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Heat exposure and occupational injuries: Review of the literature and implications

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Abstract

Purpose of review: The burden of heat-related adverse occupational health effects, as well as traumatic injuries, is already substantial. Projected increases in mean temperatures and extreme events may increase the risk of adverse heat health effects and enhance disparities among exposed workers. This article reviews the emerging literature on the relationship between heat exposure and occupational traumatic injuries and discusses implications of this work.

Recent findings: A recent meta-analysis of three case-crossover and five time-series studies in industrialized settings reported an association of increasing occupational injuries with increasing heat exposure, with increased effect estimates for male gender and age less than 25 years, although heterogeneity in exposure metrics and sources of bias were demonstrated to varying degrees across studies. A subsequent case-crossover study in outdoor construction workers reported a 0.5% increase in the odds of traumatic injuries per one °C increase in maximum daily humidex (odds ratio 1.005 [95% CI 1.003–1.007]). While some studies have demonstrated reversed u-shaped associations between heat exposure and occupational injuries, different risk profiles have been reported in different industries and settings.

Summary: Studies conducted primarily in industrialized settings suggest an increased risk of traumatic injury with increasing heat exposure, though the exact mechanisms of heat exposure's effects on traumatic injuries are still under investigation. The effectiveness of heat-related injury prevention approaches has not yet been established. To enhance the effectiveness of prevention efforts, prioritization of approaches should not only take into account the hierarchy of controls, social-ecological models, community and stakeholder participation, and tailoring of approaches to

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specific local work settings, but also methods that reduce local and global disparities and better address the source of heat exposure, including conservation informed land-use planning, built environment, and prevention through design approaches. Participation of occupational health experts in transdisciplinary development and integration of these approaches is needed.

Keywords

Heat stress; heat-related illness; traumatic injury; hierarchy of controls; social-ecological model; land-use planning; conservation; built environment; prevention through design

Introduction

The global burden of occupational injuries is estimated to account for approximately 312,000 fatal injuries (8.8% of the global burden of mortality due to unintentional injuries) in 2000, and 3.5 years of healthy life lost per 1,000 workers annually [1]. Although substantial progress has been made, certain industries, such as construction and agriculture in the United States (US), still have high rates of traumatic injury and high risks of adverse heat health outcomes [2]. The need to better understand risk factors for occupational injuries and to further refine and develop new and effective prevention approaches is apparent in research priorities such as the US National Institute for Occupational Safety and Health’s cross-sector focus on traumatic injury prevention [3].

One potential risk factor for occupational traumatic injuries that has been increasingly studied is heat exposure. In this review, *heat exposure* refers to ambient heat exposure, while *heat stress* is the net heat exposure from a combination of metabolic heat generation from heavy physical work, environmental factors such as air temperature, humidity, wind, and solar radiation, and clothing [4]. Heat stress induces *heat strain*, a physiological response in humans intended to maintain thermal equilibrium, which when overwhelmed can lead to *heat-related illnesses* such as heat stroke, which can be fatal [4]. Workers in industries at high risk for traumatic injuries are often also at high risk for heat stress. For example, construction and agricultural workers often work outdoors with exposure to elevated air temperatures, solar radiation, and high metabolic demands from heavy physical work [2].

There is an emerging literature on the relationship between heat exposure and occupational injuries [5–16]. Hereafter, injury refers to occupational traumatic injury, such as fractures, rather than work-related musculoskeletal disorders, such as carpal tunnel syndrome, that result from a combination of awkward postures, repetitive motions, and high force activities [17]. In this paper, we review the literature on the relationship between heat exposure and occupational injuries and discuss the implications of this work.

Review of current evidence for an association between heat exposure and occupational traumatic injuries

The existing literature on the relationship between heat exposure and occupational injuries is summarized in Table 1. An early study by Morabito et al. reported an association between warm weather (average daytime apparent temperature 25–28°C) and increased hospitalizations for work-related injuries from June to September, 1998 and 2003, in Central

Italy using meteorological data from one weather station [5]. Using aluminum smelter company health and safety records combined with hourly weather data (outdoor heat index was used as a surrogate for indoor heat exposure) to assess the relationship between heat and injuries in aluminum smelter workers, Fogleman et al reported increased odds of acute injuries above a heat index of 32°C [18]. Though Fogleman et al. reported that the indoor environment was open to the outside year-round, the relationship between indoor and outdoor heat exposure may not have been the same in all work areas, and different work areas may have had different risks for injury [18].

