Occupational heat exposure and injury risk in Washington State construction workers

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Abstract

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Introduction: The primary objectives of this research were to: 1) assess the relationship between heat exposure and occupational traumatic injuries in Washington State; and 2) assess heat exposure and the relationship between heat stress and psychomotor vigilance and balance in a population at high risk for injuries and heat related illness.

Methods: We conducted an epidemiologic study and a field study. First, we assessed the relationship between maximum daily humidex and Washington State Fund workers' compensation injuries in outdoor construction workers from 2000-2012 using a case-crossover design and high-resolution meteorological data. Second, we collected full-shift measurements of heat exposure and tests of psychomotor vigilance and balance in a sample of 22 commercial roofing workers in the Greater Seattle area in a repeated-measures study during the summer and fall of 2016. Heat exposure was compared across three spatial resolutions (regional, area, and personal). The association between heat stress, specifically the mean one-hour difference between the worksite wet bulb globe temperature and the recommended exposure limit (ΔREL), and PVT and balance outcomes were modeled using linear GEE.

Results: We observed a traumatic injury odds ratio (OR) in outdoor WA construction workers of 1.0053 (95% CI 1.003, 1.007) per °C change in humidex. We report a positive mean (95% confidence interval) difference between personal- and area-level temperature of 4.4 (4.1, 4.7)°C. The direction of the difference between regional and area monitors varied by site. We observed a positive (detrimental) association (0.3; 95% CI -3.0, 3.5) and a negative association (-0.9; 95% CI -1.7, -0.1) between heat stress and PVT and balance, respectively. Post hoc interaction analyses of heat stress and dehydration yielded positive associations of heat stress with psychomotor outcomes.

Conclusion: In the case-crossover study, increasing humidex was associated with increasing traumatic injury risk. In the field study of commercial roofing workers, personal temperature measurements were consistently higher than area temperature measurements, and the difference between regional and area temperatures varied in direction by site. No decrements in psychomotor vigilance or postural sway were observed with the low levels of heat stress measured in this study, however dehydration may modify this effect.

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LIST OF ACRONYMS

ACGIH	American Conference of Governmental Industrial Hygienists	
ANSI	American National Standards Institute	
BMI	Body mass index	kg/m^2
BW	Body weight	kg
CIG	Climate Impacts Group	
ET	Effective temperature	°C
FTE	Full-Time Equivalence	
GHCN	Global Historic Climate Network	
HI	Heat Index	
HR	Heart rate	bpm
HR_{max}	Maximum heart rate (220-age in years)	bpm
HRI	Heat related illness	
ISO	International Organization for Standards	
kcal	Kilocalories	$k \cdot cal^{-1}$
L&I	Labor and Industries	
MET	Metabolic equivalent	1 kcal/kg/hour
NAICS	North American Industry Classification System	
NIOSH	National Institute for Occupational Safety and Health	
OEL	Occupational Exposure Limit	
OIICS	Occupational Injury and Illness Classification System	
OSHA	Occupational Safety and Health Administration	
PRISM	Parameter-elevation Relationship of Independent Slopes Model	
PVT	Psychomotor vigilance test	
RAL	Recommended Action Limit	
REL	Recommended Exposure Limit	
RH	Relative humidity	%
SACHS	Standards Advisory Committee on Heat Stress	
T_a	Dry bulb temperature	°C
T_g	Globe temperature	°C
T_{gi}	Gastrointestinal temperature	°C
T_{nwb}	Natural wet bulb temperature	°C
T_{sk}	Skin temperature	°C
TLV	Threshold Limit Value	
TWA	Time weighted average	
SHARP	Safety and Health Assessment and Research for Prevention	
SIC	Standard Industrial Classification	
SOC	Standard Occupational Classifications	
WBGT	Wet bulb globe temperature	°C-WBGT

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DEDICATION

This dissertation is dedicated to Jake.

Chapter 1. INTRODUCTION

1.1 Burden of occupational traumatic injuries in the construction industry

Traumatic injuries are a substantial contributor to the burden of work-related injuries and illnesses in the construction industry. Reducing these injuries remains a high priority for occupational safety and health research (N. J. Anderson, Bonauto, & Adams, 2013; NORA Construction Sector Council, 2008). The lifetime risk of a fatal injury in construction tradesworkers is estimated, based on data from 2003-2007, to be 0.506%, or approximately one fatality in every 200 full-time equivalent (FTE) workers over 45 years of work (Dong, Ringer, Welch, & Dement, 2014). It is estimated that the direct cost from falls from heights at work amount to approximately $50,000 per injury, with higher costs estimated for roofing workers at $106,000 per injury (Occupational Safety and Health Administration, 2012). Considerable progress has been made in identifying factors that contribute to injury risk, addressing barriers to injury prevention, and designing interventions to reduce the risk of traumatic injuries in construction (N. J. Anderson et al., 2013; Garrett & Teizer, 2009; Holizki, McDonald, & Gagnon, 2015; Ozmec, Karlsen, Kines, Andersen, & Nielsen, 2015; Schoonover, Bonauto, Silverstein, Adams, & Clark, 2010; Siu, Phillips, & Leung, 2003; Strickland, Wagan, Dale, & Evanoff, 2017; Suárez Sánchez, Carvajal Peláez, & Catalá Alís, 2017). However, injury rates remain high. A better understanding of additional factors that contribute to injury risk may ultimately inform the development of more effective injury prevention efforts.

Each year in the State of Washington, approximately 108,000 workers experience a non-fatal work related injury (L&I, 2016). In recent years, the non-fatal work-related injury incidence rate has been about 5.0 per 100 FTE workers, with a higher rate among construction workers (6.5 to 7.4 per 100 FTE) (L&I, 2016). In Washington State, roofing workers in particular have some of the highest rates of work-related injuries (N. J. Anderson et al., 2013; Bonauto, Anderson, Rauser, & Burke, 2007; Schoonover et al., 2010) and heat related illnesses (HRIs), based on workers' compensation claims data (Bonauto et al., 2007). Occupational heat exposure has long been understood to increase the risk of HRIs such as heat stroke, which can be fatal (Bouchama & Nochel, 2002), and may also reduce work productivity (Sahu, Sett, & Kjellstrom, 2013; Sett & Sahu, 2014; Singh, Hanna, & Kjellstrom, 2015). However, further work is needed to better understand the relationship between heat exposure and other adverse health outcomes, such as traumatic injuries (Adam-Poupart et al., 2015; Garzon-villalba et al., 2016; Gasparrini et al., 2015; McInnes et al., 2017; Morabito, Cecchi, Crisci, Modesti, & Orlandini, 2006; Spector et al., 2016; Tawatsupa et al., 2013; Xiang, Bi, Pisaniello, Hansen, & Sullivan, 2014).

1.2 Human Thermal Experience

1.2.1 *Human heat balance*

The human body is designed to maintain a core temperature (T_c) of 37 °C ±1 for proper physiological and cellular function (Brengelmann, 1989). To accomplish this, thermoregulatory mechanisms are constantly adjusting in response to changing external thermal stimuli, metabolic heat production, and demands on physiological systems involved with maintaining or producing heat. Heat exchange between the human body and the surrounding environment can be described using a human heat balance approach (Eq 1.1):

$$S = M - (\pm W) \pm (R + C) \pm K - E, \quad 1.1$$

where S is the change in body heat, M is metabolic energy production, W is mechanical work, R is radiant energy exchange, C is convective energy exchange, K is conductive energy exchange, and E is evaporative heat loss (McGregor & Vanos, 2017; NIOSH, 2016; Michael N. Sawka, Leon, Montain, & Sonna, 2011). A worker is considered to be in a state of heat stress when the net lead load could result in increased storage of heat in the body (NIOSH, 2016).

Radiant, convective, and conductive energy are considered to comprise environmental heat components. In many occupational settings, environmental conditions of greatest relevance to human heat balance include radiant energy, consisting of the solar radiation or point sources of radiant heat, and convective energy from the surrounding air. Wind, while not directly included in the energy transfer equation above, can facilitate removal of heat from the surface of the skin into the environment if the skin temperature is greater than the air temperature.

Metabolic energy production is another important contributor to human energy balance in occupational settings. The human body releases heat from metabolic processes at a rate of about 4.8 kcal/1L oxygen (O_2) consumed, assuming a typical diet (Brengelmann, 1989). At rest, the average adult consumes approximately 3.5 ml O2/kg BW/minute, resulting in an average resting energy expenditure, also referred to as the basal metabolic rate, of 1 kcal/kg/hour (Brengelmann, 1989; Hills, Mokhtar, & Byrne, 2014). This resting rate is used to define one unit of the commonly used Metabolic Equivalent of Task (MET) metric, a metric used to describe the energy demands of different physical activities in a simplified format (Crider, Maples, & Gohlke, 2014). .

Physical exercise increases oxygen consumption and metabolic heat production. Contraction of skeletal muscle is relatively inefficient, resulting in the release of approximately 80% of energy as heat (Michael N. Sawka et al., 2011). Depending on exercise intensity and efficiency of oxygen consumption, metabolic heat production can increase by three to twelve times the resting rate. Metabolic heat production is ideally measured using direct calorimetery. However, metabolic heat estimates using observational methods and devices that measure movement have been developed to facilitate use of heat stress recommendations in practice and research in populations where calorimetry is not possible.

1.2.1.1 Heat indices

A number of indices exist to describe how humans experience the thermal environment. Direct indices rely solely on measurements of environmental conditions, while empirical indices are based on tested physiological responses and often incorporate metabolic heat (McGregor & Vanos, 2017). Simple empirical indices such as the Heat Index (HI) (G. B. Anderson, Bell, & Peng, 2013; NIOSH, 2016) and Humidex (Canadian Centre for Occupational Health and Safety., 2011) utilize measures of dry air temperature (T_a) and relative humidity (or dew point temperature) to describe the thermodynamic temperature and evaporative cooling potential, respectively. More involved empirical indices, such as the wet bulb globe temperature (WBGT) (American Conference of Governmental Industrial Hygienists, 2015; NIOSH, 2016; Parsons, 2013), additionally incorporate solar radiation and air movement. Rational indices such as the Thermal Work Limit (TWL) and the Universal Thermal Climate Index (UTCI) include more complex models of heat budgets (G. B. Anderson et al., 2013; NIOSH, 2016).

Clothing acts as an insulator between the human body and surrounding environment, limiting exchange of convective, radiative, and conductive energy as well as evaporative cooling. In occupational settings, personal protective equipment, such as impermeable (vapor-barrier) coveralls used to protect a worker from chemical hazards, may significantly impede heat exchange. To account for clothing, clothing adjustment factors (CAFs) that take into account increased or decreased thermal exchange potential have been developed and are used to adjust empirical indices (Bernard & Ashley, 2009).

1.2.2 *Body temperature and thermoregulation*

Heat strain describes the physiological state where the body attempts to increase removal of heat to the environment to maintain homeostasis. The target human core body temperature (T_c), also referred to as a "set-point," is 37 °C. T_c is somewhat of an elusive value for monitoring because temperature is not consistent throughout the body. T_c is ideally measured from the mixed venous blood in the right ventricle or pulmonary artery (T_{pa})—a location that is difficult to access (Brengelmann, 1987). Traditionally, surrogate measurement sites for T_c have included rectal temperature (T_{re}), esophageal temperature (T_{es}), and oral temperature (T_{or}). Bladder temperature (T_{ur}) has been used in some medical settings. Since the advent of wireless ingestible gastrointestinal temperature (T_{gi}) sensors, the use of T_{gi} measurements is increasingly common in research. Tympanic temperature (T_{ty}), measured by placing a probe next to the ear drum, has also been used as a surrogate for T_c (Benzinger, 1961). Accessibility to measurement sites using conductive devices (e.g. thermistors) as well as accuracy of the measurement in relation to true T_c has guided preferences for body site selection. T_{es} and T_{ty} respond quickly to changes in T_c but require potentially uncomfortable probe placement in areas where the risk of infection or damage to peripheral systems is of concern. T_{ty} requires consistent probe placement, which can be difficult to maintain in active subjects, such as workers performing tasks. T_{re} responds relatively slowly to changes in T_c (Brengelmann, 1987) and requires more invasive monitoring. The development of infrared (IR) technology for measuring T_c, for example over the forehead (temporal artery), has added further options for accessibility to measurement sites (Shinozaki, Deane, & Perkins, 1988), but is generally regarded to be less accurate than conductive tools. Under conditions of high thermal stress, thermoregulation primarily involves removal of heat from the body through sweating and cardiovascular adjustments.

1.2.2.1 Sweating

Sweating is the primary mechanism for heat removal from the human body. Sweating facilitates the removal of heat from the skin's surface through evaporative cooling. Sweat rates of 0.3 to 1.2 L/hour are common in workers in very hot, dry climates, but sweating up to 2 L/hour while wearing protective clothing is not uncommon (Michael N. Sawka et al., 2011). The efficiency of sweating is driven by three factors: the hydration of the individual (i.e. availability of water for sweating purposes), the relative humidity of the air and local air movement, and the wettedness of the skin. For skin that is overly wetted, sweat that beads off the skin, rather than evaporates, and does not contribute to evaporative cooling (Michael N. Sawka et al., 2011). Studies have demonstrated that rehydration with electrolyte water is twice as effective as tap water when replacing fluid lost through sweat (Morimoto & Nose, 1987).

1.2.2.2 Core to skin gradient

In order to sweat, circulation of blood from warmer, central regions of the body (i.e. splanchnic) to the cooler surface (i.e. the skin) must occur. The difference, or gradient, between T_c and skin temperature (T_{sk}) is important for efficient removal of heat from the body; the larger the gradient, the more heat can be removed per unit of blood. Heat removal is accomplished by: (1) changing the rate of blood circulation (i.e. heart rate), (2) changing the vascular resistance of the circulatory system (i.e. vasodilation or constriction), and (3) changing the volume of blood circulated (i.e. stroke volume).

1.2.2.3 Heart rate

Resting heart rate in an average adult is between 40-100 beats per minute (bpm). The maximum heart rate (HR_{max}) is estimated as 220 (bpm) – age (years), or 195 bpm on average for adults (Bernard & Ashley, 2009). For heat removal, research has demonstrated that in response to an increase in T_{sk} from 33 to 35 °C during light-intensity exercise, the HR increases by approximately 26 bpm. Narrowing the gradient by an additional 1 °C (i.e. increasing T_{sk} from 33 to 36°C) nearly doubles the effect on HR, elevating it by approximately 49 bpm (Cheuvront, Kolka, Cadarette, Montain, & Sawka, 2003; Michael N. Sawka et al., 2011). In research described by Sawka et al. 2011 of runners with an elevated T_c of 38 °C, the whole body skin blood flow (SKBF) requirements quadruple (from 1.1 to 4.4 liters per minute) when the gradient reduced by 75% (from 8 to 2 °C).

1.2.2.4 Vascular resistance changes

Vasodilation and vasoconstriction facilitate and restrict the movement of blood, respectively. These processes are particularly important for increasing or decreasing blood flow to the skin, where under conditions of maximized cutaneous vasodilation, peak skin blood flow will range from 7 to 8 L/min (Rowell, 1987; Michael N. Sawka et al., 2011). When exercise causes competitive demand for available blood flow under conditions of heat stress, splanchnic (i.e. abdomen) vasoconstriction helps maintain adequate perfusion throughout the body, while cutaneous vasodilation maximizes contact with the surface.

1.2.2.5 *Stroke volume changes*

The stroke, or pump, volume (SV) is the amount of blood pumped through the body per heartbeat. The maximum achievable stroke volume is 128 ml, resulting in a maximum cardiac output (SV_{max} * HR_{max}) of nearly 25 L/min (Rowell, 1987; Michael N. Sawka et al., 2011). The stroke volume is affected by overall cardiovascular health and hydration.

1.2.2.6 *Acclimation and acclimatization*

Acclimation and acclimatization are important mitigators of heat stress. Acclimation refers to heat tolerance for a specific range in temperatures achieved through controlled, short-duration exposures to both heat and exercise. Acclimation is usually achieved within two weeks of high-heat and exercise regiments and is lost quickly if not maintained. Acclimatization describes overall physiological adjustment to a given climate. Physiological changes associated with acclimation and acclimatization primary involve optimization of plasma volume and sweating efficiency (Kielblock, 1987; Michael N. Sawka et al., 2011).

1.2.3 *Heat-related illnesses and overwhelmed thermoregulation*

When thermoregulatory adjustments are overwhelmed, T_c starts to rise above 37°C. Exercise complicates thermoregulatory processes by adding to the internally generated, metabolic heat and diverting blood away from the skin to the extremities and skeletal musculature (NIOSH, 2016; Michael N. Sawka et al., 2011). The potential adverse effects of heat stress range from mild discomfort to, for example in the case of heat stroke, death. Heat stroke is a type of HRI characterized by an increase in T_c. Signs and symptoms of HRI depend on the type of HRI (e.g. heat stroke, heat syncope, heat exhaustion, heat rash, etc.) and include fainting, dizziness, nausea, weakness, thirst, heavy sweating, elevated body temperature, altered mental status, seizures, hot and dry skin, rash, and muscle cramps (NIOSH, 2016).

Demographic and personal factors not already described that are known to relate to heat health effects include age, gender, body mass index, body surface area, and genetic factors. Medications and preexisting medical conditions, particularly those that affect thermoregulation (e.g. cardiovascular, dermal conditions affecting sweating), also increase the risk of adverse heat health effects. Behavioral risk factors include smoking, alcohol consumption, poor sleep, and certain illicit drug use (NIOSH, 2016; Michael N. Sawka et al., 2011).

1.3 Occupational guidelines and standards for heat exposure

Recommendations and regulatory standards have been developed for occupational settings to prevent HRI. These guidelines and standards vary in their exposure metrics used and control strategies recommended.

1.3.1 *Guidance from non-governmental organizations and professional societies*

The American Conference of Governmental Industrial Hygienists (ACGIH) provides Threshold Limit Values (TLV®) and Action Limits (AL) for occupational exposures that "represent conditions under which it is believed that nearly all heat acclimatized, adequately hydrated, un-medicated, healthy workers may be repeatedly exposed without adverse health effects" (American Conference of Governmental Industrial Hygienists, 2015). The goal of the ACGIH's TLV for heat stress is to maintain a core temperature within one degree of normal (37 °C) (American Conference of Governmental Industrial Hygienists, 2015) and is based on environmental conditions, metabolic heat load, and clothing. The TLV is often presented as a reference matrix for a given WBGT and metabolic load, however direct calculation of the TLV and AL from a metabolic load (described below) is identical to the approach used by the US National Institute for Occupational Safety and Health (NIOSH) for the Recommended Exposure Limit (REL) and Recommended Alert Limit (RAL), respectively. ACGIH guidance includes how to measure and calculate WBGT, adjust for clothing, calculate metabolic rate, identify MET rates for types of activities and general occupations, utilize work-rest cycles, identify and treat heat strain, and other heat control measures. These recommendations are also created with the average, healthy, adult, worker in mind. NIOSH has based many of its material on ACGIH recommendations.

The International Organization for Standardization (ISO) publishes guidance that is held in high regard and used internationally. The ISO has developed five documents applicable to occupational heat exposure (NIOSH, 2016).

ISO7243: Hot Environments—Estimation of Heat Stress on Working Man, Based on the WBGT-index (1989)

ISO7933: Ergonomics of the Thermal Environment: Analytical Determination and Interpretation of heat Stress Using Calculations of the Predicted Heat Strain (2004)

ISO8996: Ergonomics of the Thermal Environment: Determination of Metabolic Heat

ISO9886: Ergonomics: Evaluation of Thermal Strain by Physiological Measurements (2004)

ISO9920: Ergonomics of the Thermal Environment: Estimation of Thermal Insulation and Water Vapour Resistance of a Clothing Ensemble

Similar to the ACGIH, most of these documents use the WBGT as the metric for heat exposure and assume a “normal,” healthy, adult male wearing standard single-layer work clothes.

Other organizations with heat-health recommendations for active individuals include the American Industrial Hygiene Association (AIHA) and the American College of Sports Medicine (ACSM), which provide recommendations for working and exercising in the heat, respectively. The AIHA published its recommendation document in 2003, *The Occupational Environment: Its Evaluation, Control, and Management*, with threshold recommendations similarly based on a WBGT-workload matrix. The ACSM updated its position statement, *Exertional Heat Illness During Training and Competition*, in 2007 with recommendations based on WBGT and metabolic demands (running distance in km), and fluid intake.

1.3.2 *Governmental recommendations and regulations*

In the United States, the Occupational Safety and Health Administration (OSHA) and National Institute for Occupational Safety and Health (NIOSH) work closely together as regulatory and research agencies, respectively. Currently there are no federal-level regulations specifically governing occupational heat stress under OSHA's jurisdiction, but hazardous heat conditions can and have been cited using the General Duty Clause (OSH Act, 29 USC 654), which requires employers to provide "a place of employment free from recognized hazards." As early as the 1970s, OSHA and NIOSH were working to address occupational heat stress and both developed recommended thresholds based on the WBGT-workload approach developed by the US military and ACGIH. Since that time, OSHA and NIOSH have undertaken heat-health education campaigns and produced reference materials, including NIOSH's recently updated *Criteria for a Recommended Standard: Occupational Exposure to Heat and Hot Environments* (NIOSH, 2016).

The NIOSH REL for acclimatized workers and RAL for unacclimatized workers use the worker's metabolic rate in Watts (W) to calculate a threshold WBGT value (°C). The REL or RAL can then be used to adjust work-rest schedules. The calculations for the REL and RAL are below (Eqs 1.2 and 1.3) (NIOSH, 2016).

$$REL[°C - WBGT] = 56.7 - 11.5 log_{10} M \quad 1.2$$

$$RAL[°C - WBGT] = 59.9 - 14.1 log_{10} M \quad 1.3$$

where, M is the metabolic rate in Watts.

Three U.S. states have passed legislation protecting workers from occupational heat exposure:

Minnesota's Department of Labor and Industries, Occupational Safety and Health Division passed Minnesota Rule 5205.0110, subpart 2a for indoor heat stress in 1997 (Minnesota Depatment of Labor and Industry, 2012).

California's Heat Illness Prevention Standard was passed in 2006 (Title 8, Chapter 4, § 3395) and applies to all outdoor work (NIOSH, 2016).

Washington State's Department of Labor and Industries passed the Outdoor Heat Exposure Rule in 2008 (Ch. 296-62-095, WAC). This rule applies to all work performed outdoors between May 1st and September 30th (NIOSH, 2016; Washington State Department of Labor and Industries, 2008).

Both the Washington and California regulations provide enforceable requirements for worker training and stipulate control measures that must be in place for outdoor workers, but neither specifically requires prescribed work-rest schedules or thresholds beyond which work must cease.

Other sectors of the U.S. government with recommendations for occupational heat stress include the Department of Defense (DoD) and the Mine Safety and Health Administration (MSHA). The military is credited with creation of the WBGT index in the 1950s. WBGT was developed to reduce HRI in field training camps. Currently, the DoD has two documents addressing heat stress; *Heat Stress Control and Heat Casualty Management* (TBMED 507/AFPAM 48-52, 2003) and the Navy's Environmental Health Center's technical manual *Prevention and Treatment of Heat and Cold Stress Injuries* (2007). Both documents contain similar WBGT-metabolic activity matrixes as well as educational information on control measures and health (NIOSH, 2016). MSHA's *Heat Stress in Hot U.S. Mines and Criteria for Standards for Mining in Hot Environments* (1976) and Safety Manual number 6, *Heat Stress in Mining* (2001) provide criteria for keeping mine workers safe, include acclimation schedules and rotating tasks when conditions are above 26 °C.

Some of the most extreme examples of enforceable occupational heat stress regulations are from countries in the Middle East, including Saudi Arabia and the United Arab Emirates (UAE), where outdoor work is banned during the hottest few hours of the day for the entire duration of the summer months rather than requiring a minimum temperature to be in effect. In the UAE this ban has been in effect since 2005 and includes the hours of 12:30-15:00 from June 15 through September 15 (United Arab Emirates, 2015). In Saudi Arabia, the ban is more recent and includes the hours of 12:00-15:00 from July 1st through August 31st (Abdullah, 2012).

China also suspends outdoor work in extremely hot conditions, but their regulation is based on temperature thresholds rather than calendar dates or seasons. Implemented in 2012, the *Administrative Measures on Heatstroke Prevention* regulation stipulates that on days where temperatures are forecast to reach 40°C or greater, outdoor operations must be suspended; between 37 and 40°C, work may not exceed six hours and may not occur during the hottest three hours of the day; and at temperatures greater than 35 °C, water and rest areas must be provided (Zhao et al., 2016).

Canada has not passed occupational heat legislation, but has produced a number of guidance documents (Canadian Center for Occupational Health and Safety, 2005; Occupational Health and Safety Council of Ontario, 2007) that contain recommended thresholds, control strategies, and health information. Similar to OSHA's General Duty Clause, employers in Canada are required to "take every precaution reasonable in the circumstances for the protection of a worker" (Canada's Occupational Health and Safety Act section 25(2)(h)) and could be cited for unsafe hot work environments. The Canadian Ministry of Labour recommends the ACGIH TLVs as reference values using WBGT, but also includes guidance criteria for heat stress evaluation using humidex (Occupational Health and Safety Council of Ontario, 2007).

1.4 OCCUPATIONAL HEAT-RELATED INJURY RISK

Occupational heat stress guidance and standards are based primarily on HRI risk. However, relationships between heat exposure and traumatic injuries have also been described (Adam-Poupart et al., 2015; Garzon-villalba et al., 2016; Gasparrini et al., 2015; McInnes et al., 2017; Morabito et al., 2006; Spector et al., 2016; Tawatsupa et al., 2013; Xiang et al., 2014). Physiological mechanisms through which heat may affect injury risk include changes in psychomotor and cognitive performance (Ganio et al., 2011; Mazlomi et al., 2017; Sharma, Pichan, & Panwar, 1983), impaired balance (Erkmen, Taskin, Kaplan, & Sanioglu, 2010; Lion et al., 2010; Zemková & Hamar, 2014), altered mental status and mood (Ganio et al., 2011), changes in safety behavior (Ramsey, Burford, Beshir, & Jensen, 1983), muscle fatigue (Distefano et al., 2013; Rowlinson, Yunyanjia, Li, & Chuanjingju, 2014; Zemková & Hamar, 2014), poor sleep or sleepiness (Li et al., 2017; M. N. Sawka, Gonzalez, Pandolf, & B, 1983; Tokizawa et al., 2015), dehydration (Erkmen et al., 2010; Ganio et al., 2011), and inadequate acclimatization during training (Choudhry & Fang, 2008). Potential pathways of cerebral impairment caused by heat stress include reduced blood flow due to high demands on the cardiovascular system, cerebral edema, and neuron degeneration (Michael N. Sawka et al., 2011). Most of this research has been conducted in controlled settings where prescribed activity and conditions are tested for an effect on the outcome.

1.4.1 *Field studies*

Few studies have evaluated intermediate heat-injury outcomes in workplace settings. Changes in psychomotor vigilance (Mazlomi et al., 2017; Spector et al., 2018) and postural sway (Spector et al., 2018) have been assessed in different occupational populations experiencing different levels of heat stress with mixed results. Mazlomi et al, 2017 report an association between heat stress and slower reaction times in foundry workers working under conditions of high heat stress. Spector et al. 2017 reported no association between heat exposure and psychomotor vigilance and postural sway in Washington State agricultural workers working close to recommended exposure limits for heat stress. Changes in unsafe work behavior were reported by Ramsey et al. 1983 with a u-shaped relationship with ambient temperature, where the minimum unsafe behavior was reported between 17 °C and 23 °C.

1.4.2 *Epidemiologic studies*

Epidemiologic evidence of the relationship between occupational heat exposure and injury risk is relatively limited (Table 1). Studies using large injury claims or hospitalization datasets and regional weather station monitoring data to assess the relationship between occupational heat exposure and injury risk often report reverse-U shaped relationships (Adam-Poupart et al., 2015; Morabito et al., 2006; Spector et al., 2016; Xiang et al., 2014). For construction specifically, Xiang et al. 2014 report an incident rate ratio (IRR) of 1.006 (95% CI: 1.002, 1.011) per 1 °C increase in maximum daily temperature between 14.2 °C and 37.7 °C in Adelaide, Australia. Similar risk estimates are reported by Adam-Poupart et al. 2016 in Quebec, Canada (IRR 1.003 per 1 degree increase C). Morabito et al. 2006 report the greatest effect between the temperatures of 24.8 and 27.5°C for all occupations in Italy. Spector et al. 2016 report a reverse U-shaped relationship for the agricultural industry in Eastern WA, US, with the effects peaking at humidex values between 30-33°C, compared to less than 25 °C (OR 1.15, 95% CI 1.000, 1.006). It is theorized that these relationships are not the result of true reductions in risk at high temperatures, but rather an artifact of the data attributable to a reduction in the number of people working during extreme heat later in the work-shift. This theory is supported by studies where the exposure was more precisely characterized, including Fogleman, Fakhrzadeh, and Bernard's 2005 findings of increasing odds ratios of an injury with increasing exposure above 32 °C using aluminum smelter company health and safety records and hourly weather data. Similarly, Garzon-villalba et al.'s 2016 found that rate ratios for exertional heat illness (EHI) in Deepwater Horizon disaster cleanup workers increased with increasing WBGTs. McInnes et al. 2017 found no evidence of non-linearity in young workers in Australia (IRR 1.008; 95% CI 1.001, 1.015 per 1 °C increase in maximum daily temperature) (McInnes et al., 2017)

1.5 Roofing construction

In Washington State, the highest workers' compensation injury claims rate for HRI during third quarter months (July, August, and September) was reported for the roofing industry at 161.2 injury claims per 100,000 FTE for 1995-2005 (Bonauto et al., 2007). Roofing work often involves exposure to the elements (National Center for O*NET Development, n.d.-c), high metabolic demands (National Cancer Institute, 2016), and point-sources of heat. In commercial roofing settings, built-up roofing, torch applied roofing, and single-ply roofing are the most commonly used processes. With the exception of some forms of single-ply roofing that rely on adhesives and solvents to adhere water-proofing materials to the surface, these operations involve point-sources of heat. In built-up roofing, where hot tar or asphalt is applied to the roof from a kettle, the kettle operator and workers handling the hot tar, which is often kept at 260 ºC (OSHA, 2015), are routinely exposed to radiant heat from the kettle and roofing materials. These workers may also be at risk of burns from direct contact with the tar or explosions from the kettle. In torch-applied roofing, where an open flame and hot air are used to apply localized heat to roofing materials, torch operators may receive the highest point-source exposure due to close contact with tools exceeding temperatures as high as 1000 ºC (OSHA, 2015). These torches are designed with a long arm to provide some distance between the flame end and the operator, but inevitably result in higher exposures to lower extremities that are closer to the torch end and exposure from radiant heat traveling through the vertical profile. Single-ply applications involving heat utilize large hot air welding machines as well as small, hand-held equipment for precision work around seams and hard to reach places.

