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Are workers at risk of occupational injuries due to heat exposure? A comprehensive literature review

Safety Science, 2018; 110(A):380-392

Final publication at: http://dx.doi.org/10.1016/j.ssci.2018.04.027

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Introduction

Global average temperatures have risen about 0.85°C over the last 100 years with temperatures further projected to increase by an estimated average of 3°C by 2100 to reach 1.8°C-4°C above pre-industrial times.[1] As a result, extremely hot days and warm nights have increased in number over recent decades and indications suggest that this trend will continue.[1, 2]

In addition to the adverse effects of heat exposure on the general population, occupational health and safety is also affected.[3-5] Workers in industrial sectors such as agriculture, forestry, fisheries and construction are exposed to outside temperatures and solar heat load making them vulnerable to the adverse health effects of heat exposure in hot weather.[6, 7]Furthermore, those working in hot indoor environments without air-conditioning - such as manufacturing, smelting plants, bakeries, laundries, and restaurant kitchens can also be affected.[6-8] Heat-related illnesses (HRI) such as heat cramps, heat syncope, fatigue, heat exhaustion, heat stroke and heat shock are often the well-known and documented adverse direct effects of heat on health.[9] These outcomes have been reported in the occupational setting among, for example, surface mine workers[10, 11], construction workers[12], agricultural workers[13-16] and radiation decontamination workers[17].

There is now increasing evidence that occupational heat stress is strongly associated with injuries, as an indirect effect of heat exposure.[18-24] Work-related injuries/accidents in hot conditions can be caused by physical discomfort and altered behaviour, fatigue, declining psychomotor performance, loss of concentration and reduced alertness.[9] However, the extent of injury occurrence in hot weather is poorly characterised and understood, and may represent a notable human and economic cost when combined with HRI.

In the United States, the National Institute for Occupational Safety and Health (NIOSH) estimated in 1986 that around 5-10 million workers worked in hot weather conditions for at least part of the year.[25] According to the US Bureau of Labour Statistics (BLS) Census of Fatal occupational injuries report, 144 worker deaths and around 14,022 non-fatal work injuries and illnesses involving lost days of work were reported between 2011 and 2014 due to environmental heat exposure.[26] These figures provide little information about the scale of the problem and are also unlikely to include statistics on injuries that could be attributed to heat such as falls or traffic accidents. As a result, the relative incidence of heat-related occupational injuries is unknown.

In order to summarise current literature on hot weather and occupational injuries, a comprehensive literature search was conducted. Initially, we present a systematized review of studies on heat exposure and injuries, followed by a discussion of the potential pathways to injuries.

Methods

Search strategy

Published literature on heat exposure and injuries were obtained by systematically searching PubMed, Embase, Scopus, CINAHL, Science Direct and Web of Science databases. A search strategy using a combination of controlled vocabulary [Mesh, EMTREE] and key words was developed for each of the above databases (see Table S1-supplementary file for detailed search strategy). The following keywords along with their synonyms and closely related words were used: ‘heat’, ‘heat stress’, ‘hot weather’, ‘high temperature’, ‘climate change’; combined with ‘injury’, ‘occupation’, ‘workers’, ‘work-related’ and ‘epidemiology’. Searches were not limited to year of publication and references cited in identified papers were used as a further source of literature. Additionally, unpublished studies (articles/reports/academic-theses/conference presentations) were searched in internet search engines and web-based searches for ‘grey literature’.

Inclusion and Exclusion criteria

The published studies included in the review met the following criteria:

- Original research articles in English published until 31st of January 2017.
- Studies which investigated the association between heat exposures and work-related injuries/accidents

Excluded were studies not focussing on injuries occurring in workplaces due to heat exposure, and literature reviews investigating the general population health impacts of heat. All titles and abstracts from the literature search were evaluated against the inclusion criteria for possible relevance and those references judged to be relevant were included as part of the review.

Results

Twenty-six studies (22 published and 4 unpublished) from 1922 to 2017 were selected as part of this review. Figure 1 illustrates the study selection process for this review.

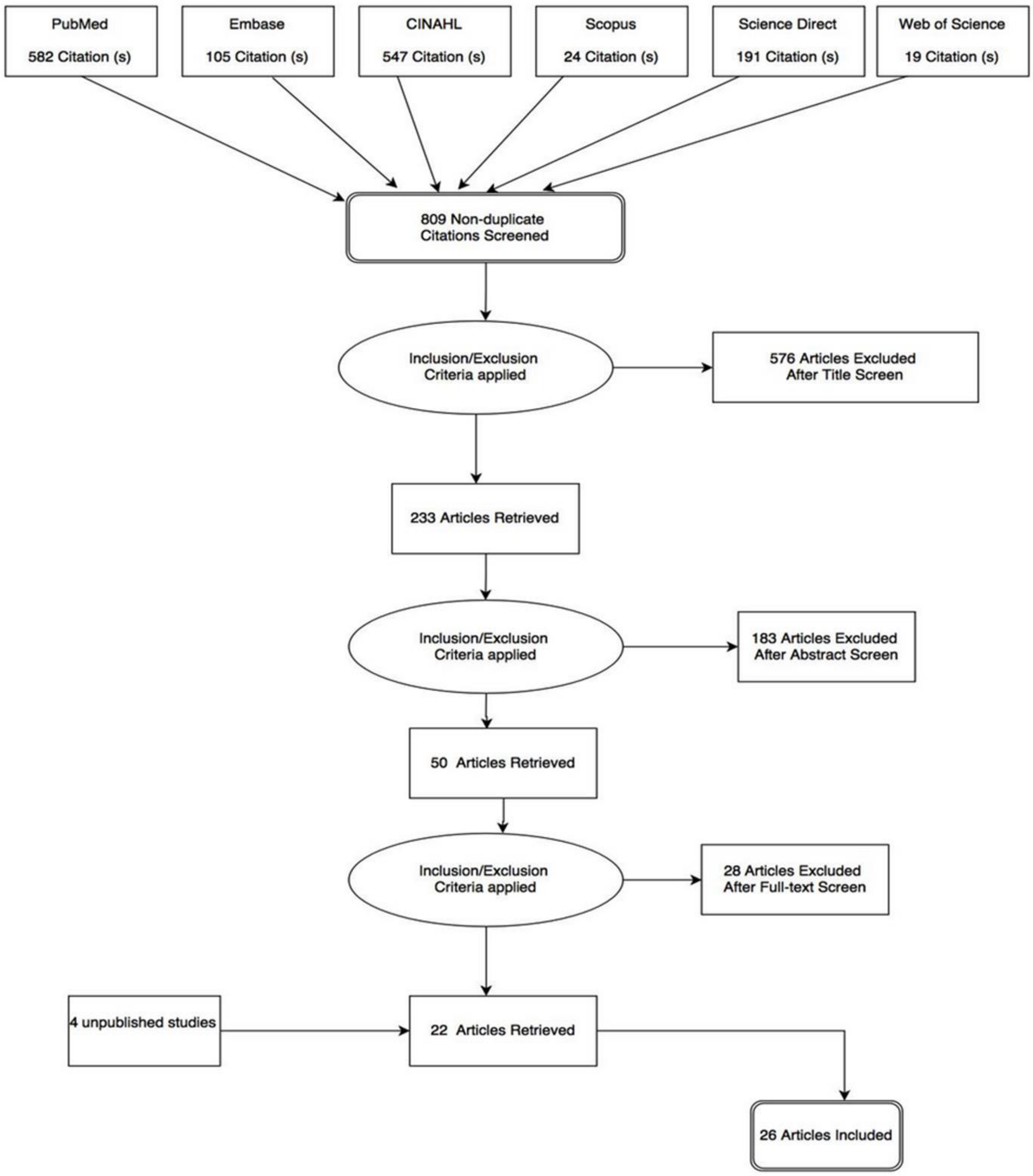

Figure 1. Flow chart of selection process for published studies.

Figure 2 shows the study location and design employed by the included studies. Most studies have been undertaken in developed countries such as North America and Australia, with fewer in developing and tropical parts of India and Thailand. The study populations were from general and specific occupational settings (n=24) and the military (n=2). The weather variables used in the studies included maximum temperature (T_{max}, n=7), minimum temperature (T_{min}, n=1), and indexes combining relative humidity and temperature, such as Apparent Temperature (n=1), Heat Index (n=1), Humidex (n=1) and Wet Bulb Globe Temperature (WBGT, n=2). The methods to evaluate the association between heat exposure variables and the risk of occupational injury used in the studies were ecological time-series studies (TS, n=5), case-crossover studies (CCO, n=3) correlational studies (n=10) and cross-sectional questionnaire surveys (n=8). The TS/CCO and correlational studies involved both non-parametric regression models such as generalised estimating equations (GEE's), generalised additive models (GAM's) and negative binomial regression (NBR) and parametric regression models. The models of the TS and CCO studies were adjusted for key potential confounders such as relative humidity (n=2), seasonal and long-term trends (day of week, year, month, n=4), weekends and public holidays (n=5) and used labour force estimates as offset (n=1). However, none of the TS or CCO studies included effects of air-pollution, a variable normally included in the temperature-health relationship analysis models.[27] The summary of the included studies (study description, methods and key findings) is provided in Table1.