Subsequent studies have been observational time-series, case-crossover, and cross-sectional studies. A meta-analysis by Binazzi et al. of the three case-crossover and five time-series studies [7–14] published between 2000 and 2018 focused on workers in Canada, US, Australia, China, Spain, and Italy and reported a statistically significant increased pooled relative risk of occupational injuries with increasing heat exposure [15]. Binazzi et al's systematic review identified heterogeneity in exposure metrics and sources of bias in published observational studies but also identified potentially interesting subgroup effects. In the main meta-analysis, effect estimates were pooled across different risk estimates, including risk estimates per 1°C increase in daily maximum temperature in both time series and case-crossover studies [7,12], daily maximum humidex categories or °C above a maximum wet-bulb globe temperature (WBGT) threshold [10,11], and for exposures above a pre-determined percentile of daily average or max temperature in other time-series studies [13]. Except for one study [12], risk of bias related to recruitment strategy was generally probably low, but half of the studies had a high or probably high risk of bias related to exposure assessment [7,9,12,13], confounding [7,9,10,13], and incomplete outcome data [8,10,12,13]. Confounding was of particular concern in time-series studies, where unlike case-crossover studies, time invariant confounders are not addressed in the design. Excluding agriculture-specific studies [11,13], the pooled relative risk of occupational injuries was estimated to be 1.002 (95% CI 0.998–1.005) for time-series studies, using a random effects model, and 1.014 (95% CI 1.012–1.017) for case-crossover studies, using a fixed effects model, which was selected due to lack of heterogeneity. Subgroup pooled estimates showed increased risks of injury with increasing heat exposure for male gender, age less than 25 years, and agriculture (though not statistically significant). Differences in the effect of heat on injury by gender and age were hypothesized to be driven by differences in gender distributions in industrial sectors and differences in age distributions by level of experience, training, preventive behaviors, and physical exertion, respectively. There was no evidence of small-study effects or publication bias.

The existing literature has relied predominately on assumptions about work outdoors and on representative weather monitoring stations that may not adequately measure regional patterns in climate or differences between microclimates. To address these limitations, Calkins et al. conducted further work using an Occupational Information Network (O*NET) [19] approach to better characterize outdoor context along with high-resolution modeled meteorological data (~1/16th resolution grid [4km x 7.5km]) [16]. Calkins et al incorporated these methods into a case-crossover study of heat exposure and 63,720 outdoor construction workers' compensation injuries from 2000–2012 in WA, US [16]. The authors reported a 0.5% increase in the odds of outdoor construction traumatic injuries per one °C increase in humidex (odds ratio [OR] 1.005 [95% CI 1.003–1.007]) with a nearly linear association of humidex with the risk of a traumatic injury [16]. Risks were elevated even above a humidex of 21°C, which is currently considered to be comfortable and not deemed high enough to recommend prevention actions [20].

Though the nearly linear association observed by Calkins et al. in construction was consistent with some studies [7,8], it was contrary to the findings of Spector et al. in agriculture [11], Xiang et al. in all industries [9], and Morabito et al. in all local industries [5], who reported reversed u-shaped associations, with injury risk declining above a maximum daily humidex of 34°C [11], a maximum daily temperature of 37.7°C [9], and a maximum daily apparent temperature of 31.7°C [5], respectively. It has been hypothesized that the reversal of effects at the upper extremes of exposures are not the result of a true reduction in risk at high temperatures, but rather reflect changes in time at risk of a work injury, or overestimation of exposure on injury days, related to risk reduction practices used to prevent heat-related illness, such as ending work shifts early on the hottest days. This practice may be less feasible specifically in construction, where, for example, noise ordinances prohibit construction activities outside of typical business hours.

In comparison with a similar case-crossover study in agriculture in the same state [11], ORs in agriculture were higher than Calkins et al.'s construction ORs at lower humidex values, potentially due to differences in safety culture, task-related hazards, and piece-rate pay in agriculture. Further work is needed to better characterize the work environment by task, job site, or other factors that could improve categorization of indoor and outdoor contexts, verify whether tasks performed on the day of injury occur outdoors, and address limitations of workers' compensation data such as likely under-reporting. Yet these studies suggest important differences in risk profiles by industry and other factors, which are critical to understand and address when tailoring prevention efforts.