Metabolic demands in roofing vary by task and often require activities such as walking, bending, and lifting, moving, or cutting materials. Some tasks, such as operating a torch or hot air welder, may involve less physical movement but still require energy from pushing, pulling, and holding equipment (Parsons, 2002; Vezina, Der Ananian, Campbell, Meckes, & Ainsworth, 2014). In addition to the standard work boots, long pants, and t-shirt often worn by construction workers, built-up applications usually require long-sleeved shirts to prevent burns from contact with hot tar; torch operators and precision workers may opt to use heat-protective Kevlar sleeves. Roofing and other construction occupations may disproportionately experience the anticipated climate-induced increases in the frequency, duration, and severity of extreme temperatures due to the nature and

Table 1.1: Existing heat-injury risk epidemiology

Reference	Geography	Exposure	Outcome Metric	Population	Time	Analysis	Results Summary
Occupational Injury Epidemiology							
Xiang et al. 2014	Adelaide, Australia	Daily outdoor T_{max}, weather stations	Work-related injury; workers compensation claims	All workers	2001-2010	GEE with piecewise linear spline	Reverse U-shape; 1°C increase in T_{max} between 14.2 °C and 37.7 °C: all (IRR 1.002, 95% CI 1.001, 1.004), construction (IRR 1.006, 95% CI 1.002, 1.011)
Adam-Poupart et al. 2015	Quebec, Canada	Daily outdoor T_{max}, weather station	Acute injury; workers compensation claims	All workers	2003-2010, May-Sept.	GLM with piecewise linear spline	Reverse U-shape; 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)
Morabito et al. 2006	Tuscany, Italy	Daily Apparent temperature	Work-related hospitalization	All workers	1998-2003, June-Sept.	Chi^2, M-W test, K-W test	Reverse U-shape; greatest effect between 24.8 and 27.5 °C
Spector et al. 2016	Eastern WA, US	Daily outdoor $humidex_{max}$, modeled grid from weather stations	Traumatic injury; workers compensation claims	Agricultural workers	2000-2012, May-Sept.	Conditional logistic regression	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
McInnes et al., 2017	Melbourne, Australia	Daily outdoor T_{max} and T_{min}, weather stations	Acute work-related injury; workers compensation claims	All workers	2002-2012	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.
Fogleman, Fakhrzadeh, and Bernard 2005	Midwest, US	Hourly outdoor heat index (HI), weather stations	Acute injury; company health and safety records	Aluminum smelter workers	1997-1999	Poisson regression, logistic	Modified U-shape; >32C to ≤38C OR 2.28 (95% CI 1.49, 3.49), >38C OR 3.52 (95% CI 1.86, 6.67)
Garzon-villalba et al. 2016	Deepwater Horizon disaster clean up	Daily outdoor $WBGT_{max}$, weather stations	Exertional heat illness (EHI) and acute injury (AI)	All workers	May 2010-March 2011	Poisson regression, logistic	$WBGT_{max}$ >20C: EHI RR 1.58 (95% CI 1.52, 1.64), AI RR 1.13 (95% CI 1.09, 1.17)
Tawatsupa et al. 2013	Thailand	Categorical survey, uncomfortable heat	Survey response (yes/no occupational injury)	Thai Cohort Study	2005	Logistic regression	OR 2.12 (95% CI 1.87, 2.42) for males

Reference	Geography	Exposure	Outcome Metric	Population	Time	Analysis	Results Summary
Construction Exposure Studies (sample)							
Montazer et al. 2013	Iran	Thermal Work Limit (TWL)	Urine specific gravity (U_{sg})	Constructio n workers	NA	ANOVA	Strong correlation between TWL and USG
Farshad et al. 2014	Iran	WBGT and TWL	U_{sg}	Constructio n workers	Sept. 2012	ANOVA, Chi^2, Friedman, M-W, t-test	Significant difference between exposed and unexposed groups
Hancher and Abd-Elkhalek 1998	Kentucky	WBGT	Productivity and cost	Constructio n workers	NA		Hot-weather productivity curves
Yang and Chan 2014	Hong Kong	Lab Ta & RH + construction uniform A or B	Perceptual strain index (PeSI), PhSI	Constructio n workers	NA	ANOVA, power functions	PeSI changes in similar manner to PhSI
Yi and Chan 2013	Hong Kong	WBGT from field data	Work-rest schedule optimization (productivity and heat stress)	Constructio n rebar workers	2010-2011, July-Sept.	Monte Carlo simulation	120:15:105 minute work:break:work in morning (WBGT 28.9 °C), 115:20:105 minute work:break:work in afternoon (WBGT 32.1 °C) with 60 minute midday break
Rowlinson and Jia 2015	NA	Categorical "hotness"	HRI cases	Constructio n workers	NA	Systematic review	Identifiable behavioral interventions and recommendation regarding institutional causal factors
Other relevant occupational heat stress studies							
Crider, Maples, and Gohlke 2014	Alabama	NA	HRI	Workers	June 29-Sept. 15, 2012	Choropleth maps	County maps of HRI per capita and weighted MET rates.
Bonauto et al. 2007	WA, US	NA	Heat related injury (HRI) claims	WA workers	1995-2005	Incidence rate (IR)	Highest 3rd quarter (Jun-Aug) rates in roofing (161.2/100,000 FTE) & fire protection (158.8/100,000 FTE)
Spector et al. 2014	Eastern WA, US	Maximum daily T_a and Heat Index, AgWeatherNet	HRI injury claims	Agricultural workers	2009-2012	t-tests, IR	HRI cases associated with work, environment, and personal risk factors.
Lundgren, Kuklane, and Venugopal 2014	Chennai, India	WBGT, 3M QuesTemp 32	Predicted Health Strain (PHS), productivity	5 different worksites	NA	t-tests	
Ramsey et al. 1983	US	WBGT on site	Unsafe work behavior	2 industrial plants	14-months	ANOVA	U-shaped curve; minimum unsafe behavior between 17 °C and 23 °C

Temperature (T_a); maximum daily temperature, (T_{max}); maximum daily humidex ($Humidex_{max}$); minimum daily temperature (T_{min}); minimum daily humidex ($Humidex_{min}$); wet bulb globe temperature (WBGT); relative humidity (RH); heat related illness (HRI); thermal work load (TWL); heat index (HI); urine specific gravity (U_{sg}); metabolic equivalent (MET).

location of their work in urban centers, often on rooftops with no shade, where the effects of urban heat islands would be greatest.

1.6 WASHINGTON STATE'S CLIMATE

The Cascade Mountain Region divides Washington State into two major climate regions: Western Washington and Eastern Washington. The western division is described as having five sub-regions identified as West Olympic-Coastal, Northeast Olympic-San Juan, Puget Sound-Lowlands, East Olympia-Cascade Foothills, and the Cascade Mountains-West (Western Regional Climate Center, n.d.). These regions are characterized by relatively mild weather, with wet and cloudy winters and relatively dry and sunny summers. Using the Koppen-Geiger Classification system (Appendix IV), this region is largely characterizes by temperate climates (Group C) of Mediterranean or ocean sub-groups (Peterson, 2016). Temperatures in Western Washington typically range from highs in the single digits (°C) in winter months and the mid-20's°C in summer months to lows of negative single digits (°C) and 10°C, respectively. Although extremes do occur, high summer month temperatures exceeding 32 °C often only occur a few times a year. Relative humidity in Western Washington generally hovers around 80% in the winter months, and ranges from 85% to 47% (or lower) in the summer months (Western Regional Climate Center, n.d.).

The eastern division is described as having five sub-regions identified as East Slope-Cascade, Okanogan-Big Bend, Central Basin, Northeastern, and Palouse-Blue Mountain (Western Regional Climate Center, n.d.). These regions are characterized by warmers summers, colder winters, and less precipitation than their eastern counterparts. The northern areas of Eastern Washington general fall under Group D of the Koppen-Geiger Classification system for continental climatic conditions, while the southern areas fall under Groups B and C for dry, arid or semiarid, conditions and temperate conditions, respectively (Peterson, 2016). Low temperatures in Eastern Washington generally range from -10 to -5 °C in winter months and hover in the high single digits in summer months. High temperatures typically range from -4 to 4 °C in winter months and 21 to 34 °C in summer months, with extreme temperatures often exceeding 40 °C each summer. Relative humidity is similar in winter months to Western Washington, how in summer months is typically ranges from 65% to 27% (Western Regional Climate Center, n.d.).

While not a product of climate, spatial and temporal variability in temperature and relative humidity resulting from microenvironments, including the presence of point sources of heat or urban design phenomena such as the urban heat island effect, influence how an individual perceives their ambient environment. Monitoring stations positioned throughout the state to report weather conditions and describe regional climate are assumed to be representative of the surrounding geographic area. For the purposes of describing trends in climate, this assumption may be valid, however for acute exposures to heat, there is increasing evidence that these stations do not represent the variability experienced by the population or capture the range in exposures over time and location, particularly when reporting summary measures at a daily resolution (Davis, Hondula, & Patel, 2016; Kuras, Hondula, & Brown-Saracino, 2015).

Climate change projections in the Pacific Northwest (Bhatt & UW Climate Impacts Group, 2016; Dalton, Mote, & Snover, 2013) (Appendix V) and globally (Stocker et al., 2013) indicate that ambient temperature will continue to increase, with increases in the frequency, severity, and duration of episodes of high temperatures over land. The extent to which these changes will affect conditions of heat stress in occupational settings is yet to be seen.

1.7 Gaps in Existing Literature

A number of gaps exist in heat assessment and heat-injury research, including: 1) the utility of personal versus area heat monitoring in different settings and populations, 2) methods for improving the accuracy of heat exposure quantification in epidemiologic assessments, 3) incorporation of metabolic heat into measures of heat exposure in research involving real-time monitoring, 4) heat exposure windows of importance for heat-related injuries, 5) mechanisms mediating the observed relationship between heat exposure and injury risk, and 6) the effect of industry-specific occupational and individual-level factors that could impact the effects of heat exposure on injury risk. Each of these gaps are described in turn below.

1.7.1 *Personal heat monitoring*

Monitoring of personal, or individually experienced, heat exposure has been increasingly used in heat-health research (Bernhard et al., 2015; Kuras et al., 2017, 2015; Mitchell et al., 2017). Personal heat exposure measurement approaches are anticipated to be particularly advantageous for populations with substantial changes in environment over time and space, where the use of personal devices may reduce the necessity for tedious time use logs and has the potential to capture interactions with microclimates at a higher resolution than is achievable using representative regional, or even area, monitoring data (Kuras et al., 2017). However, the understanding of thermal conditions captured by these personal devices and how to use personal temperature data in conjunction with heat-health recommendations based on other monitoring strategies is largely unknown. Small, durable, and reasonably affordable, devices used for individual-level monitoring typically are not outfitted with housing designed to promote air-flow and shield radiation, nor do they include the standard black globe designed to measure solar radiation. Consequently, measurements are not directly related to those captured using standard area monitors (e.g. WBGT) in many circumstances. The placement of personal devices in close proximity to the human body likely results in the inclusion of radiant heat released from the body in the measurements. This complicates comparisons with temperature recommendations based on area monitoring data, such as occupational recommendations.

1.7.2 *Enhancing heat assessment in large epidemiologic studies*

Regional weather data are often used as an indicator of heat exposure in heat-health epidemiology. While this approach is valid and provides a high-level assessment of heat in large temporal and geographic comparisons, it may not adequately measure differences between microclimates within a region, characterize the impact of indoor settings, or capture localized sources of heat that are not weather dependent, such as may be present in certain occupational settings. Metabolic heat is similarly not captured by regional weather data but is known to significantly contribute to an individual's net heat load. Development of methods to enhance the use of regional weather data is needed for more accurate epidemiologic exposure assessments. Additionally, the degree to which improved accuracy of heat in large epidemiologic studies will improve the understanding of the heat-health relationship is unknown.

1.7.3 *Incorporation of metabolic heat into measures of heat exposure in research using real-time monitoring*

Dozens of heat metrics exist describing different aspects of thermal conditions and the human perception of heat. While many of these metrics have been developed with the contribution of metabolic heat in mind, rarely is metabolic heat combined with environmental heat into a single metric. Practical considerations of available data sources and accuracy of metabolic heat estimates may limit integration of environmental and metabolic heat into one metric. Stratification by groups with similar metabolic demands or risk factors (e.g. occupational codes, tasks, ages, etc.), the most commonly use approach of accounting for metabolic demands, can be cumbersome does not capture variability resulting from individual behavior or differences in tasks within a given group. The difference between the metabolic heat-based REL and the measured WBGT is one approach that combines both sources of heat into a single number, thus facilitating comparisons and providing a point of reference. Limited research has utilized this approach to assess heat and health (Garzon-Villalba, 2016).

1.7.4 *Heat exposure windows of importance for heat-related injuries*

Occupational heat exposure is traditionally assessed as one-hour, two-hour, for full-shift time weighted average (TWA) exposures in worker and worksite assessments or as a daily (or work shift) maximum exposure in larger studies or when relying on representative (weather station) data. However, the influence of a specific exposure window, as well as the importance of cumulative versus short term exposures, on outcomes not traditionally linked with heat (e.g. injuries) is not well understood.

1.7.5 *Mechanisms in the heat-injury risk relationship*

Positive associations between heat exposure and injuries have been documented in a variety of geographic and occupational settings across a range in exposures. However, the underlying mechanisms mediating this relationship are not entirely clear. Identification of mechanisms contributing to injury risk is necessary to inform efficient, targeted interventions. Elucidation of mechanisms may also inform prevention recommendations in occupational guidelines and standards. Heat exposure has been reported in epidemiologic studies to increase the risk of injury even at relatively low-level exposures that may be well within current recommended occupational thresholds designed to prevent HRI.

1.7.6 *Industry-specific, occupational, and individual factors*

While the existing epidemiologic literature has contributed to the understanding of heat and injury risk, published research to date has primarily assessed the effect of factors such as age, gender, mechanism of injury (Adam-Poupart et al., 2015), lagged exposure (Adam-Poupart et al., 2015), and business size (Xiang et al., 2014) on injury risk in the heat for all industries combined. Adam-Poupart et al. did stratify by manual and non-manual construction occupations and reported a higher injury OR for manual occupations (1.003; 95% CI: 0.999, 1.007), than for non-manual occupations (0.992; 95% CI: 0.980, 1.005), with increasing heat exposure (Adam-Poupart et al., 2015). Xiang et al. assessed specific occupations, including “tradespersons and related workers” and “labourers and related workers,” and reported injury ORs of 1.002 (95% CI: 1.001, 1.005) and 1.005 (95% CI: 1.001, 1.010), respectively, with increasing heat exposure (Xiang et al., 2014). Gaps exist for construction industry-specific analyses, which have yet to describe how factors such as age, business size, mechanism of injury, time of day, and work experience affect injury risk in the heat.

1.8 SPECIFIC AIMS

There are two overall goals of this research: (1) assess the relationship between heat exposure and traumatic injuries recorded in workers’ compensation data; and (2) assess heat exposure, heat strain, and the relationship between heat stress and two potential mediators of the heat-injury risk relationship—psychomotor vigilance and postural sway—in a population at high risk for both injuries and heat related illness. These studies build on previous work completed in other industries by researchers at the University of Washington, including epidemiologic (Spector et al., 2016) and field studies in agricultural workers (Quiller, 2016; Spector et al., 2018; Spector, Krenz, & Blank, 2015). In this dissertation, enhancement of methods used in previous studies is accomplished through novel approaches aimed at understanding heat exposure misclassification, identifying outdoor occupations, enhancing heat exposure assessment in field data collection using new technologies, and applying these methods to construction and roofing workers.

This research will accomplish the overall goals through the following Specific Aims:

Aim 1. Assess the relationship between outdoor apparent temperature and occupational injuries recorded in Washington State (WA) Labor and Industries workers' compensation claims data for the construction industry.

Hypothesis 1. Increased outdoor ambient apparent temperature is positively associated with increased occupational injuries in warm month conditions in WA.

Aim 2. Characterize the exposure to heat in a sample of commercial roofing workers in the greater Seattle, WA area.

Sub Aim 2a. Quantify differences in heat exposure measured using regional-, area-, and personal-level monitoring approach for temperature and WBGT.

Hypothesis 2a. Air temperature measured at the personal-level in an outdoor occupational setting with point sources of heat and high metabolic demands is higher and characterized by greater variability than temperature measured at the area- and regional-levels.

Sub Aim 2b. Characterize heat stress.

Aim 3. Characterize heat strain and assess the relationship between heat stress and injury risk, as evidenced by changes in psychomotor performance, in a sample of commercial roofing workers in the greater Seattle, WA area.

Sub Aim 3a. Characterize heat strain.

Sub Aim 3b. Assess the relationship between heat stress and psychomotor performance (psychomotor vigilance and postural sway).

Hypothesis 3b. A positive association exists between increased ambient temperature and decrements in psychomotor vigilance and postural sway.

The research gaps addressed by the above aims are outlined in Table 1.2. Successful completion of these aims will result in an improved understanding of heat stress, heat strain, the relationship between ambient heat and occupational injuries, and whether impaired psychomotor performance may contribute to heat-related injury risk in outdoor construction workers. The proposed research is expected to have an important impact on the construction industry and workforce by informing efforts targeting the reduction in occupational injuries, thus potentially improving health and productivity and decreasing costs associated with injuries.

Table 1.2: Organization, aims, and research gaps addressed

<table>
<tr><th>Chapter</th><th>Study</th><th colspan="2">Aims</th><th>Gaps (section 1.7) in research addressed</th></tr>
<tr><td>Chapter 2</td><td>Epidemiologic study using occupational injuries recorded in Washington State (WA) Labor and Industries workers' compensation claims data for the construction industry</td><td colspan="2">Aim 1. Assess the relationship between outdoor apparent temperature and occupational traumatic injuries.</td><td>#2—Enhancing heat assessment in epidemiologic studies
#6—Industry-specific occupational and individual factors</td></tr>
<tr><td>Chapter 3</td><td rowspan="4">Field study using repeated measures in a sample of commercial roofing workers in the greater Seattle, WA area.</td><td rowspan="2">Aim 2. Characterize the exposure to heat.</td><td>2a. Quantify differences in heat exposure measured at three spatial resolutions.</td><td>#1—Personal heat monitoring
#4—Heat exposure windows</td></tr>
<tr><td rowspan="3">Chapter 4</td><td>2b. Characterize heat stress.</td><td rowspan="3">#1—Personal heat monitoring
#3—Incorporating metabolic heat into assessment using real-time monitoring
#4—Heat exposure windows
#5—Mechanisms in the heat-injury risk relationship
#6—Industry-specific occupational and individual factors</td></tr>
<tr><td rowspan="2">Aim 3. Assess the relationship between heat stress and psychomotor vigilance and postural sway.</td><td>3a. Characterize heat strain.</td></tr>
<tr><td>3c. Assess the relationship between heat stress and psychomotor vigilance and postural sway.</td></tr>
</table>

Chapter 2. HEAT EXPOSURE AND INJURY RISK IN WASHINGTON STATE OUTDOOR CONSTRUCTION WORKERS: A CASE-CROSSOVER STUDY USING HIGH RESOLUTION METEOROLOGICAL DATA AND WORKERS' COMPENSATION INJURY CLAIMS.

2.1 ABSTRACT:

Objectives: The primary objective of this study was to assess the relationship between heat exposure and occupational injuries in construction workers.

Methods: The relationship between maximum daily humidex, a measure of apparent temperature, and Washington State Fund workers' compensation injuries in outdoor construction workers was assessed using a case-crossover design with time-stratified referent selection. Warm month (March-October) adult outdoor construction traumatic injury claims from 2000-2012 were spatiotemporally joined with high-resolution meteorological data. Conditional logistic regression with linear splines was used to assess the association between maximum daily humidex and injuries.

Results: There were 63,720 traumatic injuries during the study period. The traumatic injury odds ratio (OR) was 1.0053 (95% CI 1.003, 1.007) per one °C change in humidex. In the splines analyses, we observed a nearly linear association between humidex and the risk of a traumatic injury. Stratified analyses suggested higher risk in younger (18-24 years) and older (over 54 years)

workers, workers with lower extremity injuries, workers with less job experience, smaller employers, workers working in Western Washington, and time of injury before 12:30 pm.

Conclusions: In this study of Washington outdoor construction workers, increasing maximum daily humidex was associated with increasing traumatic injury risk. Further work should explore mechanisms of the association between heat exposure and traumatic injuries. Injury prevention efforts in construction should address heat-related risk factors, particularly for high-risk workers. In addition, heat awareness campaigns should address outcomes beyond heat-related illness.

2.2 INTRODUCTION

In the construction industry, the burden of traumatic injuries is substantial and exceeds the reported burden of illnesses, both in the frequency of reported events as well in the mean workers' compensation costs (Bonauto et al., 2007). Considerable progress has been made in identifying factors that contribute to injury risk, addressing barriers to injury prevention, and designing interventions to reduce the risk of traumatic injuries in construction (N. J. Anderson et al., 2013; Garrett & Teizer, 2009; Holizki et al., 2015; Ozmec et al., 2015; Schoonover et al., 2010; Siu et al., 2003; Strickland et al., 2017; Suárez Sánchez et al., 2017). However, injury rates remain high. Reducing construction worker injuries continues to be a top priority for occupational health research and a goal of the United States National Institute for Occupational Safety and Health (NIOSH) National Occupational Research Agenda (NORA) for construction (NORA Construction Sector Council, 2008). A better understanding of additional factors that contribute to injury risk may ultimately inform the development of more effective injury prevention efforts.

Occupational heat exposure has long been understood to increase the risk of HRIs such as heat stroke, which can be fatal (Bouchama & Nochel, 2002), and may also reduce worker productivity

(Sahu et al., 2013; Sett & Sahu, 2014; Singh et al., 2015). The relationship between heat exposure and other adverse health outcomes, such as traumatic injuries, have received minimal attention until relatively recently (Adam-Poupart et al., 2015; Garzon-villalba et al., 2016; Gasparrini et al., 2015; McInnes et al., 2017; Morabito et al., 2006; Spector et al., 2016; Tawatsupa et al., 2013; Xiang et al., 2014). Within this growing body of literature, the odds ratio (OR) of a traumatic injury has been reported to be 1.006 (95% CI: 1.002, 1.011) (Xiang et al., 2014) and 1.008 (McInnes et al., 2017) per one °C increase in maximum daily temperature for the construction industry and for young workers (<25 years of age), respectively, in Australia. The OR for traumatic injuries in Washington State agricultural workers has been reported to be 1.15 for humidex (a function of temperature and dew point) values between 30-33°C, compared to less than 25 °C (Spector et al., 2016). An injury incidence rate ratio (IRR) of 1.003 per one °C increase in maximum daily temperature has been reported for the construction industry in Quebec, Canada (Adam-Poupart et al., 2015).

The potential for heat exposure in construction workers is substantial. Exposure to heat, where heat is defined as energy transfer to and from the human body, includes exposure from environmental (or ambient) conditions, metabolic heat production, and the insulating properties of clothing or other near-skin barriers (Kuras et al., 2017; McGregor & Vanos, 2017; NIOSH, 2016; Michael N. Sawka et al., 2011). Construction workers may be subject to high outdoor temperatures with or without solar radiation and task-related point sources of heat, high metabolic demands, and personal protective equipment (including clothing) that place them at high risk for heat stress. In Washington State (WA), Bonauto et al (2007) reported that the construction industry experienced the highest workers' compensation incidence rate for HRI between 1995-2005 at 12.1 per 100,00

FTE (Bonauto et al., 2007). Among the subsectors at greatest risk, four of the top five were classified within the construction industry.

The mechanisms through which heat may contribute to the risk of a traumatic injury are still under investigation. Research in exercise, human physiology, and occupational settings report heat-related changes in cognitive performance (Mazlomi et al., 2017; Sharma et al., 1983) and psychomotor vigilance (Ganio et al., 2011)—critical functions, which when impaired have been documented to compromised balance, mental status, and response time after exercise or in conditions of hyperthermia (Distefano et al., 2013; Ganio et al., 2011; Nardone, Tarantola, Giordano, & Schieppati, 1997; Zemková & Hamar, 2014). These factors have in turn been linked to injury risk in occupational settings (Garrett & Teizer, 2009; Rowlinson et al., 2014; Sharma et al., 1983). Other factors associated with heat stress, such as muscle fatigue or cramping and dehydration, have also been shown to negatively affect performance, particularly when experienced in conjunction with one another (Distefano et al., 2013; Rowlinson et al., 2014). Inadequate acclimatization, which can be influenced by work organization and acclimatization training, could also influence injury risk in the heat (Choudhry & Fang, 2008). An increase in unsafe work behaviors at extreme temperatures has additionally been reported and may contribute to the risk of injury in the heat, although it is unclear whether this finding is related to cognitive performance effects or behavioral factors such as irritability (Ramsey et al., 1983). Further research in needed to elucidate the role of these factors in the development of heat-related injuries.

While the existing literature has contributed to the understanding of heat and injury risk, published research to date has primarily assessed the effect of factors such as age, gender, mechanism of injury (Adam-Poupart et al., 2015), lagged exposure (Adam-Poupart et al., 2015), and business size (Xiang et al., 2014) on injury risk in the heat for all industries combined. In addition, the existing literature has predominantly relied on representative weather monitoring stations that may not adequately measure regional patterns in climate or differences between microclimates. Yet each industry has substantial differences in working population characteristics, heat exposures, and other injury risk factors. Adam-Poupart et al. conducted a stratified analysis by manual and non-manual construction occupations and reported a higher injury OR for manual occupations (1.003; 95% CI: 0.999, 1.007), than for non-manual occupations (0.992; 95% CI: 0.980, 1.005), with increasing heat exposure (Adam-Poupart et al., 2015). Xiang et al. assessed specific occupations, including "tradespersons and related workers" and "labourers and related workers", and reported injury ORs of 1.002 (95% CI: 1.001, 1.005) and 1.005 (95% CI: 1.001, 1.010), respectively, with increasing heat exposure (Xiang et al., 2014). Gaps exist for construction industry-specific analyses, which have yet to describe how factors such as age, business size, mechanism of injury, time of day, and work experience affect related injury risk in the heat.

The purpose of this study was to assess the relationship between outdoor apparent temperature and traumatic occupational injuries in Washington outdoor construction workers. This study adds to the existing literature though the use of high-resolution meteorological data, methods for identifying outdoor occupations, and exploration of factors that may modify the effect of heat on injuries in this population, with the ultimate aim of informing heat-related traumatic injury prevention efforts.

2.3 Methods

We assessed the relationship between maximum daily humidex, a measure of apparent temperature, and occupational injuries in outdoor construction workers using a case-crossover design with time-stratified referent selection and linear splines. Occupational injury data were obtained through the Washington State Fund workers' compensation system and spatiotemporally paired with high-resolution meteorological data.

2.3.1 *Heat exposure*

Meteorological data were produced using the Parameter-elevation Relationships of Independent Slopes Model (PRISM) by researchers at the University of Washington (UW) Climate Impacts Groups (CIG). Developed at Oregon State University, this model combines climate data from the National Oceanic and Atmospheric Administration's (NOAA) Global Historic Climate Network Daily (GHCN) monitoring station database with geographic features to produce modeled weather conditions on a ~1/16th resolution grid (4 km x 7.5 km) (Daly, Taylor, & Gibson, 1997; Hamlet & Lettenmaier, 2005; Maurer, Wood, Adam, & Lettenmaier, 2002; Salathe, 2013; The PRISM Climate Group, 2013), where each grid point represents the center of each grid cell. Data from 1910 through 2012 are currently available for the Pacific Northwest, including the entire State of Washington, and have been used for other research investigating the relationship of heat and health effects (Calkins, Isaksen, Stubbs, Yost, & Fenske, 2016; Isaksen et al., 2015; Isaksen, Yost, Hom, & Fenske, 2014; Jackson et al., 2010; Spector et al., 2016). These data include daily values for relative humidity (mean), temperature (minimum/mean/maximum), and cumulative precipitation. Additionally, daily humidex has been calculated for each grid cell (minimum/mean/maximum) using the equation (Eq 2.1) below.

Chapter 2.1

$$f(T,H) = T + (5/9)(v - 10), \quad v = 6.112(10^{[7.5T/237.7+T]})(H/100), \qquad 2.1$$

where T is air temperature (°C), H is relative humidity (%), and v is vapor pressure (Canadian Center for Occupational Health and Safety, 2005).

Exposure was defined as the maximum daily humidex at the grid point of the closest Euclidean distance to the injury location. Humidex was selected as the preferred metric for this study because Barnett et al. 2010 demonstrated improved prediction of mortality in the Pacific Northwest when compared with other measures of temperature and apparent temperature (Barnett, Tong, & Clements, 2010). The maximum daily exposure was used to describe the magnitude of extreme temperatures and likely overlapped with the hottest period of standard work shifts. As heat stress includes both ambient heat exposure and internal metabolic heat generation, estimates of metabolic equivalent (MET) values were assigned to the occupation corresponding to each injury using data provided by the National Cancer Institute (National Cancer Institute, 2016; Tudor-Locke, Ainsworth, Washington, & Troiano, 2011). These estimates are based on data from the Compendium of Physical Activities and American Time Use Survey (ATUS) and have been used in other occupational health research (Crider et al., 2014).

2.3.2 *Injuries and case definition*

The outcome dataset included all accepted Washington State Fund workers' compensation injury claims with injury dates between 2000 and 2012. The State Fund is administered by WA State's Department of Labor and Industries and funded by employer and employee premiums. Coverage through the State Fund is required for all businesses that have employees, are not owned by sole proprietors, and do not qualify for, or have not acquired, self-insurance—about two-thirds of the state's work force. This dataset includes variables pertaining to the injury location, worker demographics, work and employer characteristics, and injury and claim characteristics. Cases were defined as repeat or first occurrence traumatic injuries occurring of adult (≥18 years old) outdoor construction workers (Figure 1.1).

- *Traumatic injuries* were defined using American National Standards Institute (ANSI) and Occupational Injury and Illness Classification System (OIICS) codes as described in Spector et al. (2016). Injuries characterized as work-related musculoskeletal disorders (WMSDs) were not included in the final case definition(Spector et al., 2016). While there is some evidence of a relationship between extreme environmental temperatures and WMSDs (Barro et al., 2015; Majumder, Shah, & Bagepally, 2016), WMSD typically develop over time and were therefore not included in the case definition of traumatic injuries, which are acute.
- *Construction workers* were defined as working in both the construction industry and a construction occupation using standardized coding systems. Construction industry codes included sector 23 of the North American Industrial Classification System (NAICS) or major groups 15-17 of the Standard Industrial Classification (SIC) system and occupation codes included major group 47 of the Standard Occupation Classification (SOC) system.
- *Outdoor occupations* were defined using the Occupational Information Network (O*NET) as SOCs assigned a context greater than or equal to 50% for “outdoor work, exposed to weather conditions”. The O*NET program was developed by the North Carolina Department of Commerce and is sponsored by the US Department of Labor (USDOL) and the Employment and Training Administration (ETA) (National Center for O*NET Development, n.d.-a). It provides information on “standardized and occupation-specific descriptors” using surveys from a random sample of business owners and workers. For estimates of the frequency of outdoor work, exposed to weather conditions, survey

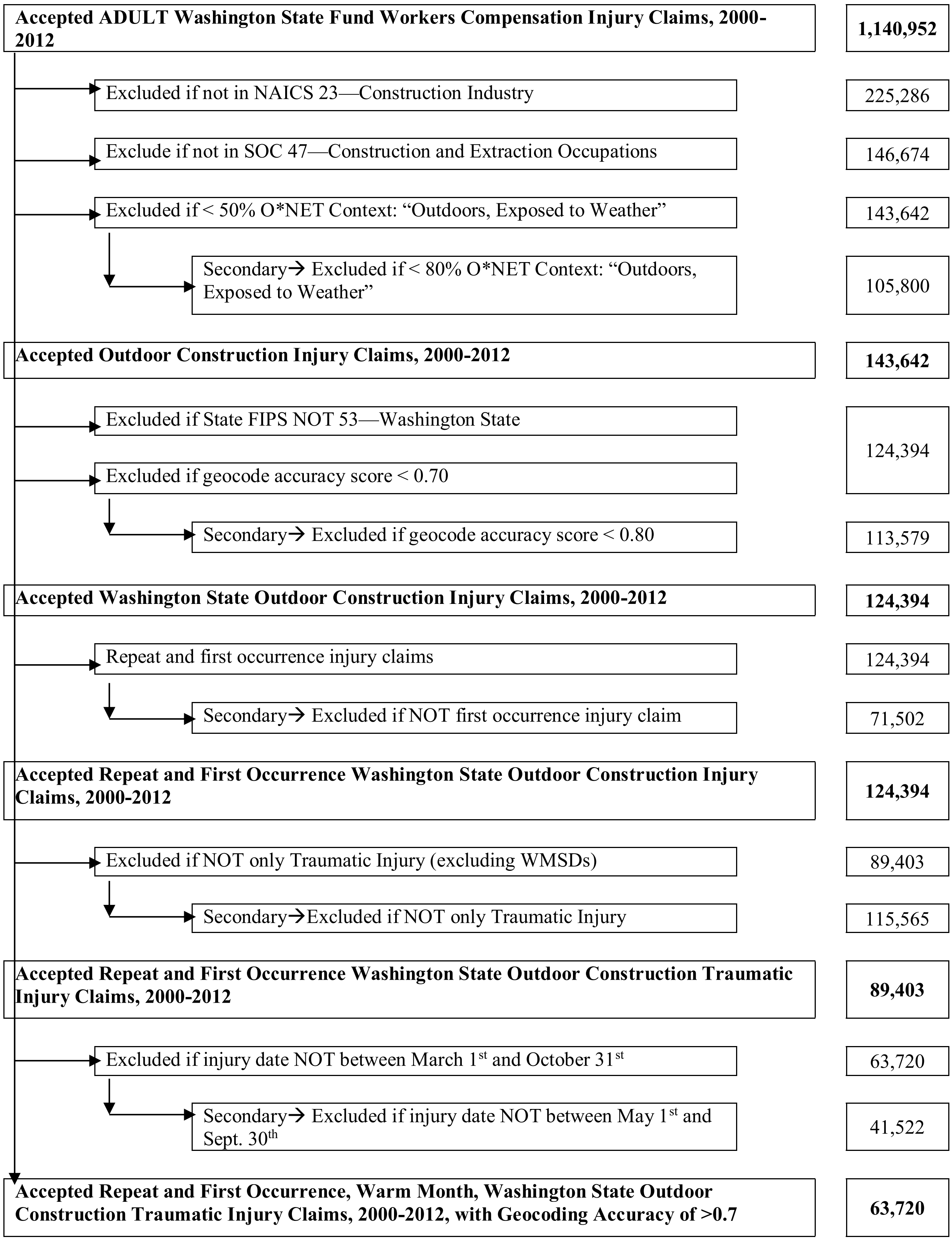


Figure 2.1: Injury claim case definition with the number of claims meeting the criteria.

respondents are asked to rank how often their job (classified by SOC) requires outdoor work on a scale of 1 to 5, where 1 is “never” and 5 is “everyday”(National Center for O*NET Development, n.d.-b). An average survey response of 3 is equivalent to a “context” of 50% (National Center for O*NET Development, n.d.-c).