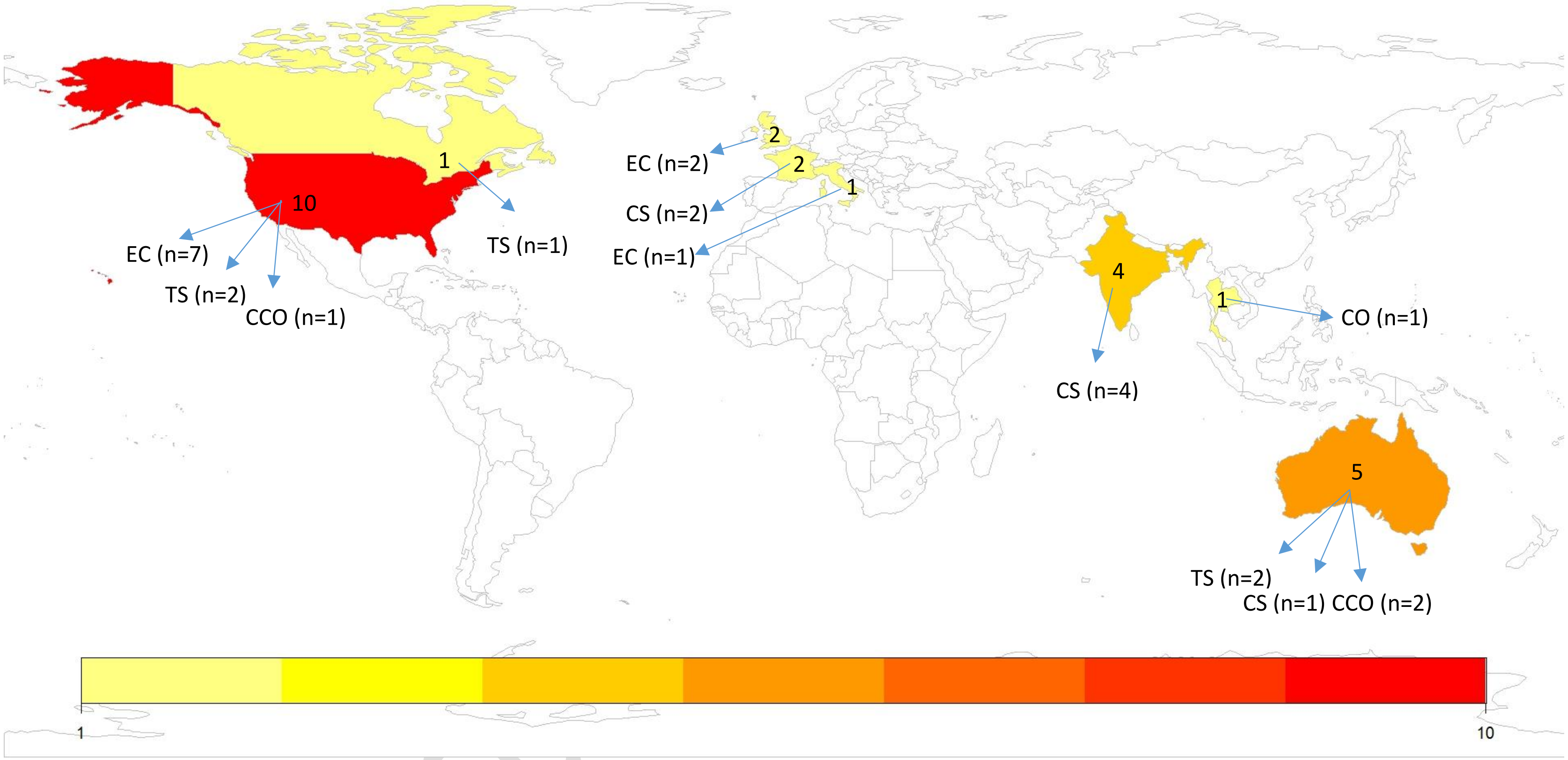

Figure 2. Distribution of studies assessing heat exposure and occupational injuries by study country and study design.

TS- Time-series; EC- Ecological correlation; CS- Cross-sectional; CCO- Case-crossover; CO- Cohort study. Colour indicates the number of publications per country.

Risk of accidents/injuries

The relationships between temperature and occurrence of workplace injuries/accidents have been examined by several studies. Consistent with the literature on heat effects on morbidity and mortality, this association between heat exposure and occurrence of injury/accidents is typically described as a U-, V-, or J-shaped curve whereby injuries increase up to a certain threshold (e.g. around 30°C, depending on each individual study) following which they decline, possibly due to workers modifying work practices at extreme temperatures.[18, 19, 23, 28-30] The associations between heat and injuries among different occupational categories are discussed below.

Heat-associated injuries in the workforce

A relationship between heat exposure and occurrence of injury/accidents was first established by Osborne et al in 1922.[31] They found that fewer accidents occurred in three British munitions factories when temperatures were around 19-20°C, while higher frequencies of accidents occurred at both higher and lower temperatures.[31] However, in 1971, a study of 2,367 accidents in four industrial workshops in the UK found no significant increase in accidents at higher temperatures while in half the workshops more accidents occurred at temperatures below 20°C.[32]

In a 2005 study by Fogleman et al conducted at a US aluminium smelter, a significant increase in acute injury rates was observed (Odds Ratio (OR) = 2.3) when the heat index was above 32°C.[23] Bernard and Fogleman[33] categorised 'heat stress levels' (HSL) as being 'low' when the WGBT was 0-3°C above the threshold limit value (TLV) of 29°C WBGT and 'high' when the HSL was 3°C WGBT above TLV. They reported an increase in the rate of acute musculoskeletal disorders at both low and high HSL with corresponding ORs of 1.8 (95% CI: 1.1-2.9) and 2.4 (95% CI: 1.4-4.3) respectively.[33] Significantly increased rates of acute injuries were found at high TLV (OR=1.7 95% CI: 1-2.9) compared to low TLV (OR=1.4 95% CI: 0.9-2.2). [33]

Moreover, in a study of hospital admissions in Tuscany, Italy, Morabito and co-workers (2006), found that the peak occupational accident rate occurred on days characterised by high, but not extreme thermal conditions.[19] No association was found for outdoor workers such as those employed in construction, land and forestry occupations but a significant increase in injuries occurred between the 10^{th} and 90^{th} percentile of temperature range.[19] Similarly, Xiang et al (2014) conducted a study assessing the association between high temperature and work-related injuries in Adelaide, South Australia, during 2001-2010, and found that injuries occur in moderately hot conditions when workers can suffer from impaired mental judgment and concentration.[28] The authors found a reversed U-shaped relationship between T_{max} and total workers' injury claims. This divergence in the shape of the relationship was attributed to adaptive behaviours at extreme temperatures resulting in the decline of work-related injuries.[28] The absence of denominator data for calculating work-related injury rates was noted. The study reported that a 1°C increase in T_{max} was associated with 0.2% increase in injury claims up to 37°C, after which injury risk significantly dropped.[28] A log-linear relationship was reported between outdoor temperatures and injury claims in Quebec, Canada.[29] The findings were similar to those of Xiang et al (2014)[28] in that a 0.2% increase in daily injury claims was observed with each 1°C increase in daily T_{max}.[29] Both the Adelaide and Quebec studies identified key vulnerable groups that included: males, younger workers (< 24 years), outdoor, physical occupations and industries, tradespersons, and workers in small and medium sized businesses. [28, 29]

Another study in Melbourne, Australia also reported positive associations between temperature and injuries using a case-cross over approach.[34] The authors did not find any evidence of non-linearity in the relationship between maximum temperature and injuries which contrasts with the studies in Adelaide[28] and Italy[19]. Compared to other studies mentioned previously, the authors used daily T_{min} as the exposure metric and found a stronger curvi-linear relationship with injuries - a finding unique in this literature.[34] Female workers, young workers (aged 25-35 years) and older workers (>55 years), those engaged in light and limited physical demand work, and those working in regulated indoor climates, vehicle or cabs, were found to be at risk when daily T_{min} was high.[34] The key vulnerable groups identified using daily T_{max} were similar to those reported by Xiang et al (2014)[28] and Adam-Poupart et al (2015)[29], but also included workers engaged in heavy physical work. [34]

Higher estimates of work-related occupational accidents and injuries associated with ambient temperatures were reported in a 20-year US (unpublished) study of 71,218 occupational injuries and fatalities from 1990-2010 targeted at "temperature-sensitive industries" such as construction, agriculture, forestry and utilities servicing industries. [35, 36] It was reported that on days with T_{max} between 32°C and 37°C, accident rates increased by 8.2%, and by 30% on days with T_{max} above 37°C. Injuries were associated with a 4% increase on days with T_{max} between 21°C and 27°C, and 30% for days above 37°C.[35, 36] Relative to days of T_{max} between 15°C and 21°C, rates were higher when temperatures were extremely high or low. [35, 36] Several recent studies by Spector et al (2016), Hiles (2012) and Garzon-Villalba et al (2016) using other meteorological indices such as Humidex and WBGT have also shown that increases in injuries occur at higher temperatures. [37-39]

Two studies were also conducted amongst military personnel. A study of US army combat trainees found that the incidence of injuries was higher in summer than in fall, with a dose-response relationship observed between incidence and average daily maximum temperature.[40] In a study of national guard troops involved in disaster relief work (sandbagging), days with highest T_{max} translated into higher HRI rates with higher rates observed in females (RR=3.1) than in males.[41] The authors concluded that high ambient temperature, high humidity and prolonged exertion can be the determinants of injuries. [41]

Apart from the evidence from ecological studies, eight cross-sectional studies that investigated heat exposure as a risk factor for occupational injuries were also identified. These studies relying on self-reported injury data obtained through surveys, covered a range of workers from general (all workers) to workers in specific industries (both outdoors and indoors) where heat exposure was a known risk factor (e.g. miners, construction, iron and steel and textile industry workers). One study of textile industry workers in India showed a higher prevalence of injuries during summer months when outdoor ambient temperatures ranged between 42ºC and 48ºC.[42] Similar findings were also reported in other cross-sectional studies conducted in India, France and Australia where injury prevalence among workers exposed to high temperatures ranged from 9.2% to 49%.[12, 43-47] Additionally, a large national cohort study of 58,495 workers in Thailand provided substantial and statistically significant evidence of the relationship between heat stress and occupational injuries.[18] In this study, occupational heat stress was prevalent in 20% of the surveyed workers who also had a greater odds of serious occupational injuries. Interestingly, this study adjusted for several important covariates such as age, income, education, account of existing illness, alcohol consumption, smoking status, sleeping hours, job location and nature of the work.[18]

Effects of heatwaves

Heatwaves are prolonged periods of excessively hot weather with impacts that can differ from those of single high temperature days. In a study from Adelaide, South Australia, Xiang et al (2014) found no significant difference in overall workers' compensation claims during heatwaves compared to non-heatwaves[48] but noted that wounds, lacerations, amputations and burns were the types of injuries strongly associated with heatwaves.[48] In a case-cross over study of construction worker claims in Adelaide, Rameezdeen and Elmualim (2017) found that the severity of work-related accidents/injuries is governed by worker characteristics, type of work, work environment and the direct cause of the injury (i.e. agency of accident) .[49] They reported that during heatwaves, workers in the civil engineering sub-sector, older workers and those employed in small-sized companies were at higher risk of severe accidents.[49]

Types of occupational injuries associated with heat exposure

Most of the reviewed studies have reported on total occupational injuries (both acute and serious), while some ecological and cross-sectional studies [12, 18, 29, 37, 43, 48] have focussed on specific types of injuries sustained in hot conditions. Notwithstanding, some studies have mentioned increased risks for injuries arising from 'slips, trips and falls', 'exposure to harmful substances', 'contact with objects/equipment', 'by hitting objects', 'blunt forces', 'wounds, lacerations and amputations', 'burns', 'minor cuts', 'scrapes', 'being hit by moving objects', 'contusions' and 'fractures' [18, 48] in association with heat exposure.