There have been few studies that have examined the relationship between heat exposure and injury risk in low- and middle-income tropical countries, where rapid urbanization and the cash economy drive heavy workloads in very hot and humid conditions. A cross-sectional analysis published by Tawatsupa et al. in 2005 examined survey data from 58,495 paid workers in Thailand using self-reported data on heat stress (exposure to uncomfortable high temperatures in the past year) and injuries (serious injuries that occurred at the workplace) [6]. The study reported an increased risk of injury (adjusted OR 2.12, 95% CI 1.87–2.42 for males, and adjusted OR 1.89, 95% CI 1.64–2.18 for females) among participants who reported being exposed to heat stress often, compared to never/rarely exposed. A statistically significant dose-response relationship in injury risk was observed for increasing exposure categories (never/rarely, sometimes, and often) in both males and females. Though the Tawatsupa et al. study is subject to biases related to its cross-sectional survey design, reliance on self-reporting of both exposure and outcome potentially producing correlated errors, and missing information about the time and location of heat exposure relative to injury, it provides a rare window into heat-related occupational injuries in tropical, rural settings.

Though these studies, taken together, suggest an association between occupational heat exposure and occupational traumatic injuries, findings must be interpreted with several important limitations in mind. First, exposure assessment has relied on the most accessible heat exposure metrics such as those based air temperature and humidity rather than net heat exposure, or heat stress, which includes metabolic heat generation from heavy physical work, environmental factors such as air temperature, humidity, wind, and solar radiation, and clothing. Second, the use of administrative data sources such as workers' compensation claims data, which rely on recognition and reporting, as the source of injury outcomes data in many of these studies may result in incomplete capture of all injury cases, particularly less severe cases.

Potential mechanisms for the association between occupational exposure to heat and traumatic injuries

Mechanisms underlying the relationship between occupational exposure to heat and traumatic injuries are not fully elucidated, and most mechanistic studies have been performed in controlled laboratory settings. Several mechanisms have been investigated, including: impaired balance [21–24]; changes in safety behavior [25]; muscle fatigue [23,26,27] and dehydration [22,28], particularly in conjunction with one another; poor sleep or sleepiness [29–31]; inadequate acclimatization [32], which can be influenced by inadequate acclimatization schemes or work organization; and unsafe work behaviors, though it is unclear whether this finding is related to effects on cognitive performance or behaviors related to discomfort and irritability under heat stress conditions [25].

Research in exercise, human physiology, and occupational settings report heat-related changes in cognitive performance [33,34] and psychomotor vigilance [28], which may influence mental status, dexterity for complex motor tasks, and response time after exercise or in conditions of hyperthermia [23,26,28,35–37]. These effects may in turn increase the risk of occupational injury [27,33,38]. Ambient temperature increases are thought to initially improve cognitive performance before having deteriorative effects beyond some temperature threshold [39–41]. Complex tasks are more susceptible to effects of heat stress [37,42–44]. While short bouts of low or moderate activity can improve performance on simple or complex cognitive tasks [39,45,46], longer and more intense bouts of activity, dehydration, and thermal comfort can decrease it [37,43,47–49]. Potential pathways of cerebral impairment caused by heat stress include reduced blood flow due to high demands on the cardiovascular system related to dehydration and evaporative cooling [50].

A cross-sectoral (public health and conservation) series of studies in agricultural communities in East Kalimantan, Indonesia sought to address the gap in the literature on heat exposure and cognitive performance in tropical rural industrializing settings. An experimental study from this series randomized 363 acclimatized, adult workers in rural communities to deforested versus forested settings to perform a representative work task for 90 minutes [51]. Scores on a validated general cognitive assessment test (range: 1–18) and episodic memory test (range: 1–10) were compared in participants performing a generalizable task in a deforested compared to a forested area. Participants in deforested settings answered, on average, one less question (−0.94, 95% CI: −1.80- −0.19) or recalled one word less (−0.88, 95% CI: −1.50- −0.20) on the tests, respectively, with stronger effects in male compared to female participants [52], and also spent up to an average of 5.17 more minutes with an estimated core body temperature exceeding 38.5°C [51]. While the mechanism of heat exposure's effects on traumatic injuries is still under investigation, heat effects on cognition have been demonstrated in different settings, including field settings, internationally.