2.3.3 *Geocoding and spatial pairing*

Each injury claim included an indicator of whether the injury occurred at the worksite as well as three address location fields: the accident address as reported by the worker, the address of the first medical provider who treated the worker, and the business address of the employer. All available addresses were first geocoded using Geocoder::US 2.0 with TIGER/LINE® 2014 reference data from the US Census Bureau (Erle, 2009; Spector et al., 2016) to obtain latitude/longitude coordinates. One address was then assigned to each injury using the approach outlined in Figure 2.2. In all cases, accident locations were assigned when available. In remaining cases, unless the injury was reported to have occurred on the employer’s premise, the address of the first medical provider was assigned. Only injury claims with addresses with a minimum geocoding accuracy score of 0.7 were included in the analysis. The geocoding accuracy score describes how well the input address matches the address of the reference data on a scale of 0 to 1, where 1 is a perfect match (Erle, 2009). Spatial joining of the assigned injury coordinates with the meteorological grid point coordinates was executed in ESRI ArcGIS (ESRI 2011, n.d.) using the nearest neighbor function. For each joined coordinated pair, the corresponding meteorological data were then pulled for all dates associated with the injury claim (injury date and referent dates) and for the day prior to the injury and referent dates.

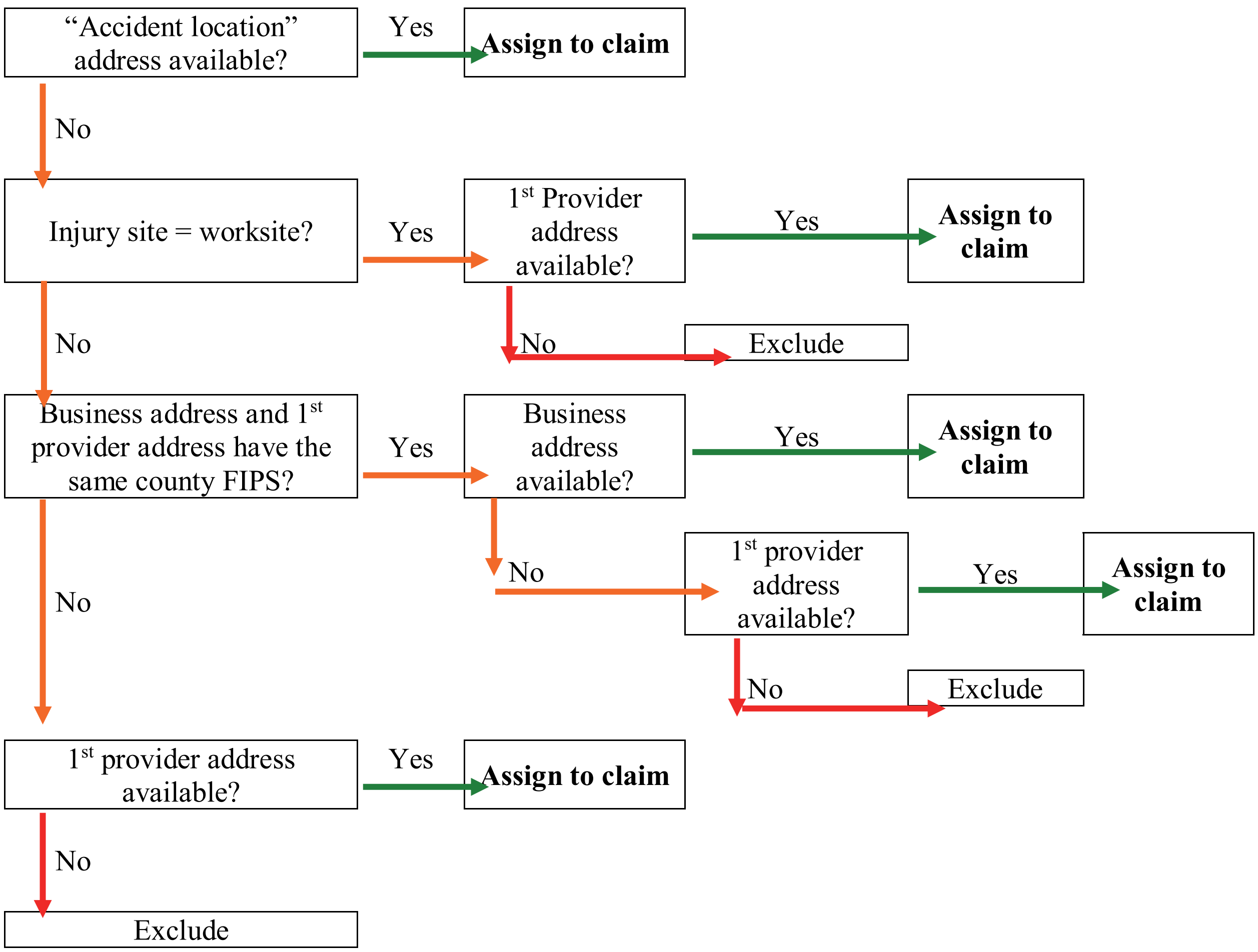


Figure 2.2: Address Assignment Schematic

2.3.4 *Referent selection*

Time-stratified referent selection was used to select referent dates (Janes, Sheppard, & Lumley, 2005). Referent dates were selected as days in the calendar month in which the injury occurred, on the same day of the week, excluding major holidays. This approach controls for seasonality and day of the week, respectively. Referent dates that occurred prior to the claimant's first day of employment with the employer of injury were excluded. The start date of employment at the employer of injury was determined using the self-reported start date recorded on the injury claim form. Employment Security Data (ESD) were also used to determine whether the employer reported the claimant to be working in the current and previous quarter. ESD data contains information on the hours and wages of a given business' employees for unemployment and insurance purposes. The severity of the injury may influence the time at risk in the rare case of fatalities or in cases where claimants are removed from work to recover from the injury. Including referent dates that fall after the occurrence of an outcome may introduce bias, but when these extreme cases are rare, the bias introduced by the inclusion of these referent dates is less than the bias reduced by the bidirectional design (Lumley & Levy, 2000).

2.3.5 *Analyses*

Exposures on injury dates at injury locations were compared to exposures on referent dates at the same location. Analyses were performed for the warmer months of the year, March 1st – October 31st, within Washington State. This window was selected to be inclusive of calendar days where temperatures exceeded the 95th percentile of full-year maximum daily humidex for all of WA State (34.1 °C), while balancing the inclusion of cold weather and subsequently cold weather-related injury risk factors, such as slippery surfaces due to ice and decreased dexterity from cold temperatures or extra clothing.

Descriptive statistics were calculated for worker demographics, work and employer characteristics, injury and claim characteristics, and exposures on injury and referent days. The variability in exposures on injury and referent days within each worker (i.e. stratum) was described as the mean of strata standard deviations.

We assessed the relationship between maximum daily humidex humidex and traumatic injuries using conditional logistic regression implemented with the clogit function from the survival package (Therneau, 2015; Therneau & Lumley, 2016) in RStudio (RStudio Team, 2015). Based on previous studies, a non-linear effect was anticipated (Spector et al., 2016; Xiang et al., 2014). Linear splines were used, with three knots selected *a priori* as 25, 29, and 34 °C humidex, using guidance from two sources. The lower knot was selected as the lowest threshold recommended by the Canadian Center for Occupational Health and Safety's (CCOHS) guidance for humidex limits aimed at reducing the risk of heat-related illness (25 °C) (Canadian Center for Occupational Health and Safety, 2005). The upper knot was selected as the value identified by Spector et al. (2016) as an inflection point in the relationship between humidex and traumatic injury risk in agricultural workers in Washington State (34 °C). The middle knot was selected as the midpoint between the upper and lower knot. Model fit was explored for other CCOHS recommended thresholds and lower humidex values using the Akaike Information Criterion (AIC). Based on model fit, the knots were adjusted to 21, 25, and 37 °C humidex. Results using the best-fit knots are reported alongside those using the *a priori* knots.

Secondary analyses were conducted for dry temperature, a one-day lag in exposure, continuous exposure (no splines), and categorical exposure (17-20, 21-24, 25-29, 30-34, 35-39, and ≥40 °C, compared to a reference category (<17 °C). Knots for the spline analysis using dry temperature were set as the mean of all temperature values for a given humidex knot, rounded to the nearest 10^{th}: 19.3, 22.7, and 32.2 °C dry temperature. Effect modification was explored through stratified analyses, including by climate region (eastern vs. western WA), size of the employer (≤10, 10-49, and ≥50 employees), time of day the injury occurred (5:31-9:30, 9:31-12:30, 12:31-16:30, and 16:31-19:30), age of the worker (18-24, 25-34, 35-44, 45-54, and ≥55 years old), MET (<4, 4 to 5, and >5), experience (more vs. less, where more experience was defined as either working in the previous quarter based on ESD data or self-report of working for the employer at least 90 days), OIICS event (falls, bodily reaction and exertion, and other), and body part injured (upper extremity, lower extremity, trunk, and multiple body parts).

Sensitivity analyses were conducted to explore the more restricted case definitions of ≥80% outdoor context, geocoding accuracy score ≥8.0, May 1st through September 30th, claims assigned the accident address only, claims with less than two days between the injury and first medical provider, only new, first occurrence injury claims, and claims with less than seven days of time loss. Time loss indicates the number of days a claimant was unable to work due to a work-related injury or illness. The first three days of time away from work are considered a waiting period and are not compensated when an injury requires less than two weeks of time off; however, for injuries requiring more than two weeks of time off, the first three days are retroactively compensated (RCW51.32.090).

The Washington State Institutional Review Board reviewed the study protocol and determined the study to be exempt.

2.4 RESULTS

2.4.1 *Worker demographics and injury claims*

Of the 225,286 adults in the construction industry Washington State Fund workers' compensation injury claims form 2000-2012, 63,720 met the case definition (Figure 2.1). Of these workers, 97.9% were male, with a mean age of 34 years old and mean body mass index (BMI) of 27.2 kg/m^2. The most common NAICS sub-sector was “specialty trades contractors” (67.1%) followed by “construction of buildings-residential” (18.1%). Most workers were classified in

Table 2.1: Injury claim descriptive statistics

Worker demographics and work and employer characteristics		
Injury claims	n	63720
Age	mean (sd)	34.1 (10.8)
Age categories	n (%)	
18 to 24		14179 (22.3)
25 to 34		21758 (34.1)
35 to 44		15645 (24.6)
45 to 54		9320 (14.6)
≥55		2818 (4.4)
Male gender	n (%)	62392 (97.9)
BMI	mean (sd)	27.2 (4.6)
Employer size	n (%)	
<10		23090 (36.2)
10-50		22079 (34.7)
≥50		15303 (24.1)
Days employed by employer	mean (sd)	718.17 (1430.6)
More experience (by age category)	n (%)	50990 (80.0)
18 to 24		10420 (73.5)
25 to 34		17646 (81.1)
35 to 44		17646 (82.3)
45 to 54		7677 (82.4)
≥55		2364 (83.9)
SOC	n (%)	
Construction trades workers		54426 (85.4)
Supervisors		6106 (9.6)
Other construction and related workers		2558 (4.0)
Helpers, construction trades		453 (0.7)
Extractor workers		177 (0.3)
NAICS	n (%)	
Specialty trade contractors		42354 (67.1)
Construction of buildings-residential		11407 (18.1)
Construction of buildings-non-residential		5292 (8.4)
Heavy and civil engineering construction		4107 (6.5)
Outdoor context ≥80%	n (%)	47152 (74.0)
MET	n (%)	
< 4		18694 (29.3)
4 to 5		15329 (24.1)
>5		29694 (46.6)
Injury and Claim Characteristics		
Injury in PM hours	n (%)	23002 (40.2)
Injury hour	n (%)	
0001-0530		564 (1.0)
0531-0930		13817 (24.1)
0931-1230		19841 (34.7)
1231-1630		20281 (35.4)
1631-1930		1870 (3.3)
1931-2400		851 (1.5)
Day of the week	n (%)	
Mon		12972 (20.4)
Tue		12764 (20.0)
Wed		12560 (19.7)
Thu		12293 (19.3)
Fri		10508 (16.5)
Sat		1974 (3.1)
Sun		649 (1.0)
Western Washington	n (%)	50779 (79.7)
OIICS-body part	n (%)	
Upper Extremity		36555 (57.4)
Lower Extremity		13712 (21.5)

Trunk		7584 (11.9)
Multiple Body Parts		3819 (6.0)
Neck		1479 (2.3)
Head		403 (0.6)
Other Body Parts/Body Systems/Nonclassifiable		168 (0.3)
OIICS-source	n (%)	
Parts & Materials		17965 (28.2)
Structures & Surfaces		12736 (20.0)
Tools, Instruments, & Equipment		10869 (17.1)
Other Sources		9729 (15.3)
Person, Plants, Animals, and Minerals		3704 (5.8)
Nonclassifiable		2784 (4.4)
Machinery		2692 (4.2)
Containers		1377 (2.2)
Vehicles		958 (1.5)
Furniture & Fixtures		880 (1.4)
Chemicals & Chemical Products		26 (0.0)
OIICS-event	n (%)	
Bodily Reaction & Exertion		27776 (43.6)
Falls		21338 (33.5)
Fires & Explosions & Other Events/Exposures		7569 (11.9)
Exposure to Harmful Substances/Environments		3070 (4.8)
Contacts with Objects & Equipment		2098 (3.3)
Nonclassifiable		1200 (1.9)
Transportation Accidents		489 (0.8)
Assaults & Violent Acts		135 (0.2)
OIICS-nature	n (%)	
Open wounds		24898 (39.1)
Surface wounds & bruises		15354 (24.1)
Muscles, tendons, ligaments, joints		10409 (16.3)
Bones, nerves, spinal cord		6878 (10.8)
Multiple traumatic injuries and disorders		4721 (7.4)
Other traumatic injuries and disorders		1050 (1.6)
Intracranial injuries		299 (0.5)
Effects of environmental conditions		110 (0.2)
Chemical burns		1 (0.0)
Compensation outcome	n (%)	
Medical Only		49168 (77.2)
Time Loss		11682 (18.3)
Kept on Salary		2467 (3.9)
Total Permanent Disability		328 (0.5)
Loss of Earning Power		44 (0.1)
Fatal		31 (0.0)
Days of time loss	mean (sd)	54.7 (284.0)
Days between injury and 1st medical provider	mean (sd)	13.14 (78.8)
Assigned address	n (%)	
Accident		32391 (50.8)
Provider		30159 (47.3)
Business		1170 (1.8)
No previous claim	n (%)	37648 (59.1)

SOC minor group "construction trades" (85.4%) and 74% worked in an outdoor context of ≥80% (Table 2.1). The majority of claimants (80%) were considered to have more experience (as defined above). The mean (standard deviation) number of days employed by the employer of injury was 718.2 (1,430.6) days. Slightly more claims were associated with small employers (<10 workers, 36.2%) than with large employers (50 or more workers, 24.1%). The SOC-assigned metabolic activity exceeded five METs in 46.6% of claimants. Those occupations that exceeded five METs were carpenters (SOC 472031; MET 6), construction craft laborers (SOC 472061; MET 6), and structural iron and steel occupations (SOC 472221; MET 7.5).

Most injuries tended to occur during normal business hours of 5:30 am to 4:30 pm (94.2%), Monday-Friday (95.9%), in western Washington (79.9%). The largest percentage of injuries occurred between 12:31-16:30 (35.4%). The accident address was assigned to 50.8% of claims as the injury location, followed by 47.3% assigned to the provider address. The most commonly injured body parts were the upper extremities (57.4%), followed by the lower extremities (21.5%). Injuries were most often the result of bodily reaction and exertion (43.6%) or falls (33.5%), from parts and materials (28.2%), structures and surfaces (20.0%), and tools, instruments, & equipment (17.1%). Most claims did not involve time loss (77.2%). 328 (0.5%) claims resulted in total permanent disability, and there were 31 fatalities.

2.4.2 *Exposure*

For the March-October period, the mean (interquartile range (IQR)) humidex on injury and referent days was 21.6 (15.6, 26.9) °C and 21.4 (IQR 15.5, 26.8) °C, respectively (Table 2.2). The mean of within strata (injury and corresponding referent days) standard deviations was 4.3 °C. For the May-September period, the mean humidex on injury and referent days was 25.4 (IQR 21.1, 29.4)°C and 25.3 (IQR 21.0 and 29.3)°C, respectively. There was a mean of 3.4 referent days per injury day. Eastern WA tended to be characterized by a slightly higher mean humidex and within strata standard deviation than western WA.

2.4.3 *Inferential analysis*

The odds ratios (OR) and 95% confidence intervals (95% CI) for the association between humidex and traumatic injuries in adult, outdoor construction workers from March-October in WA are presented in Table 2.3. For both the *a priori* and best-fit spline analyses and the six-group exposure category analyses, we observed higher odds ratios for a traumatic injury higher heat exposure. In the *a priori* analysis, the OR of traumatic injuries per °C change in maximum daily humidex was 1.0046 (95% CI 1.002, 1.007), 1.0052 (95% CI 0.995, 1.015), 1.0066 (95% CI 0.995, 1.018), and 1.0075 (95% CI 0.998, 1.017) for maximum daily humidex < 25 °C, from 25–29 °C, from 29–34 °C, and ≥ 34 °C, respectively. In the best-fit analysis, the OR of traumatic injuries per °C change in maximum daily humidex was 1.0034 (95% CI 1.000, 1.007), 1.0087 (95% CI 1.000, 1.017), 1.0045 (95% CI 1.000, 1.009), and 1.0131 (95% CI 0.999, 1.028) for maximum daily humidex < 21 °C, from 21–25 °C, from 25–37 °C, and ≥ 37 °C, respectively. Using continuous exposure and no splines, the OR was 1.0053 (95% CI 1.003, 1.007) per one °C change in humidex. In the categorical analysis, the injury ORs for each humidex category relative to the referent category (<17 °C), were 1.0131 (95% CI 0.983, 1.044), 1.0406 (95% CI 1.007, 1.076), 1.0493 (95% CI 1.012, 1.088), 1.0916 (95% CI 1.045, 1.140), 1.0828 (95% CI 1.022, 1.148), and 1.2469 (95% CI 1.143, 1.360) for a humidex of 17–20 °C, 21–24 °C, 25–29 °C, 30–34 °C, 35–39 °C, and ≥ 40 °C, respectively. Per one °C increase in dry temperature, the OR was 1.0042 (95% CI 1.000, 1.009), 1.0123 (95% CI 1.002, 1.023), 1.0058 (95% CI 1.000,

Table 2.2: Exposure characteristics (maximum daily humidex)

		n	Mean (SD)	Median (IQR)	Number of strata containing categories (days (injury; referent))
March - October	Injury days	63,720	21.6 (8.0)	21.6 (15.6, 26.9)	-
	Referent days	218,239	21.4 (8.0)	21.5 (15.5, 26.8)	-
	Mean of within strata SDs = 4.3	-	-	-	-
	Humidex categories	-	-	-	
	<17				33,119 (19,344; 67,209)
	17-20				34,485 (10,702; 36,913)
	21-24				38,152 (12,326; 41,854)
	25-29				33,888 (11,910; 40,816)
	30-34				20,605 (6,198; 20,723)
	35-39				9,288 (2,368; 8,121)
	≥40				3,327 (869; 2,593)
May - September	Injury days	41,522	25.4 (6.4)	25 (21.1, 29.4)	-
	Referent days	142,251	25.3 (6.4)	24.9 (21, 29.3)	-
	Mean of within strata SDs = 4.6	-	-	-	-
	Humidex categories	-	-	-	-
	<17				11,186 (3,720; 12,910)
	17-20				21,260 (6,561; 22,966)
	21-24				30,922 (10,479; 35,991)
	25-29				31,527 (11,398; 39,183)
	30-34				20,248 (6,127; 20,488)
	35-39				9,277 (2,366; 8,114)
	≥40				3,327 (869; 2,593)
Western WA	Injury days	50,779	21.2 (7.4)	21.3 (15.6, 26.3)	-
	Referent days	173,972	21 (7.4)	21.2 (15.5, 26.1)	-
	Mean of within strata SDs = 4.1	-	-	-	-
	Humidex categories	-	-	-	-
	<17				26,501 (15,542; 53,961)
	17-20				28,518 (8,994; 31,124)
	21-24				31,603 (10,501; 35,703)
	25-29				27,016 (9,785; 33,696)
	30-34				14,959 (4,392; 14,535)
	35-39				5,391 (1,180; 3,875)
	≥40				1,622 (382; 1,068)
Eastern WA	Injury days	12,941	23.1 (9.8)	23.1 (15.6, 30.6)	-
	Referent days	44,267	23.1 (9.8)	23.1 (15.4, 30.7)	-
	Mean of within strata SDs = 5.1	-	-	-	-
	Humidex categories	-	-	-	-
	<17				6,618 (3,802; 13,248)
	17-20				5,967 (1,708; 5,789)
	21-24				6,549 (1,825; 6,151)
	25-29				6,872 (2,125; 7,120)
	30-34				5,646 (1,806; 6,188)
	35-39				3,897 (1,188; 4,246)
	≥40				1,705 (487; 1,525)

Table 2.3: Model results for a priori and best-fit splines and secondary analyses. Significant results are in bold.

		Exposure (°C)	OR	95% CI
a priori knots: 25, 29, & 34		< 25	**1.0046**	**(1.002, 1.007)**
		25 to 29	1.0052	(0.995, 1.015)
		29 to 34	1.0066	(0.995, 1.018)
		> 34	1.0075	(0.998, 1.017)
best-fit knots: 21, 25, & 37		< 21	1.0034	(1.000, 1.007)
		21 to 25	**1.0087**	**(1.000, 1.017)**
		25 to 37	**1.0045**	**(1.000, 1.009)**
		> 37	1.0131	(0.999, 1.028)
Secondary Analyses				
Humidex		Continuous	**1.0053**	**(1.003, 1.007)**
	6 groups	17 to 20	1.0131	(0.983, 1.044)
		21 to 24	**1.0406**	**(1.007, 1.076)**
		25 to 29	**1.0493**	**(1.012, 1.088)**
		30 to 34	**1.0916**	**(1.045, 1.140)**
		35 to 39	**1.0828**	**(1.022, 1.148)**
		≥ 40	**1.2469**	**(1.143, 1.360)**
Dry Temperature		Continuous	**1.0072**	**(1.005, 1.009)**
	best-fit knots: 21, 25, & 37	< 19.3	1.0042	(1.000, 1.009)
		19.3 to 22.7	**1.0124**	**(1.002, 1.023)**
		22.7 to 32.2	**1.0058**	**(1.000, 1.011)**
		> 32.2	**1.0227**	**(1.003, 1.042)**
Humidex - Lag of 1 Day		Continuous	**1.0052**	**(1.003, 1.007)**
	best-fit knots: 21, 25, & 37	< 21	**1.0112**	**(1.008, 1.015)**
		21 to 25	**0.9865**	**(0.978, 0.995)**
		25 to 37	**1.0092**	**(1.005, 1.014)**
		> 37	0.9994	(0.984, 1.014)

n= 281946, number of events= 63717

1.011), and 1.0225 (95% CI 1.003, 1.042) for maximum daily temperature < 19.3 °C, from 19.3-22.7 °C, from 22.7-32.2 °C, and ≥ 32.2 °C, respectively. The analysis of a one-day lag in exposure resulted in statistically significant ORs per one °C change in humidex up to 21 °C and from 25-37 °C of 1.0061 (95% CI 1.002, 1.010) and 1.0067 (95% CI 1.002, 1.011), respectively. The ORs for humidex between 21-25 and above 37 were 1.0013 (95% CI 0.993, 1.010) and 1.0023 (95% CI 0.987, 1.017), respective, per one °C change in humidex and were not statistically significant.

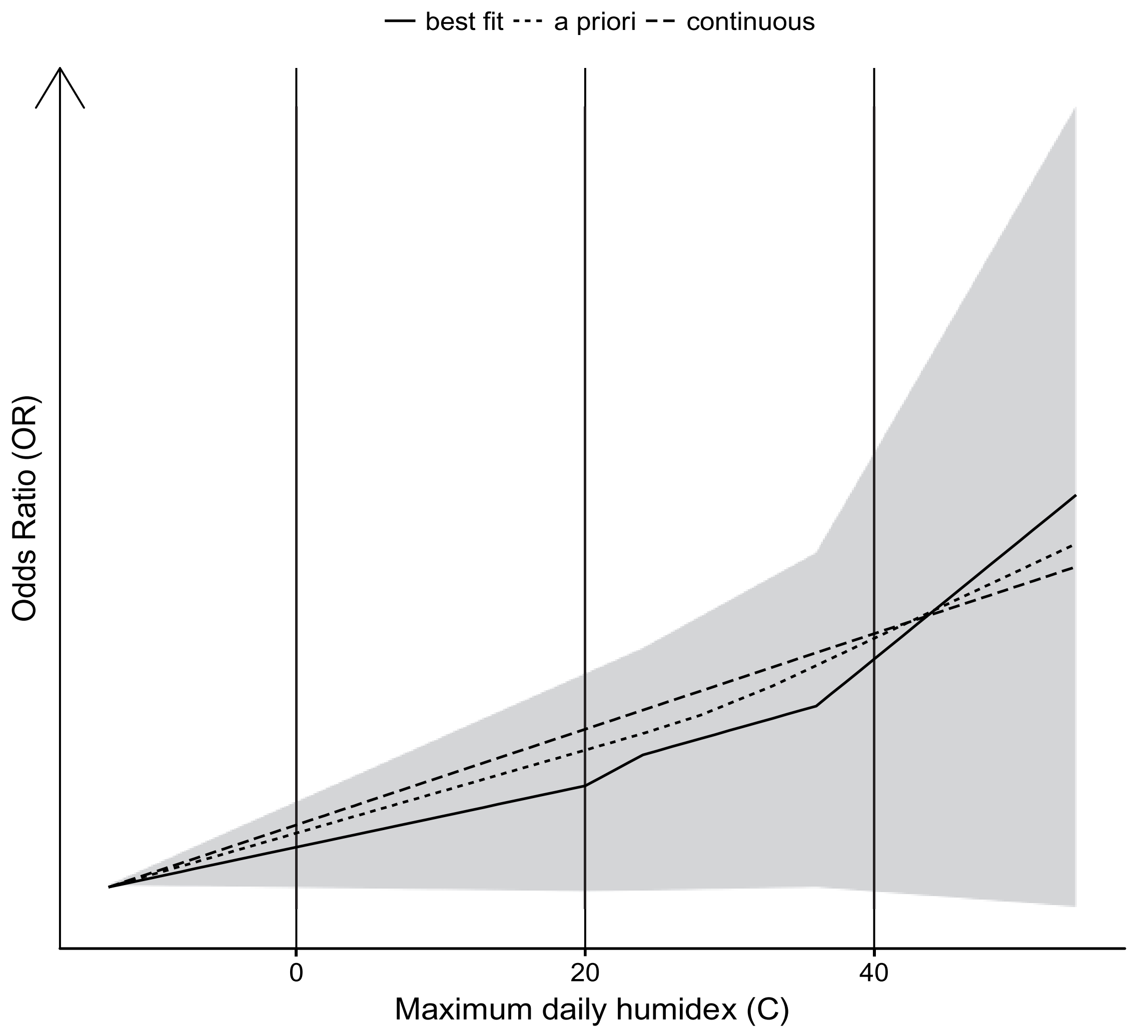


Figure 2.3: Comparison of odds of injury risk in analyses using a priori splines, best-fit splines, and continuous exposures. Confidence interval displayed for best-fit analysis.

Stratified and sensitivity analysis results using the continuous humidex model are depicted in Figure 2.4. Overall, there was considerable overlap in the confidence intervals across categories. Analysis by age category revealed a higher OR for younger (18 to 24 year old) and older (over 54 years) worker claims. Lower extremity injury claims were also characterized by a higher OR as were those associated with less worker experience. Lower ORs were observed for injuries occurring later in the afternoon and for the large employer size (≥50 employees). The OR for Eastern Washington was slightly lower than for Western Washington. Sensitivity analyses did not result in substantially different relationships between humidex and traumatic injuries.