Potential pathways to injuries

It is unclear how heat exposure exacerbates the risk of physical injury. However, studies included in this review have shown that injuries can be in addition or secondary to, HRI's and can be caused by physiological, psychological, personal behavioural and organisational (work-related) factors as summarized in Figure 4.

To better understand the physiological factors, it is important to know how the body maintains its heat balance and how it reacts in hot environments. Humans are homoeothermic and internal body temperature varies only slightly within a very narrow range around the 37°C 'set point'.[50-53]Although changes in body temperature can occur from hour to hour and even day-to-day, these fluctuations are usually not more than about 1°C as the body is well equipped to regulate internal temperature with dual control systems operating at the neural and hormonal level.[50-53] Thermoregulation controlled by the hypothalamus in the brain ensures heat balance via heat loss mechanisms such as radiation, convection, conduction and evaporation of sweat (Figure 3). Serious health risks can arise when the heat burden exceeds heat loss and the core body temperature rises to 39°C or more. The heat burden imposed on the body can be from the combination of expended energy; external environmental sources including high air temperature, high relative humidity, lack of air movement, radiation from the sun or hot surfaces/sources, and non-climatic parameters such as internal heat generation and clothing.[16, 54]

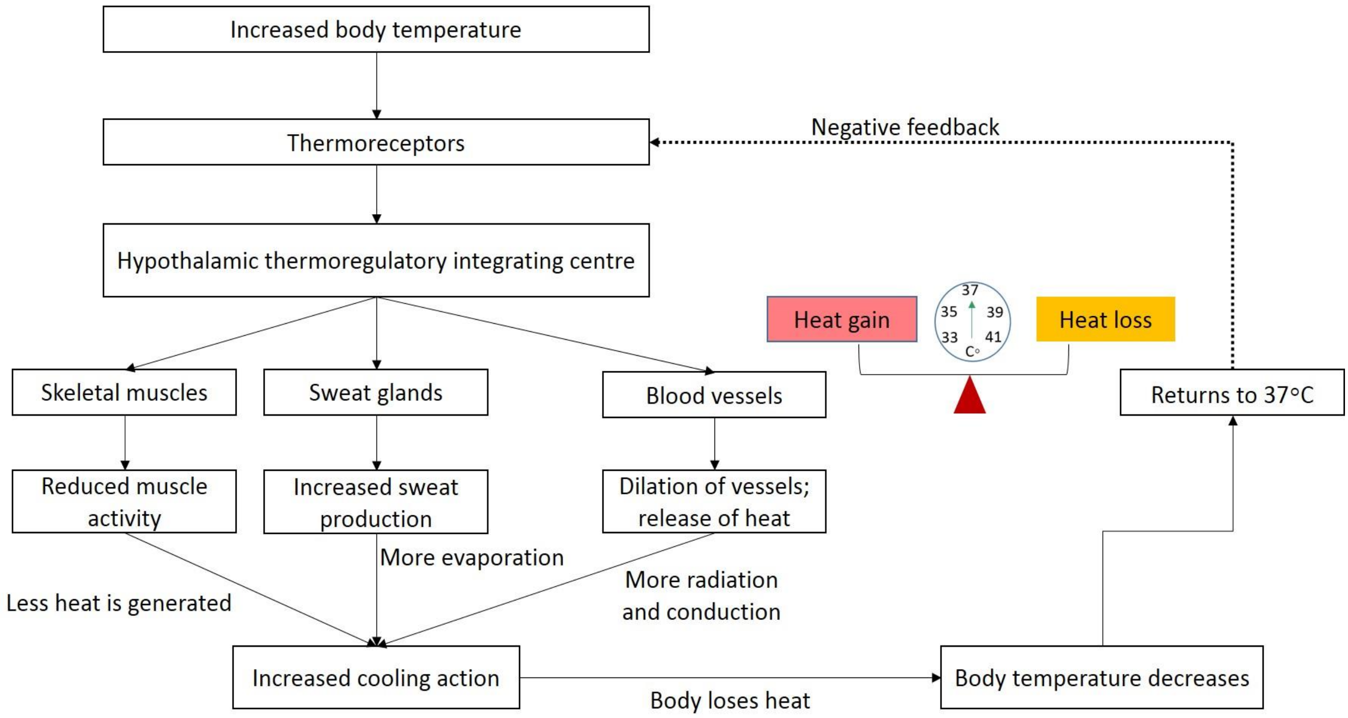

Figure 3. Normal thermoregulatory mechanism.

Source: Modified from Parsons K (2014), Sherwood L (2015), Kenney WL, Wilmore J, Costill D (2015), Astrand P-0 (2003) and Powers SK HE (2015).[50-53, 55]

The physiological factors that pre-dispose an individual to physical injury correspond to the thermoregulatory system's capability to deal with temperatures above or below the set-point. Firstly, changes in blood circulation due to the inability of skin surfaces to lose heat results in pooling of blood in the lower extremities.[50] This in turn means that there is less blood supply to the vital organs including the brain, causing problems such as dizziness and fainting potentially leading to an injury (for e.g., falls).[50]

Secondly, while radiation, conduction and convection work effectively when the surrounding temperature is lower than skin temperature, at higher temperatures the body's salt and water stores can be depleted due to continuous sweating. This results in an electrolyte imbalance that leads to heat cramps and dehydration if the lost body fluids are not continuously replenished.[55] These effects can overwhelm the body's thermoregulatory systems resulting in symptoms of HRI. The progression of these symptoms may impair workers' ability to work safely, increasing the incidence of workplace injuries[21] that occur due to loss of concentration, decreased postural stability, cognitive function and perceptual motor skills.[37, 56-59]

Thirdly, the nature of work can play a role in causing injury. As metabolic rate is associated with muscular work, the total amount of heat produced is proportional to the intensity of work performed.[33] Muscle fatigue can occur if the blood pH level drops due to the increased muscle glycogen degradation, the rise of carbohydrate metabolism and lactate accumulation. [55, 60] Furthermore, highly-reactive molecules such as ‘free-radicals’ can be increased in the skeletal muscles. As a result, muscle strength can decline and affect workers’ performance, eventually pre-disposing them to injuries.[55, 60]

The physiological effects experienced by workers during hot weather conditions may be psychologically linked to increased risk taking behaviour which may translate into accidents/injuries. Ramsay (1983) used a measure for risky behaviour termed the “Unsafe Behaviour Index” (UBI), and identified a U-shaped relationship between unsafe work behaviours and thermal exposure whereby UBI was minimum between 17-23^{o}C WGBT, but increased above 23^{o}C WBGT.[61] The depletion of cognitive function due to heat as explained by the “psychological zone of maximal adaptability” validates and further explains this ‘U-shaped’ relationship.[62] In this model an individual’s performance is affected as their attention and concentration to their task declines with heat, resulting in unsafe behaviours. Interestingly, the decline in cognitive functions starts with minor elevations of the body temperature and the ability to perform tasks and productivity can be affected before a diagnosable heat-related disorder occurs.[62-66] A review of 160 studies assessed workers undertaking basic/mental tasks such as arithmetic, writing, coding, time estimation and reaction time and tasks requiring demanding perceptual motor skills including: tracking, vigilance, machine operation and complex/dual tasks. Significant decrements in the perceptual motor skills among workers engaged in such tasks compared to those engaged in basic/mental tasks was observed at temperature ranges of 30-33^{o}C WGBT.[67]

Lastly, organisational and personal behavioural factors can also lead to injuries. These include reduced use of personal protective equipment due to discomfort in the heat, and slippery palms, grip loss or visibility problems due to sweating. [9, 13, 16, 20, 68] Other influencing factors can be requirement to wear impermeable protective clothing, and lack of supervision and training in heat stress prevention.

