concentration.[62,63] Despite subjective sensations of warmth and discomfort – which often give cause for concern or alarm - the accompanying physiological responses of core temperature and sweat rate were generally well within tolerable levels.

Health impacts of occupational heat stress in Australia

Apart from the normal thermoregulatory and subjective responses, heat stress may also impact worker health in terms of heat exhaustion and occasionally heat stroke. While not captured in the present review as physiological markers of heat strain (core temperature) were not measured in the workplace, Donoghue, Sinclair and Bates investigated the thermal conditions and personal risk factors and the clinical characteristics associated with 106 cases of heat exhaustion in the deep mines at Mt Isa, QLD.[64] The overall incidence of heat exhaustion was 43.0 cases / million man-hours of underground work with a peak incidence rate in February at 147 cases / million-man hours. Specific to this review the workplace thermal conditions were recorded in 74 (70%) cases. Air temperature and humidity were very close to those shown in Table 2 but air velocity was lower averaging 0.5 ± 0.6 m·s^{-1} (range 0.0–4.0 m·s^{-1}). The incidence of heat exhaustion increased steeply when air temperature >34°C, wet bulb temperature >25°C and air velocity <1.56 m·s^{-1}. These observations highlight the critical importance of air movement in promoting sweat evaporation in conditions of high humidity.[12,23,65] The occurrence of heat exhaustion in these conditions contrasts with the apparent rarity of heat casualties in sheep shearers who seem to work at higher H_{prod} (~350–400 W)[14] compared to the highest value measured in mines (~180 Wm^{-2}; 360 W for a 2.0 m^2 worker; personal communication – Graham Bates), and in similar ambient air temperatures and air velocity but much lower humidity. Symptoms of heat exhaustion also caused soldiers to drop out from forced marches.[66]

Self-pacing presumably maintains tolerable levels of strain but implies that increasing environmental heat stress would affect work performance and productivity. Shearers' tallies declined by about 2 sheep per hour from averages of about 17 sheep per hour when T_a exceeded 42°C; shearing ceased on a day when T_a reached 46°C.[14] Bush firefighters spent less time in active work in warmer weather. Although their active work intensity was not affected their overall energy expenditure was slightly reduced.[32] In the Defense Force marches not all soldiers, particularly females, were able to complete the tasks in the allotted times, with failure rates being most common in warmer conditions.[5] The lower physiological responses of non-heat acclimatised search and rescue personnel operating in the Northern Territory compared to acclimatised personnel likely reflected a behavioral response to avoid excessive stress and strain.[67]

Current gaps in knowledge and considerations

Only three studies were identified that examined in situ occupational heat stress in the Australian construction industry. Since workers in this industry, which is one of the largest sectors in Australia, typically experience the greatest amount of outdoor environmental heat exposure, this is a clear knowledge gap that needs addressing. There also seems to be a paucity of information for the agriculture/horticulture sector, particularly for manual labor jobs such as fruit picking and grape harvesting, which are usually performed in hot weather, often by foreign workers on temporary work visas.

No occupational heat stress studies were captured for the Australian Capital Territory (ACT) or Tasmania. The climate within the ACT is similar to New South Wales and Victoria, however only a few studies were found for occupations in these states (Table 1). Tasmania is Australia's coldest state or territory, however the military data examined presently emphasizes that high levels of heat strain can be experienced by workers under relatively cool conditions for occupations requiring high rates of H_{prod}. The most prominent industrial sectors in Tasmania are forestry, agriculture and manufacturing. According to the limited data from other state/territories, H_{prod} may be relatively low in agriculture and likely manufacturing, however forestry work probably elicits distinctly higher H_{prod} values, and should be assessed in greater detail.

There are virtually no female data available for Australian occupational heat stress settings. While according to the Australian Bureau of Statistics many of the examined industries are male-dominated,[68] the disparity between male and female data far exceeds the ratio of males to females in all sectors assessed. The assessment of occupational heat stress in Australia of female workers should therefore be an urgent priority.

With the exception of data obtained via personal communication (Graham Bates, 2016), none of the mining studies in the present review measured H_{prod} values. The Thermal Work Limit (TWL), which is widely used in the Australian mining industry, is defined as the limiting metabolic rate that a worker can sustain in a given thermal environment over a specific work shift.[69] This system has been purportedly successful in reducing heat-related injuries and the mechanization of many mining jobs likely means that H_{prod} is generally low.

In addition to external pacing, the high H_{prod} from many military studies was partially due to the carrying of heavy loads, ranging from 20 to 42 kg. It is worth noting however that the majority of these studies covered were fitness assessment trials and the H_{prod} levels associated during active duties, with the exception of patrols in the Northern Territory, are unclear.

Finally, the findings of the present review highlight the necessity to adopt a standardized methodology for characterizing and managing occupational heat stress in Australia in the future. Such an approach will enable a more comprehensive comparison across different occupations than possible here. Based on the present findings we propose the following measurements are necessary: i) metabolic rate, preferably using

VO_2 measured with indirect calorimetry; ii) total body mass, so that H_{prod} can be normalized for body size (i.e. in Wkg^{-1}); iii) as many of the separate environmental parameters (i.e., ambient air temperature, mean radiant temperature, air velocity and absolute humidity) as possible, as opposed to a single WBGT value as this alone does not indicate the specific source of environmental stress – for example, similar WBGT values (28–29°C) were reported for power station maintenance in northern NT with a T_a and P_a of 30°C and 33 hPa[70] and electrical utility work in southern NT with a T_a and P_a of 39°C and 6 hPa[71]; iv) if possible, the evaporative and dry heat transfer resistance properties of clothing worn, which were poorly defined in the studies captured in this review; and v) deep body core temperature. On only 2 occasions have all these variables been measured in hot occupational environments in Australia: *Project Aquarius* [for Bushfire fighting][23,72] in the 1990s and *Studies of Heat Stress in Selected Occupations in South Australia* [for sheep shearers, railway maintenance, zinc cathode strippers, carpenters, lead refinery operators] in the 1980s.[14,17,26,30,73]

Summary

The present review provides information on which predictions of heat stress risk can be made for a range of occupations across much of Australia. Despite being a hot country, occupational heat stress risk is relatively mild for most industries assessed by virtue of the self-regulated pacing of work possible in most jobs. Heat stress risk appears highest in military-related activities even when carried out in cooler environments, principally due to the high rates of metabolic heat production needed to complete these tasks and probably the clothing worn. Future research should address the clear lack of data on female workers and occupational activities within the agriculture/horticulture sector.

Disclosure of potential conflicts of interest

No potential conflicts of interest were disclosed.

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