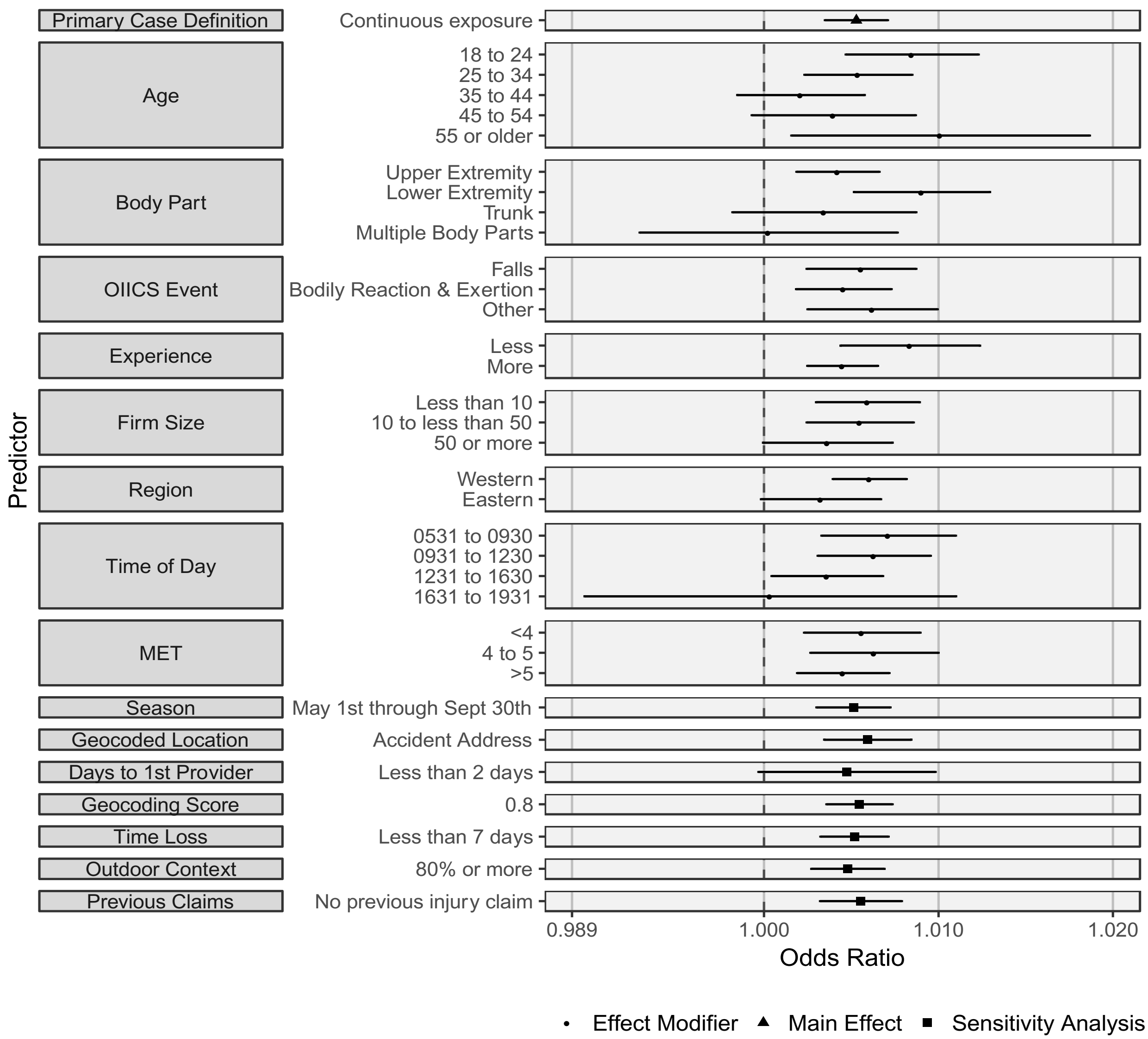


Figure 2.4: Stratified and sensitivity analyses.

2.5 DISCUSSION

Our findings of an association of increasing occupational heat exposure with increasing risk of traumatic injuries in WA outdoor construction contributes to the growing body of evidence suggesting occupational heat exposure impacts the health and safety of workers beyond HRI. Our results of potentially higher risk in younger and older workers, workers with lower extremity injuries, workers with less job experience, smaller employers, workers working in Western Washington, and time of injury before 12:30 pm provide opportunities for further study of the nuances of this phenomenon in outdoor construction workers. A better understanding of these nuances could lay the groundwork for construction injury prevention approaches that address the role heat plays in the risk of an injury.

In the best-fit spline analysis, increasing humidex during warmer months of the year was characterized by a nearly linear association with the risk of a traumatic injury. A similar trend in effect estimates was seen in the *a priori* spline, continuous, and categorical exposure analyses. This positive relationship is consistent with findings in the existing literature. In a study using a similar modeling approach and population of interest, Xaing et al. reported an injury incidence rate ratio (IRR) of 1.006 (95% CI: 1.002, 1.011) per degree °C increase in maximum daily temperature between 14.2 and 37.7 °C for construction workers in Adelaide, Australia (Xiang et al., 2014). This increase is on the same order of magnitude as the ORs reported in this study for the continuous analyses using maximum daily humidex (OR 1.005 per degree °C; 95% CI: 1.003, 1.007) and maximum daily temperature (1.007 per degree °C; 95% CI: 1.005, 1.009). Similarly, Adam-Poupart et al. reported an IRR of 1.003 (95% CI: 1.000, 1.006) per degree °C increase in maximum daily temperature in Quebec, Canada for construction workers, and McInnes et al. reported an OR of 1.008 (95% CI: 1.001, 1.015) per degree °C increase maximum daily temperature in young workers (<25 years of age) in Melbourne, Australia (McInnes et al., 2017). Using wet bulb globe temperature (WBGT) as the metric for exposure, Garzon-Villalba et al.'s study of acute injuries in Deep Water Horizon disaster cleanup workers reported a relative risk (RR) for acute injury of 1.13 (95% CI: 1.09, 1.17) above a maximum WBGT of 20 °C (Garzon-villalba et al., 2016). While WBGT was not used in this study, the effect estimates are on a similar order of magnitude to those found in this analysis.

In a study of agricultural workers in Eastern Washington using a categorical exposure approach, Spector et al. report a peak OR of 1.15 for a maximum daily humidex between 30-33 °C, relative to < 25 °C (Spector et al., 2016). This estimate is higher than the OR reported for a similar range in exposure in this study (OR 1.09 for a maximum daily humidex between 30-34 °C, relative to <17 °C). The higher OR in agriculture at lower humidex values may reflect differences in safety culture, task-related hazards that are not characterizable with the available data, or payment method, since piece-rate pay is more common in agricultural work and has been reported to be associated with more symptoms of HRI and heat strain than hourly-payment methods (Spector et al., 2015).

Consistent with McInnes et al (McInnes et al., 2017) and Adam-Poupart et al(Adam-Poupart et al., 2015), who report linear relationships between increasing heat and increasing injury risk, we report a near-linear relationship, with only slight non-linearity was observed in the best-fit spline analysis and categorical exposure analysis. In the analysis using splines, we report greater per °C increases in the OR at humidex between 21-25 °C and above 37 °C. The ranges in exposures associated with these steeper slopes are noteworthy because they fall at humidex values considered to be comfortable and at values above which periods of rest are recommended for workers who are unacclimatized or are completing heavy physical work, respectively (Canadian Centre for Occupational Health and Safety., 2011).

The near-linear trend in our results are, however, contrary to the findings of Spector et al [(3)], Xiang et al (Xiang et al., 2014), and Morabito et al (Morabito et al., 2006), who report a reversed u-shaped association between increasing heat and the risk of injury. While heat exposure metrics and populations vary by study, injury risk has been reported to decline above a maximum daily temperature of 37.7 °C (Xiang et al., 2014), maximum daily apparent temperature of 31.7 °C (Morabito et al., 2006), and maximum daily humidex of 34 °C (Spector et al., 2016). 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 exposure misclassification related to risk reduction practices used to prevent HRI, such as ending work shifts early on the hottest days. Work organization and behavior is challenging to characterize using population data, such as workers' compensation claims, emergency department visits, or hospitalizations and may lead to exposure misclassification. These factors, however, may be more accurately characterized in workplace studies. Fogleman et al (Fogleman et al., 2005) used aluminum smelter company health and safety records combined with hourly weather data to assess the relationship between heat and injuries in aluminum smelter workers. In Fogleman et al's study, where work hours and hourly weather data were known, acute injury ORs were observed above exposures of 32°C.

Unlike in agriculture, less flexibility to modify work hours to avoid working during the hottest part of the day may exist in construction. For example, noise and light ordinances may prohibit construction activities outside of typical business hours. The pace of work may also be driven by pressure to complete a task due to weather or material considerations, putting workers in a position where they are unable to adequately self-pace or practice recommended work-rest cycles. In addition, adjustment of work processes so that easier or less strenuous tasks can be completed during periods of high heat stress, when workers often experience greater fatigue and productivity is expected to wane, may be unattainable due to scheduling constraints and the nature of the tasks needing to be completed. For example, framers may rush to finish load-bearing walls prior to the delivery of trusses so as to avoid rescheduling the delivery for potentially a much later date. Roofing workers may feel pressure to complete the water proofing of a building before the end of the shift if the weather forecast indicates any chance of rain. Workers often need to work within local regulations and accommodate the schedule of other trades (such as an elevator operator).

Large employers (50 or more employees) were characterized by a lower injury effect estimate in stratified analyses than medium and smaller employers, although confidence intervals of effect estimates for different categories of employer size overlapped. This finding is consistent with findings by Xiang et al. where medium employers (20-199 employees) and large employers (≥200 employees) were characterized by lower injury effect estimates than small-sized employers (1-19 employees) (RR 1.004 and 1.000 compared with 1.007, respectively) (Xiang et al., 2014). Larger employers in our study may have greater capacity to implement heat risk prevention strategies, are required to have Safety Committees in Washington (WAC 296-800-130), and are more likely to have the financial capacity to utilize health and safety technology and employ dedicated health and safety specialists. There are also trends in employer size by other industry characteristics. Smaller companies are more commonly involved residential work and larger companies in commercial work (Holizki et al., 2015), and this may result in different occupation- or task-related risk factors by employer size. Additional support for small businesses may be indicated to effectively prevent heat-related traumatic injuries.

We did not find evidence suggestive of effect modification by MET level. Contributions to occupational heat stress include environmental conditions, metabolic activity, and clothing. In this study, metabolic activity was evaluated using MET estimates developed from the ATUS. Metabolic activity is notoriously difficult to assess accurately, and values provided at an occupational level cannot describe the variability in metabolic demands across tasks or even individuals conducting similar work. Further work is needed to more accurately assess metabolic activity in order to assess its contribution to occupational heat-related injuries.

Age is a known risk factor for heat-related health effects. We report that younger (18-24 years of age) and older (over 54 years) claimants exhibited greater heat-related injury risk, although confidence intervals of effect estimates for different categories of age overlapped. In a setting with high metabolic demand and high ambient heat, older individuals may be more susceptible to the effects of heat due to decreased skin blood flow (Holowatz & Kenney, 2010) and decreasing cardiac capacity (Armstrong & Kenney, 1993), as well as have a higher prevalence of pre-existing conditions. Young workers may be more likely to exert rather than pace themselves, may be more likely to be assigned tasks with higher metabolic demands than their older counterparts, and have been reported to display more negative attitudes towards safety and personal protective equipment (Lombardi, Verma, Brennan, & Perry, 2009; Siu et al., 2003). In other similar research, higher risk estimates have been reported for workers less than 25 years of age per °C increase in maximum daily temperature in Australia (McInnes et al., 2017) and in Canada (Adam-Poupart et al., 2015). None of these studies report higher risks for older workers, except for McInnes et al (2017), by minimum daily temperature.

Less experience was also characterized by a higher injury effect estimate with less precision than more experience in stratified analyses. We observed slightly less experience in the youngest age category, with 73% of claimants age 18-24 categorized as having more experience compared with 80% for the full population. Claimants over 54 years of age were observed to have the most experience (84%). Experience was defined as working in the previous quarter, according to ESD data, or working for the employer for at least 90 days according the self-report data on the injury claims form. This definition does not describe experience acquired over longer periods of time that could influence a worker's tasks, responsibilities, standing with an employer, or perceived job security. However, this definition of experience is expected to reflect familiarity with processes and tasks performed during the referent window as well as acclimatization to environmental conditions present within a work environment. Research by Choudhry et al describes how actual experience, in addition to training, is required to adequately prepare workers for the conditions present on a job site, including the presence of heat and fast-paced work (Choudhry & Fang, 2008).

There were several possible factors that could contribute to a smaller effect in Eastern WA than Western WA. The climate in Washington State is characterized by two distinct regions that are separated by the Cascade Mountains: a relatively milder western region and an eastern region with hotter, drier summers and colder winters. These different climates may affect patterns of acclimatization (timing and threshold tolerance) and could trigger differences in heat-related practices. These regions are also characterized by different economic and development profiles with a larger, booming urban center in Western WA (Seattle-Tacoma) compared to Eastern WA. The injury claims data were dominated by claims in the western region (80%). In addition to the implications for precision of estimates, Western Washington data likely drove the knot selection for the best-fit selection of spline model to a greater extent than the Eastern WA claims.

We observed higher ORs for injuries to the lower extremities than other parts of the body, although, again, confidence intervals of ORs for body part categories overlapped. Of these injuries, the most common precipitating event was falls (48%). In comparison, falls accounted for 34% of injuries in the full dataset. This is consistent with existing literature attributing 50-60% of lower extremity injuries to falls in non-military settings (Mackenzie & Fowler, 2008). Research investigating the mechanisms suspected in the relationship between heat and traumatic injuries have focused on the potential relationship between decrements to balance and cognitive performance, including vigilance—mechanisms identified to increase the risk of falls—and conditions characterized by heat stress. Changes in balance resulting from fatigue have been documented in controlled settings related to extreme muscle fatigue (Parijat & Lockhart, 2008) and exercise in hot conditions (Distefano et al., 2013), as well as in review articles of exercise-induced fatigue (Zemková & Hamar, 2014). The association between fatigue and heat has been documented in similar controlled settings (Ganio et al., 2011; Nielsen, Hyldig, Bidstrup, González-Alonso, & Christoffersen, 2001). In some of this work, changes in cognitive performance have also been documented. Ganio et al (Ganio et al., 2011) reported increased tension and anxiety as well as vigilance and memory errors occurred under conditions of hyperthermia and dehydration; Mazlomi et al (Mazlomi et al., 2017) reported higher levels of stress hormones, including cortisol, in foundry workers working in high WBGT conditions; and Sharma et al (Sharma et al., 1983) reported a greater effect of heat on psychological functions with humidity was also high. Other factors may also contribute to the relationship between heat and traumatic injuries as well, such as changes in safe work practices (Ramsey et al., 1983).

There are a number of potential explanations for why risk might decrease with later work-shift hours that should be explored further. Tasks may differ by time of day. For example, tasks earlier in the day may include more active movement to set up the site and move materials into place in preparation for more stationary activities in later hours. Changes in task could affect metabolic contribution to heat stress as well as traditional risk factors for injuries (e.g. trip hazards). Heat exposure in the morning may also have been low enough so that workers did not recognize early signs of HRI or heat strain, such as excessive sweating. These lower exposures would also likely not have triggered HRI awareness or intervention tactics that may have been utilized later in the day. Diurnal patterns have also been observed in vigilance and balance research, where performance was worse in early morning tests. In field studies with agricultural workers in WA State, Spector et al (Spector et al., 2018) observed significantly longer mean reaction time and a greater number of lapses measured using a psychomotor vigilance test (PVT) as well as longer mean total path length, a measure of postural sway, in pre-shift assessments (i.e. prior to a mean shift start time of 06:00). Further research should investigate specific tasks and associated metabolic heat production throughout the work-shift, construct task-related injury risk factor profiles by time of day, and better characterize vigilance and postural sway within workers over time and between workers.

2.6 Strengths and Limitations

A strength of this study is our novel approach to identify workers more likely to be working outside. Separation of outdoor and indoor environments is particularly important for analyses of heat in settings where the presence of air conditioning is inconsistent, such as construction sites in the Pacific Northwest. In settings where air conditioning is available, the indoor environment may be characterized by reasonably predictable cooler conditions. However, even when indoors, construction work may occur prior to the installation or use of air conditioning or in areas of a building not typically climate controlled, leading to unpredictable thermal conditions. Xiang et al's study (Xiang et al., 2014) included a high level separation of indoor and outdoor exposures by grouping the construction sector with "agriculture, forestry, and fishing" and "electricity, gas, and water" under the name "outdoor industries". While this approach is an improvement over analyses of all industries combined, it still includes some occupations with predominantly indoor work. Our analysis takes advances this approach by excluding occupations within the construction industry identified with less than 50% O*NET context outside. By restricting the inclusion criteria for injury claims, we minimize non-differential exposure misclassification and reduce bias of results towards the null. 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.

The availability of both high-resolution meteorological data and injury location addresses enabled spatial pairing of the outdoor conditions with the injury location at a higher resolution than has been achievable in other studies of heat exposure and traumatic injuries in construction. This approach to assigning environmental exposures also reduced the potential exposure misclassification introduced by using one monitoring station per large geographic area (representative weather stations) or aggregating across political boundaries (city-, county-, etc.). These approaches do not account for variations in weather conditions and climate associated with geographic features. The use of representative stations or mean exposures across political boundaries also inherently minimizes the presence of extremes.

This study has several limitations. First, in nearly half of the claims, accident address was either missing or not complete enough to be geocoded accurately. As a result there may have been exposure misclassification from assigning the address of the first medical provider to the injury location. Out sensitivity analysis suggests this missing data did not substantially alter the estimate in the primary analysis.

Second, we were unable to take into account variability in clothing. Clothing is an important consideration when assessing heat stress since it can act as an insulating barrier between the body and the environment. WA workers' compensation records do not contain systematic information about a claimant's clothing at the time of injury. We explored the use of personal protective equipment (PPE) that would necessitate inclusion of a clothing adjustment factor by occupation (SOC) using O*NET survey responses and expert opinion, but ultimately deemed clothing-related PPE to be too difficult to quantify. Therefore, we did not stratify by clothing and assumed that workers wore the same clothing on the day of injury and referent days.

The third limitation of this study was that we did not take into account solar radiation. In occupational settings, the wet bulb globe temperature (WBGT) is often considered to be the gold standard for measuring environmental heat and is central to recommendations by the United States National Institute for Occupational Safety and Health (NIOSH), American Conference of Governmental Industrial Hygienists (ACGIH), International Organization of Standardization (ISO), US Armed Services, American College of Sports Medicine, and other organizations(NIOSH, 2016). The WBGT assesses solar radiation through the black globe temperature. Adjustment factors that take into account solar radiation have been used to estimate WBGT from dry temperature and relative humidity alone (Bernard & Barrow, 2013). While the validity of these calculations has been demonstrated (Bernard & Barrow, 2013) use of this approach still hinges on knowledge of the presence or absence of solar radiation to inform use of the appropriate equation: WBGT in the sun or WBGT in the shade. In large studies such as this one, where a metric for clouds or solar radiation is not available in the meteorological data and there exists substantial spatiotemporal variability in weather conditions, calculation of the WBGT may increase non-differential misclassification of exposure. We therefore did not pursue estimation of WBGT in this study. We were also unable to take into account differences in worker microclimates influenced by point sources of heat, shade, or shift breaks. We assumed claimants were working on the same job site and under the same conditions on referent days. Potential shifts in work location, whether between multiple sites or even conditions within a site, may have influenced a claimant's exposure on injury and referent days.

Forth, we were unable to adjust for several potential time-varying confounders. At the individual level, the task a worker performed may change as a result of an injury, where a claimant who returned to work after an injury may have been placed on light duty, laterally shifted to a different crew or worksite, or altered how he or she performed the task. Tasks may also change as a result of the heat, where the claimant adjusted the timing of tasks to optimize productivity or comfort in different weather conditions. The tasks also had the potential to change at the worksite or employer level as a result of administrative controls or implementations aimed at the same outcomes. Changes to worksite safety practices or awareness of HRI-prevention could also change as a result of an injury or heat conditions. If such changes were implemented after injuries occurred early in the referent window or due to high heat exposure, results would likely be biased toward the null.

2.7 Conclusions

Environmental heat exposure in outdoor construction workers in Washington State is positively associated with traumatic injuries. For this population, we report a nearly linear association with the risk of an injury at exposures lower than thresholds recommended in occupational health and safety guidelines for heat stress controls based on HRI risk. Stratified analyses suggested higher risk in younger (18-24 years) and older (over 54 years) workers, for lower extremity injuries, workers with less job experience, smaller employers, workers working in Western Washington, and time of injury before 12:30 pm, although there was there was overlap in confidence intervals of effect estimates across categories. Further research is needed to better characterize metabolic heat production within occupational groups, understand the mechanism of association between heat exposure and traumatic injuries, and formally explore effect modification by key factors. The findings in this study suggest that injury prevention efforts in construction should address heat-related risk factors, particularly for high-risk workers. Additionally, this information could be used to inform combined heat stress and injury prevention efforts in the highest risk construction workers as well as expand broad occupational heat awareness campaigns to address outcomes beyond heat-related illness.

Chapter 3. A COMPARISON OF OCCUPATIONAL HEAT EXPOSURE MEASURED AT THREE SPATIAL RESOLUTIONS IN COMMERCIAL ROOFING WORKERS: IMPLICATIONS FOR HEAT HEALTH RESEARCH AND PRACTICE.

3.1 Abstract

Background: Exposure to heat is known to adversely affect health. In occupational settings, heat exposure is traditionally quantified using area monitoring devices. Data from weather stations and personal monitoring devices have also been used to assess heat-health relationships. The objective of this analysis was to compare how regional-, area-, and personal-level measurement approaches influence the quantification of environmental heat exposure in an occupational setting.

Methods: Full work-shift measurements of heat were collected in a sample of 22 commercial roofing workers in the Greater Seattle area in a repeated-measures study during the summer and fall of 2016. Measurements were made using county weather stations at the regional-level (RL), 3M™ QUESTemp™ 36 Heat Stress Monitors at the area-level (AL), and hygrochron iButtons at the personal-level (PL). Using the area monitor as the baseline, we described differences in air temperature and wet bulb globe temperature (WBGT) measured at the personal and regional levels as the difference from the area monitor, where a positive difference indicated a higher temperature at the personal or regional level than measured at the area level. The Newey-West estimator was used to adjust for temporal autocorrelation. Differences between worksites were quantified as the standard deviation of the means from analyses stratified by site.

Results: We report a positive mean (95% confidence interval) difference between PL-AL temperature of 4.4 (4.1, 4.7) °C and WBGT of 1.5 (1.3, 1.8)°C-WBGT, and a difference between RL-AL temperature of 0.2 (-0.3, 0.6) °C-WBGT. The direction of the difference between regional and area monitors varied by site with a standard deviation of site-specific mean differences of 1.04 °C. We observed variability in heat exposure in PL measurements that was not captured at the AL.

Conclusions: Personal measurement data were observed to be consistently higher than area data, but the difference between regional and area monitors varied in direction by site. Differences in heat measurements based on AL, RL, PL approaches may have implications for epidemiologic study inferences and for workplace health and safety practice, where area-level measurements are typically used in conjunction with occupational heat stress guidelines.

3.2 INTRODUCTION

Heat exposure can increase the risk of heat related illness (Bonauto et al., 2007; Kerr, Casa, Marshall, & Comstock, 2013; NIOSH, 2016; Parsons, 2002; Michael N. Sawka et al., 2011; Spector et al., 2014), which may be fatal if not treated promptly (Bouchama & Nochel, 2002;

Parsons, 2002; Michael N. Sawka et al., 2011). Heat stress in occupational settings may also reduce performance and productivity (Lundgren et al., 2014; Mckinnon et al., n.d.; Sahu et al., 2013; Zander, Botzen, Oppermann, Kjellstrom, & Garnett, 2015), increase the risk of a traumatic injury (Adam-Poupart et al., 2015; Fogleman et al., 2005; Garzon-villalba et al., 2016; McInnes et al., 2017; Morabito et al., 2006; Spector et al., 2016; Xiang et al., 2014), and adversely affect overall quality of life through morbidity related to repeated exposure such as kidney damage. Recent research suggests a relationship between heat exposure and acute kidney injury in US agricultural workers (Moyce et al., 2017), and repeated intermittent dehydration related to heavy physical work in hot conditions is hypothesized to contribute to chronic kidney disease of unknown origin (CKDu), an emerging epidemic in Central America, Sri Lanka, and other areas of the world (Orantes Navarro et al., 2015; Rajapakse, Shivanthan, & Selvarajah, 2016).

Thorough evaluation of the human thermal experience, or human heat balance, requires calculation of energy produced through metabolic processes, energy transferred to and from the human body from the surrounding environment, and the impact of factors influencing the efficiency of energy transfers, such as clothing (McGregor & Vanos, 2017; Parsons, 2002; Michael N. Sawka et al., 2011). Precise quantification of these factors is often problematic because of the inherent challenges in estimating energy from numerous sources that may be in multiple forms (radiation, convection, and conduction) and the perpetually changing nature of environmental conditions and metabolic demands. Variability in heat removal efficiency between and within individuals based on physical fitness, medical conditions, medications, age, and other factors (Parsons, 2002; Michael N. Sawka et al., 2011) also complicates quantification efforts. Over the past century, many rational, empirical, and direct indices have been developed to describe how humans perceive and respond to the environmental conditions of their thermal environment (Brake & Bates, 2002;

Epstein & Moran, 2006; McGregor & Vanos, 2017; Parsons, 2002). The choice of indices depends on the setting, availability of input parameters, exposures and outcomes of interest, regional climate, and spatiotemporal scale. At a minimum, these metrics rely on climatic conditions. While comparisons between these metrics have been conducted in a number of settings (Barnett et al., 2010; Parsons, 2002), few comparisons have been reported where the same metric is measured at different spatial and temporal scales (Basu & Samet, 2002; Bernhard et al., 2015; Kuras et al., 2015).

3.2.1 *High risk population: Roofing construction workers*

In Washington State, the highest workers' compensation injury claims rate for heat related illness (HRI) during third quarter months (July, August, and September) was reported for the roofing industry at 161.2 injury claims per 100,000 FTE for 1995-2005 (Bonauto et al., 2007). Roofing work often involves exposure to the elements (National Center for O*NET Development, n.d.-c), high metabolic demands (National Cancer Institute, 2016), and point-sources of heat, such as in torch-applied roofing, where an open flame and hot air are used to apply localized heat to roofing materials (OSHA, 2015).

Metabolic demands in roofing vary by task and often require activities such as walking, bending, and lifting, moving, or cutting materials. Some tasks, such as operating a torch or hot air welder, may involve less physical movement but still require energy from pushing, pulling, and holding equipment (Parsons, 2002; Vezina et al., 2014). In addition to the standard work boots, long pants, and t-shirt often worn by construction workers, built-up applications usually require long-sleeved shirts to prevent burns from contact with hot tar; torch operators and precision workers may opt to use heat-protective Kevlar sleeves. Roofing and other construction occupations may disproportionately experience the anticipated climate-induced increases in the frequency, duration, and severity of extreme temperatures due to the nature and location of their work in urban centers, often on rooftops with no shading, where the effects of urban heat islands would be greatest.

3.2.2 *Heat exposure assessment approaches at different spatial scales*

In population level heat assessments, data collected through meteorological services (e.g. weather stations) provide representative measurements for large geographic regions that can be used to calculate direct indices, such as the wet bulb globe temperature (WBGT), humidex, or heat index. These data are often available free of charge at up to a daily, if not sub-hourly, resolution for current and historic conditions and are increasingly accessible with the growing use of smart phones and robust networks of weather monitoring stations (King-TV, n.d.; The Weather Company LLC, n.d.). Weather station data are appealing for retrospective assessments, comparisons between different regions, and remote monitoring. In some settings, models have been used to improve the spatial resolution of the data (Daly et al., 1997). However, even with high-resolution meteorological data, point-sources of heat and microclimates are likely not captured.

Increased precision of heat exposure measurements for an individual or group at a particular site can be accomplished through the use of small, portable weather stations or area heat stress meters. This approach can provide data at a higher temporal resolution and is particularly advantageous in settings where a representative weather station is not expected to capture environmental conditions, such as indoor settings (e.g. a factory) and underground (e.g. a mine). Heat stress meters are used to provide heat stress assessments for populations with particularly high risks of adverse heat-health outcomes, such as outdoor workers, and have been used as a basis for heat stress recommendations for the military, workers, and athletes (Havenith & Fiala, 2016; NIOSH, 2016; Parsons, 2002). In occupational settings, a direct index, the wet bulb globe temperature (WBGT), is usually captured by a WBGT meter positioned as close as possible to the work area, or with several monitors "when the conditions vary substantially in the work area" (OSHA, 2017). This approach is designed to assess the conditions of the job site rather than individual exposures (American Conference of Governmental Industrial Hygienists, 2015) and can be inadequate in assessing individual exposures when individuals move rapidly and repeatedly between different environments (e.g. from hot attics to air-conditioned vehicles) or when resources (e.g. financial, equipment, etc.) are sparse. WBGT monitors may cost between $500 to $4000, depending on the model and data logging needs.

Monitoring of personal, or individual, heat exposure has been increasingly used in heat health research (Bernhard et al., 2015; Kuras et al., 2017, 2015; Mitchell et al., 2017). Availability of monitoring devices that are small, affordable, accurate, having data logging capabilities, and capture parameters necessary to directly calculate heat indices facilitates mapping of an individual's thermal environment over time and space, when paired with GPS or location data and time use surveys (Kuras et al., 2017). When coupled with personal-health, fitness, and physiology tracking technology (e.g. heart rate monitors, activity monitors, etc.) there exists the potential for individualized heat stress assessments and recommendations; a hugely prospect that is incredibly advantageous for monitoring and intervention, as well as education, purposes. However, approach is not without challenges, including identification of the best approach for affixing a device to an individual so it captures the ambient environment rather than unintentional environments such as within an individual's jacket pocket and precise understanding of how temperature measured on these devices compares with other monitoring strategies. Understanding how these measurements relate to traditional monitoring approaches is critical for interpreting measurements in the context of existing heat health guidelines and for research.

3.2.3 *Study objective*

The purpose of this study was to assess how different monitoring approaches (regional-, area-, and personal-level) influence the quantification of environmental heat exposure in a sample of commercial roofing workers in the Greater Seattle area. We hypothesized that in this population, where task-specific point sources of heat are common and access to shade is rare, air temperature measured at the personal-level would be higher and characterized by greater variability than temperature measured at the area and regional level.

3.3 METHODS

Regional-, area-, and personal-level environmental heat exposures were measured in commercial roofing workers in the Greater Seattle area during the summer and fall of 2016 as part of a larger repeated measures study designed to assess the relationship between occupational heat stress, heat strain, and traumatic injury risk.

3.3.1 *Study population & recruitment*

Commercial roofing workers were selected for the study population because roofing workers are at high risk for adverse heat health effects (Bonauto et al., 2007), primarily work outdoors performing tasks that require high metabolic demands (National Cancer Institute, 2016; National Center for O*NET Development, n.d.-c), and often use task-specific point-sources of heat such as hot-air torches (OSHA, 2015). Commercial, rather than residential, roofers were targeted for this study to facilitate larger within-site sample sizes and to more easily allow for measurements over multiple days per participant within the study's geographic region.

Roofing companies in the Greater Seattle area were recruited during the winter and spring of 2016 to participate in the study using contacts through the University of Washington's Department of Construction Management. Enrolled companies provided a letter of consent to participate and facilitated access to job sites with the site owners and general contractors, when applicable. Participants were recruited from enrolled companies during small on-site safety meetings as well as during an all-hands meeting—a large, quarterly safety meeting attended by all employees within a company. Eligibility criteria are described in Chapter 4. Study researchers participated in safety orientations on a site-by-site basis at the request of the general contractor or lead health and safety specialist for each job site. All study procedures were approved by the University of Washington Human Subjects Division, and participants provided written informed consent in advance of study participation.

3.3.2 *Data collection*

All data collection was performed at the worksite for the full work-shift. Monitoring days were selected based on two criteria: weather conditions and participant availability. We aimed to assess each worker on one "hot" and one "cool" day. Forecasted weather conditions were monitored closely through the National Weather Service. Days with forecasted maximum temperatures of 25°C or greater were anticipated to be "hot days," and days with forecasted maximum temperatures of 22°C or lower were anticipated to be "cool days". At the end of each sampling day, reclassification of the day as either hot or cool was performed based on area-level measurements taken at the worksite. Days that did not meet the originally anticipated classifications were reclassified such that the maximum temperature on cool days did not exceed 25°C and each participant's hot day was a minimum of 5°C hotter than his cool day. Each participant's monitoring days were scheduled a minimum of three days apart and, when possible, repeated measures were performed at the same worksite.

3.3.3 *Environmental measurements*

Environmental measurements of heat were collected at three levels: personal, area, and regional (Table 3.1). Personal-level (PL) measurements were collected using DS1923-F5 hygrochron iButtons (Maxim Integrated; Son Jose, CA, U.S.) attached to the workers' clothing using blue fobs and carabiner-style attachments at approximately hip height. Workers were instructed not to cover the devices with clothing or personal protective equipment (PPE). This location on the body was selected based on research indicating that measurements taken from iButtons attached at foot, waist, and neck height do not significantly differ on individuals exercising outdoors (Dumas, Jagger, & K.W., 2016), considerations for potential task-related point-sources of heat directed at the roofing surface and workers' boots that could impact the vertical heat profile, and attainable consistency in placement given differences in required personal protective equipment (PPE) such as fall-protection harnesses by site. The devices measured and logged air temperature (T_a) and relative humidity (RH) at two-minute intervals for the duration of the work-shift and remained on the workers during breaks.