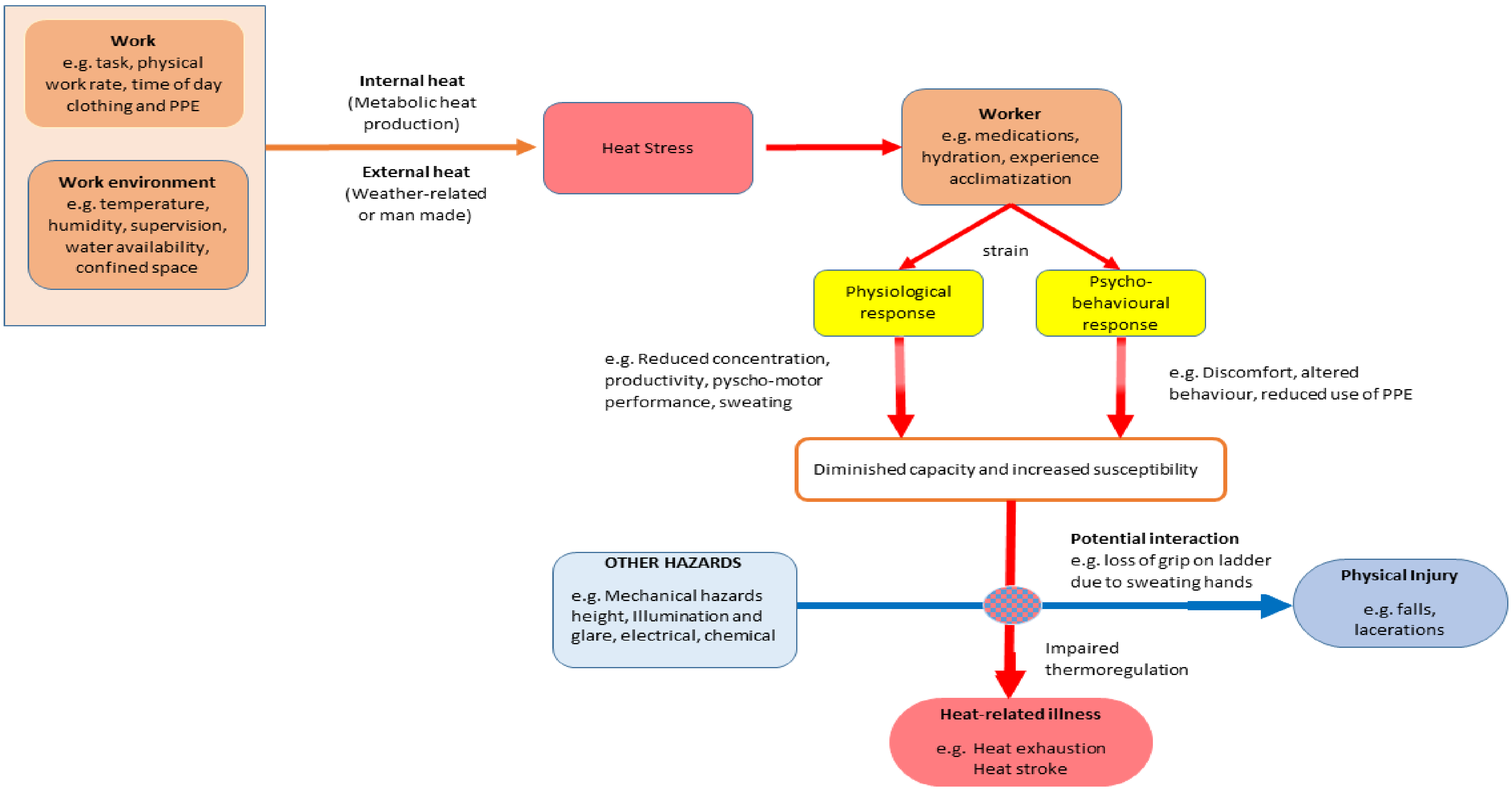

Figure 4. Schematic illustration of factors leading to occupational heat stress, heat strain, illness and injuries.

257 Adapted from: Makinen TM and Hassi J (2009), Kjellstrom T et al (2016) and ILO Encyclopaedia of Occupational Health and Safety.[69-71]

Preventative strategies and barriers

The adverse effects of heat strain are preventable. A range of organisations have promulgated occupational criteria on heat health hazard recognition, evaluation and control.[72-75] Reducing heat exposure for outdoor workers can involve increasing ventilation, modifying clothing, or providing shields/shade against radiant heat/solar radiation.[72-75] In addition to these, safer-work practices such as provision of drinking water, acclimatization, suitable work-rest intervals, rearrangement of work tasks to cooler parts of the day, education and training on the hazards of work in hot environments, and awareness of heat-related illness symptoms, are also key in reducing workplace heat exposure. [72-75] These critical health and safety strategies for working in hot weather are also mentioned in the regulations and guidelines of different countries such as USA, UK, Canada, Australia, New Zealand, Hong Kong, Japan and China. It is noted however, that there are few or no specific regulations and codes for heat stress prevention in developing countries such as Thailand, India, Costa Rica and South Africa.[76, 77]

Despite many standards that refer to a 'general duty of care provision', the health hazards of working in hot weather are not specifically addressed in current occupational health and safety (OH&S) legislation and policies.[78, 79] As a result, less conscientious employers may be more likely to be non-compliant with these standards and guidelines for different reasons. A recent study in Adelaide found that accidents in small-sized businesses increased with daily T_{max} [28] and compensation claims from small-sized construction companies are over-represented during heatwaves[49] possibly due to their lack of compliance/ management of current OH&S policies. The authors recommend that small-sized businesses be targeted for "policies and practice of adaptation and preventative measures". [28, 49]

In Canada, 7 out of 13 provinces require employers to implement administrative and engineering controls for both indoor and outdoor workers to reduce heat exposure.[56] Although tough heat-specific laws protecting workers from heat exposure were enacted in the state of California and Washington (USA) in 2010, poor compliance of heat standards by employers was reported in 2012 during inspector audits. [80] In a recent survey of workers in Adelaide, about 56% of workers suggested the need for more heat-related training, while 64% suggested the need for heat-related regulations and guidelines.[43] Although heat stress management policies sometimes entail a cessation of work when temperatures are extreme, whether workplaces comply with this guideline is unknown. Only 20% of workers surveyed in a South Australia study selected "ceasing work" as a heat prevention measure. [43, 81]

Table 1. Characteristics of studies on the association between heat exposure and work-related injuries.

Study[a]	Population	Heat exposure indicator	Outcome indicator	Methods	Main results
Ramsay et al (1983) [61]	Manufacturing plant and foundry workers	WBGT	Unsafe behaviour index (UBI) n= 17,841 n= 1734 as UBI	ANOVA, quadratic model controlled for worker's metabolic workload, job risk group, time of day and day of week.	"U"-shaped relationship Minimum UBI occurred between 17-23°C WBGT Metabolic workload is also significantly related to UBI
Dellinger AM et al (1996) [41]	National guard troops	T_{max}	Medical claims of illness and injuries (HRI) Illness (n=95) Injuries (n=119)	Fisher exact tests	Overall 19.3% injuries; Males: 16% and Females: 42% Women greater risk for HRI than men (RR=3.07; 95% CI: 1.09-8.68). Days with T_{max} coincided with highest HRI rates and higher HRI rates at the beginning of the relief work declining over time
Knapik JJ et al (2001) [40]	US army subjects attending basic combat training	Average T_{max} and Minimal dry bulb	Retrospective injury data post training Injury categories: -All injuries -Overuse injury -Traumatic injuries -time-loss injuries	Pearson chi-square test, Logistic regression and Pearson product moment correlation coefficients	Higher incidence of injury during summer (30.8° C -36.1° C) than fall (14.5° C -26.1° C). Men had twice higher risk of all injuries and time-loss injuries in summer than women Dose-response relationship identified between Injury incidence and average T_{max} (between 16.2° C and 34.2° C) with correlations ranging from 0.92 to 0.97 for time-loss injuries and all injuries respectively.

Nag PK and Nag A (2001) [42]	Textile industry workers	Heat exposure as risk factor	Questionnaire data containing accident reports n= 4125	Descriptive	The prevalence of accidents were significantly higher in summer months (May-June) when outdoor temperatures were between 42^o C and 48^o C.
Foggleman et al (2005)[23]	Aluminium smelter	HI- 11 thermal categories, Considered relative humidity	Acute injury (lacerations, punctures and musculoskeletal disorders- strains, sprains and hernias) n=557 cases	Ratio of number of accidents using number of acute injury cases and person-hours Poisson regression, Logistic regression-	Modified U-shaped relationship between thermal category and the occurrence of acute injuries. Higher odds ratio occurred below-7^o C & above 32^o C. *Between 33^o C and 38^o* OR=2.28 (95%CI:1.49-3.49) *Over 38^{o}C* OR=3.52 (95%CI:1.86-6.67) Young workers – high risk of acute injuries
Morabito M et al (2006)[19]	Hospital admissions	AT [Daily AT max, AT_{24} and AT_{day}] percentiles; <25th 25-50th 50-75th >75th	work-related accidents N=835	Mann-Whitney U Test and Kruskal-Wallis Test Lags up to 1 day Excluded holidays and weekends	Peak accidents on current days (lag=0) characterised by high and not extreme thermal conditions (3rd quartile – average AT_{day} = 24.8^o C -27.53^o C)

Bhattacherjee A et al (2007)[45]	Coal miners	Heat exposure as risk factor	Occupational injuries	Chi-square independence test and logistic regression	28.5% of occupational injuries were due to heat exposure with a crude RR of 1.35 (95%CI: 1.03-1.78).
Chau N et al (2008)[44]	All workers	Heat exposure as risk factor	Occupational injuries	Association analysed by crude odds ratio (OR) and 95% confidence intervals	Heat exposure was observed in 18.6% of occupational injuries making it a risk factor (OR=2.29; 95% CI :1.73-3.01)
Tawatsupa B et al (2013)[18]	All workers	Heat stress measure: "never", "sometimes" and "often"	Frequency of Occupational injuries occurring in workplace both agricultural and non-agricultural (none, once, twice, thrice and more than four times)	Logistic regression	Statistically association of heat with occupational injury (OR 2.12, 95% CI: 1.87-2.42 for males and 1.89, 95% CI: 1.64-2.18 for females). Type of injuries: Blunt force (24%)**,** Stab-cut (21%)**,** Fall (18%) Males were more likely to have stab-cut or blunt force injury while falls were more observed in females. Socio-economic factors (income, job location-rural), health behaviours and status (smoking, drinking, less sleep, obesity, existing illness) and nature of work (fast paced) had strong and significant influence on the relationship between heat stress and occupational injury.

Xiang et al (2014) [28]	All workers	Daily T_{max} Daily T_{min}	Work injury claims (n=125 267)	Generalised estimating equation with negative binomial distribution; piece wise linear spline function Restrictions to warm season (October –March) Weekdays Model adjusted for: Day of week, Calender month and Long-term trends	Reversed U-shaped relationship between daily T_{max} and overall worker's injury claims. 0.2% increase in injuries per 1°C increase in T_{max} for up to 37.7° C No delayed effects of temperature above threshold. Vulnerable groups: Male workers, younger workers aged below 24 years, and those working in the 'construction', 'agriculture, forestry and fishing' and 'electricity, gas and water' industries

Xiang et al (2014)[48]	All workers	Daily T_{max}, Daily T_{min} Heatwave: $T_{max} \geq 35$ for three or more consecutive days	Work injury claims (n=125 267)	Generalised estimating equation models with negative binomial distribution Restrictions to warm season (October –March) Weekdays Model adjusted for: Day of week, Calender month and Long-term trends	A 6.2% increase in compensation claims was observed for outdoor industry workers during heatwaves. Workers in 'agriculture, forestry and fishing' and 'electricity, gas and water' had significant increase in injury claims. Type of injuries: Being hit by moving objects (9.7%), chemicals and other substances (20%) and heat, electricity and other environmental factors (39%) contributed to the increased injury claims during heat waves.