Implications and future directions

Current evidence suggests an association between heat exposure and occupational injuries, and there are plausible potential mechanisms for this association. Effect estimates and risk profiles of heat-related occupational injuries differ in different industries and settings, suggesting a need to tailor prevention approaches in different settings. Heat exposure does not occur in a vacuum – the built and natural environment, the regulatory environment, and other factors will continually affect the level of heat exposure and therefore risks to heat-related occupational health, including occupational injuries. In addition, the risk of adverse occupational health effects caused by heat exposure is likely to increase as mean temperatures, in addition to the frequency and severity of heat waves, are projected to increase in the future with climate change [53–55]. Focusing on heat-related injury prevention efforts at the individual or workplace level is important, but factors beyond the worker and workplace must be considered to achieve a larger impact.

Existing approaches to the prevention of adverse heat effects—Two frameworks that have been used to guide intervention development for the prevention of heat health effects relevant to heat-related injuries are: 1) the traditional hierarchy of controls framework (Fig. 1a); and 2) the social-ecological model (SEM) [56] (Fig. 1b). The hierarchy of controls is a framework rooted in industrial hygiene that characterizes hazards – in this case, heat stress – into categories of elimination/substitution, engineering controls, training & administrative controls, and personal protective equipment (PPE) on a continuum of 'strongest' (e.g. elimination) to 'weakest' (PPE use, which relies on individual behavior) [57]. Care must be taken not to introduce risk factors for other adverse occupational health outcomes while attempting to reduce heat exposure. For example, changing work organization to include night work in order to reduce heat exposure may introduce risk factors for injuries such as reduced visibility and disruption in sleep.

The hierarchy of controls has been appropriately informed by research in specific industries and working populations in order to tailor heat stress controls to these workers. For example, qualitative work in Latinx agricultural workers in the US suggests that heat prevention training that does not address certain beliefs may not be effective [58]. These findings have been integrated into heat training materials for this population [59,60]. However, training is not a strong control per the hierarchy of controls, and the effectiveness of integrating findings on the relationship between heat exposure and traumatic injuries on reductions in injury outcomes has not yet been demonstrated.

Though the hierarchy of controls remains a useful framework, it is not sufficient for addressing factors outside the workplace that may also influence occupational health. Recent work underlines the importance of addressing occupational and ‘non-occupational’ factors with the goal of improving well-being [61,62] and addressing larger global trends in the nature of occupational health [63]. The SEM, which has been adapted for occupational health, addresses this gap by incorporating not only individual, inter-personal, and employer-level factors but also community-level factors, with the underlying premise that addressing only one level is not sufficient [64]. Studies evaluating heat-related injury prevention interventions aimed at multiple levels simultaneously, within and outside the workplace, have not yet been published.

Though neither is sufficient, the hierarchy of controls and SEM frameworks inform one another. For example, approaches that target SEM levels that rely on individual behavior are usually not as effective as those that do not, as indicated by the hierarchy of controls. Most workplace controls occur at the employer SEM level, though effective PPE use also relies on personal behavior at the individual SEM level. Importantly, many aspects of prevention are beyond the control of an individual worker, and intervention approaches must therefore ultimately address overarching policies or other systemic changes at the workplace and other levels (Fig. 1).

Expanded approach to enhance impact—The strongest control in the hierarchy of controls is hazard elimination, or at least reduction, yet this is minimally integrated into the current prioritization of heat prevention interventions, at least for outdoor workers. In existing climate change and occupational health frameworks, factors such as deforestation and urbanization are acknowledged as contextual factors, and resulting increases in ambient temperatures drive research, surveillance, and risk assessment and management priorities [65]. We propose to expand current approaches by bringing these contextual factors into direct consideration in the prioritization of prevention approaches. More specifically, we propose incorporating conservation-informed land use planning and built environment considerations (Fig. 1c), in addition to hierarchy of controls and social-ecological approaches, the relationships between them, and relevant policies and plans, into the prioritization of prevention approaches (Fig. 1). Notably, conservation-informed land use planning and built environment changes include system-wide changes that may extend geographically and politically beyond the highest (community) SEM level. This expanded approach (Fig. 1c) could be used specifically to prioritize heat-related injury prevention efforts.