Area-level (AL) measurements were collected at the worksites using a 3M™ QUESTemp™ 36 Heat Stress Monitor (3M; St Paul, MN, U.S.). The device was mounted on a tripod at approximately one meter above the surface of the work site. Due to restricted access on many of the worksites, researchers asked the study participants to position the area monitor in a location

Table 3.1: Monitoring devices by level and environmental variable.

Level	Device(s)	Monitoring frequency	T_a	T_g	T_{nwb}	T_{dew}	RH	V
Personal	Hygrochron iButtons	2 minutes	✓				✓	
Area	3M QuesTemp 36	3 minutes	✓	✓	✓		✓	
Regional	NOAA weather station	1 minute	✓			✓		✓

Air temperature (T_a), black globe temperature (T_g), natural wet bulb temperature (T_{nwd}), dew point temperature (T_{dp}), relative humidity (RH), and pressure (V)

that was as close as possible to their work area, was representative of work conditions (i.e. in the sun if the workers were in the sun), and would not be in the way of work-related tasks. Participants were asked to re-position the monitoring device in the event the work moved to a different area during the shift. The QUESTemp collected dry temperature (T_a), black-globe temperature (T_g), natural wet bulb temperature (T_{nwb}), and relative humidity (RH) at three-minute intervals and remained on the worksite during breaks. Prior to data collection, the QUESTemp was factory calibrated and tested against the iButtons in a controlled, indoor setting to verify consistency of measurements across monitoring devices.

The regional-level (RL) measurements were sourced from National Oceanic and Atmospheric Administration (NOAA) Automated Surface Observing System (ASOS) for weather stations at county airports in the two counties in which monitoring occurred: Seattle Tacoma International Airport and Everett Snohomish County Airport (National Climate Data Center (NCDC), n.d.). This data source was selected for consistency with other similar assessments of personal heat exposure (Basu & Samet, 2002; Bernhard et al., 2015; Kuras et al., 2015) as well as epidemiologic studies assessing the heat and heat related health effects at a city or regional level (Bernard & Barrow, 2013; Lemke & Kjellstrom, 2012; Lin, Wang, Chiang, Peng, & Yang, 2013; Nguyen, Schwartz,

& Dockery, 2014; Rhea et al., 2012; White-Newsome et al., 2012) and is representative of data that may be available to the population of interest from local weather services, phone weather applications, etc. Weather station observation data were available at one minute intervals (National Oceanic and Atmospheric Administration, Department of Defense States, Federal Aviation Administration, & United States Navy, 1998) for dry temperature (T_a) and dew point temperature (T_{dp}).

3.3.4 *Metabolic heat production*

Metabolic heat production resulting from physical activity was estimated using hip-mounted ActiGraph GT3Xs and accompanying ActiLife software (ActiGraph; Pensacola, FL, U.S.). These tri-axial accelerometers measured changes in movement on three planes that were then converted to estimates of daily (kcal/day) and hourly (kcal/hour) mean energy expenditure (EE) using proprietary filters and the Freedson VM3 equation (Sasaki, John, & Freedson, 2011). Since the area- and personal-level exposure monitors measured heat at a higher temporal resolution (e.g. every 6 min), hourly EE values were assigned to all time intervals within a given hour; for example, the EE for 13:00 to 14:00 was assigned to time intervals from 13:00, 13:06, 13:12, 13:18, … to 13:54. This allowed for calculation of rolling hourly averages over the entire workshift. Hourly metabolic activity is relevant to occupational recommendations that are often based on hourly interventions such as work-rest cycles (American Conference of Governmental Industrial Hygienists, 2015; NIOSH, 2016).

In order to compare the values produced from the ActiGraphs with NIOSH and ACGIH occupational recommendations for heat exposure, the participant's daily resting (or basal) energy expenditure (REE) was calculated using the Mifflin-St. Jeor Equation (Eq **Error! Reference source not found.**) for males.

$$REE = 9.99 weight + 6.25 height - 5 age + 5, \tag{3.1}$$

where *REE* is in kcal/day, *weight* is in kg, *height* is in cm, and *age* is in years (Mifflin et al., 1990). Daily REEs were converted to kcal/hour and added to the hourly estimates of EE, which were then converted to Watts by multiplying by 1.163.

3.3.5 *Clothing and worksite characteristics*

Additional data were collected by researcher observation and photographs, including worker clothing and worksite characteristics, such as the height of the building and proximity to water, other buildings, and trees. Workers reported roofing processes and task-related point-sources of heat during the shift directly to research staff. Characteristics of roofing processes used in the previous week were assessed using an adapted computer-assisted survey instrument administered electronically using hand-held tablets (Spector et al., 2015). This information was used to descriptively inform the understanding of differences across worksites.

3.3.6 *Exposure metrics*

The primary metric used for comparison of heat exposure in this analysis was temperature (T_a), which was directly available at all three spatial resolutions. Two direct indices of heat exposure were calculated for use in secondary analyses: wet bulb globe temperature (WBGT) and Humidex. All methods and results pertaining to Humidex are reported in Appendix X. WBGT was reported by the area-level monitoring device (QUESTemp). Regional- and personal-level WBGT was calculated from temperature and relative humidity using the following equations:

$$RH = 100\left[e^{\left((17.625*T_{dp})/(243.04+T_{dp})\right)} / e^{\left((17.625*T_a)/(243.04+T_a)\right)}\right] \quad 3.2$$

$$P_v = (RH/100)\left(0.61067e^{(17.27*T_a)/(T_a+237.2)}\right), \quad 3.3$$

$$T_{pwb} = 0.0376 + 5.79P_v + (0.388 - 0.0465P_v)T_a \quad 3.4$$

$$T_{nwb} = 0.0376 + 5.79P_v + (0.388 - 0.0465P_v)T_a + 1.0, \quad 3.5$$

$$T_g = T_a + \Delta T_{g-a}, \quad 3.6$$

$$WBGT_{outdoors} = 0.7(T_{nwb}) + 0.2(T_g) + 0.1(T_a), \quad 3.7$$

where T_{dp} is the dew point temperature (°C), RH is relative humidity (%), T_a is dry bulb temperature (°C), P_v is vapor pressure (kPa), T_{nwb} is the natural wet bulb temperature (°C), T_{pwb} is the psychometric wet bulb (°C), T_g is the globe temperature (°C), $\Delta T_{g\text{-a}}$ is the difference in globe temperature from the dry bulb temperature measured using the QuesTemp at the area-level (°C), and $WBGT_{outdoors}$ (°C-WBGT) (Bernard & Barrow, 2013). This approach to calculating WBGT from meteorological data is accurate within a 95% confidence interval of 2 °C-WBGT. Liljegren et al. 2008 (Liljegren, Carhart, Lawday, Tschopp, & Sharp, 2008) present an approach with greater precision (within 95% CI of 1 °C-WBGT), however it requires additional parameters not available in the personal monitoring data .

3.3.7 *Occupational thresholds*

Two occupationally relevant exposure thresholds were calculated using equations 8 and 9 below: 1) the U.S. National Institute for Occupational Safety and Health (NIOSH) Recommended Exposure Limit (REL) for acclimatized workers; and 2) the Recommended Action Limit (RAL) for unacclimatized workers (NIOSH, 2016). These equations are identical to those used by the

American Conference of Governmental Industrial Hygienists (ACGIH) Heat Stress/Strain Threshold Limit Value (TLV) and Action Limit (AL) (ACGIH, 2008).

$$REL = 56.7 - 11.5 log_{10} M, \quad 3.8$$

$$RAL = 59.9 - 14.1 log_{10} M, \quad 3.9$$

where the *REL* and *RAL* are in °C-WBGT and *M* is the metabolic rate in watts (joules/second) (Garzon-Villalba, 2016; NIOSH, 2016) calculated as the mean metabolic rate for the study population.

3.3.8 *Statistical Analysis*

Descriptive statistics were used to summarize measurements, including T_a, RH (since it is used to calculate personal and regional WBGT), and WBGT for the full study and by exposure classification ("hot" and "cool" days). The differences in temperature measurements across the three levels were calculated using the area level measurements as the reference. To account for different measurement frequencies of each monitoring device, six minute intervals were calculated for data at all three levels for calculation of the differences. Means were calculated from the difference at each six-minute interval between two datasets (each personal or regional dataset and the corresponding area data) before averaging across time. A positive difference indicated the measurement of heat at a given level (PL or RL) was greater than at the AL.

In the primary analysis, differences in T_a across monitoring levels were described using descriptive statistics and box and whisker plots for different shift activity categories (full work shift, time working only, and breaks only) and grouped into eight exposure categories (<10, 10-15, 15-20, 20-25, 25-30, 30-35, 35-40, and 40-45°C) by the AL as well as by the PL or RL. Paired t-tests were conducted to test for statistically significant differences across monitoring levels. The

Newey-West estimator was used to adjust for temporal autocorrelation (Zeileis, Lumley, Berger, & Graham, 2017). Differences were also stratified by exposure classification (hot and cool days), worksite ID, metabolic activity (for PL-AL only), date, and time of day. The impact of the site on the difference between monitoring levels was described as the mean and standard deviation of site-specific differences for both the PL-AL ad RL-AL analyses.

Secondary analyses were conducted using WBGT, measured at the AL and calculated for the PL and RL, as the metric of heat exposure using a similar approach to the primary analysis. Additionally, the number of days and total number of monitored shifts during which the WBGT met or exceeded the NIOSH heat stress/heat strain REL and RAL were compared across all three monitoring levels. Since occupational thresholds are designed for one hour time weighted average (TWA) exposures, the rolling hourly-mean WBGT was calculated for all three levels such that the value at a given time represents the previous hour (e.g. WBGT at 13:00 is the mean of 12:01-13:00). The earliest time at which the WBGT exceeded a threshold was compared for days where multiple levels exceeded a threshold.

All analyses were conducted using R, and figures were produced using the ggplot2 package. (R Development Core Team, 2011). The Newey-West estimator was implemented using the sandwich package (Zeileis et al., 2017), and rolling means were calculated using the zoo package in R (Zeileis, Grothendieck, Ryan, Urlich, & Andrews, 2018).

3.4 RESULTS

3.4.1 *Sampling, work, and worker characteristics*

Twenty-two commercial roofing workers from two companies in the Greater Seattle area participated in the study during the summer and fall of 2016 (Table 3.2). Of these participants, twenty participated on cool days, twenty-one participated on hot days, and one completed an additional hot day, resulting in a total of 42 full-shifts measured throughout the study. Due to monitoring device error, two cool days and one hot day were removed from the analysis for a total of 39 shifts. These 39 shifts were collected across 13 days (six hot and seven cool) at seven worksites with a mean of three workers monitored per day.

All participants were male with a mean (standard deviation) age of 43 (12) (Table 3.2). Shifts typically started around 6:45 and ended around 15:04. All participants took a lunch break, with a mean duration of 38 minutes, and 34 of the 39 shifts included a morning break, but no shift included an afternoon break. The median number of days between repeated measures was fourteen, and the repeated measures were collected on the same worksite in sixteen of the seventeen workers who completed both hot and cool day measurements.

Worksites varied in physical characteristics as well as roofing processes. Sites ranged in height from one to fourteen stories tall and were located across downtown urban, residential, and industrial settings. Access to and utilization of shade varied by site. None of the sites had consistent access to shade during work activities. On three sites, workers came off the roof during lunch break and sat under trees or other more formal structures attached to the building. On two sites, the workers remained on the roof during lunch breaks, but had shade access either from covered sections of the building itself or man-made structures using portable tents. The remaining two sites had inconsistent access and use of available shade.

The most commonly used roofing processes in this study were torch applied (“torchdown”) roofing, followed by single-ply applications involving hot work. Of the seven sites and 39 shifts monitored, only one site, where three participants completed both days of participation (totaling six shifts), used a heat-free single-ply membrane application. One site, where only one cool-day shift was monitored, used a built-up roofing application involving hot tar. However even on sites

Table 3.2: Sampling characteristics and worker demographics

	Statistic	Full study (hot and cool days)	Hot days	Cool days
Companies	n	2	2	2
Sites	n	7	6	7
Days	n	13	6	7
Participants	n	22	21	18
Participants per day	mean (sd)	3 (1)	3.5 (0.5)	2.6 (1.3)
Participants with repeated measures	n	17	-	-
Repeated measures at same worksite	n_{yes}/n	16/17	-	-
Time between repeated measures (days)	median (min, max)	14 (9, 83)	-	-
Work characteristics by **shifts** monitored	number of shifts	39	21	18
Start time (H:M)	mean (sd)	6:45 (00:23)	6:40 (00:22)	6:51 (00:23)
End time (H:M)	mean (sd)	15:04 (00:53)	14:48 (1:06)	15:29 (00:37)
AM break (yes no)	n_{yes}/n	34/39	19/21	16/18
AM break duration (minutes)	mean (sd)	20 (1)	22 (9)	20 (7)
Lunch break duration (minutes)	mean (sd)	38 (10)	35 (9)	40 (11)
Used hot process during shift	n_{yes}/n	18/39	11/21	7/18
Participant demographics				
Age (years)	mean (sd)	43 (12)		
Gender	% male	100		
Metabolic load for all shifts combined				
Rest (≤116 W)	% of time	1.4%	1.1%	1.6%
Light (117-233 W)	% of time	38.8%	46.3%	31.7%
Moderate (234-349 W)	% of time	45.9%	48.5%	43.4%
Heavy (350-465 W)	% of time	8.7%	0.0%	16.9%
Very Heavy (≥466 W)	% of time	5.2%	4.1%	6.4%

with similar roofing materials and methods, monitoring days captured different stages within these processes, such as tearing off old roofing material, laying down new roofing material, and general site safety, set up, or material unloading. Tasks also ranged between and within workers even on the same worksite. Participants reported tasks involving hot tools or materials on eleven of the twenty-one hot day shifts, and seven of the eighteen cool day shifts, with more of these activities being completed in late morning or afternoon (Table 3.2).

3.4.2 *Exposure characteristics*

The mean (interquartile range) temperature (T_a) of all six-minute interval, area level data was 20.1 °C (16.1 °C, 24.1 °C) for the full study (Table 3.3). Hot and cool days were characterized by a mean (IQR) T_a of 24.3 °C (21.5 °C, 26.8 °C) and 16.7 °C (14.0 °C, 19.5 °C), respectively. The mean (minimum, maximum) within person difference in maximum shift AL T_a between hot and cool sampling days was 7.5 °C (4.3 °C, 12.4 °C). Exposure characteristics for humidity and WBGT are available in Table 3.3.

3.4.3 *Metabolic heat production*

The mean (standard deviation) energy expenditure for the study population was moderate at 270.4 W (105.4 W), with a slightly higher mean on cool days (278.8 W [106.0 W]) than on hot days (262.7 W [104.3 W]). Energy expenditure peaked between 8:00 – 9:00 on cool days and 7:00 – 8:00 on hot days and then steadily decreased with increasing hours throughout the shift as well as increasing ambient temperature. For the study as a whole, participants spent 1.4%, 38.8%, 45.9%, 8.7%, and 5.2% of their time in rest (≤116 W), light (117-233 W), moderate, (234-349 W) heavy (350-465 W), and very heavy (≥466 W) metabolic loads, respectively (NIOSH, 2016) (Table 3.2).

On cool days, slightly more time was categorized as heavy or very heavy, with reduced time in light and moderate categories, while on hot days the opposite was observed.

Table 3.3: Exposure characteristics by monitoring level and metric for the full study, hot days only, and cool days only. Statistics include the number of (six-minute average) measurements (n), mean, and interquartile range (IQR).

Day	Level	n	Air Temperature (°C)	WBGT (°C-WBGT)	Relative Humidity (%)
All	Personal	3241	25.6 (22.1, 29.1)	22.9 (20.6, 25.6)	51.9 (42.1, 63.6)
	Area	1101	20.1 (16.1, 24.1)	20.4 (16.5, 24.5)	50.1 (33.0, 66.7)
	Regional	1113	20.2 (15.6, 24.3)	18.9 (15.9, 22.4)	61.4 (45.9, 75.6)
Hot	Personal	1682	28.2 (25.1, 31.3)	24.7 (23.1, 26.7)	47.4 (36.1, 57.2)
	Area	493	24.3 (21.5, 26.8)	23.9 (22.8, 25.9)	37.4 (27.7, 40.7)
	Regional	496	25.1 (22.1, 28.4)	22.2 (20.7, 23.9)	48.0 (36.2, 57.6)
Cool	Personal	1559	22.7 (19.8, 25.9)	21.0 (18.8, 23.5)	60.6 (48.2, 70.4)
	Area	608	16.7 (14.0, 19.5)	17.6 (14.7, 20.8)	60.4 (43.6, 75.3)
	Regional	617	16.3 (13.3, 19.4)	16.2 (13.7, 18.4)	72.2 (62.2, 83.6)

The greater n in the personal data compared with the area and regional data is attributable to monitoring of multiple subjects per worksite (area monitor).

3.4.4 *Primary analysis*

We observed the hypothesized positive difference between the PL-AL, indicating higher temperature measured in the personal monitors. In this study, the mean (95% confidence interval) difference in the PL-AL T_a was 4.4 (4.1, 4.7) °C for the full shift. The mean difference during work activities only was slightly higher, while during breaks it was observed to be lower (Table 3.4). Without accounting for differences between sites, the mean (95% confidence interval) of the RL-AL difference in T_a was 0.2 (-0.3, 0.6) °C. The difference during activities was identical, however breaks were characterized to be slightly higher.

When stratified by the seven worksites monitored in this study, the mean RL-AL differences calculated using the Newey-West estimator differed by a standard deviation of 1.04 (Table 3.5), with negative relationships observed in two sites, strongly positive relationships observed in three sites, and weaker positive relationships observed in the final two sites. Variability was observed in the site-specific comparison of PL-AL differences as well (SD 0.88), although all differed in the same direction.

Table 3.4: Differences in exposure by level. Statistics include number of measurements (n), mean, standard error (se), and 95% confidence intervals (95% CI) using Newey-West estimator.

		Temperature (°C)			WBGT (°C-WBGT)		
		n	**Mean**	**95% CI**	**n**	**Mean**	**95% CI**
Δ Personal - Area	Full Shift	3241	4.4	(4.1, 4.7)	3241	1.5	(1.3, 1.8)
	Work Activities	2870	4.6	(4.3, 5.0)	2870	1.7	(1.4, 2.0)
	Break Activities	344	3.0	(2.2, 3.8)	344	0.5	(-0.3, 1.2)
Δ Regional - Area	Full Shift	1113	0.2	(-0.3, 0.6)	1113	-1.6	(-2.0, -1.1)
	Work Activities	1003	0.2	(-0.3, 0.6)	1003	-1.5	(-2.0, -1.0)
	Break Activities	110	0.4	(-0.3, 1.0)	110	-1.9	(-2.4, -1.3)

When assessed by temperature category, the pattern in the magnitude of the difference between PL-AL during work activities changed based on the level used to construct the categories (Table 3.6). By AL, the mean difference slightly decreased from 5.6 at T_a <10 °C to 3.9 at T_a between 30-34 °C (the highest observed AL T_a range), but by PL, the difference increased from 0.9 at T_a <10 °C to 11.1 at T_a between 40-44 °C. When stratified by hot and cool monitoring days, the PL- AL difference within each PL T_a category was greater on cool days than hot days (Figure 3.1). This was also the case when compared across shift hours, with a noticeably greater difference during mid-day when participants were on lunch break and the hot-day differences were minimized (Figure 3.3a). In the RL-AL differences, the change across categories was substantially smaller than in the PL-AL comparison. By RL T_a category, the trend was similar to in the PL-AL analysis by PL T_a category, however the difference started negative in the <10 °C category and increased to a positive value in the 30-34 °C category. By AL T_a category, the mean difference dipped in the middle categories from a positive to a negative difference. When stratified by hot and cool days or by time, the RL-AL differences showed little to no difference by hot versus cool monitoring day (Figure 3.2) and no obvious change in the pattern during break periods (Figure 3.3b). However, hot and cool day differences did diverge in the later hours of the shift, with the hot days characterized by an increasingly positive difference and the cool days hovering slightly below zero (Figure 3.3b).

Table 3.5: Differences in exposure levels by site. The mean and standard deviation of the site-specific mean differences between levels is presented along with the site-specific mean, standard error, and 95% confidence intervals of the difference between levels calculated using the Newey-West estimator.

			Temperature				**WBGT**			
			Mean	**SD**			**Mean**	**SD**		
Δ Personal - Area			4.60	0.88			1.80	0.88		
Δ Regional - Area			0.05	1.04			-1.59	0.58		
	Site	**n**	**Mean**	**SE**	**95% CI**		**Mean**	**SE**	**95% CI**	
Δ Personal - Area	A	417	3.57	0.33	2.91	4.22	0.98	0.46	0.07	1.90
	B	524	3.57	0.42	2.73	4.41	1.35	0.40	0.54	2.16
	C	413	4.76	0.43	3.89	5.62	1.84	0.21	1.42	2.27
	D	687	4.15	0.28	3.60	4.71	1.11	0.20	0.71	1.50
	E	482	5.56	0.33	4.91	6.21	2.09	0.25	1.59	2.59
	F	638	4.81	0.35	4.11	5.50	1.66	0.27	1.12	2.20
	G	80	5.76	0.74	4.28	7.25	3.59	0.44	2.71	4.47
Δ Regional - Area	A	168	-1.35	0.31	-1.98	-0.72	-2.57	0.96	-4.49	-0.66
	B	154	0.75	0.89	-1.03	2.52	-1.34	1.01	-3.36	0.67
	C	209	0.26	0.81	-1.35	1.87	-0.68	0.50	-1.68	-1.22
	D	175	0.61	0.18	0.25	0.98	-1.76	0.27	-2.29	-1.22
	E	162	0.77	0.38	0.01	1.53	-1.86	0.83	-3.52	-0.20
	F	165	0.86	0.38	0.11	1.61	-1.38	0.24	-1.86	-0.90
	G	80	-1.53	0.43	-2.40	-0.66	-1.56	0.60	-2.76	-0.35

3.4.5 *Secondary analyses*

The mean (95% confidence interval) of the PL-AL difference in WBGT was 1.5 (1.3, 1.8) °C-WBGT, 1.7 (1.4, 2.0) °C-WBGT, and 0.5 (-0.3, 1.2) °C-WBGT for the full shift, during work activities only, and during breaks, respectively (Table 3.4). The mean (95% confidence interval) of the RL-AL difference in WBGT was -1.6 (-2.0, -1.1) °C-WBGT, -1.5 (-2.0, -1.0), and -1.9 (CI -2.4, -1.3) °C-WBGT for the full shift, during work activities only, and during breaks, respectively (Table 3.4). All differences observed by site in the RL-AL analysis were negative with a standard deviation of site means of 0.58 (Table 3.5).

Table 3.6: Difference in exposure by temperature (°C) category during work activities only. Statistics include the number of (six-minute average) measurements (n), mean, standard error (se), and 95% confidence intervals (95% CI).

		By Area Ta (°C)					By Personal/Regional Ta (°C)				
		n	**Mean**	**SE**	**95% CI**		**n**	**Mean**	**SE**	**95% CI**	
Δ Personal - Area Ta	less than 10	59	5.6	0.99	3.7	7.6	3	0.9	0.05	0.8	1.0
	10 to 14	213	4.9	0.28	4.4	3.2	67	2.6	0.28	2.1	3.2
	15 to 19	991	5.0	0.24	4.6	5.5	345	3.3	0.29	2.7	3.9
	20 to 24	884	4.5	0.20	4.1	4.9	891	4.1	0.21	3.7	4.6
	25 to 29	656	4.2	0.24	3.7	4.6	960	4.9	0.29	4.3	5.4
	30 to 34	47	3.9	0.44	3.0	4.7	491	5.6	0.32	5.0	6.3
	35 to 39	-	-	-	-	-	104	7.4	0.63	6.2	14.9
	40 to 44	-	-	-	-	-	9	11.1	1.88	7.4	14.9
Δ Regional - Area Ta	less than 10	30	2.3	1.54	-0.8	5.4	28	-0.5	0.63	-1.8	0.7
	10 to 14	146	-0.4	0.35	-1.1	0.3	204	-0.6	0.50	-1.6	0.4
	15 to 19	336	-0.1	0.33	-0.8	0.5	274	-0.5	0.28	-1.1	0.0
	20 to 24	275	-0.1	0.25	-0.6	0.4	275	0.4	0.43	-0.4	1.3
	25 to 29	189	1.2	0.31	0.6	1.8	173	1.3	0.24	0.8	1.8
	30 to 34	15	0.2	0.26	-0.3	0.8	49	1.8	0.57	0.7	3.0

Using the mean energy expenditure of the study population, 270.4 W, the NIOSH REL was determined to be 28.7 °C and the RAL 25.6 °C-WBGT. The REL was never exceeded in the rolling hourly-mean RL monitoring data, however it was exceeded on two days in the rolling hourly-mean AL data and on three hot days in the rolling hourly-mean PL data. The RAL was exceeded on one day in the RL data, five days in the AL data, and all six hot days as well as three cool days in the PL data. Comparing the number of shifts measured (at the PL level) or represented (at the AL and RL levels), no shifts, eight shifts, and six shifts exceeded the REL using RL data, AL data, and PL data, respectively. Four shifts, eighteen shifts, and twenty-seven shifts exceeded the RAL using RL data, AL data, and PL data, respectively. Using the day in which all three levels exceeded the RAL for comparison (Figure 3.4), the earliest time at which the rolling mean WBGT for the previous hour exceeded the RAL in the RL, AL, and PL data was at 11:48, 10:06, and 8:54, respectively. For the REL, this occurred at 12:42 and 10:36 in the AL and PL data, respectively. We did not observe a consistent difference in the time of first exceedance by task or process in the PL.

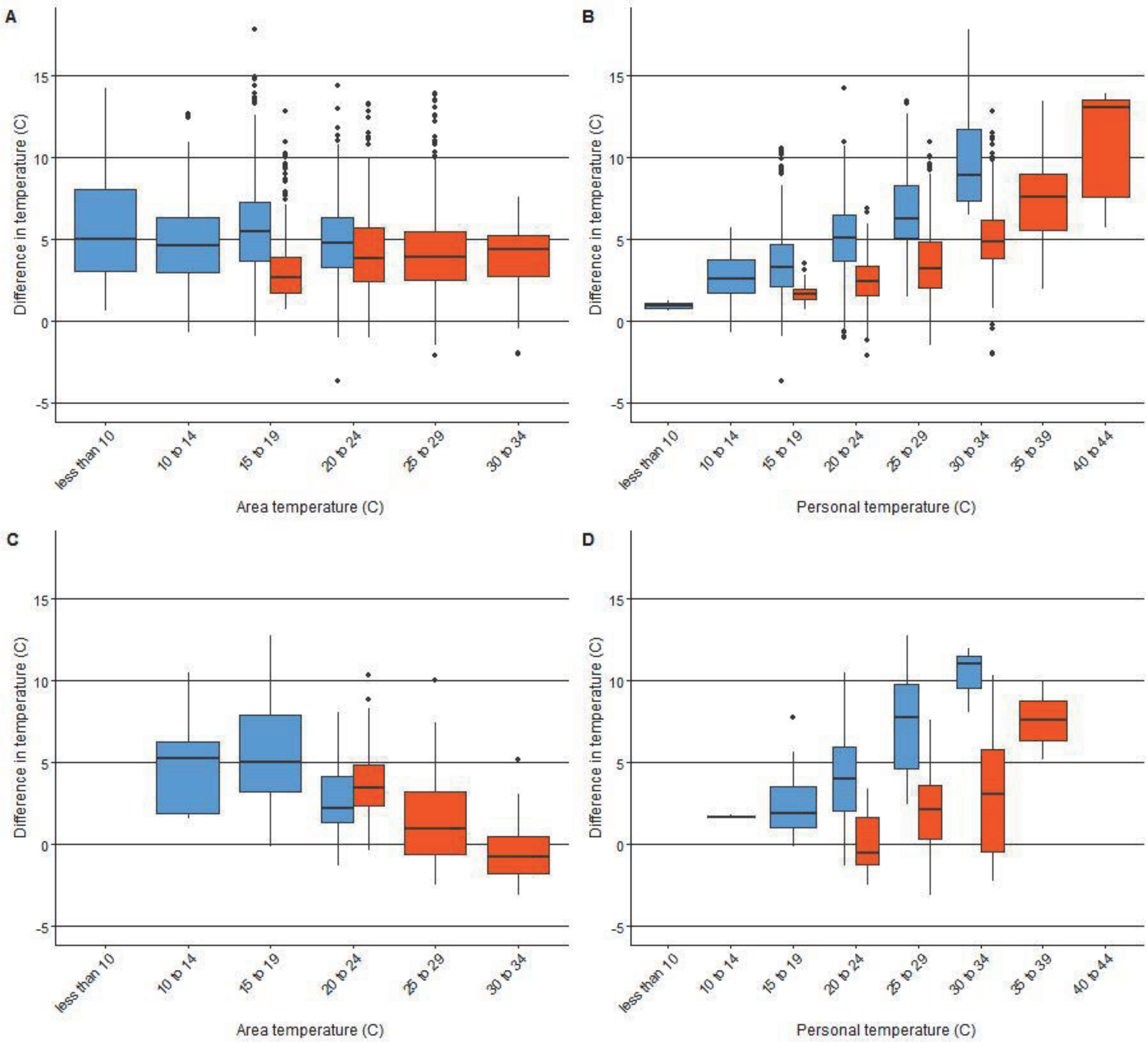


Figure 3.1: Difference in PL-AL Ta by exposure categories stratified by hot (red bars) and cool (blue bars) days. (*A*) Work periods by AL T_a. (*B*) Work periods by PL T_a. (*C*) Break periods by AL T_a. (*D*) Break periods by PL T_a.