Biswas MJ et al (2014)[46]	Iron and steel workers	Heat exposure as risk factor	Questionnaire and interview of workers history of injuries Exposed group: Steel melting Rolling mill Quality control Non-exposed: Maintenance and administration department	Descriptive analysis	Injuries were reported in 18.7% of workers with higher prevalence in exposed group than non-exposed group (94.6% vs 5.34%).

Adam-Popart A et al (2015)[29]	All workers	Daily T_{max} Considered relative humidity	Work-related injuries (n=374 078)	Generalised linear model with negative binomial distributions Lag effects considered (lags 1 and 2; mean of lags 0-1 and mean of lags 0-1-2) Model adjusted for: Day, Month, Year, 2-week holiday in construction sector, Public holidays, Relative humidity and Monthly working population	Log-linear relationship between temperature and injuries. 0.2% increase in daily compensation claims with each increase in T_{max} Statistical significant IRRs were found for industrial sectors involving both outside and inside work. Types of injuries: Slips, trips and falls, Contact with objects/equipment, Exposure to harmful substances
Jain AA, et al (2015)[47]	Iron and steel workers	Heat exposure as risk factor	Questionnaire data supplemented by clinical examination and review of medical records (n=200)	Chi-square test	Out of 127 workers exposed to high temperatures, 98 (77.2%) had history of injury. Significant statistical association was found between injury and exposure to heat (X^2=33.97, df=1, p<0.0001

Dutta P et al (2015)[12]	Construction workers	Heat exposure as risk factor	Cross-sectional survey with anthropometric measurements (n=219)and focus groups (n=4)	Descriptive analysis	12.8% workers reported injured at work of which 9.2% of injuries were in summer compared to 14.7% in winter. However, new workers with <36 months of experience reported injuries in summer Types of injuries: Minor cuts/scrapes/minor injuries, fractures/falls
Xiang J et al (2016)[43]	Outdoor industrial workers	Heat exposure as risk factor	Questionnaire survey among apprentices, trainees (n=511) and established workers (n=238)	Descriptive analysis	25.9% workers reported experiencing heat-related injuries at work during very hot weather. Types of injuries: Burns (54.1%)**,** Falls, slips and trips (44.3%)**,** By hitting objects (27.8%)**,** By being hit by moving objects (10.3%) 25.2% of workers reported witnessed injuries to co-worker during hot weather. Most injuries were due to falls, slips and trips (55%) and burns (42.3%).
Spector JT et al (2016)[37]	Outdoor agricultural workers	Maximum daily humidex (HX) categories; <25 25-29 30-33 >34	Traumatic injury claims (n=12,213)	Conditional logistic regression	Increasing risk of traumatic injuries with maximum daily humidex value up to 33 Compared to humidex <25 25-29: OR=1.14 (95% CI: 1.06-1.22) 30-33:OR=1.15 (95% CI: 1.06-1.25) >34: OR=1.10 (95% CI: 1.01-1.20) High risk of traumatic injuries for Cherry harvest duties occurring during June-July

McInnes J et al (2016)[34]	All workers	Daily T_{max} and T_{min}, Included relative humidity	Work-related injury claims (n=46,940)	Conditional logistic regression Restricted to warm months (November –March)	Positive associations between temperature and injuries T_{max} and Injuries: Non-linear relationship T_{min} and injuries: Curvilinear (U-shaped) Overall Vulnerable groups: Young workers, Males, Physically demanding occupation
Garzon-Villalba XP et al (2016)[39]	BP deep water horizon oil spill clean-up workers	$WBGT_{max}$	Occurrence of Exertion heat illness (EHI) and acute injuries (AI) AI= 1619 EHI=1707	Descriptive, Poisson regression model	Statistically significant increase of EHI and AI above $WBGT_{max}$ of 20º C (RR 1.40 and RR 1.06/º C) 13% increase of AI was observed with a 1 increase of WBGT. Severity of event was statistically significant for AI as the RR increased from 1.13 to 1.15 and significant cumulative effect from prior day's $WBGT_{max}$ for EHI was significant.

Rameez-deen R and Elmualim A. (2017)[49]	Construction workers	Daily T_{max} Daily T_{min} Heatwave: $T_{max} \geq 35$ for three or more consecutive days	Work-related injuries (n=29,438)	Descriptive, Chi-square statistics	Slight over-representation but no statistical significant association with number of accidents. Expenditure in major accidents was more than twice among >55 years and higher for new workers during heatwaves. Vulnerable groups: Experienced workers, male workers, those aged <35 years and >55 years, those working in small and medium sized companies, in the civil sub-sector and employed as Bricklayer, carpenter, electrician, mechanics and plant operator.

[a] These studies are ordered by date of publication. T_{max}- Maximum temperature; T_{min}- Minimum temperature; WBGT- wet-bulb globe temperature; AT- Apparent temperature; HI- Heat Index; HX- Humidex; EHI- Exertional heat illness; AI: acute injuries; UBI-unsafe behaviour index; HRI-heat-related illness

Discussion

This review summarises evidence published to date regarding the role of meteorological elements, particularly hot temperature, in occupational injury causation. Despite differences in study design and analysis strategies, evidence presented in this review indicates an association between heat and work-related injuries.

Vulnerable subpopulations identified include male workers, younger workers aged 15-24 years, outdoor and indoor workers.(28, 29, 34, 37) Increased risk of occupational injuries was found among the 'electricity', 'manufacturing', 'utilities', 'transport', 'agriculture', 'fishing' and 'construction' industries.(28, 29) As well as heat stress, the kinds of injuries sustained during hot weather included 'wounds, lacerations and amputations', 'burns', 'falls', 'cuts', 'fractures', 'slips', and 'trips'.(18, 48) Although associations were established, the mechanism underlying occupational injuries attributed to hot weather remains unclear. However, in this review we have identified both direct and in-direct risk factors (Figure 4) by which exposure to heat may lead to occupational injuries. This needs to be further investigated in future studies to explain the underlying mechanism.

It is known that cognitive and physical performance can be affected by exposure to excess heat. The likelihood of unsafe behaviours leading to injuries and illnesses are higher when factors such as judgement, concentration, coordination, endurance, strength, vision and comfort are influenced by physiological changes induced by heat and dehydration.(62, 82-84) Physical workload was considered in only two studies (29, 34) that found significant associations between maximum temperature and heavy physical work and minimum temperature and light and medium strength occupations.

Apart from these factors, many studies have also attempted to hypothesize a long list of other factors that may pre-dispose an individual to experience a higher risk of workplace injuries in hot conditions. These include: sweaty palms, fogged up safety glasses, accidental contact with hot surfaces, physical demanding work, lack of training and skills, ageing-induced dysfunctional thermoregulatory mechanisms, use of heavy impermeable PPE's, workplace pressures, poor hydration behaviours and attitudes to strenuous work.(16, 28, 34, 85, 86) A cohort study undertaken in Thailand, though limited on its reliance on qualitative measures of occupational injuries and heat exposure as reported by participants, provided important evidence of heat stress risk by taking into account several of the above factors.(18) Future quantitative studies also need to investigate specific at-risk occupations as type of work, body posture and movement also determine an individual's response to heat stress. (75)

Apart from standard climate descriptors such as maximum and minimum temperature that are used to assess workplace heat risks by policy makers, supervisors and safety professionals, other metrics such as apparent temperature, heat index, Humidex and WBGT can also be used.[75] WBGT is a heat stress metric that was developed for US military in the 1950s and is now used more broadly in industrial and sporting sectors, incorporating air temperature, humidity, wind speed and solar radiation.[87, 88] Heat Index (also known as apparent temperature or Humidex) is a combined metric of air temperature and humidity.[89] These thermal composite indices provide a more comprehensive picture of the hazards posed by heat to an individual or group of workers than air temperature alone. Hence, studies using a more comprehensive index may provide more robust estimates of thermal comfort and risk of heat stress. Importantly, behavioural factors, clothing and personal protective equipment; levels of physical exertion and personal factors (age, health, medications etc.) also influence how our bodies react to heat.[75]

Apart from studies using onsite heat stress measurements, most of the included studies have relied on weather data from fixed-site monitoring stations, thus raising the issue of bias from exposure misclassification as they may not adequately capture individual exposures to temperatures recorded at central monitoring stations. This limitation of ecological study designs can only be addressed by empirical studies using individual measurements across a range of industries and in hazardous locations (such as construction sites) that would give more precise exposure estimates than ecological studies. However, the impracticality and expense involved in conducting these studies justifies the use of administrative databases such as workers' compensation data covering many types of work, workers and workplaces, and spanning extended periods of time advantageous to public health researchers.

Ideally, using the number of workers on a given day as the denominator would produce precise estimates of rates of injury risk in an industry or occupation type. At present this has only been undertaken in onsite studies [38, 39] that have used workplace injury records provided by employers. Access to reliable and meaningful population denominators in broader spatial scale studies such as those using worker compensation databases at a city/regional level is difficult, as raised by Xiang et al (2014)[28]. Adam-Poupart et al (2014)[29] used the log of regional monthly working populations as an offset in their generalised linear model to estimate the association between temperature and injury risks. Two studies [34, 37] have attempted to overcome this limitation by employing a case-cross over study design whereby each case is its own control.