Prioritized approaches should better address the source of heat exposure and should focus on populations disproportionally exposed to and/or vulnerable to excessive heat – now and in the future. This includes populations experiencing local climate disparities as well as populations directly affected by large-scale land-use decisions such as tropical deforestation in developing countries, which can ultimately also affect workers in developed countries through global temperature changes. For example, low-latitude, poorer, tropical countries are already experiencing hot, humid climates and are projected to have the most extreme future temperatures [66–68]. Though there may be more flexibility in work organization in subsistence compared to industrial agricultural settings, agricultural populations in these countries, particularly in small-holder agricultural settings, may have limited adaptive capacity and infrastructure (e.g., electricity, running water, and full-service health centers) to address adverse health effects from increasing temperatures [69]. Yet, there are over 570 million households farming on small agricultural plots (<10 hectares), primarily for subsistence purposes, globally [70].

Although heat stress is not as pronounced in certain developed countries as it is in tropical developing countries, vulnerability factors still contribute to local heat health disparities. In Washington State (WA), US, a project integrating on-the-ground experiences and perspectives of community members with published research identified factors contributing to disparities in how WA communities experience and cope with the climate change-related hazards [71]. These factors included population characteristics, such as race/ethnicity, wealth, educational attainment, occupation, political voice and the strength of community organizations [71]. Communities of color, indigenous peoples, communities with lower incomes, and Latinx agricultural workers tended to face the greatest risks of adverse effects of climate change [71].

We now give one example of conservation-informed land-use planning in a rural tropical setting and one example of a built environment approach in an urban setting, noting hierarchy of controls and SEM considerations for both, though we acknowledge that there are many other examples. Conservation-informed land-use planning in this context involves first identifying the most promising land-use strategies from a conservation perspective that may also reduce the risk of adverse health effects. Different land-use scenarios that involve forests in rural tropical subsistence settings could influence occupational health through a combination of local cooling in the short term (i.e. shade as an ‘engineering’ control at the community/employer SEM levels, combined with appropriate administrative controls such as avoiding work during the hottest part of the day) *and* contributions to climate change mitigation (i.e. reduction in heat exposure itself, including outside of the rural tropical area) in the long term. In rural tropical areas, forests can play a role not only in local cooling but also in climate change mitigation [72]. Importantly, forests provide cooling services through evaporation and transpiration [73,74]. A study in East Kalimantan, Indonesia, found that ambient temperatures were 2.6–8.3 °C cooler in forests compared to open (deforested) areas [75]. Forests also absorb greenhouse gases, and their exceptionally high carbon sequestration means that conserving these habitats is critical for achieving global emissions goals and contributing to climate change mitigation [76]. Comparisons of projected effects of different land-use scenarios under different future climate scenarios on health and economic outcomes could inform local decision-making if appropriately disseminated. Not only could implementation of conservation-informed land-use planning that is beneficial to health influence occupational health and well-being, but it also aligns with international climate goals, including the Paris Agreement and the United Nation’s Sustainable Development Goals [68]. Importantly, public health considerations also offer an opportunity to strengthen the case for tropical forest conservation. The connection between forest health and human health is likely to be more locally resonant than the more traditional conservation arguments which focus on biodiversity or carbon storage – arguments that have failed to halt deforestation trends [77].

Notably, this type of work involves multi-stakeholder partnerships, which is already an integral approach in modern occupational health and has been acknowledged as critical for addressing the effects of climate change on occupational health and safety [65,78]. Translation of this work into practice also involves transdisciplinary collaboration between sectors, such as between conservation and public health, which entails investment in novel approaches to cultivating partnerships, convening and managing diverse teams, ensuring all have an equal voice, and investing in learning skills that are not currently covered in most training programs [79]. The participation of occupational health experts in these conversations is critical to ensuring occupational health considerations are included in decision-making.

An example in an urban setting combines elements of the built environment with the well-established concept of prevention through design, where prevention considerations are included up front in designs, processes, and work organization that impact workers [80]. In particular, roofing construction workers are often exposed to ambient heat as well as high metabolic demands, and depending on the process used, they are additionally exposed to point-sources of heat. Common processes in commercial roofing settings include built-up roofing, which involves hot tar from a kettle, torch-applied roofing, and single-ply roofing, which involves adhesives and solvent and sometimes also hot-air equipment. In an urban setting, in addition to heat exposure from roofing tasks and point-sources of heat, roofers may be exposed to heat from urban heat island effects at work and at home. To best protect worker health and promote well-being, city- or higher-level adaptation strategies that account for the roofing process type (e.g. prioritizing processes with the least worker heat exposure from point sources, along with appropriate engineering and administrative heat controls, at the employer SEM level) *and* the degree to which the type of roof may reduce urban heat island effects (e.g. prioritizing cool roofs [81]), while taking care not to substitute other serious hazards for heat in the alternative process, could be prioritized if practical. This type of approach would also require transdisciplinary collaborations and again underlines the importance of ensuring occupational health experts are at the table with urban planners, the construction community, and other key stakeholders.