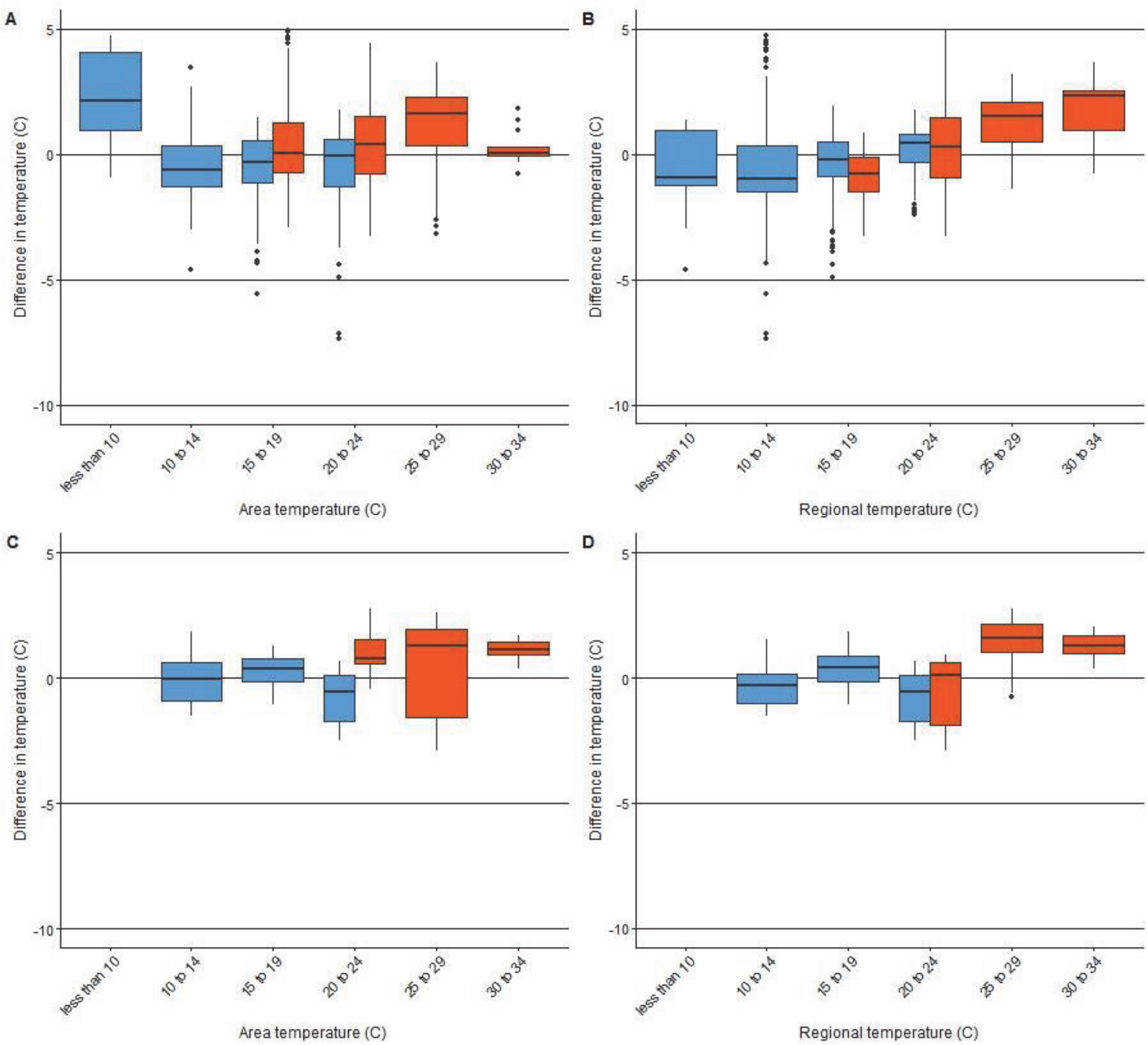
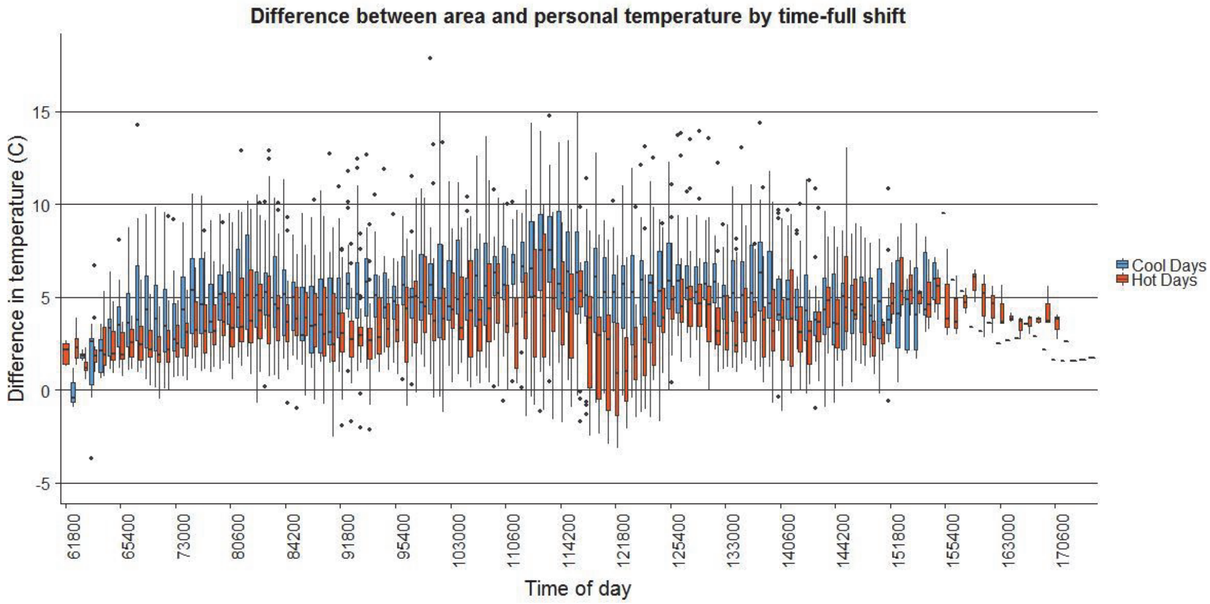


Figure 3.2: Difference in RL-AL Ta by exposure categories stratified by hot (red bars) and cool (blue bars) days. (*A*) Work periods by AL T_a. (*B*) Work periods by RL T_a. (*C*) Break periods by AL T_a. (*D*) Break periods by RL T_a.

A



B

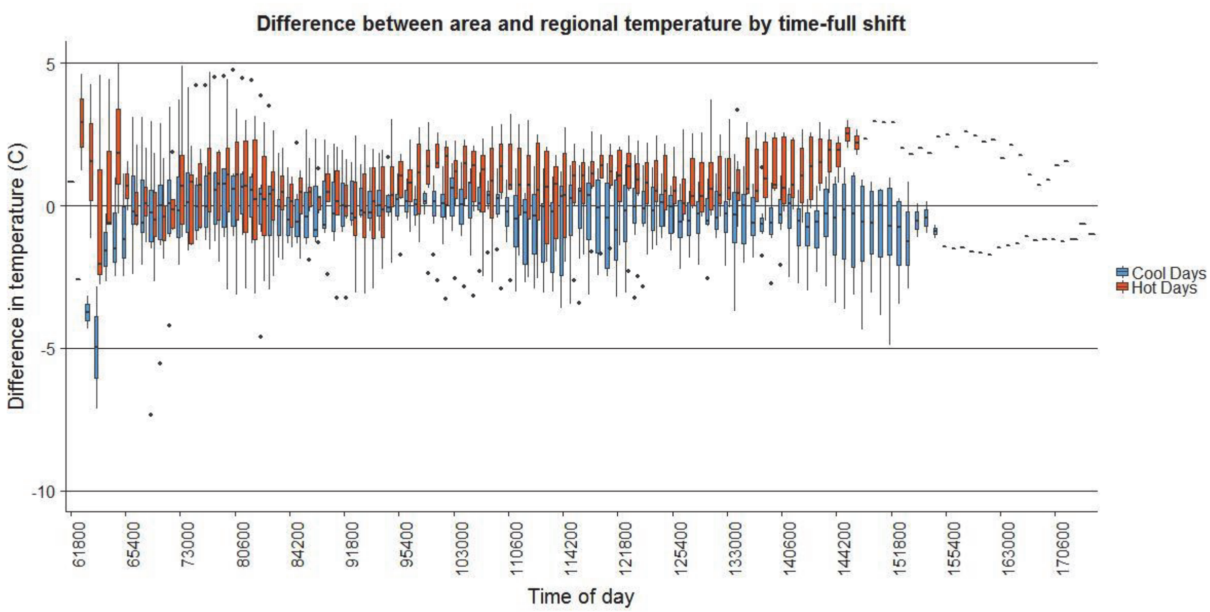
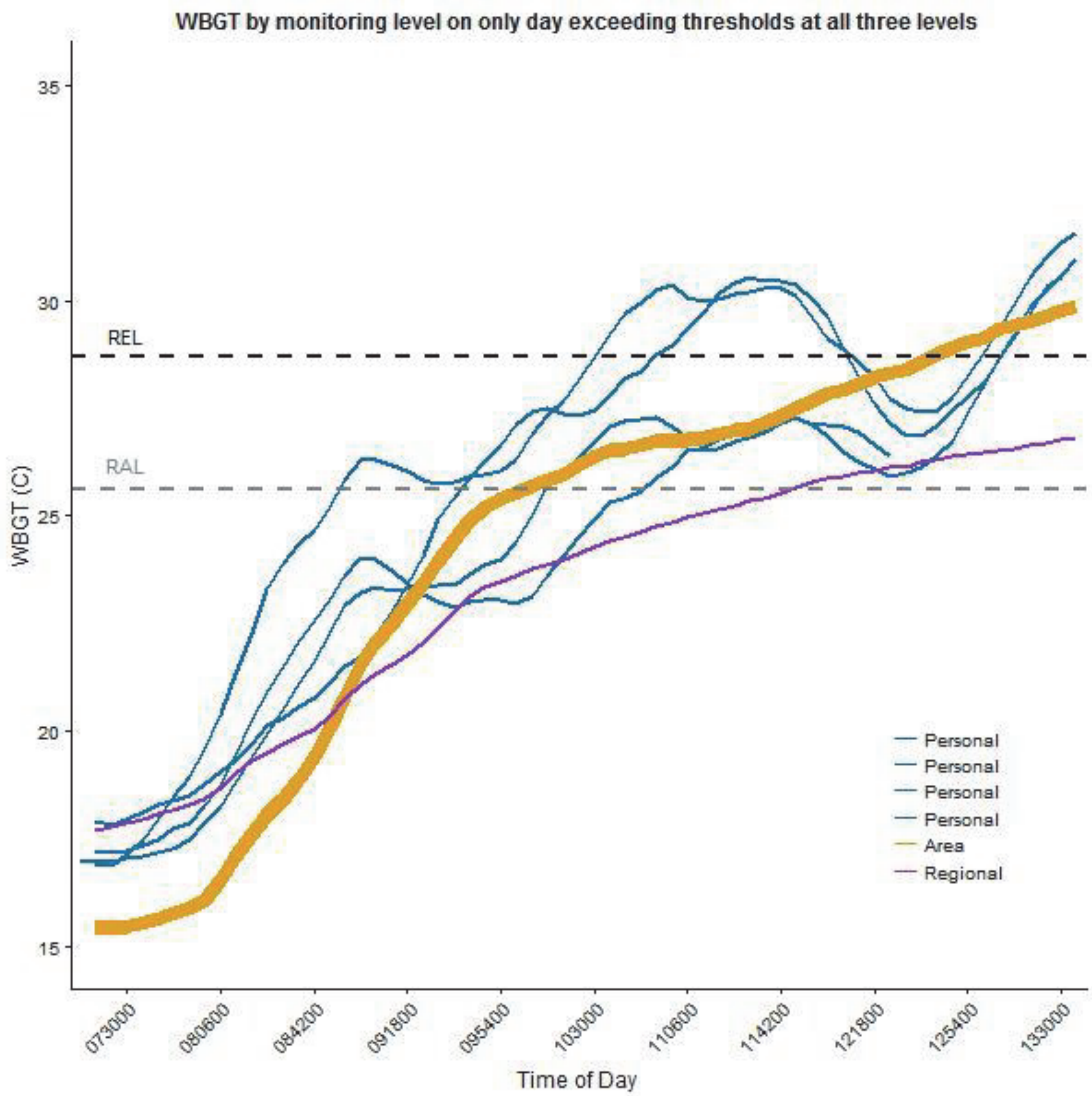


Figure 3.3: Difference in PL-AL and RL-AL Ta by time stratified by hot (red bars) and cool (blue bars) days. (*Top*) PL-AL by time of day. (*B*ottom) RL-AL by time of day. Median lunch break start and end times were 11:55 and 12:30.

Figure 3.4: Exposure on the two days with area level exceedance of NIOSH REL for 270.4 W metabolic activity



3.5 Discussion

This is the first published study that we are aware of to compare heat exposure metrics measured at three distinct spatial resolutions—regional-, area-, and personal- (or individual-) levels—in an occupational setting with exposure to outdoor weather conditions, work-related metabolic demands, and process-dependent point-sources of heat. We report a positive difference in air temperature and WBGT at the PL compared to the AL. The difference between the RL and AL temperature varied by site, with some sites exhibiting negative differences and others positive. All of the site-specific differences in the RL-AL WBGT were negative, indicating the area WBGT was on average higher across all sites monitored in this study. These findings inform the interpretation and application of different monitoring strategies and sources of exposure data to research and practice.

Our overall finding—a mean difference in temperature of 4.4 °C from personal to area (PL-AL) and relatively similar regional and area temperatures (Table 3.4)—demonstrates that area and regional measurements have the potential to underestimate the magnitude of temperatures experienced at the personal level. The variability observed in the mean difference between the RL-AL observations by site suggests the presence of microclimates within the geographic area represented by meteorological weather data. These differences may be the result of variability in environmental conditions, work-related sources of heat, or, most likely, a combination of the two, including the presence of dark impermeable surfaces, proximity to building ventilation, heat-producing machinery, etc. (Oke, 1982; Rosenzweig, Solecki, & Slosberg, 2006; Taha, 1997). These results are consistent with results reported by Kuras et al (2015), where neighborhood T_a measurements, collected use iButtons placed in trees in the South End in Boston, MA were slightly higher than weather station data from Logan International Airport during a summer heat wave (Kuras et al., 2015), demonstrating a site-specific difference in temperature.

The magnitude and direction of the PL-AL observations suggest that area monitors inadequately capture differences within and between workers on a worksite, such as those resulting from point-sources of heat emitted closer to the workers than the area monitoring device, movement between sun and shade, and human-emitted long wave radiation or heat removed from the body through convective energy transfer (McGregor & Vanos, 2017; Parsons, 2002). While not directly comparable, this strong positive difference is inconsistent with results reported by Bernhard et al (2015) for occupational heat exposure in groundskeepers in Alabama, where temperature measured at the personal level was slightly lower than weather station data. Differences between the occupational settings of groundskeepers and roofers, including less impermeable surfaces and the absence of point-sources of heat in groundskeeping work, may explain these contrary findings. Two other studies comparing PL T_as with weather station data also report lower PL T_as than RL T_as, but monitor different populations and include time indoors, often with air conditioning, in the analysis (Basu & Samet, 2002; Kuras et al., 2015).

Utilization of breaks to reduce occupational heat stress in high heat environments and/or from tasks requiring high metabolic demand is strongly recommended in occupational settings (Brake & Bates, 2002; Hsie, Hsiao, Cheng, & Chen, 2009; Mckinnon et al., n.d.; NIOSH, 2016; OSHA, 2011). We observed a smaller mean difference in T_a during breaks than during work in the PL-AL comparison (Table 3.4). This change in the difference between the PL-AL suggests that workers were seeking cooler, shaded environments and reducing metabolic activity during these periods of intentional rest, a behavioral practice that was observed by study researchers, however none of the participants were observed to take breaks indoors or in climate controlled settings (such as a personal vehicle with air conditioning). This difference is particularly dramatic when higher temperatures were recorded (Figure 3.1, 3.3a). In contrast, RL and AL measurements were not significantly influenced by personal break behavior, and RL-AL differences were similar during breaks and work (Figure 3.2, 3.3b). In secondary analyses, the difference in WBGT levels between breaks and work followed similar trends to the analysis of T_a.

We observed a greater positive mean difference in PL-AL T_a at higher PL T_a than lower PL T_a (Figure 3.1b). In contrast, the PL-AL difference remained relatively consistent during work activities across AL T_a categories (Figure 3.1a). PL temperatures exhibited greater variability. For example, PL temperatures of 40 °C and 35 °C, the lower ends of the highest two categories in Figure 3.1b, correspond with AL T_as in the same category (25-29 °C), when adjusted using the mean difference from each PL category (11.1 °C and 7.4 °C, respectively). While Figure 3.1a suggests a relatively consistent median PL-AL difference of ~5°C, applying a uniform "adjustment factor" to AL measures in order to estimate PL T_a is likely not appropriate given the observed variability in PL T_a.

When stratified by exposure days (cool and hot), the difference between PL-AL by PL T_a was noticeably higher on cool days than hot days (Figure 3.1b). We identify several potential contributing factors to this difference. First, convective heat transfer away from a source of heat, such as a hot air torch, is largely driven by the thermodynamic properties of air. Hot and cool air mix to achieve a state of equilibrium, and hot air is less dense and characterized by greater buoyancy (Parsons, 2002). As a result, in an open-air worksite heat released in a worker's immediate surroundings may dissipate before reaching an area monitor. On cool days, this phenomenon may be more prominent, leading to greater PL-AL differences. Had area and personal monitors been compared in a non-climate controlled enclosed setting, it is possible that the area monitor would have better captured the heat emitted from point-sources of heat. Second, the attachment of the personal devices to participants' clothing, while necessary so as not to interfere with tasks or PPE, may have also captured human emitted long wave radiation. In this study, we estimated slightly higher mean metabolic activity on cool days than hot days, with 23.3% of shift hours on cool days spent in the heavy and very heavy metabolic activity categories, but only 4.1%

of shift hours on hot days spent at that intensity. A cooler environment may allow workers to sustain longer periods of work at higher metabolic rates. Greater metabolic heat may have therefore been released from the body on cool days and captured in the PL monitors.

Personal sensors may also have captured convective heat in the boundary layer next to the body—a layer of air that forms at the juncture between the warmer human body and cooler air in the surrounding environment (Parsons, 2002). Preliminary results from a separate experimental study of exercising participants in the sun and shade, where T_a was measured using the personal devices attached to participants as well as at two, five, and ten feet away, suggest that monitors attached to the participant capture the release of some body heat but that this dissipates by two feet away from the participant. Preliminary results also suggest that, while monitors positioned facing the sun capture some of the effects of solar radiation, monitors in the shade or facing away from the sun do not. Further research is needed to identify the impact of body heat and the boundary layer on personal devices, particularly when used in conjunction with clothing characterized by different insulation factors.

We observed a smaller mean decrease in relative humidity (RH) on hot days in the PL data than in the RL and AL data when compared with cool days and the full-study mean (Table 3.3), however this comparison does not take into account differences in worksite observed in for temperature and WBGT. Relative humidity (RH) is inversely related to temperature. It describes the amount of moisture in the air as a percentage of the moisture holding capacity of the air. As T_a increases, the holding capacity of the air increases, thus resulting in a smaller relative humidity for the same amount of moisture (absolute humidity). The observed higher RH (smaller decrease) in the PL at higher T_as compared with the AL and RL indicates that there may have been additional moisture added to the air near the personal monitoring devices, such as in the form of sweat, particularly on hot days. We also observed lower RH values in the AL than anticipated based on the RH observed at the RL for similar T_as. This may have resulted from differences in microclimates, such as more impermeable surfaces (Hass, Ellis, Mason, Hathaway, & Howe, 2016)on the worksites or from device error, however the AL monitoring device was calibrated by the manufacturer shortly before the start of the study.

3.5.1 *Implications for Practice*

AL monitoring for occupational heat stress in laboratory settings has been the basis for many of the existing occupational exposure recommendations (American Conference of Governmental Industrial Hygienists, 2015; OSHA, 2017; Parsons, 2013). However, area monitors are often expensive, present logistical challenges for deployment across multiple work locations simultaneously, and may poorly capture variability within and between workers. Regional monitoring data are convenient when monitoring outdoor workers across a large area from a remote location and can be accessed through websites and weather applications, but similarly are unable to capture variability between sites and are only directly applicable to outdoor settings. Individualized heat exposure assessments through the use of personal monitoring equipment may provide enhancement to the monitoring resolution at the worksite. However, occupational guidelines and standards were not designed to utilize personal data.

We explored how the monitoring level influenced whether the WBGT exceeded occupational recommendations (Figure 3.4). We report a positive difference in WBGT between the PL-AL and a negative difference between the RL-AL. Based on the AL measurements, the NIOSH Recommended Exposure Limit (REL) was exceeded on two study days and the Recommended Action Limit (RAL) was exceeded on five study days. At the RL, neither of the AL-identified REL exceedances were captured, and only one of the five days exceeding the RAL at the AL was captured. Underestimation of exposure using RL data could result in failure to implement heat illness and injury prevention interventions, including alternating work-rest cycles. Interestingly, while the PL data resulted in more days where a shift exceeded the REL, a greater number of shifts exceeded the REL in the AL data. This suggests that when using AL data on a worksite with substantial variability in tasks-related sources of heat, both high and low exposures may not be accurately captured. Overestimating exposures has implications for productivity, as work activities may be unnecessarily restricted, and for compliance, as workers may be less likely to carry out heat safety behaviors if PL exposures are lower than exposures measured at the area monitor.

The influence of metabolic heat on PL monitoring devices is a potential concern when using PL data for direct heat stress management. In these settings, human emitted heat is likely present, but not accounted for in AL measurements. While use of personal monitors may provide valuable information regarding a worker's microenvironment, additional research is necessary to understand the relationship between PL heat exposure and health effects and to validate existing occupational recommendations in field settings using PL measurements.

3.5.2 *Implications for research*

We report that RL data, which are commonly used in epidemiologic studies, likely provide inaccurate estimates of temperature for physically active populations and populations working in certain microenvironments, with or without additional point-sources of heat. We observed different directions in the relationships between measurements at the AL and RL by site, depending on the metric used for comparison. This presents a challenge in comparing exposures assessed using different metrics across different heat-health studies. A better understanding of how these relationships differ for different metrics between regional and area monitors in different settings and climates is needed to inform recommendations for consistent exposure assessment approaches.

We found that PL data better characterize the potential range in exposures on a worksite. Integration of some metric of metabolic heat should be considered in future studies to avoid heat stress exposure misclassification, including when assessing cooler days when higher intensity tasks may be more likely to be performed. Further research is needed to understand the effect of spatially refined heat exposure estimates on the relationship between heat exposure and health in epidemiologic studies. Once metabolic contributions to PL measurements, and the relationship between PL measurements and health effects, are better understood, PL data have the potential to inform research aimed at understanding acceptable exposure periods and potential differences in the relationship between heat and health for intermittent exposures compared with continuous exposures (NIOSH, 2016).

3.6 Limitations

This study has a number of limitations. Task observations were not optimal in this study. Access to the workers and worksite on monitoring days was often limited to staging areas in adjacent parking lots. The lead researcher was granted access to the physical work area on three of the seven worksites for varying amounts of time. In this population, video recordings of task were not a viable alternative due to industry-imposed limitations. There was also inconsistent reporting of tasks across the population. The roofing process was reported in all cases, but the stage of the process varied over time on some sites. We were not able to collect refined task or movement-based information to inform the estimates of energy expenditures.

Further work should be conducted to better understand what exactly iButtons measure in different settings and how to adapt them for better comparison to AL devices. While the personal monitoring devices used in this study possess many practical characteristics for studying heat exposure in field settings (precision, accuracy, small device size, durability, and affordability) and have been used in other settings (Basu & Samet, 2002; Bernhard et al., 2015; Kuras et al., 2015), they do not measure a true dry temperature shielded from solar radiation (Kuras et al., 2017). Given the movement of participants on the worksite, it is unlikely that these devices were subject to long periods of sustained direct solar radiation. However, solar radiation may have influenced measurements, and further research is needed to quantify the impact of solar radiation on personal monitoring devices with different use patterns, placement on the body, and potential solar radiation shields (Holden, Klene, F. Keefe, & G. Moisen, 2013).

The population was recruited from roofing companies with existing relationships with an academic institution and therefore may represent roofing companies with a greater/higher commitment to health and safety. As a result, results may not be generalizable to all commercial roofing companies. The small sample size may have reduced study power. Research involving industry participation can be challenging to facilitate. In this study, data collection was not only limited by the number of companies willing to be involved, eligible workers interested in volunteering, and approval from general contractors and/or site owners, but also by a weather condition-dependent design.

3.7 CONCLUSIONS

This study contributes a better understanding of the differences between heat exposure measured using three levels of data: publically-accessible regional weather station data with limited spatial resolution; area-monitoring data captured by expensive monitors that are currently considered the gold-standard in occupational settings; and personal monitoring data captured by affordable sensors that likely also sense metabolic and convective heat in addition to ambient heat. We report no statistically significant difference between regional weather station temperature and temperature measured using gold standard area monitoring equipment in the study population. We observed higher heat exposure during work activities with substantial variability between and within workers in PL measurements that was not captured at the AL. These findings have implications for both heat health research and practice.

Chapter 4. HEAT STRESS, HEAT STRAIN, PSYCHOMOTOR VIGILANCE, AND POSTURAL SWAY IN COMMERCIAL ROOFING WORKERS

4.1 ABSTRACT

Introduction: Epidemiologic evidence suggests that heat stress increases the risk of occupational traumatic injuries. However, potential mechanisms underlying this relationship are not well understood.

Methods: Commercial roofing workers were monitored on one hot and one cool work-shift in the Great Seattle area during the summer and fall of 2016 for environmental heat exposure, metabolic heat generation, physiological heat response (heat strain), and dehydration. Psychomotor vigilance (mean reaction time and minor lapses) and balance (postural sway) were measured during the lunch break (psychomotor vigilance outcomes only) and at the end of the shift. The association between heat exposure, quantified as the mean difference between the recommended exposure limit (REL) and the worksite wet bulb globe temperature (WBGT) (ΔREL) one-hour prior to the

break or end of shift, and the mean reaction time, minor lapses, and postural sway were modeled using linear GEE with an exchangeable correlation structure.

Results: Twenty-two workers were monitored over 39 individual shifts. Most participants did not exceed the REL during the work shift. However, workers on average exhibited moderate heat strain (mean physiological strain index 3.8), and 40% of participants were dehydrated (urine specific gravity ≥1.030) by the end of the shift on hot days. We observed a positive association between heat stress and psychomotor vigilance (0.3; 95% CI -3.0, 3.5) and a negative association between heat stress and postural sway (-0.9; 95% CI -1.7, -0.1). Post hoc analyses of an interaction between heat stress and dehydration demonstrated positive associations between heat stress and postural sway, as well as reaction time, in dehydrated participants.

Conclusion: In this population of commercial roofing workers, no decrements in psychomotor vigilance or postural sway were observed with the relatively low levels of heat stress measured in this study. However dehydration may modify the effect of heat stress on injury risk. Adequate hydration should be supported in occupational settings with high risks for heat stress and traumatic injuries.

4.2 Introduction

Traumatic injuries are a substantial contributor to the burden of work-related injuries and illnesses in the construction industry and remain a high priority for occupational safety and health research (N. J. Anderson et al., 2013; NORA Construction Sector Council, 2008). The lifetime risk of a fatal injury in construction tradesworkers is estimated, based on data from 2003-2007, to be 0.506%, or approximately one fatality in every 200 full-time equivalent (FTE) workers over 45 years of work (Dong et al., 2014). It is estimated that the direct cost from falls from heights at work amount to approximately $50,000 per injury, with higher costs estimated for roofing workers at $106,000 per injury (Occupational Safety and Health Administration, 2012).

The potential contribution of heat exposure to traumatic injury risk has been evaluated in epidemiologic studies. These studies have suggested an increased risk of injury in different climates and occupational settings. Construction-specific studies have reported a traumatic injury odds ratio (OR) of 1.0053 (95% CI 1.003, 1.007) per °C increase in humidex in Washington State outdoor construction workers [Chapter 2], an injury OR of 1.006 (Xiang et al., 2014) and 1.008 (McInnes et al., 2017) per one °C increase in maximum daily temperature for the construction industry and for young workers (<25 years of age), respectively, in Australia, and an injury incidence rate ratio (IRR) of 1.003 per one °C increase in maximum daily temperature in Quebec, Canada (Adam-Poupart et al., 2015). Similar results have been reported for general industry and other specific industries, such as an OR for Washington State agricultural workers of 1.15 for humidex values between 30-33°C, compared to less than 25 °C (Spector et al., 2016). Despite the growing evidence of a relationship between heat exposure and traumatic injury risk, considerable gaps exist in our understanding of physiological mechanisms mediating the observed relationship.

Physiological mechanisms through which heat may affect injury risk that have been evaluated include changes in psychomotor and cognitive performance (Ganio et al., 2011; Mazlomi et al., 2017; Sharma et al., 1983), impaired balance (Erkmen et al., 2010; Lion et al., 2010; Zemková & Hamar, 2014), altered mental status and mood (Ganio et al., 2011), changes in safety behavior (Ramsey et al., 1983), muscle fatigue (Distefano et al., 2013; Rowlinson et al., 2014; Zemková & Hamar, 2014), poor sleep or sleepiness (Li et al., 2017; M. N. Sawka et al., 1983; Tokizawa et al., 2015), dehydration (Erkmen et al., 2010; Ganio et al., 2011), and inadequate acclimatization during training (Choudhry & Fang, 2008). Heat strain and heat related illness literature describe numerous potential pathways of cerebral impairment with heat stress, including reduced blood flow due to high demands on the cardiovascular system, cerebral edema, and neuron degeneration (Michael N. Sawka et al., 2011). Mechanistic research has been conducted primarily in controlled laboratory settings. Few studies have evaluated intermediate outcomes in workplace settings.

Changes in psychomotor vigilance (Mazlomi et al., 2017; Spector et al., 2018) and postural sway (Spector et al., 2018) have been assessed in different occupational populations experiencing different levels of heat stress with mixed results. Mazlomi et al, 2017 report an association between heat stress and slower reaction times in foundry workers working under conditions of high heat stress. Spector et al. 2017 reported no association between heat exposure and psychomotor vigilance and postural sway in Washington State agricultural workers working close to recommended exposure limits for heat stress. In Washington State, construction workers have higher rates of heat-related illness (Bonauto et al., 2007) and traumatic injury (Marcum, Chin, Anderson, & Bonauto, 2017), and may have higher heat exposures, than agricultural workers. In roofing occupations, we anticipate task-specific point sources of heat, including hot roofing materials and tools (e.g. hot air torches), would contribute to higher levels of environmental heat (OSHA, 2015).

4.2.1 *Study objective*

The primary object of this study was to assess the relationship between occupational heat stress and psychomotor vigilance and postural sway, factors that may affect traumatic injury risk, in a sample of commercial roofing workers at the worksite. We hypothesized that a positive association exists between increasing heat stress and decrements in psychomotor vigilance and postural sway.

4.3 Methods

A repeated measures field study was conducted among commercial roofing workers in the Greater Seattle area in Washington State during the summer and fall of 2016.

4.3.1 *Study Population and Recruitment*

Commercial roofing companies in the Greater Seattle area were recruited to participate in the study using contacts through the University of Washington's Department of Construction Management. Participants were recruited from enrolled companies during small on-site safety meetings as well as during an all-hands meeting—a large, quarterly safety meeting attended by all employees within a company. Study researchers participated in safety orientations on a site-by-site basis at the request of the general contractor or lead health and safety specialist for each job site. Addition recruitment and eligibility criteria are described in Chapter 3.

4.3.2 *Data Collection*

All data collection was performed at the worksite for the full work-shift. Monitoring days were selected based on two criteria: weather conditions and participant availability. We aimed to assess each worker on one exposed ("hot") day where the maximum work shift temperature was ≥ 25°C and one unexposed ("cool") day were the maximum works shift temperature was ≤ 22°C, measured with an onsite, area, monitor. Each participant's monitoring days were scheduled a minimum of three days apart and, when possible, repeated measures were performed at the same worksite. Participants were asked to arrive 30 minutes before the scheduled start of the work shift so study-related activities would not delay the start of work. Additional data collection details are described in Chapter 3.

4.3.3 *Individual characteristics*

We collected self-reported occupational experience, work factors and behaviors, indicators of acclimatization, medical conditions, demographic information, history of heat-related illness symptoms, sleep quality in the past week, and Epworth sleepiness scale questions (ESS) (MW, 1991) for each participant with an electronic survey administered on hand-held tablets in English and Spanish. The ESS asks the individual to rate how likely he is to fall asleep during a number of situations, such as sitting and reading, as no change, slight chance, moderate change, or high chance. The full surveys were administered on each participant's first day of monitoring, and abbreviated surveys containing questions concerning time-varying variables were administered on each subsequent day. Workers were given the option to complete the survey during the lunch break, after the shift ended, or a combination of the two. In the event a worker required assistance completing the survey, researchers were available to answer questions.

4.3.4 *Hydration*

Participants were provided urine collection cups in brown paper bags and given verbal instructions for urine collection. Participant hydration status was assessed pre- and post-shift using urine specific gravity (U_{sg}), measured with a calibrated, handheld refractometer (Atago A300CL, Tokyo, Japan). Refractometry has been used successfully in field settings (Bates & Schneider, 2008; Donoghue, Sinclair, & Bates, 2000; Spector et al., 2018) and provides a reliable measure of hydration. In this study, all samples were evaluated by two researchers at the worksite to ensure consensus of the readings.