Despite these caveats, evidence is growing of the relationship between heat and impaired worker health and safety. As suggested by one study, providing information on risk factors and appropriate training and awareness to prevent such incidents is highly crucial to tackle this issue effectively.[28] This lends support to the argument that reducing exposure to heat by implementation of appropriate engineering and preventative control strategies may result in a reduction in the number of workplace accidents/injuries. Guidance documents have been released by various health and occupational groups and government authorities that provide guidelines and recommendations for workers (for detailed review, see McInnes et al 2016).[78] However, at present, there is little focus specifically on injury prevention in moderately hot, as distinct from extremely hot, thermal conditions. Hence, modifications to OH&S policies and design of evidence-based training plans for workers and supervisors may be needed.

There are some limitations in this study. Although multiple databases were searched using a number of keywords, the possibility of missing studies reporting negative associations between hot weather and work-related injuries cannot be ignored. We have addressed publication bias to an extent in this review with the inclusion of both published and unpublished studies. Gaps identified in this review warrant further investigation to elucidate the complex mechanisms involved, and better characterise workers at risk based on occupations, physical activity level (sedentary/moderate/heavy) and co-morbidities. Further research is needed to examine how other factors mentioned previously (behavioural, personal and climatic) may modify/confound the already established relationship between temperature and workplace injuries to get a more accurate picture of the effect. This is particularly important with projections of further rises in global temperatures that range between 1^{o}C and 5^{o}C by 2070 (depending on the greenhouse gas emissions) may increase the risk of heat-associated injuries and illnesses for those employed outdoors.

The lag-effects of temperature on the occurrence of injuries also needs to be further investigated as injuries may not potentially occur on the same day as the heat exposure. Further work is also required to look at impacts of heatwaves in terms of intensity and duration using newly proposed metrics such as the Excess Heat Factor.[90] There also exists limited research on the economic impact of heat on the occurrence of occupational injuries and the cost to the health sector and more work is needed. Practical economic implications could be associated with improved worker safety through averted injuries, poor health outcomes and lost productivity.

Conclusion

This review presents an evidence base addressing hot weather hazards and associated direct and in-direct risk factors for occupational injury. The need for targeted interventions and workplace policies focussed on preventative strategies is highlighted. Results from studies included in this review indicate a strong but variable relationship between outdoor temperature and risk of workplace injuries that vary by worker demographics (age, gender, occupations and industries). However, the mechanisms underlying the occurrence of these injuries remain unclear. With the influence of global warming resulting in higher temperatures and more hot days, we might expect to see a rise in occupational accidents and injuries and associated productivity losses, the impact of which may be reduced by adaptation of specific behavioural and workplace controls among workers of vulnerable occupational groups and industries.

Acknowledgements

The authors would like to acknowledge funding from the Australian Government through the Australian Research Council (ARC Discovery Project Grant -DP160103059). B.M.V is supported by the University of Adelaide Faculty Of Health Sciences Divisional Scholarship.

References:

1. IPCC. Fifth Assessment Report. Geneva: Intergovernmental Panel on Climate Change 2014.

2. Steffen W and Hughes L. The Critical Decade 2013: Climate change science, risks and response. Canberra: Climate Commission Secretariat; 2013.

3. Song X, Wang S, Hu Y, Yue M, Zhang T, Liu Y, et al. Impact of ambient temperature on morbidity and mortality: An overview of reviews. Sci Total Environ. 2017;586:241-54. DOI: 10.1016/j.scitotenv.2017.01.212.

4. Kovats RS, Hajat S. Heat stress and public health: a critical review. Annu Rev Public Health. 2008;29:41-55. DOI: 10.1146/annurev.publhealth.29.020907.090843.

5. Page LA, Hajat S, Kovats RS, Howard LM. Temperature-related deaths in people with psychosis, dementia and substance misuse. Br J Psychiatry. 2012;200(6):485-90. DOI: 10.1192/bjp.bp.111.100404.

6. Lundgren K, Kuklane K, Gao C, Holmer I. Effects of heat stress on working populations when facing climate change. Ind Health. 2013;51(1):3-15.

7. Heidari H, Golbabaei F, Shamsipour A, Rahimi Forushani A, Gaeini A. Outdoor occupational environments and heat stress in IRAN. Journal of Environmental Health Science and Engineering. 2015;13:48. DOI: 10.1186/s40201-015-0199-6. Cited in: PMC.

8. Health Council of the Netherlands. Heat stress in the workplace. The Hague: Health Council of the Netherlands; 2008.

9. Jackson LL, Rosenberg HR. Preventing heat-related illness among agricultural workers. J Agromedicine. 2010;15(3):200-15. DOI: 10.1080/1059924x.2010.487021.

10. Miller V, Bates G. Hydration of outdoor workers in north-west Australia. Journal of Occupational Health and Safety Australia and New Zealand. 2007;23:79-87.

11. Hunt AP, Parker AW, Stewart IB. Symptoms of heat illness in surface mine workers. International Archives of Occupational and Environmental Health. 2013;86(5):519-27. DOI: 10.1007/s00420-012-0786-0.

12. Dutta P, Rajiva A, Andhare D, Azhar GS, Tiwari A, Sheffield P, et al. Perceived heat stress and health effects on construction workers. Indian Journal of Occupational and Environmental Medicine. 2015;19(3):151-8. DOI: 10.4103/0019-5278.174002.

13. Bethel JW, Harger R. Heat-related illness among Oregon farmworkers. Int J Environ Res Public Health. 2014;11(9):9273-85. DOI: 10.3390/ijerph110909273.

14. Kearney GD, Hu H, Xu X, Hall MB, Balanay JA. Estimating the Prevalence of Heat-Related Symptoms and Sun Safety-Related Behavior among Latino Farmworkers in Eastern North Carolina. J Agromedicine. 2016;21(1):15-23. DOI: 10.1080/1059924x.2015.1106377.

15. Mirabelli MC, Quandt SA, Crain R, Grzywacz JG, Robinson EN, Vallejos QM, et al. Symptoms of Heat Illness Among Latino Farmworkers in North Carolina. American journal of preventive medicine. 2010;39(5):468-71. DOI: 10.1016/j.amepre.2010.07.008. Cited in: PMC.

16. Spector JT, Krenz J, Blank KN. Risk Factors for Heat-Related Illness in Washington Crop Workers. J Agromedicine. 2015;20(3):349-59. DOI: 10.1080/1059924x.2015.1047107.

17. Kakamu T, Hidaka T, Hayakawa T, Kumagai T, Jinnouchi T, Tsuji M, et al. Risk and preventive factors for heat illness in radiation decontamination workers after the Fukushima Daiichi Nuclear Power Plant accident. J Occup Health. 2015;57(4):331-8. DOI: 10.1539/joh.14-0218-OA.

18. Tawatsupa B, Yiengprugsawan V, Kjellstrom T, Berecki-Gisolf J, Seubsman SA, Sleigh A. Association between heat stress and occupational injury among Thai workers: findings of the Thai Cohort Study. Ind Health. 2013;51(1):34-46.

19. Morabito M, Cecchi L, Crisci A, Modesti PA, Orlandini S. Relationship between work-related accidents and hot weather conditions in Tuscany (central Italy). Ind Health. 2006;44(3):458-64.

20. Harduar Morano L, Bunn TL, Lackovic M, Lavender A, Dang GT, Chalmers JJ, et al. Occupational heat-related illness emergency department visits and inpatient hospitalizations in the southeast region, 2007-2011. Am J Ind Med. 2015;58(10):1114-25. DOI: 10.1002/ajim.22504.

21. Harduar Morano L, Watkins S, Kintziger K. A Comprehensive Evaluation of the Burden of Heat-Related Illness and Death within the Florida Population. Int J Environ Res Public Health. 2016;13(6). DOI: 10.3390/ijerph13060551.

22. Basu R. High ambient temperature and mortality: a review of epidemiologic studies from 2001 to 2008. Environ Health. 2009;8:40. DOI: 10.1186/1476-069x-8-40.

23. Fogleman M, Fakhrzadeh L, Bernard TE. The relationship between outdoor thermal conditions and acute injury in an aluminum smelter. International Journal of Industrial Ergonomics. 2005;35(1):47-55. DOI: http://dx.doi.org/10.1016/j.ergon.2004.08.003.

24. The National Institute for Occupational Safety and Health. Heat Stress. CDC; 2015 [updated July 19,2016; cited 2016 22 Jul]. Available from: http://www.cdc.gov/niosh/topics/heatstress/

25. Gubernot DM, Anderson GB, Hunting KL. The epidemiology of occupational heat exposure in the United States: a review of the literature and assessment of research needs in a changing climate. Int J Biometeorol. 2014;58(8):1779-88. DOI: 10.1007/s00484-013-0752-x.

26. Bureau of Labor Statistics. Occupational Injuries/Illnesses and Fatal Injuries Profiles. Washington DC: BLS; 2016 [cited 2016 28 Jul]. Available from: http://data.bls.gov/gqt/RequestData

27. Buckley JP, Samet JM, Richardson DB. Commentary: Does air pollution confound studies of temperature? Epidemiology. 2014;25(2):242-5. DOI: 10.1097/ede.0000000000000051.

28. Xiang J, Bi P, Pisaniello D, Hansen A, Sullivan T. Association between high temperature and work-related injuries in Adelaide, South Australia, 2001-2010. Occup Environ Med. 2014;71(4):246-52. DOI: 10.1136/oemed-2013-101584.

29. Adam-Poupart A, Smargiassi A, Busque MA, Duguay P, Fournier M, Zayed J, et al. Effect of summer outdoor temperatures on work-related injuries in Quebec (Canada). Occup Environ Med. 2015;72(5):338-45. DOI: 10.1136/oemed-2014-102428.

30. Lao J, Hansen A, Nitschke M, Hanson-Easey S, Pisaniello D. Working smart: An exploration of council workers' experiences and perceptions of heat in Adelaide South Australia. Saf Sci. 2016;82. DOI: 10.1016/j.ssci.2015.09.026.

31. Osborne EE, Vernon HM, Muscio B. The influence of temperature and other conditions on the frequency of industrial accidents. London: British Industrial Fatigue Research Board; 1922.

32. Powell P. 2000 Accidents: A Shop Floor Study of their Causes Based on 42 Months Continuous Observation. London: National Institute of Industrial Psychology; 1971.