Conclusions

Studies suggest an association between heat exposure and occupational injuries, with different risk profiles in different industries and settings. There is a need to address the burden of occupational heat health effects, particularly given projected increases in mean temperatures and extreme events that may increase risks of adverse heat health effects and enhance disparities. To enhance impact, prioritization of prevention approaches should not only consider the hierarchy of controls in the workplace, SEMs, local and global climate disparities, community and stakeholder participation, and tailoring of prevention approaches to specific local work settings, but should also consider approaches that better address the source of heat exposure, beyond the worksite. These approaches include conservation-informed land use planning, built environment, and prevention through design approaches that align with larger national research agendas and international climate goals. It is critical that occupational health experts are at the table for these transdisciplinary discussions and initiatives, which require novel approaches to cultivating partnerships, convening and managing diverse teams, investing in learning, and ensuring all have an equal voice.

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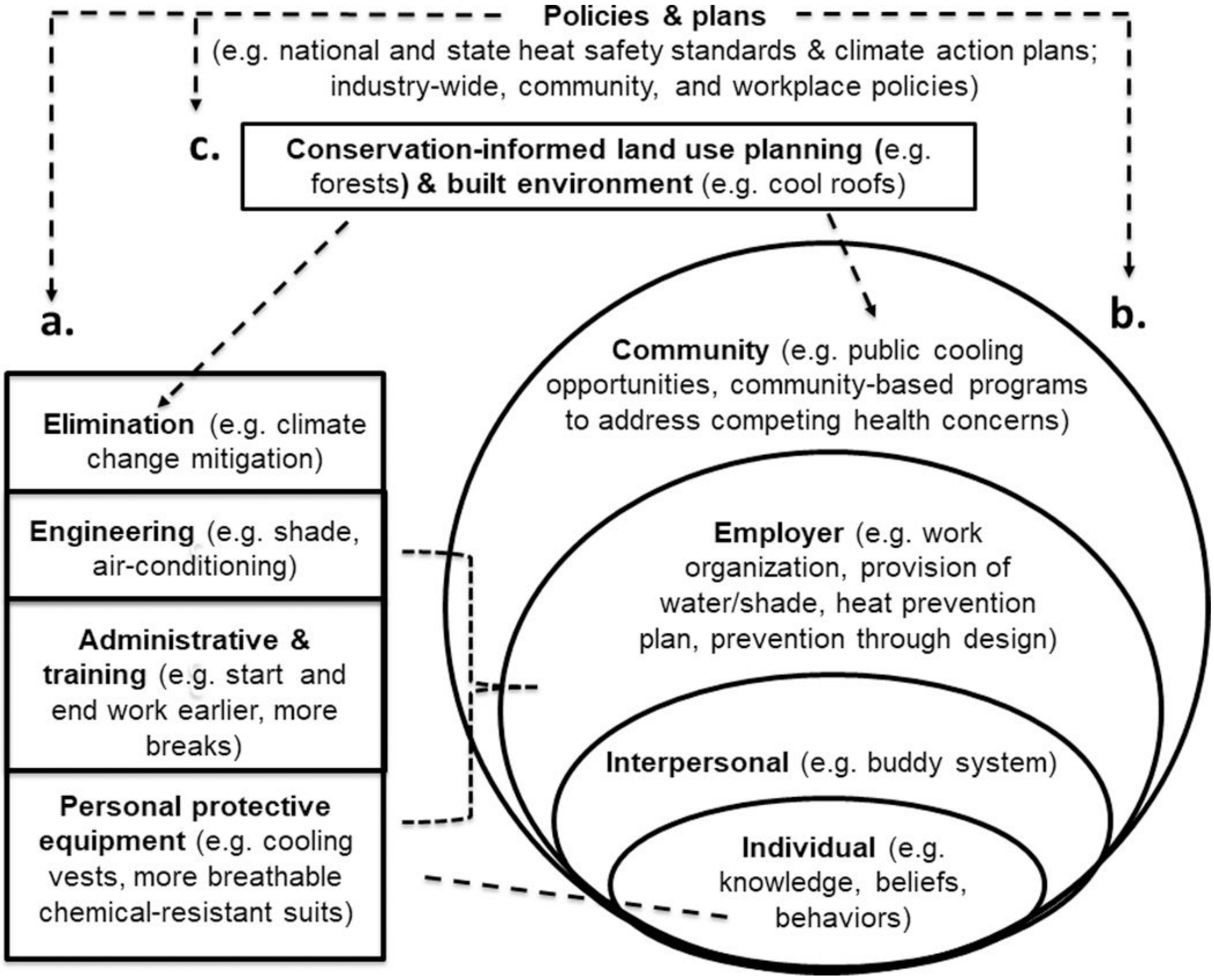