4.3.5 *Heat stress*

Occupational heat stress assessment includes measures of environmental heat, metabolic heat, and clothing. A worker is considered to be in a state of heat stress when the net heat load "results in an increase in heat storage in the body" (NIOSH, 2016).

Environmental heat (wet bulb globe temperature and air temperature) and metabolic heat (energy expenditure in Watts) were measured and estimated, respectively, as described in Chapters 3. In brief, metabolic production was estimated from physical movement using hip-mounted ActiGraph GT3Xs (ActiGraph; Pensacola, FL, U.S.). These tri-axial accelerometers measured changes in movement on three planes that were then converted to estimates of daily (kcal/day) and hourly (kcal/hour) mean energy expenditure (EE) using proprietary filters and the Freedson VM3 equation (Sasaki et al., 2011) in the accompanying ActiLife software (ActiGraph; Pensacola, FL, U.S.). To account for metabolic heat not directly attributable to activity, each participant's daily resting (or basal) energy expenditure (REE) was calculated using the Mifflin-St. Jeor Equation (Eq 4.1) for males.

$$REE = 9.99\,weight + 6.25\,height - 5\,age + 5, \qquad 4.1$$

where *REE* is in kcal/day, *weight* is in kg, *height* is in cm, and *age* is in years (Mifflin et al., 1990). Daily REEs were converted to kcal/hour and added to the hourly estimates of EE, which were then converted to Watts by multiplying by 1.163.

Environmental heat was monitored at the worksite ("area") using a 3M^{TM} QUESTemp^{TM} 36 Heat Stress Monitor (3M; St Paul, MN, U.S.) and for each individual worker ("personal") using DS1923-F5 hygrochron iButtons (Maxim Integrated; Son Jose, CA, U.S.). The area monitor was mounted on a tripod at approximately one meter above the surface of the work site. Due to restricted access on many of the worksites, researchers asked the study participants to position the area monitor in a location that was as close as possible to their work area, was representative of work conditions (i.e. in the sun if the workers were in the sun), and would not be in the way of work-related tasks. Participants were asked to re-position the monitoring device in the event the work moved to a different area during the shift, however the monitor remained on the worksite during breaks. The QUESTemp measured dry temperature (T_a), black-globe temperature (T_g), natural wet bulb temperature (T_{nwb}), and relative humidity (RH) at three-minute intervals. Additionally, the QUESTemp calculated wet bulb globe temperature (WBGT) using equation 4.2 below.

$$WBGT_{outdoors} = 0.7\left(T_{nwb}\right) + 0.2\left(T_g\right) + 0.1\left(T_a\right), \qquad 4.2$$

where T_a is dry bulb temperature (°C), T_{nwb} is the natural wet bulb temperature (°C), T_g is the globe temperature (°C), and *WBGT* is wet bulb globe temperature (°C-WBGT).

Personal monitors were attached to the workers' clothing using blue fobs and carabiner-style attachments at approximately hip height. Workers were instructed not to cover the devices with clothing or personal protective equipment (PPE). The devices measured air temperature (T_a) and relative humidity (RH) at two-minute intervals for the duration of the work-shift and remained on the workers during breaks. Prior to data collection, the QUESTemp was factory calibrated and tested against the iButtons in a controlled, indoor setting to verify consistency of measurements across monitoring devices.

We used two metrics to describe heat exposure in this analysis. The primary metric was the ΔREL (Eqs 4.3 & 4.4), describes the relationship between the WBGT and the NIOSH Recommended Exposure Limit (REL) for heat exposure estimated from metabolic activity, and the secondary metric was air temperature (T_a) measured by personal monitoring devices. The calculation for the REL and the approach to the ΔREL are identical to the heat stress threshold limit value (TLV) and the ΔTLV from the American Conference of Governmental Industrial Hygienists (ACGIH) (ACGIH, 2008; NIOSH, 2016). The REL and ΔREL were calculated using equations 4.3 and 4.4.

$$REL[°C-WBGT]=56.7-11.5\log_{10} M, \qquad 4.3$$

$$\Delta REL[°C-WBGT] = WBGT_{outdoors} - REL, \qquad 4.4$$

where *REL* is the recommended exposure limit for $WBGT_{outdoors}$ (°C-WBGT), $WBGT_{outdoors}$ is the WBGT measured and calculated by the QUESTemp for outdoor conditions (°C-WBGT), and *M* is metabolic heat (W) (NIOSH, 2016). A negative ΔREL indicates the area WBGT was below the REL, while a positive ΔREL indicates the WBGT exceeded the REL.

Exposure windows consisting of the one-hour prior to the lunch break and one-hour prior to the end of the shift were used to quantify heat exposure. One-hour windows are traditionally used to assess continuous occupational heat exposure and are suitable for standard work schedules (five days of work with two days of rest per week, 8 hours of work per day, a 30-minute lunch break, and two 15-minute breaks) (ACGIH, 2009). Sensitivity analyses were conducted with two-hour windows for both the primary and secondary exposure metrics (ΔREL and T_a, respectively). Two-hour windows are more appropriate for intermitted or irregular exposures (ACGIH, 2008, 2009; NIOSH, 2016). Workers were free to take breaks per their usual activity, and many of the two-hour windows included break time.

Clothing characteristics were assessed through researcher-observations and documented using photographs. Workers were consistently observed wearing conventional one-layer work attire, corresponding to a clothing adjustment factor of zero, using the ACGIH TLV approach (ACGIH, 2008; Bernard & Ashley, 2009; NIOSH, 2016).

4.3.6 *Heat strain*

Heat rate (HR) and core temperature (T_c) were monitored continuously throughout the work shift and used to quantify the level of heat strain in the study population. Heat strain describes the "physiological response to the heat load experienced by a person, in which the body attempts to increase heat loss to the environment in order to maintain a stable body temperature" (NIOSH, 2016). A worker was considered to be in a state of heat strain when his heart rate exceeded 180 beats per minute (bpm) minus his age for a minimum of three consecutive minutes or when his core body temperature exceeded 38.5 °C or 38 °C for acclimatized and unacclimatized workers, respectively (ACGIH, 2008, 2009; NIOSH, 2016).

HR was monitored during the work shift using Polar® T31 chest strap heart rate monitors (Polar Electro Inc., Bethpage, NY, USA) at 20 second intervals. Core body temperature (T_c) was measured as the gastrointestinal temperature (T_{gi}) using CorTemp® Ingestible Core Body Temperature Sensors (HQInc. Palmetto, LF, USA) at 20 second intervals. HR and T_{gi} data were processed to remove biologically implausible values, impute short runs of missing data, and calculate rolling median values. Rolling medians were calculated for all HR and T_{gi} data using the "zoo" package in R (Zeileis et al., 2018) as a rolling, five-integer window. Additional details are available in the Appendix.

In addition to established heat strain thresholds, overall physiological strain was calculated using the Physiological Strain Index (PSI) developed by Moran, Shitzer, and Pandolf 1998. This index produces a value of physiological strain on a 10-point scale where 3-4 is considered mild physiological strain, 4-6 is moderate, 6-8 is high, and 8-10 is very high. This index incorporates simultaneous measures of core body temperature and heart rate, using the following equation (Eq 4.5).

$$PSI = 5\left(T_{git} - T_{gi0}\right)\left(39.5 - T_{gi0}\right)^{-1} + 5\left(HR_t - HR_0\right)\left(\left(HR_{max}\right) - HR_0\right)^{-1}, \quad 4.5$$

where T_{git} is the gastrointestinal temperature at a given time, T_{gi0} is the baseline gastrointestinal temperature taken at the beginning of the shift, HR_t is the heart rate at a given time, HR_0 is the resting heart rate, and HR_{max} is the maximum heart rate for the individual calculated as 220-age (Moran et al., 1998).

Resting heart rate and initial core temperature are necessary for calculating the PSI. Resting heart rate was measured as a 30-second radial pulse and was taken by the lead field researcher after the pre-shift PVT test (a period of 5 minutes where participants were not moving). Initial core temperature was calculated as the mean of three readings measured using an Extech IR200 infrared thermometer (FLIR Commercial Systems Inc, Nashua, NH, USA) directed as instructed at the forehead.

4.3.7 *Psychomotor vigilance*

Psychomotor vigilance was assessed using similar methods to those described by Spector et al. 2018 (Spector et al., 2018). Psychomotor vigilance is measured using stimuli that require a response from the test taker. For this study, a 5-minute tablet version of the PVT-Touch test was used to test the reaction time of participants. The PVT-Touch method was developed and tested to be as accurate and intuitive to users as possible, with minimal delays in response from the software itself (Kay et al., 2013). Psychomotor vigilance task (PVT) tests have been extensively used in sleep-deprivation studies (Skornyakov et al., 2015; Hans P A Van Dongen & Dinges, 2005) as well as for other studies where cognitive impairment is expected, such as from dehydration (Ganio et al., 2011). The two measures of interest from the PVT include the mean reaction time (RT) in milliseconds (ms) and the number of minor lapses in response (ML), defined as a response that takes greater than 500 ms (Basner, Mollicone, & Dinges, 2011; Lee, Bardwell, Ancoli-Israel, & Dimsdale, 2010). The test was administered pre-shift, at the beginning of the lunch break, and post-shift on Android touchscreen tablet computers (Asus Eee Pad Transformer Prime 10.1 inch screen, ASUS Computer International, Fremont, CA, USA). Participants were instructed to sit holding the tablet in both hands and to use their dominant thumb for all responses. Noise-cancelling headphones were provided to minimize worksite and staging area distractions.

4.3.8 *Postural sway*

Balance was assessed as postural sway with a Nintendo Wii force plate, using similar methods described by Spector et al. 2018 (Spector et al., 2018). The Nintendo Wii balance board method has been validated (Clark et al., 2010) against the gold standard, force plates (Haas & Burden, 2000). Postural sway is measured as the change in the weight distribution across a force plate around the center of pressure (COP) (Clark et al., 2010; Haas & Burden, 2000). The path created by the change in pressure, laterally and anterior-posteriorly, is calculated as the total path length (TPL) in centimeters (cm). The test is completed with the eyes open and closed to measure different mechanisms in balance impairment. Impaired balance with the eyes closed would be interpreted as disruption or distortion of the proprioception or vestibular function (Khasnis & Gokula, 2003). Impaired balance with the eyes open would be interpreted as cerebral dysfunction (Lanska, 2002) or disruption of visual systems (Zemková & Hamar, 2014). Numerous potential pathways of cerebral impairment are document for exertional heat stress/stroke, such as reduced blood flow due to high demands on the cardiovascular system, cerebral edema, and neuron degeneration (Michael N. Sawka et al., 2011). Less evidence of heat-related vestibular or proprioception damage exists (Michael N. Sawka et al., 2011).

To calculate the TPL, raw data were initially processed using the LABview Program (National Instruments Corporation, Austin, TX, USA) (LabView Professional Development System, 2014) to extract the middle 30-seconds of each 60-second test, where start and stop times correspond to when participants stepped on and off the board, respectively. The TPL for the COP for each test was then calculated using the following equations (Eq 4.6-8).

$$ML = \left(|X_2 - X_1| + |X_3 - X_2| \ldots |X_n - X_{n-1}|\right), \quad 4.6$$

$$AP = \left(|Y_2 - Y_1| + |Y_3 - Y_2| \ldots |Y_n - Y_{n-1}|\right), \quad 4.7$$

$$TPL = \sum\left[\sqrt{\left(|X_2 - X_1|^2 + |Y_2 - Y_1|^2\right)} + \ldots \sqrt{\left(|X_n - X_{n-1}|^2 + |Y_n - Y_{n-1}|^2\right)}\right], \quad 4.8$$

where *ML* is the medial-lateral path length, *AP* is the anterior-posterior path length, *TPL* is the total path length, and *n* indicates the total number of center of pressure (COP) samples (Halverson, 2013).

The balance tests were administered pre- and post-shift in the staging area on a level platform within a two-sided structure to minimize peripheral distractions.

4.3.9 *Statistical analyses*

We characterized participant demographics, work characteristics, and other individual-level characteristics using descriptive statistics for the full study and by hot and cool monitoring days. We summarized heat stress and measures of heat strain full-shift and the one- and two-hour windows prior to each test. The number of participants who exceeded ACGIH thresholds (ACGIH, 2008) of heat stress and heat strain were also calculated.

The relationships between heat exposure and psychomotor vigilance and postural sway were assessed using linear generalized estimating equations (GEE) with an exchangeable correlation structure grouped by participant. GEE provides a comparison of population means, however when a linear model is used, it is very similar to a linear mixed model approach (LME) but less sensitive to model misspecification due to the sandwich form of the variance estimate (Hubbard et al., 2016). Given the repeated measures study design and multiple tests within each day, we used an exchangeable working correlation structure, which assumes an equal correlation between observations within subjects (Hubbard et al., 2016). Participants who reported a medical diagnosis in the questionnaire of sleep problems, including obstructive sleep apnea, or conditions affecting balance, including stroke or problems with the inner ear, were excluded from the PVT and postural sway analyses, respectively.

Primary analyses assessed the relationship between the one-hour mean area ΔREL and the 1) mean reaction time (RT) during lunch break and post shift tests in the PVT analysis and 2) total path length with eyes open tested post shift in the postural sway analysis. Secondarily, we assessed exposure using the one-hour mean personal T_a and outcomes using minor lapses (ML) for the PVT analysis and total path length with eyes closed for the postural sway analysis. Two-hour exposure windows were assessed in a sensitivity analysis. Pre-shift tests were excluded from analyses for several reasons. First, there were insufficient exposure data prior to pre-shift tests. Second, diurnal variability in psychomotor vigilance associated with circadian rhythms has been described, with early morning vigilance consistently worse than early afternoon vigilance (Hans P A Van Dongen & Dinges, 2005). Third, the repeated measure design captured multiple tests per participant. We verified the absence of learning behavior or a practice effect with repeated tests.

We adjusted models of the effects of heat on PVT and postural sway (models 1) for confounding by a delay of greater than 13 minutes (reference: less than 13 minutes) between the exposure window and time the test was administered (models 2). Postural sway research suggests TPL returns to baseline within approximately 13 minutes after exercise (Fox, Mihalik, Blackburn, Battaglini, & Guskiewicz, 2008) or 20 minutes after exercise (Erkmen et al., 2010). The limited research assessing the relationship between PVT and exercise, heat, and dehydration has yet to identify a consistent recovery window. Additionally, model 2 for the PVT analysis adjusted for confounding by the time of the test (continuous variable), since psychomotor vigilance is strongly affected by diurnal patterns of circadian rhythm and homeostatic pressure (Hans P A Van Dongen & Dinges, 2005). Vigilance is typically optimal during early-mid afternoon. Epworth sleepiness was included as a categorical precision variable in the PVT analysis (PVT model 3) (unlikely to be excessively sleepy [reference], average daytime sleepiness, and may be excessively sleepy). Higher levels of daytime sleepiness have been shown to significantly increase the number of minor lapses and reaction time on PVT tests (Li et al., 2017). Fully adjusted models (PVT model 4 and postural sway model 3) additionally adjusted for continuous variables of age in years, and body mass index (BMI) in kg/m^2. Caffeine intake has been known to affect PVT outcomes (H. P.A. Van Dongen et al., 2001) but was excluded from the analysis due to relatively minimal reported consumption during the work shift (five shifts before the lunch test and two before the post-shift test).

In two post-hoc analyses, we tested for interaction effects of post shift dehydration (hydrated [U_{sg} <1.025] [reference], mildly dehydrated [$U_{sg} \geq 1.025$ & U_{sg} <1.030], and dehydrated [$U_{sg} \geq 1.030$]) and a delay of 13 minutes (reference: less than 13 minutes) in the fully adjusted models of heat (one-hour mean ΔREL) and psychomotor vigilance and postural sway. Urine specific gravity is known to lag behind plasma osmolality (a more precise, but invasive, measure of dehydration). In studies of rehydration in dehydrated athletes, subjects' plasma osmolality returned to a euhydrated state within an hour of recovery with substantial fluid intake, but U_{sg} remained elevated (Oppliger, Magnes, Popowski, & Gisolfi, 2005). However since times between beginning of the lunch break and the end of the shift always exceeded one hour and information on fluid consumption during the shift was not collected, the lunch tests were excluded from the analysis testing for an interaction effect of dehydration.

All analyses were conducted using RStudio. GEE analyses were completed using the "geepack" package. All study procedures were approved by the University of Washington Human Subjects Division and participants provided written informed consent in advance of study participation.

4.4 Results

4.4.1 *Sampling, worker, and work characteristics*

Twenty-two commercial roofing workers were monitored on thirteen days at seven worksites in the summer and fall of 2016. We monitored a mean of three workers on each sampling day and captured repeated measures (both hot and cool days) in seventeen of these workers, for a total of thirty-nine monitored work shifts (Table 4.1). All but one worker with repeated measures completed both days of participation at the same worksite. All shifts started at approximately 6:45 (SD 23 minutes) and ended around 15:04 (SD 53 minutes). On average, shifts monitored on exposed "hot" days ended slight earlier than shifts monitored on unexposed "cool" days. Further details pertaining to data collection are summarized in Chapter 3.

All participants were male with a mean (SD) age of 43 (12) years and body mass index (BMI) of 28 (4) kg/m^2. Only two participants (9%) had less than one year of roofing experience, and thirteen

(59%) had ≥10 years (Table 4.1). All participants reported starting outdoor work in 2016 before the month of May.

Table 4.1: Worker demographics and characteristics, n (%), mean (sd), or ratio (n_{yes}/n).

	Statistic	**Full study (hot and cool days)**	**Hot days**	**Cool days**
Demographics				
Age (years)	Mean (SD)	43 (12)	44 (13)	46 (11)
Male gender	n (%)	22 (100%)	21 (100%)	18 (100%)
Years of roofing work experience				
>1	n (%)	2 (9%)		
1-2	n (%)	2 (9%)		
3-5	n (%)	2 (9%)		
6-9	n (%)	3 (14%)		
≥10	n (%)	13 (59%)		
BMI	Mean (SD)	28 (4)	26 (2)	28 (4)
Sleep quality				
Good	n (%)	31 (79%)	16 (26%)	15 (83%)
Bad	n (%)	8 (21%)	5 (24%)	3 (17%)
Sleepiness scale				
Unlikely abnormally sleepy (0-7)	n (%)	10 (45%)		
Average daytime sleepiness (8-9)	n (%)	5 (23%)		
May be excessively sleepy (10-15)	n (%)	7 (32%)		
Are excessively sleepy (16-24)	n (%)	0 (0%)		
Work characteristics				
Shifts	n (%)	39 (100%)	21 (54%)	18 (46%)
Start time (H:M)	Mean (SD)	6:45 (23 min)	6:40 (22 min)	6:51 (23 min)
End time (H:M)	Mean (SD)	15:04 (53 min)	14:48 (66 min)	15:29 (37 min)
AM break (yes no)	n_{yes}/n	34/39	19/21	16/18
AM break duration (minutes)	Mean (SD)	20 (1)	22 (9)	20 (7)
Lunch break duration (minutes)	Mean (SD)	38 (10)	35 (9)	40 (11)
Used hot process during shift	n_{yes}/n	18/39	11/21	7/18

Based on survey responses for outdoor work and activity, participants were considered acclimatized in this study. When asked the number of days during the past week in which each worker had performed work or exercise activities outside that caused sweating, only one participant reported less than three days; of the remaining thirty-eight responses, twenty-six reported five or more days. While the gold standard for heat acclimation requires targeted exercise and heat exposure regimes, two-hour windows of elevated metabolic activity in hot conditions is sufficient to achieve acclimatization (ACGIH, 2009).

On thirty-one (79%) of the monitored shifts, participants reported sleeping well ("good") in the past week, with the remaining eight (21%) reporting sleeping poorly. On the Epworth Sleepiness Scale (MW, 1991), no participants' sleepiness score fell in the "are excessively sleepy" category (16-24 points), but seven (32%) received scores indicating they "may be excessively sleepy" (10-15 points). Of these seven, only one reported ever being told by a medical professional that he had a sleep-related condition.

4.4.2 *Hydration*

Hydration assessed pre- and post-shift is summarized in Table 4.2. Urine specific gravity (U_{sg}) greater than 1.030 was used as a cutoff for frank dehydration (Bates & Schneider, 2008; Farshad et al., 2014; Montazer et al., 2013), however participants with U_{sg} ≥1.025 and <1.030 were considered mildly dehydrated (Oppliger et al., 2005). Three participants were unable to provide post-shift samples due to reduced access to worksite facilities after the shift ended. The mean (interquartile range) pre- and post-shift U_{sg} were 1.023 (1.019, 1.029) and 1.027 (1.024, 1.030), respectively. Seven (18%) and ten participants (28%) were classified as dehydrated pre- and post-shift, respectively. On hot days, 40% of participants were dehydrated by the end of the shift; half of these participants (4/8) started the shift dehydrated, one started in a mildly dehydrated state, and the remaining three began the shift hydrated. On cool days, only two participants were dehydrated at the end of the shift and both started in a state of mild dehydration. Three participants transitioned from being dehydrated (one participant) or mildly dehydrated (two participants) pre-shift to a state of euhydration post-shift. Changes in hydration status pre- and post-shift are summarized in Appendix Table A.1 for all days, hot days, and cool days.

Table 4.2: Hydration levels.

	Pre shift			Post Shift		
	n	Mean (IQR) U_{sg}	n (%) $U_{sg} \geq$ 1.030	n	Mean (IQR) U_{sg}	n (%) $U_{sg} \geq$ 1.030
Full Shift	39	1.023 (1.019, 1.029)	7 (18)	36	1.027 (1.024, 1.030)	10 (28)
Hot	21	1.024 (1.021, 1.029)	5 (24)	20	1.028 (1.025, 1.031)	8 (40)
Cool	18	1.022 (1.018, 1.028)	2 (11)	16	1.026 (1.022, 1.028)	2 (13)

IQR interquartile range; U_{sg} urine specific gravity

4.4.3 *Heat stress*

The mean (interquartile range) area ΔREL was -7.4 °C (-9.9, -4.3 °C), -6.5 °C (-9.0, -3.5 °C), and -4.8 °C (-6.5, -2.6 °C) for the full shift, one-hour prior to lunch, and one-hour prior to the end of the shift, respectively (Table 4.3). The ΔREL over a two-hour monitoring window was similar to the one-hour windows, although slightly more negative. None of the full-shift or pre-lunch mean ΔRELs exceeded zero, and only three of the one-hour (and two of the two-hour) mean ΔRELs prior to the end of the shift exceeded zero. The mean (interquartile range) personal temperature (T_a) was 25.6 °C (22.1, 29.1 °C), 27.7 °C (24.6, 30.9 °C), and 29.1 °C (25.7, 32.3 °C) for the full shift, one-hour prior to lunch, and one-hour prior to the end of the shift, respectively.

Individually monitored mean activity indicated moderate energy expenditure with a mean (interquartile range) of 270 W (191, 324 W), 278 W (192, 321 W), and 247 W (177, 311 W) for the full shift, one-hour prior to lunch, and one-hour prior to the end of the shift, respectively

(Appendix Table A.2). The corresponding REL for a mean energy expenditure of 270 W is 28.7 °C-WBGT. The mean (interquartile range) area WBGT was 21.4 (18.0, 24.8) °C-WBGT, 22.5 (19.8, 25.4) °C-WBGT, and 24.1 (23.5, 26.1) °C-WBGT for the full shift, one-hour prior to lunch, and one-hour prior to the end of the shift, respectively, including both hot and cool days (Appendix Table A.2).

Table 4.3: Exposure characteristics of area ΔREL °C and personal temperature (T_a) °C.

		n	**Area ΔREL (°C)** Mean (IQR)	**Area ΔREL (°C)** n subjects ΔREL>0	**Personal T_a (°C)** Mean (IQR)
Full Shift		3241	-7.7 (-10.8, -4.4)	0 (0%)	25.6 (22.1, 29.1)
Hot		1682	-5.3 (-7.1, -3.2)	0 (0%)	28.2 (25.1, 31.3)
Cool		1559	-10.2 (-13.9, -6.4)	0 (0%)	22.7 (19.8, 25.9)
Pre lunch	1-hour	400	-6.5 (-9.0, -3.5)	0 (0%)	27.7 (24.6, 30.9)
	2-hours	788	-7.1 (-9.9, -3.9)	0 (0%)	26.7 (23.9, 29.3)
Pre shift end	1-hour	383	-4.8 (-6.5, -2.6)	3 (9%)	29.1 (25.7, 32.3)
	2-hours	771	-4.9 (-6.6, -2.8)	2 (6%)	29.1 (26.0, 31.6)

IQR interquartile range; REL recommended exposure limit; n (%) subjects who exceeded the threshold at any point in shift

4.4.4 *Heat strain*

Core temperature (T_c) exceeded 38.5 °C, the threshold for heat strain in acclimatized workers, in four (10%) of participant shifts, but did not remain elevated through the end of the shift. No participant exceeded a T_c of 38.5 °C during the one-hour exposure windows prior to the lunch break or end of shift (Table 4.4). Heart rate exceeded the threshold for heat strain in 17 (44%) participant shifts. Eight (21%) and seven (18%) participants exceeded the heat rate threshold during the one-hour prior to lunch and one-hour prior to the end of shift, respectively. Based on the mean PSI (3.8), participants were on average moderately strained throughout the study. Time series plots containing exposure and measures of heat strain were compared for the population. For these time series plots, rolling mean hourly ΔRELs were calculated such that the mean ΔREL at a given time represents the previous hour. Visual inspection of the time series data illustrated very similar temporal trends in personal temperature, energy expenditure, heart rate, and core temperature.

Table 4.4: Measures of heat strain including heart rate (HR) bpm, core temperature as gastrointestinal temperature (T_{gi}) °C, and physiological strain index (PSI).

			HR (bpm)		T_{gi} (°C)		PSI	
		n	**Mean (IQR)**	**n (%) subj. HR>180-age**	**Mean (IQR)**	**n (%) subj. T*gi* > 38.5 C**	**Mean (IQR)**	**n (%) subj. PSI>7**
Full Shift		58626	104 (89, 115)	17 (44)	37.4 (37.2, 37.7)	4 (10)	3.8 (3.0, 4.6)	7 (18)
Hot		31665	104 (90, 116)	9 (43)	37.5 (37.3, 37.7)	3 (14)	4.0 (3.2, 4.7)	6 (29)
Cool		26961	103 (86, 114)	8 (44)	37.4 (37.2, 37.7)	1 (6)	3.5 (2.6, 4.3)	3 (17)
Pre lunch	1-hour	7210	107 (92, 118)	8 (21)	37.6 (37.4, 37.8)	0 (0)	4.2 (3.2, 5.0)	3 (8)
	2-hours	14294	105 (89, 116)	9 (23)	37.5 (37.3, 37.8)	2 (5)	3.9 (3.0, 4.8)	4 (22)
Pre shift end	1-hour	6882	107 (92, 118)	7 (18)	37.6 (37.5, 37.8)	0 (0)	4.1 (3.4, 4.8)	2 (5)
	2-hours	13871	108 (94, 119)	11 (28)	37.6 (37.5, 37.8)	0 (0)	4.2 (3.5, 4.8)	5 (13)

IQR interquartile range; n (%) subjects who exceeded the threshold at any point in shift

4.4.5 *Psychomotor vigilance and postural sway*

Psychomotor vigilance measured during the lunch break and post shift as well as postural sway measured post-shift are summarized in Table 4.5. Two participants were excluded from the PVT analysis, and three were excluded from the analysis of postural sway for medical conditions anticipated to impact the outcome. The mean reaction time (standard deviation) for the psychomotor vigilance test was 415 (98) ms and 406 (85) ms during lunch breaks and post shift, respectively, for the full study. The mean number of minor lapses (standard deviation) measured during lunch breaks and post shift was 5.7 (6.6) and 6.2 (9.0), respectively. The mean (standard deviation) total path length (TPL) measured post-shift was 38.6 (13.6) cm and 59.6 (21.4) cm for eyes open and eyes closed, respectively. The mean PVT reaction time and TPLs measured with the eyes open and eyes closed were higher on cool days in the study than hot days. PVT and balance tests occurred slightly later in the afternoon on cool days.

4.4.6 *Association between heat exposure, psychomotor vigilance, and postural sway*

GEE results for the primary and secondary analyses are reported in Tables 4.6 and 4.7. We observed an effect of -0.9 (-1.7, -0.1) cm in postural sway measured as the total path length with eyes open per one °C increase in the ΔREL in the fully adjusted models. Similar results were observed using personal T_a as the metric for heat exposure in the postural sway analysis, with a mean (standard deviation) effect of -0.8 (-1.4, -0.2) cm. Analyses with eyes closed were not statistically significant. In the psychomotor vigilance analyses, we observed a mean (standard deviation) effect of 0.3 (-3.0, 3.5) ms in reaction time per one °C increase in the ΔREL and a mean (standard deviation) effect of -0.5 (-3.2, 2.2) ms per one °C increase in personal T_a. Sensitivity analyses using two-hour exposure windows did substantially not affect the inference (Appendix Table A.3).

In post hoc analyses of an interaction between heat stress and hydration (Table 4.8), we observed a mean (standard deviation) effect of -0.7 (-1.0, -0.3) cm in total path length with eyes open per °C increase in the ΔREL. We observed overall positive effects, indicating poorer performance, of being dehydrated and negative effects, indicated improved performance, of being mildly dehydrated compared with euhydrated participants in both the intercept and the effects of heat

Table 4.5: Measures of psychomotor vigilance and balance.

	All Days				Hot Days				Cool Days			
	Lunch Break		Post Shift		Lunch Break		Post Shift		Lunch Break		Post Shift	
	n	Mean (SD)	n	Mean (SD)	n	Mean (SD)	n	Mean (SD)	n	Mean (SD)	n	Mean (SD)
Psychomotor vigilance test (PVT)	36		35		20		19		16		16	
Reaction time (ms)		415 (98)		406 (85)		415 (96)		400 (61)		416 (104)		413 (109)
Minor lapses (count)		5.7 (6.6)		6.2 (9.0)		6.1 (7.1)		4.7 (6.6)		5.2 (6.1)		7.9 (11.2)
Postural sway			32				17				15	
Total path length eyes open (cm)				38.6 (13.6)				34.4 (10.0)				43.3 (15.9)
Total path length eyes closed (cm)				59.6 (21.4)				54 (18.5)				65.9 (23.2)

SD standard deviation

Table 4.6: Effect estimates (Est.), standard error (SE), and 95% confidence intervals (95% CI) for primary exposure (1-hr area ΔREL) and both primary and secondary psychomotor vigilance and balance outcomes. Significant results are in bold.