33. Bernard T. Occupational Heat Stress. Occupational Ergonomics: CRC Press; 2012. p. 737-64.

34. McInnes JA, Akram M, MacFarlane EM, Keegel T, Sim MR, Smith P. Association between high ambient temperature and acute work-related injury: a case-crossover analysis using workers' compensation claims data. Scand J Work Environ Health. 2017;43(1):86-94. DOI: 10.5271/sjweh.3602.

35. Page L. Ambient Temperature and Occupational Accidents [Thesis]. Williamstown: Williams College; 2016.

36. Page L, Sheppard S. Heat Stress: the impact of ambient temperature on occupational injuries in the US. Working Paper Series: Williams College; 2016.

37. Spector JT, Bonauto DK, Sheppard L, Busch-Isaksen T, Calkins M, Adams D, et al. A Case-Crossover Study of Heat Exposure and Injury Risk in Outdoor Agricultural Workers. PLoS One. 2016;11(10):e0164498. DOI: 10.1371/journal.pone.0164498.

38. Hiles MH. Relationships of Heat Stress Levels to Heat-Related Disorders and Acute Injury During Deepwater Horizon Cleanup Operations. [Graduate Theses and Dissertations.]: University of South Florida; 2012.

39. Garzon-Villalba XP, Mbah A, Wu Y, Hiles M, Moore H, Schwartz SW, et al. Exertional heat illness and acute injury related to ambient wet bulb globe temperature. Am J Ind Med. 2016;59(12):1169-76. DOI: 10.1002/ajim.22650.

40. Knapik JJ, Canham-chervak M, Hauret K, Laurin MJ, Hoedebecke E, Craig S, et al. Seasonal variations in injury rates during US Army Basic Combat Training. Annals of occupational hygiene. 2002;46(1):15-23.

41. Dellinger AM, Kachur SP, Sternberg E, Russell J. Risk of heat-related injury to disaster relief workers in a slow-onset flood disaster. Journal of occupational and environmental medicine / American College of Occupational and Environmental Medicine. 1996;38(7):689-92.

42. Nag PK, Nag A. Shiftwork in the hot environment. J Hum Ergol (Tokyo). 2001;30(1-2):161-6.

43. Xiang J, Hansen A, Pisaniello D, Bi P. Workers' perceptions of climate change related extreme heat exposure in South Australia: a cross-sectional survey. BMC Public Health. 2016;16:549. DOI: 10.1186/s12889-016-3241-4.

44. Chau N, Bourgkard E, Bhattacherjee A, Ravaud JF, Choquet M, Mur JM. Associations of job, living conditions and lifestyle with occupational injury in working population: a population-based study. Int Arch Occup Environ Health. 2008;81(4):379-89. DOI: 10.1007/s00420-007-0223-y.

45. Bhattacherjee A, Bertrand JP, Meyer JP, Benamghar L, Otero Sierra C, Michaely JP, et al. Relationships of physical job tasks and living conditions with occupational injuries in coal miners. Ind Health. 2007;45(2):352-8.

46. Biswas MJ, Koparkar AR, Joshi MP, Hajare ST, Kasturwar NB. A study of morbidity pattern among iron and steel workers from an industry in central India. Indian J Occup Environ Med. 2014;18(3):122-8. DOI: 10.4103/0019-5278.146909.

47. Jain AA AN, Kale KM, Doibale MK,. Work Related Injuries and Some Associated Risk Factors among Workers in Iron and Steel Industry. Scholars Journal of Applied Medical Sciences. 2015;3(2):901-5.

48. Xiang J, Bi P, Pisaniello D, Hansen A. The impact of heatwaves on workers' health and safety in Adelaide, South Australia. Environ Res. 2014;133:90-5. DOI: 10.1016/j.envres.2014.04.042.

49. Rameezdeen R, Elmualim A. The Impact of Heat Waves on Occurrence and Severity of Construction Accidents. Int J Environ Res Public Health. 2017;14(1). DOI: 10.3390/ijerph14010070.

50. Parsons K. Human Thermal Environments: The Effects of Hot, Moderate, and Cold Environments on Human Health, Comfort, and Performance. 3rd ed. Boca Raton, FL: CRC press; 2014.

51. Sherwood L. Human physiology: from cells to systems. 9th ed. Boston, MA: Cengage learning; 2015.

52. Kenney WL, Wilmore J, Costill D. Physiology of Sport and Exercise. 6th ed. Champaign, IL: Human kinetics; 2015.

53. Åstrand P-O. Textbook of work physiology: physiological bases of exercise. 4th ed. Champaign,IL: Human Kinetics; 2003.

54. Sawka MN, Leon LR, Montain SJ, Sonna LA. Integrated physiological mechanisms of exercise performance, adaptation, and maladaptation to heat stress. Compr Physiol. 2011;1(4):1883-928. DOI: 10.1002/cphy.c100082.

55. Powers SK and Howley ET. Exercise physiology : theory and application to fitness and performance. 9th ed. New York: McGraw-Hill Education; 2015.

56. Jay O, Kenny GP. Heat exposure in the Canadian workplace. Am J Ind Med. 2010;53(8):842-53. DOI: 10.1002/ajim.20827.

57. Ganio MS, Armstrong LE, Casa DJ, McDermott BP, Lee EC, Yamamoto LM, et al. Mild dehydration impairs cognitive performance and mood of men. Br J Nutr. 2011;106(10):1535-43. DOI: 10.1017/s0007114511002005.

58. Zemkova E, Hamar D. Physiological mechanisms of post-exercise balance impairment. Sports Med. 2014;44(4):437-48. DOI: 10.1007/s40279-013-0129-7.

59. Distefano LJ, Casa DJ, Vansumeren MM, Karslo RM, Huggins RA, Demartini JK, et al. Hypohydration and hyperthermia impair neuromuscular control after exercise. Med Sci Sports Exerc. 2013;45(6):1166-73. DOI: 10.1249/MSS.0b013e3182805b83.

60. Ross JA, Shipp EM, Trueblood AB, Bhattacharya A. Ergonomics and Beyond: Understanding How Chemical and Heat Exposures and Physical Exertions at Work Affect Functional Ability, Injury, and Long-Term Health. Hum Factors. 2016 Aug;58(5):777-95. DOI: 10.1177/0018720816645457.

61. Ramsey-JD, Burford-CL, Beshir-MY, Jensen-RC. Effects of workplace thermal conditions on safe work behavior. Journal of Safety Research. 1983;14:105-14.

62. Hancock PA, Vasmatzidis I. Effects of heat stress on cognitive performance: the current state of knowledge. Int J Hyperthermia. 2003;19(3):355-72. DOI: 10.1080/0265673021000054630.

63. Hancock PA, Vasmatzidis I. Human occupational and performance limits under stress: the thermal environment as a prototypical example. Ergonomics. 1998;41(8):1169-91. DOI: 10.1080/001401398186469.

64. Epstein Y, Keren G, Moisseiev J, Gasko O, Yachin S. Psychomotor deterioration during exposure to heat. Aviat Space Environ Med. 1980;51(6):607-10.

65. Chen ML, Chen CJ, Yeh WY, Huang JW, Mao IF. Heat stress evaluation and worker fatigue in a steel plant. AIHA journal : a journal for the science of occupational and environmental health and safety. 2003;64(3):352-9.

66. Grandjean AC, Grandjean NR. Dehydration and cognitive performance. J Am Coll Nutr. 2007;26(5 Suppl):549S-54S.

67. Ramsey JD. Task performance in heat: a review. Ergonomics. 1995;38(1):154-65. DOI: 10.1080/00140139508925092.

68. Johansson B, Rask K, Stenberg M. Piece rates and their effects on health and safety - a literature review. Appl Ergon. 2010;41(4):607-14. DOI: 10.1016/j.apergo.2009.12.020.

69. Makinen TM, Hassi J. Health problems in cold work. Ind Health. 2009;47(3):207-20.

70. Kjellstrom T, Briggs D, Freyberg C, Lemke B, Otto M, Hyatt O. Heat, Human Performance, and Occupational Health: A Key Issue for the Assessment of Global Climate Change Impacts. Annu Rev Public Health. 2016;37:97-112.

71. Raouf A. Part VIII: Accidents and Safety Management- Accident Prevention:Theory of Accident Causes. In: Saari J, editor. ILO Encyclopaedia of Occupational Health and Safety. Online ed2012.

72. Parsons K. Occupational health impacts of climate change: current and future ISO standards for the assessment of heat stress. Ind Health. 2013;51. DOI: 10.2486/indhealth.2012-0165.

73. The American Conference of Governmental Industrial Hygienists (ACGIH). ACGIH Heat Stress and Strain TLV. https://www.acgih.org/forms/store/ProductFormPublic/heat-stress-and-strain-tlv-r-physical-agents-7th-edition-documentation. Accessed 1 May 2012.

74. Corleto RD, Firth I, Mate J. A guide to managing heat stress: developed for use in the Australian environment. Tullamarine Victoria: The Australian Institute of Occupational Hygienists Inc (AIOH); 2013.

75. Jacklitsch B WW, Musolin K, Coca A, Kim J-H, Turner N. Cincinnati, . NIOSH Criteria for a Recommended Standard: Occupational Exposure to Heat and Hot Environments. OH: U.S. Department of Health and Human Services,: National Instittute for Occupational Safety and Health (NIOSH); 2016.

76. Crowe J, van Wendel de Joode B, Wesseling C. A pilot field evaluation on heat stress in sugarcane workers in Costa Rica: What to do next? Glob Health Action. 2009;2. doi:10.3402/gha.v2i0.2062.

77. Mathee A, Oba J, Rose A. Climate change impacts on working people (the HOTHAPS initiative): findings of the South African pilot study. Glob Health Action. 2010;3(1). DOI: http://dx.doi.org/10.3402/gha.v3i0.5612.

78. McInnes JA, MacFarlane EM, Sim MR, Smith P. Working in hot weather: a review of policies and guidelines to minimise the risk of harm to Australian workers. Inj Prev. 2016. DOI: 10.1136/injuryprev-2016-042204.