Fig. 1.

Different frameworks applicable to the prevention of adverse heat health outcomes for use in prioritizing prevention approaches in populations disproportionately exposed to and/or vulnerable to excessive heat now and in the future, locally and globally: **a** hierarchy of controls; **b** social-ecological model; and **c** a + b + additional elements of conservation-informed land use planning and built environment. Potential relationships between elements, including overarching policies and plans, are shown with dotted lines/arrows

Table 1.

Studies on the relationship between heat exposure and occupational injuries

Reference	Design/ data structure	Geo-graphical scope	Heat exposure metric; data source	Outcome metric; data source	Study population	Time-frame	Analysis	Results summary
Fogleman et al. 2005	Time-Series	Aluminum smelting plant in the Midwestern US	Hourly outdoor heat index; regional outdoor dry bulb temperature and relative humidity	Acute injury (first aid and recordable cases); company health and safety records	Aluminum smelter workers	1997–1999	Poisson regression, logistic regression	>32°C to ≤38°C OR 2.28 (95% CI 1.49, 3.49), >38°C to ≤43°C OR 3.52 (95% CI 1.86, 6.67)
Morabito et al. 2006	Time-Series	Tuscany, Italy	Maximum and mean daytime apparent temperatures; air temperature, relative humidity, wind velocity from one weather station	Work-related accidents/ injuries; inpatient hospital discharge data	Workers in all industries	1998–2003, June, July, and Sept.	Kruskal-Wallis H test with chi-squared approxima-tion	Reverse U-shape for mean injuries by mean daytime apparent temperatures; mean (standard deviation) number of injuries per quartile of mean daytime apparent temperatures: <22.1°C: 1.6 (1.4); 22.1–24.9°C: 1.7 (1.4); 24.9–28.3°C: 1.9 (1.5); ≥28.3°C: 1.4 (1.4); chi-squared=8.3, P=0.039
Tawatsupa et al. 2013	Cross-sectional	Thailand	How often experienced uncomfortable high temperatures in past 12 months (often, sometimes, rarely, never); self-reported survey	Self-reported serious occupational injury (interfered with daily activities and/or required medical treatment) in past 12 months; self-reported survey	Thai Cohort Study participants who reported working for income	2005	Logistic regression	ORs (compared to rarely/never): often OR 2.12 (95% CI 1.87, 2.42), sometimes OR 1.54 (95% CI 1.36, 1.74) for males; often OR 1.90 (95% CI 1.64, 2.18), sometimes OR 1.24 (95% CI 1.08, 1.42) for females. P value for trend (both genders) < 0.001.
Xiang et al. 2014	Time-series	Adelaide, Australia	Daily T_{max}; one weather station	Work-related injury; workers' compensation claims	Workers in all industries	2001–2010, Oct.-March	GEE with piecewise linear spline	Reverse U-shape; Per 1°C increase in T_{max} between 14.2 °C and 37.7 °C: all industries (IRR 1.002, 95% CI 1.001, 1.004), construction (IRR 1.006, 95% CI 1.002, 1.011), agriculture (IRR 1.007, 95% CI 1.001, 1.013), electricity/gas/ water (IRR 1.029, 95% CI 1.002, 1.058)
Adam-Poupart et al. 2015	Time-series	Quebec, Canada	Daily T_{max}; one weather station per region	Acute work-related injury; workers' compensation claims	Workers in all industries	2003–2010, May-Sept.	GLM	Per 1°C increase in T_{max}: all (IRR 1.002, 95% CI 1.001, 1.003), construction (IRR 1.003, 95% CI 1.000, 1.006), forestry/ logging/support (IRR 1.011, 95% CI 1.001, 1.020), transportation/warehousing (IRR 1.005, 95% CI 1.001, 1.009)
Spector et al. 2016	Case-crossover	Eastern Washington State, US	Daily humidex_{max}; modeled grid from weather stations (approx. 7.0 by 4.5 km resolution)	Traumatic work-related injury; workers' compensation claims	Agricultural workers	2000–2012, May-Sept.	Conditional logistic regression	Reverse U-shape; OR 1.14 (95% CI 1.06, 1.22), 1.15 (95% CI 1.06, 1.25), 1.10 (95% CI 1.01, 1.20) for humidex_{max} 25–29, 30–33, and ≥ 34, respectively, compared to <25°C

Reference	Design/ data structure	Geo-graphical scope	Heat exposure metric; data source	Outcome metric; data source	Study population	Time-frame	Analysis	Results summary
Garzon-Villalba et al. 2016	Time-series	Deepwater Horizon disaster clean up, including from bases in five southern US states	Daily $WBGT_{max}$; estimated from dry bulb temperatures and average due point temperatures from weather stations	Acute work-related injury; employer-generated incident forms	All workers	May 2010-March 2011	Poisson regression	Per °C-$WBGT_{max} > 20$: RR 1.13 (95% CI 1.09, 1.17)
McInnes et al., 2017	Case-crossover	Melbourne, Australia	Daily T_{max} and T_{min}; weather stations	Acute work-related injury; workers' compensation claims	Workers in all industries	2002–2012, Nov.-Mar.	Conditional logistic regression	Per 1°C increase in T_{max}: OR 1.008 (95% CI 1.001, 1.015) and 1.008 (95% CI 1.001, 1.016) in young (<25 years) workers and heavy (>20 kg) physically demanding jobs
Martinez-Solanas et al., 2018	Time-series	Spain	Daily T_{max} and T_{min}; one weather station per municipality	Work-related injury; registry of occupational injuries (Spanish National System provided by Spanish Labor Administration)	Workers in all industries	1994–2013, May-Sept.	Distributed lag nonlinear models, pooled using multi-variate meta-regression	2.40% (95% CI 2.09, 2.68) of all occupational injuries attributed to heat
Ricco, 2018	Time-series	Trento, Italy	Daily T_{max} and average temperature; weather stations	Work-related injury; workers' compensation claims	Agricultural workers	2000–2013, May-Sept.	Poisson regression	OR 1.12 (95% CI 1.01, 1.24), 1.13 (95% CI 1.01, 1.25) for average temperature >95th percentile, compared to <75th percentile for lag 0 and lag 1, respectively; OR 1.14 (95% CI 1.03, 1.27) for T_{max} >95th percentile, compared to <75th percentile
Sheng et al., 2018	Case-crossover	Guangzhou, China	Daily T_{max} and T_{min}; weather stations	Work-related injury; workers' compensation claims	Workers in all industries	2011–2012, May-Oct.	Conditional Poisson regression	Per 1°C increase in T_{max}: RR 1.014 (95% CI 1.012, 1.017); RR manufacturing 1.019 (95% CI 1.015, 1.022); RR finance, property, and business services 1.014 (95% CI 1.009, 1.019)
Calkins et al., 2019	Case-crossover	Washington State, US	Daily $humidex_{max}$; modeled grid from weather stations (approx. 7.0 by 4.5 km resolution)	Traumatic work-related injury; workers' compensation claims	Outdoor construction workers	2002–2012	Conditional logistic regression with linear spines	Per 1°C $humidex_{max}$: OR 1.005 (95% CI 1.003, 1.007)

Confidence Interval (CI); Generalized Estimating Equations (GEE); Generalized Linear Models (GLM); Incidence Rate Ratio (IRR); Odds Ratio (OR); Maximum daily humidex ($Humidex_{max}$); Maximum daily temperature (T_{max}); Minimum daily temperature (T_{min}); Relative Risk (RR); United States (US); Maximum wet bulb globe temperature ($WBGT_{max}$)