79. Safe Work Australia. Model Work Health and Safety Act. Canberra2016. Available from: http://www.safeworkaustralia.gov.au/sites/swa/about/publications/pages/model-work-health-safety-act

80. California Code of Regulations. Heat Illness prevention. Subchapter 7, Section 3395. [updated Accessed 20 March 2017]. Available from: https://www.dir.ca.gov/title8/3395.html

81. Australian Construction F, Mining and Energy Union (CFMEU),. Inclement weather- Heat Policy. 2013 [cited 2017 20 March]. Available from: http://www.cfmeu.asn.au/branch/sa/campaign/inclement-weather-heat-policy

82. Kenefick RW, Sawka MN. Hydration at the work site. J Am Coll Nutr. 2007;26(5 Suppl):597S-603S.

83. Sawka MN, Francesconi RP, Young AJ, Pandolf KB. Influence of hydration level and body fluids on exercise performance in the heat. JAMA. 1984;252(9):1165-9.

84. Murray B. Hydration and physical performance. J Am Coll Nutr. 2007;26(5 Suppl):542S-8S.

85. Xiang J, Bi P, Pisaniello D, Hansen A. Health impacts of workplace heat exposure: an epidemiological review. Ind Health. 2014;52(2):91-101.

86. Spector JT, Krenz J, Rauser E, Bonauto DK. Heat-related illness in Washington State agriculture and forestry sectors. Am J Ind Med. 2014;57(8):881-95. DOI: 10.1002/ajim.22357.

87. Yaglou CP, Minard D. Control of heat casualties at military training centers. AMA archives of industrial health. 1957 Oct;16(4):302-16.

88. Parsons K. Heat stress standard ISO 7243 and its global application. Ind Health. 2006 Jul;44(3):368-79.

89. Anderson GB, Bell ML, Peng RD. Methods to calculate the heat index as an exposure metric in environmental health research. Environ Health Perspect. 2013 Oct;121(10):1111-9. DOI: 10.1289/ehp.1206273.

90. Nairn JR, Fawcett RJ. The excess heat factor: a metric for heatwave intensity and its use in classifying heatwave severity. Int J Environ Res Public Health. 2014;12(1):227-53.

Table S1: Search strategy: terms, databases, limitations and number of articles for review.

Databases	**Strategy**	**Number of hits**	**Number imported into Endnote**
PubMed Filters: English, humans.	#1 Heat stress[tw] OR Heat stress disorders[mh] OR Hot temperature[mh] OR heat[tw] OR hot weather[tw] OR hot temperature*[tw] OR high temperature*[tw] OR ambient temperature*[tw] OR heatwave*[tw] OR heat wave*[tw] OR climate change[mh] OR climate change*[mh] OR global warming[mh] OR outdoor[tw] OR thermal exposure[tw] OR solar radiation [tw] OR sun exposure [tw] OR UV-index [tw] #2 (Industry[mh:noexp] OR Industry[tw] OR Industries[tw] OR Industrial[tw] Environmental Exposure[mh:noexp] OR Occupational Exposure[mh:noexp] OR Occupation health [mh] OR Work[tw] OR workplace[tw] OR work-related[tw] OR workplace[mh] OR employment[tw] OR employment[mh] OR occupation*[tw] OR employee*[tw]) OR company*[tw] OR AGRICULTURE INDUSTRY[mh:noexp] OR FORESTRY[mh] OR Forestry[tw] OR building site*[tw] OR WORKER*[TW] OR Occupational Health and safety[tw]) #3**(**Workers' compensation [mh] OR Wounds and injuries[mh] OR Accidental falls[mh] OR FALLS[TW] OR Accidents, occupational[mh] OR injur*[tw] OR accident*[tw]) OR ((accident[tiab] OR accidents[tiab] OR injury[tiab] OR injuries[tiab] OR "Wounds and Injuries"[Mesh] OR "injuries" [Subheading]))) #4 Epidemiol*[tw] OR Morbidit*[tw] OR INCIDENC*[TW] OR PREVALENC*[TW**]** #5 #1 AND #2 AND #3 AND #4	324976 2583579 1422576 2416824	582
Embase Filters: English, humans.	#1 'high temperature':ab,ti OR 'high temperatures':ab,ti AND 'hot temperature':ab,ti OR 'hot temperatures':ab,ti OR 'high ambient temperature':ab,ti OR 'high ambient temperatures':ab,ti OR 'ambient temperature':ab,ti OR 'ambient temperatures':ab,ti OR 'outdoor temperature':ab,ti OR 'outdoor temperatures':ab,ti OR heatwaves:ab,ti OR 'heat stress'/exp OR 'heat stress' OR 'heat stress disorders':ab,ti OR 'global warming':ab,ti OR 'climate change'/exp OR 'climate change' OR 'thermal exposure'/exp OR 'thermal exposure' OR heatwave:ab,ti OR 'extreme heat'/exp OR 'extreme heat' #2 work:ti OR worker*:ab,ti OR employment:ti OR 'occupational health':ti OR workplace:ab,ti OR 'work place':ab,ti OR 'work environment'/exp OR 'workman compensation'/exp OR 'industry'/exp #3 ('injury'/exp OR accident:ab,ti OR accidents:ab,ti OR injury:ab,ti OR injuries:ab,ti) OR ('heat injury':ab,ti OR Injur* OR 'accident'/exp OR injur*:ab,ti OR accident*:ab,ti OR harm* OR wound* OR 'fall'/exp OR falling* OR (work* NEAR/1 injur*):ti OR (work* NEAR/1 injur*):ti,ab)	128716 556688	

	#4 epidemiologic* NEXT/1 (stud* OR survey*) OR 'case control study'/syn OR (population OR hospital) NEXT/5 'based case control' OR 'case control' NEXT/3 (analys* OR design* OR evaluation* OR research OR stud* OR survey* OR trial*) OR 'case comparison' NEXT/5 (analys* OR stud*) OR 'cohort analysis'/syn OR ('case base' OR 'case matched' OR 'case referent' OR cohort OR concurrent OR incidence OR longitudinal OR followup OR 'follow up' OR prospective OR retrospective OR 'cross-sectional' OR prevalence) NEXT/1 (analys* OR design* OR evaluation* OR research OR stud* OR survey* OR trial*) OR 'prospective method' OR 'crossover procedure'/syn OR 'retrospective study'/syn OR morbidit* #5 #1 AND #2 AND #3 AND #4	2572431 2369019	105
Scopus	#1 TITLE-ABS-KEY("heat" OR "Heatwave" OR "Hot temperature" OR "Hot weather" OR "Thermal exposure" OR "Ambient temperature" OR "High temperature" OR "High ambient temperature" OR "Heat stress" OR "Climate change" OR "Outdoor temperature" OR "Heat exposure" OR "environmental temperature") #2 TITLE-ABS-KEY ("Work-related" OR "Occupation" OR "Work" "Workplace" OR "Outdoor industry" OR "workplace" OR "Indoor industry" OR "Worker's compensation") #3 (TITLE-ABS-KEY ("Occupational injury" OR "Work injury" OR "Accident" OR "Wound" OR "Damage" OR "Work-related injury" OR "incident" OR "Fall risk" OR "falling" OR "occupational accident")) OR (TITLE-ABS KEY (accident OR accidents OR injury OR injuries)) #4 TITLEABSKEY ("Epidemiology" OR "Morbidity" OR "Prevalence" OR "Incidence") #5 #1 AND #2 AND #3 AND #4	2067185 45900 3068939 2334640	

			24
CINAHL Filters: English, Humans, Narrow by Subject Major: - wounds and injuries - occupational safety - stress, occupational - occupational diseases - environmental health - occupational exposure - work environment - occupational health - occupational-related injuries - public health - environmental exposure	#1 MH heat OR Ti heat* OR AB heat* OR TX heat* OR TX heatwave* OR TX hot temperature* OR TX hot weather OR TX High temperature* OR TX thermal exposure* TX ambient temperature* OR TX high ambient temperature* OR TX HEAT STRESS OR TX CLIMATE CHANGE* OR TX outdoor temperature* OR TX heat exposure* #2 TX work-related OR TX work* TX workplace OR TX employment OR TX employee* OR TX occupation OR TX company OR TX industry #3 TX occupational injur* OR TX work injur* OR TX "work injur* " OR MH accident OR TX accident* OR TX work-related injur* OR TX incident* TX worker's compensation OR TX wounds and injuries OR TX accidental falls OR TX falls #4 TI epidemiology OR AB epidemiology OR TX epidemiology OR MH epidemiology OR TX morbidit* #5 #1 AND #2 AND #3 AND #4	106501 405191 304385 352267	547
Science Direct Filter : Journals only, English	#1 "heat" OR "Heatwave" OR "Hot temperature" OR "Hot weather" OR "Thermal exposure" OR "Ambient temperature" OR "High temperature" OR "High ambient temperature" OR "Heat stress" OR "Climate change" OR "Outdoor temperature" OR "Heat exposure" OR "environmental temperature" #2 "Occupational injury" OR "Work injury" OR "Accident" OR "Wound" OR "Damage" OR "Work-related injury" OR "incident" OR "Fall risk" OR "falling" OR "occupational accident" #3 "Work-related" OR "Occupation" OR "Work" "Workplace" OR "Outdoor industry" OR "workplace" OR "Indoor industry" OR "Worker's compensation" #4 "Epidemiology" OR "Morbidity" OR "Prevalence" OR "Incidence" #5 #1 AND #2 AND #3 AND #4	2,988,712 **30537** 9572 **2,441,583**	191
Web of Science	#1 **TITLE:** (("extreme weather" OR "ambient temperature" OR "extreme heat" OR Heat OR "high temperature" OR "high temperatures" OR "Heat wave" OR "Heat waves" OR temperature OR temperatures OR "temperature extremes")) #2 **TITLE:** ((injur* OR trauma OR wound* OR accident*))	904285	

	#3 **TITLE:** ((work* OR workplace* OR occupation* OR worker*)) #4 #1 AND #2 AND #3	425877 560650	 19
TOTAL RESULTS			**1468**