		Est.	SE	95% CI	Est.	SE	95% CI	Est.	SE	95% CI	Est.	SE	95% CI
PVT		**Model 1**			**Model 2**			**Model 3**			**Model 4**		
Reaction Time	Intercept	**400.9**	**12.4**	**(376.1, 425.8)**	**445.7**	**57.5**	**(330.7, 560.7)**	**420.1**	**58.5**	**(303.2, 537.1)**	**626.5**	**197.3**	**(231.8, 1021.1)**
	ΔREL	-0.6	1.9	(-4.4, 3.2)	-0.2	2.0	(-4.2, 3.8)	0.2	1.7	(-3.3, 3.7)	0.3	1.6	(-3, 3.5)
	Time of test				0.0	0.0	(-0.1, 0.1)	0.0	0.0	(-0.1, 0.1)	0.0	0.0	(-0.1, 0.1)
	Delay in test (> 13 min)				-2.7	13.3	(-29.4, 24)	-5.4	13.3	(-32, 21.2)	-9.0	14.5	(-38.1, 20.1)
	Sleepiness [ref: unlikely abnormally sleepy												
	Average daytime sleepiness							13.2	29.0	(-44.8, 71.3)	3.2	31.2	(-59.2, 65.7)
	May be excessively sleepy							63.5	45.4	(-27.3, 154.2)	**77.0**	**37.9**	**(1.2, 152.7)**
	Age (years)										**-3.0**	**1.5**	**(-5.9, -0.1)**
	BMI (kg/m2)										-2.9	6.0	(-15, 9.1)
Minor Lapses	Intercept	**5.2**	**1.3**	**(2.6, 7.7)**	6.3	3.8	(-1.3, 13.9)	**3.5**	**3.9**	**(-4.3, 11.3)**	17.0	16.4	(-15.8, 49.9)
	ΔREL	-0.1	0.2	(-0.4, 0.3)	-0.1	0.2	(-0.5, 0.3)	0.0	0.2	(-0.4, 0.4)	0.0	0.2	(-0.4, 0.3)
	Time of test				0.0	0.0	(0, 0)	0.0	0.0	(0, 0)	0.0	0.0	(0, 0)
	Delay in test (> 13 min)				1.5	1.4	(-1.3, 4.2)	1.1	1.2	(-1.4, 3.5)	0.5	1.2	(-2, 2.9)
	Sleepiness [ref: unlikely abnormally sleepy												
	Average daytime sleepiness							0.9	1.9	(-2.8, 4.6)	0.3	2.2	(-4.1, 4.6)
	May be excessively sleepy							**7.2**	**3.3**	**(0.6, 13.8)**	**8.1**	**2.9**	**(2.3, 13.9)**
	Age (years)										-0.2	0.1	(-0.4, 0)
	BMI (kg/m2)										-0.2	0.5	(-1.2, 0.8)
Postural sway		**Model 1**			**Model 2**			**Model 3**					
TPL Eyes Open	Intercept	**32.6**	**2.7**	**(27.2, 38)**	**39.5**	**4.6**	**(30.4, 48.7)**	17.8	14.5	(-11.2, 46.8)			
	ΔREL	**-1.0**	**0.4**	**(-1.8, -0.3)**	**-0.8**	**0.4**	**(-1.6, 0)**	**-0.9**	**0.4**	**(-1.7, -0.1)**			
	Delay in test (> 13 min)				-8.3	4.5	(-17.3, 0.7)	-4.9	3.9	(-12.7, 2.9)			
	Age (years)							0.3	0.2	(-0.1, 0.7)			
	BMI (kg/m2)							0.1	0.4	(-0.7, 0.9)			
TPL Eyes Closed	Intercept	**52.6**	**6.2**	**(40.3, 64.9)**	**59.7**	**9.5**	**(40.7, 78.7)**	48.6	28.9	(-9.2, 106.4)			
	ΔREL	-1.2	0.7	(-2.7, 0.3)	-1.1	0.7	(-2.6, 0.4)	-1.0	0.7	(-2.4, 0.4)			
	Delay in test (> 13 min)				-10.1	8.3	(-26.7, 6.5)	-1.7	10.0	(-21.7, 18.3)			
	Age (years)							**0.7**	**0.3**	**(0.1, 1.3)**			
	BMI (kg/m2)							-0.8	0.8	(-2.4, 0.8)			

Table 4.7: Effect estimates, standard error (SE), and 95% confidence intervals (95% CI) for secondary exposure (1-hr personal temperature (Ta) °C) and both primary and secondary psychomotor vigilance and balance outcomes. Significant results are in bold.

		Est.	SE	95% CI	Est.	SE	95% CI	Est.	SE	95% CI	Est.	SE	95% CI
PVT		**Model 1**			**Model 2**			**Model 3**			**Model 4**		
Reaction Time	Intercept	**432.9**	**53.0**	**(326.8, 538.9)**	**468.7**	**85.3**	**(298.1, 639.4)**	**442.5**	**78.3**	**(286, 599)**	**632.2**	**201.0**	**(230.2, 1034.3)**
	Ta	-1.0	1.4	(-3.8, 1.8)	-0.7	1.5	(-3.6, 2.2)	-0.7	1.4	(-3.6, 2.2)	-0.5	1.4	(-3.2, 2.2)
	Time of test				0.0	0.0	(-0.1, 0)	0.0	0.0	(-0.1, 0.1)	0.0	0.0	(-0.1, 0.1)
	Delay in test (> 13 min)				-0.8	13.1	(-27.1, 25.4)	-2.6	13.2	(-29.1, 23.8)	-6.8	14.3	(-35.3, 21.7)
	Sleepiness [ref: unlikely abnormally sleepy												
	Average daytime sleepiness							13.3	30.6	(-47.8, 74.4)	3.0	32.1	(-61.2, 67.2)
	May be excessively sleepy							63.0	47.8	(-32.6, 158.7)	76.6	40.5	(-4.5, 157.6)
	Age (years)										**-3.0**	**1.5**	**(-6, -0.1)**
	BMI (kg/m2)										-2.5	6.1	(-14.8, 9.7)
Minor Lapses	Intercept	8.9	4.6	(-0.2, 18.1)	11.3	5.9	(-0.4, 22.9)	8.0	5.2	(-2.4, 18.3)	20.3	17.5	(-14.7, 55.2)
	Ta	-0.1	0.1	(-0.4, 0.1)	-0.1	0.2	(-0.4, 0.2)	-0.1	0.2	(-0.4, 0.2)	-0.1	0.1	(-0.4, 0.2)
	Time of test				0.0	0.0	(0, 0)	0.0	0.0	(0, 0)	0.0	0.0	(0, 0)
	Delay in test (> 13 min)				1.8	1.4	(-1, 4.5)	1.5	1.3	(-1, 4)	0.8	1.3	(-1.7, 3.4)
	Sleepiness [ref: unlikely abnormally sleepy												
	Average daytime sleepiness							1.0	2.0	(-3, 4.9)	0.3	2.2	(-4.1, 4.8)
	May be excessively sleepy							**7.3**	**3.6**	**(0.1, 14.5)**	**8.2**	**3.2**	**(1.8, 14.6)**
	Age (years)										**-0.2**	**0.1**	**(-0.4, 0)**
	BMI (kg/m2)										-0.2	0.5	(-1.2, 0.8)
Postural sway		**Model 1**			**Model 2**			**Model 3**					
TPL Eyes Open	Intercept	**63.9**	**9.9**	**(44.1, 83.7)**	**69.3**	**10.1**	**(49.1, 89.5)**	**58.0**	**18.8**	(20.4, 95.6)			
	Ta	-0.9	0.3	**(-1.5, -0.3)**	**-0.9**	**0.3**	**(-1.4, -0.3)**	**-0.8**	**0.3**	**(-1.4, -0.2)**			
	Delay in test (> 13 min)				-8.2	4.3	(-16.9, 0.4)	-4.7	3.8	(-12.3, 2.9)			
	Age (years)							0.3	0.2	(-0.1, 0.7)			
	BMI (kg/m2)							-0.2	0.5	(-1.2, 0.8)			
TPL Eyes Closed	Intercept	**88.3**	**18.1**	**(52.2, 124.4)**	**93.5**	**17.8**	**(58, 129.1)**	**101.5**	**27.9**	(45.7, 157.3)			
	Ta	-1.0	0.6	(-2.2, 0.2)	-0.9	0.6	(-2.2, 0.3)	-1.1	0.6	(-2.3, 0.1)			
	Delay in test (> 13 min)				-10.3	7.8	(-25.9, 5.4)	-0.6	9.2	(-19, 17.8)			
	Age (years)							**0.6**	**0.3**	**(0, 1.2)**			
	BMI (kg/m2)							-1.4	0.8	(-3, 0.2)			

stress. Being dehydrated and mildly dehydrated had mean (standard deviation) effects of 17.2 (11.9, 22.6) cm and -9.8 (-19.0, -0.6) cm, respectively, compared with euhydrated participants.

The interaction effect between the ΔREL and level of hydration was 3.0 (2.5, 3.5) cm in dehydrated participants (U_{sg}≥1.030) and -0.1 (-1.4, 1.2) cm compared with hydrated participants, per degree °C increase in the ΔREL. The stronger positive effects of dehydration reversed the direction of the main effect of the ΔREL. Reaction time in the post hoc analysis of psychomotor vigilance, we observed a mean (standard deviation) effect of 0.3 (-9.4, 10.0) ms in reaction time per °C increase in the ΔREL. The overall effect in dehydrated participants was negative, while the effect in mildly dehydrated participants was positive, however the intercept in mildly dehydrated participants was negatively affected. Being dehydrated and mildly dehydrated had mean (standard deviation) effects of -40.6 (-121.3, 40.1) ms and -18.5 (-142.0, 105.8) ms, respectively. The interaction effects of the level of hydration and the ΔREL was -2.0 (-14.7, 10.8) ms in dehydrated participants and 4.2 (-19.7, 29.0) ms in mildly dehydrated participants.

In post hoc analyses of an interaction between heat stress and a delay of greater than 13 minutes between the work shift and the tests (Table 4.9), we observed positive effects, indicating poorer performance, and negative effects, indicating improved performance, in the analyses of postural sway (total path length with eyes open) and psychomotor vigilance (reaction time), respectively, in participants completing the test more than 13 minutes after the end of the shift. We observed a mean (standard deviation) effect of -1.3 (-2.1, -0.5) cm in total path length with eyes open per °C increase in the ΔREL, a 4.2 (-8.0, 16.5) cm effect of a delay in the test, and an interaction effect of 2.0 (0.5, 3.5) cm per °C increase in the ΔREL in participants who completed the tests after 13

Table 4.8: Post hoc analysis of an interaction between hydration and the primary exposure (1-hr area ΔREL) for primary psychomotor vigilance and balance outcomes. Significant results are in bold.

		Est.	SE	95% CI
PVT				
Reaction Time	Intercept	**777.8**	**255.7**	**(266.5, 1289.1)**
	ΔREL	0.3	4.8	(-9.4, 10.0)
	Time of test	-0.1	0.1	(-0.3, 0.1)
	Delay in test (> 13 min)	-3.5	32.6	(-68.7, 61.7)
	Sleepiness [ref: unlikely abnormally sleepy			
	Average daytime sleepiness	4.6	37.8	(-70.9, 80.1)
	May be excessively sleepy	77.6	39.6	(-1.7, 156.8)
	Hydration [ref: U_{sg}<1.025]			
	Mildly dehydrated (1.025≥U_{sg}<1.030)	-18.5	62.1	(-142.7, 105.8)
	Dehydrated (U_{sg}≥1.030)	-40.6	40.3	(-121.3, 40.1)
	Age (years)	-2.7	1.4	(-5.6, 0.1)
	BMI (kg/m2)	-4.0	5.5	(-15.1, 7.0)
	ΔREL * mildly dehydrated	4.2	11.9	(-19.7, 28)
	ΔREL * dehydrated	-2.0	6.4	(-14.7, 10.8)
Postural sway				
TPL Eyes Open	Intercept	41.5	27.8	**(-14, 97.1)**
	ΔREL	**-0.7**	**0.2**	(-1.0, -0.3)
	Delay in test (> 13 min)	**-11.2**	**2.5**	(-16.2, -6.2)
	Hydration [ref: U_{sg}<1.025]			
	Mildly dehydrated (1.025≥U_{sg}<1.030)	**-9.8**	**4.6**	(-19, -0.6)
	Dehydrated (U_{sg}≥1.030)	**17.2**	**2.7**	(11.9, 22.6)
	Age (years)	**0.4**	**0.2**	**(0.0, 0.7)**
	BMI (kg/m2)	-0.5	1.1	(-2.7, 1.7)
	ΔREL * mildly dehydrated	-0.1	0.7	(-1.4, 1.2)
	ΔREL * dehydrated	**3.0**	**0.2**	(2.5, 3.5)

minutes. In postural sway, we observed a mean (standard deviation) effect of 0.5 (-2.8, 3.8) ms in reaction time per °C increase in the ΔREL, a -15.4 (-86.2, 55.5) ms effect of a delay in the test, and an interaction effect of -1.2 (-15.2, 12.8) ms per °C increase in the ΔREL in participants who completed the tests after 13 minutes.

Table 4.9: Post hoc analysis of an interaction between a delay in the test and the primary exposure (1-hr area ΔREL) for primary psychomotor vigilance and balance outcomes. Significant results are in bold.

		Est.	SE	95% CI
PVT				
Reaction Time	Intercept	**628.7**	**196.6**	**(235.5, 1021.9)**
	ΔREL	0.5	1.6	(-2.8, 3.8)
	Test timing (post-shift)	0.0	0.0	(-0.1, 0.1)
	Delay in test (> 13 min)	-15.4	35.4	(-86.2, 55.5)
	Sleepiness [ref: unlikely abnormally sleepy			
	Average daytime sleepiness	2.9	31.4	(-59.9, 65.8)
	May be excessively sleepy	75.9	37.1	(1.6, 150.1)
	Age (years)	-3.0	1.5	(-5.9, 0.0)
	BMI (kg/m2)	-2.9	6.0	(-14.9, 9.1)
	ΔREL * delay in test (>13 min)	-1.2	7.0	(-15.2, 12.8)
Postural sway				
TPL Eyes Open	Intercept	43.2	26.2	(-9.1, 95.6)
	ΔREL	**-1.3**	**0.4**	**(-2.1, -0.5)**
	Delay in test (> 13 min)	4.2	6.1	(-8,.0 16.5)
	Age (years)	0.2	0.1	(-0.1, 0.5)
	BMI (kg/m2)	-0.7	1.0	(-2.7, 1.3)
	ΔREL * delay in test (>13 min)	**2.0**	**0.7**	**(0.5, 3.5)**

4.5 DISCUSSION

In this small field study of heat exposure in commercial roofing workers, we report no worsening of psychomotor vigilance or balance performance with increasing heat stress. Most participants did not exceed the heat REL during the work shift as characterized by area WBGT and individual estimates of metabolic heat. However, workers on average exhibited moderate heat strain (mean physiological strain index 3.8), and 40% of participants were dehydrated (urine specific gravity ≥1.030) by the end of the shift on hot days compared to 13% on cool days. In post hoc interaction analyses of hydration, we observed a positive relationship between heat stress and postural sway with eyes open in dehydrated participants and a positive association between heat stress and reaction time on PVT tests in mildly dehydrated participants.

There are several possible reasons for the observed absence of an effect of heat stress on psychomotor vigilance or balance performance in the overall study population. It is possible heat exposures were not substantial enough to observe an effect in our study. Mozlomi et al. reported a significant association between WBGT and poor cognitive performance in foundry workers (Mazlomi et al., 2016). The exposure reported by Mazlomi et al. was higher both in metabolic heat production (between 366-407 W) and environmental heat (30.81-35.41 °C-WBGT) (Mazlomi et al., 2016) than in our study (mean metabolic heat of 273 and 235 W and WBGT of 25.2 and 26.2 °C-WBGT in exposed workers one hour prior to lunch and the end of shift, respectively). The predominantly negative ΔRELs measured in this study suggest occupational exposures were likely not high enough to result in heat accumulation in the body in all participants (ACGIH, 2009; NIOSH, 2016).

However, the absence of an effect of heat stress on psychomotor vigilance or balance performance in the overall study population is not entirely consistent with epidemiologic studies, which suggest an effect of heat on injury risk at comparable exposures in the larger construction population in Washington State [Chapter 2]. In Chapter 2, we report an OR of 1.005 (95% confidence intervals 1.003, 1.007) per °C increase in temperature across the full range in maximum daily temperatures during warm months, with a higher OR of 1.012 (95% CI 1.002, 1.023) per °C degree increase in temperature between 19.3 and 22.7 °C—temperatures that were observed during the course of this study. It is possible that the outcome measures of interest were not adequately captured, or that the mechanism of increased risk of traumatic injury in the heat does not involve altered postural sway or vigilance. In this study, the tests used for assessing changes in cognitive performance and postural sway have been validated in controlled settings (Clark et al., 2010; Haas & Burden, 2000; Kay et al., 2013; Lee et al., 2010; Tokizawa et al., 2015), but not in field settings. Other mechanisms that may mediate the relationship between heat exposure and traumatic injuries, including muscle fatigue (Distefano et al., 2013; Rowlinson et al., 2014), changes in mood (Ganio et al., 2011), and unsafe work behaviors (Ramsey et al., 1983), were not assessed in this study. Further research in needed to refine tests of injury risk appropriate for field settings and to elucidate the role of other factors in the development of heat-related injuries.

We report similar trends in the association between heat stress and postural sway using both the gold standard measure of heat, where environmental conditions (area WBGT) and metabolic heat were measured separately and then combined into one metric (ΔREL), and personal temperature monitoring, where metabolic heat released from the body may be measured by the monitoring device in addition to environmental conditions. While neither effect was significant, the analysis of personal temperature and psychomotor vigilance resulted in a negative effect; a reversal of the direction observed with the ΔREL. Individual variability in heat exposure and response is a known challenge in assessing and characterizing population effects of heat. While we did not observe substantial heat stress in the population overall, we did observe the occurrence of heat strain, primarily driven by elevated heart rates, in a large percentage of the population. The question of whether individual-level heat exposure monitoring is necessary and how to interpret personal-monitoring data has received significant attention in heat-health research recently (Kuras et al., 2017)[Chapter 3]. Further research is needed to better understand the role and utility of personal monitoring in heat health studies such as this one.

A substantial percentage of participants reported excessive sleepiness (35% of participants met criteria indicating they “may be excessively sleepy” on the Epworth sleepiness scale). Sleepiness as well as sleep deficits have been demonstrated to adversely affect cognitive performance (Basner et al., 2011; Li et al., 2017; Skornyakov et al., 2015; Hans P A Van Dongen & Dinges, 2005), which can increase injury risk (Quadri et al., 2011). As expected, we found an association between higher sleepiness score categories (particularly "may be excessively sleepy") and mean reaction time in fully adjusted models. Approaches for supporting adequate quality and quantities of sleep in construction workers should be explored in future studies.

The magnitude of dehydration observed in our study was within what has been observed in other studies of construction workers. In a study of sixty construction workers in Iran, Montazer et al. 2013 reported a mean U_{sg} of 1.026 (+/- 0.005) and 1.0213 (+/- 0.0054) in workers exposed to the sun and control workers working in the shade, respectively. The percentage of the study population considered dehydrated with a U_{sg} exceeding 1.030 was slightly lower than we report, at 12.72% of exposed workers and 0.58% of the control population (Farshad et al., 2014; Montazer et al., 2013).

We observed a positive relationship between heat stress and postural sway with eyes open in dehydrated participants in post-hoc analyses. A plausible physiological basis for heat to affect balance with the eyes open exists (Lanska, 2002; Michael N. Sawka et al., 2011; Zemková & Hamar, 2014). Studies have reported decreased postural performance immediately following exercise that induced mild dehydration and fatigue (Lion et al., 2010) and poorer balance performance following one hour of intense exercise (75-85% maximum heart rate) (Erkmen et al., 2010). The lack of an association between heat and postural sway with the eyes closed was anticipated in this study. Mechanisms for impairment of balance with the eyes closed are less likely to be affected by heat (Michael N. Sawka et al., 2011).

We also observed a positive association between heat stress and reaction time on PVT tests in mildly dehydrated participants, but a negative association in dehydrated participants, although these associations were not statistically significant. Dehydration has been reported to have adverse effects on cognitive performance, mood, and balance in controlled settings (Zemková & Hamar, 2014). Ganio et al. 2011 report increased visual vigilance errors, slower memory response latency, and greater fatigue and anxiety in subjects with greater than 1% decrease in body mass loss (Ganio et al., 2011). Future studies should investigate whether dehydration mediates the effects of heat stress on balance performance and vigilance, and to what extent intense exercise versus heat stress might contribute to this effect.

4.5.1 *Limitations*

This study has several important limitations. First, researcher observations of tasks and worksite characteristics were extremely limited. As a result, this study relies on imperfect surrogate measures of metabolic activity. Metabolic heat production is ideally measured more directly via oxygen consumption (V_{O2}) (Michael N. Sawka et al., 2011) and is known to vary substantially across the population. Numerous occupation- and task-specific estimates of metabolic activity exist and are useful when comparing large populations, however these estimates fail to capture individual variability in metabolic demands as well as the effects of self-pacing, and require detailed activity logs or observations to accurately capture temporal changes in task. Video-monitoring has been used with some success (Distefano et al., 2013; Freedson, Bowles, Troiano, & Haskell, 2012), but was not an acceptable tool per employers for use in this study. In this study, we estimated activity using tri-axial accelerometers to measure acceleration across three planes: vertical, horizontal, and lateral. These monitors have been used in a number of occupational and exercise settings to capture movement and estimate metabolic heat exposure (Hills et al., 2014;

Spector et al., 2018). For tasks where metabolic demands primarily result from physical movement, such as running or jumping, these monitors perform well (Rowlands & Stiles, 2012; Sasaki et al., 2011). However, for tasks where movement across these planes is minimal, but work being done on an object is substantial, such as slowly pushing or pulling a heavy object, the tri-axial accelerometers likely underestimate metabolic demands. In this study, underestimation of the metabolic contribution to heat exposure may have resulted in a more negative ΔREL, potentially biasing the results towards the null.

Second, restricted access to worksites required pre- and post-shift testing be completed in an adjacent staging area. For some worksites, the staging area was immediately adjacent to the worksite, such as a parking lot next to a two-story building where the roof was accessible from a ladder, but for others the travel between the worksite and staging area required walking through air an conditioned building or waiting for an elevator to descend from the fourteenth-floor work area to a parking structure below the building. For these worksites, mid-day PVT tests, requiring easily moveable hand-held tablets, were completed in the work area, but the delay between work activities and the administration of the PVT and postural sway tests at the end of the shift was up to an hour long. In controlled laboratory studies, the effects of exercise on postural sway reduced to baseline within 13 minutes (Fox et al., 2008). The fixed effects of a 13 minute delay in the test was include in the GEE analyses.

The positive association observed in the post hoc interaction analysis of heat stress and postural sway may in part be due to unaccounted for activity completed after the shift ended. Some participants were observed to continue being highly active after the shift ended and area environmental data collection ceased. Future research is needed to develop and validate tests that can be used in field settings to assess for psychomotor changes that may mediate the relationship between heat stress and injury risk.

Third, diurnal patterns in psychomotor vigilance are strongly associated with circadian rhythm and homeostatic pressure, where the greatest deficits in performance typically occur in early morning hours and improve to a peak performance in the early afternoon (Hans P A Van Dongen & Dinges, 2005). In this study, we addressed diurnal patterns by 1) conducting the PVT test at multiple points throughout the day, 2) limiting the analysis to tests where homeostatic pressure was limited and information on recent exposure and sleep activity was available, and 3) adjusting for the time of the test in the analyses. PVT was tested at three points throughout the day (pre-shift, pre-lunch, and post-shift) on exposed (hot day) and unexposed (cool day) work shifts in most participants. Lunch and post shifts tests generally occurred around the same time of day within participants, although variability between participants on different worksites was observed and on some worksites the hot day, post shift test was conducted slightly earlier than the cool day test. While the pre-shift test was also administered at approximately the same time of day for all workers, this test was problematic due to a lack of information on recent sleep behavior, including the time the individual had been awake that morning, and the absence of exposure data prior to the test. When multiple tests on an individual are not available, the difference from the pre-shift test has been used to account for variability between subjects when quantifying the effects of temperature of psychomotor vigilance (Spector et al., 2018). Since this study administered multiple PVT tests using a repeated measures design where exposures were compared within participants, individual variability was accounted for in the design and the pre-shift PVT was excluded.

Forth, worksites varied in the level and types of distractions. To minimize the effect of distractions from other workers, traffic, or overall stimuli, noise-cancelling headphones were provided during the PVT test, and a tent structure was used during the postural sway test, but there may still have been an effect on worker performance. The presence of distractions in the testing area may have increased the presence of noise in the data by inflating the reaction time and total path length measured in PVT and postural sway tests, respectively. This may have affected our ability to measure changes attributable to the predictor of interest. Assuming the level of distractions was consistent on each worksites and not associated with cooler or warmer environmental conditions, this limitation would have biased our results towards the null.

Fifth, the small sample size restricted our ability to adjust for confounders, effect modifiers, and precision variables in the analyses. Variables of interest to this analysis that we were unable to adjust for include sleep quality, due to minimal variability in responses across the small population; fatigue, which was ascertained throughout the day from a questionnaire that yielded limited variability in responses; tasks, which varied substantially between workers and days; and roofing processes, which were relatively similar across all workers. Finally, the study population was recruited from companies with strong commitments to occupational safety and health. Self-pacing and adequate hydration was often encouraged within work crews. As a result, the metabolic demands as well as adherence to heat illness and injury prevention may not be representative of all commercial roofing workers.

4.6 CONCLUSIONS

In this repeated measures field study of commercial roofing workers, improvements in postural sway and slight decrements in psychomotor vigilance were associated with increasing heat exposure. In post hoc analyses of the interaction between hydration and heat stress, increasing heat stress was associated with worsening balance in dehydrated participants and longer reaction times in mildly dehydrated participants. Further work is needed to optimize injury risk outcome measures for use in field settings, investigate other mechanisms of increased injury risk in heat exposed workers, and evaluate hydration status as an effect modifier of the relationship between heat stress and traumatic injury risk. Adequate hydration should be supported in occupational settings with high risks for heat stress and traumatic injuries.

Chapter 5. DISCUSSION

5.1 OVERVIEW

In this dissertation, we assessed the relationship between environmental heat and traumatic injury workers' compensation claims in outdoor construction workers in WA State, measured and compared heat at three spatial resolutions in a sample of commercial roofing workers across a range in summer and fall exposures, characterized the presence of heat strain in relation to the occurrence of heat stress above recommended exposure thresholds in these workers, and assessed the association between heat stress and psychomotor vigilance and postural sway. The methods used in this series of studies build upon methods used in previous studies by: introducing novel methods for identifying outdoor workers and methods for improving the accuracy of heat exposure quantification in epidemiologic assessments; exploring the utility of personal versus area heat monitoring in different settings and populations; exploring heat exposure windows of importance for heat-related injuries; exploring the effect of industry-specific, occupational, and individual-level factors that could impact the effects of heat exposure on injury risk; and testing for an effect of heat on mechanisms anticipated to mediate the observed relationship between heat exposure and injury risk in a field setting

5.1.1 *Key findings*

Key findings for each chapter and aim are summarized in Table 5.1. We observed an increasing risk of a traumatic workers compensation injury claim associated with increasing heat exposure in outdoor construction workers in a case-crossover study. The traumatic injury odds ratio (OR) of 1.0053 (95% CI 1.003, 1.007) per one °C change in humidex. We observed near-linearity in an analysis using linear splines, however some of highest incremental effects occurred at relative low exposures (21 to 25 one °C humidex) and very high exposures (≥37 one °C humidex). Younger (18-24 years) and older (over 54 years) workers, workers with lower extremity injuries, workers with less job experience, smaller employers, workers working in Western Washington, and time of injury before 12:30 pm were associated with high risk.

In the repeated measures field study of commercial roofing workers, we observed a consistent positive difference between temperature monitored at the personal level and area (worksite) level. The mean difference between temperatures monitored at regional weather stations and worksite monitors varied by worksite, with regional data consistently lower than worksite monitors on two sites, consistently higher on three sites, and approximately the same on the remaining two.

Participants in this study rarely exceeded the NIOSH REL based on WBGT measured at worksites and estimates of individual metabolic activity. Heat strain was experienced primarily through elevated heart rate, but core temperature monitored using ingestible sensors rarely exceeded the threshold for heat strain of 38.5 °C for acclimatized workers. Increasing heat stress did not result in decrements in postural sway or psychomotor vigilance. However, in post hoc analyses of the interaction between hydration and heat stress, increasing heat stress was associated with worsening postural sway in dehydrated participants and longer reaction times in mildly dehydrated participants.

Table 5.1: Key findings.

<table>
<tr><th>Chapter</th><th>Study</th><th colspan="2">Aims</th><th>Key findings</th></tr>
<tr><td>Chapter 2</td><td>Epidemiologic study using occupational injuries recorded in Washington State (WA) Labor and Industries workers' compensation claims data for the construction industry</td><td colspan="2">Aim 1. Assess the relationship between outdoor apparent temperature and occupational traumatic injuries.</td><td>• Traumatic injury odds ratio (OR) of 1.0053 (95% CI 1.003, 1.007) per one °C change in humidex.
• Potentially higher risk in younger (18-24 years) and older (over 54 years) workers, workers with lower extremity injuries, workers with less job experience, smaller employers, workers working in Western Washington, and time of injury before 12:30 pm</td></tr>
<tr><td>Chapter 3</td><td rowspan="4">Field study using repeated measures in a sample of commercial roofing workers in the greater Seattle, WA area.</td><td rowspan="2">Aim 2. Characterize the exposure to heat.</td><td>2a. Quantify differences in heat exposure measured at three spatial resolutions.</td><td>• Mean (95% confidence interval) difference between personal and area temperature of 4.4 (4.1, 4.7) °C and WBGT of 1.5 (1.3, 1.8)°C-WBGT.
• The mean difference between regional and area temperature varied in direction and magnitude by site.</td></tr>
<tr><td rowspan="3">Chapter 4</td><td>2b. Characterize heat stress.</td><td rowspan="3">• Participants rarely exceeded the NIOSH REL.
• Adverse effects of heat stress were minimal except in dehydrated participants.
• Improvements in postural sway and slight decrements in psychomotor vigilance were associated with greater heat exposure.
• In post hoc analyses of the interaction between hydration and heat stress, heat stress was associated with worsening balance and longer reaction times in dehydrated or mildly dehydrated participants.</td></tr>
<tr><td rowspan="2">Aim 3. Assess the relationship between heat stress and psychomotor vigilance and postural sway.</td><td>3a. Characterize heat strain.</td></tr>
<tr><td>3c. Assess the relationship between heat stress and psychomotor vigilance and postural sway.</td></tr>
</table>

5.1.2 *Comments on approach and methodology*

In the case-crossover approach used for the epidemiologic study (Chapter 2), we paired high-resolution meteorological data with the geocoded location of the injury to improve the accuracy of weather-related heat exposure assessment. Additionally, we restricted claims to those occurring in outdoor construction workers using O*NET. In the field study (Chapters 3 and 4), we were able to collect repeated measures in a small sample of workers on both hotter and cool days in a typical warm month season in the Greater Seattle area. This facilitated within person comparisons of the effects of heat on psychomotor vigilance and postural sway. Environmental conditions were measured at multiple spatial scales along with high-temporal resolution measures of physiological characteristics (heart rate and core temperature). We did experience challenges in conducting tests of psychomotor vigilance and postural sway, including challenges in limiting the presence of distractions and completing the tests in a timely manner.

5.1.3 *Implications for practice*

Our findings of an association between heat and traumatic workers compensations injuries in construction workers, including at relatively low levels of meteorologically-driven heat add to the understanding of the burden of heat stress. Findings suggest the need for heat-related injury prevention interventions and awareness in conditions of lower heat exposure than for HRI. In occupations where the risk of injury is high, addressing heat exposure in injury reduction strategies may help prevent injuries.

While further research is needed to elucidate the mechanisms mediating the relationship between heat and injury risk, suboptimal hydration appeared to worsen the effects of heat stress on postural sway and psychomotor vigilance. Efforts to further support optimal hydration in workers should be pursued.

5.1.4 *Implications for research*

We demonstrate the feasibility of methods used to improve the accuracy of heat exposure assessment and definition of outdoor working populations in heat-injury research through the use of higher resolution meteorological data and application of the O*NET system. Further research should be conducted evaluating the necessity of greater accuracy in heat exposure assessment in heat-injury epidemiology. Research into personal monitoring devices in settings with high metabolic and radiant sources of heat (including solar) is needed to better understand the comparability of personal monitoring devices and individually monitored temperature to gold standard measures of heat. Sub-shift differences in task (hourly or sub-hourly) and the proximity of workers to one another may be necessary to fully understand the causal factors resulting in higher temperatures from personal monitoring devices.

The challenges we experienced in trying to test for changes in balance and cognitive performance suggest these tests need to be further optimized for field studies. Future work should attempt to further minimize the time between the end of the shift (or the end of activity) and the test, develop evaluations that do not rely on extensive equipment or set-up time to facilitate easier movement around a worksite, and structures and tools designed to eliminate distractions. Additionally, future research should aim to capture skin temperature and fluid balance (beverage consumption, sweating, etc.).

5.2 CONCLUSION

The research presented in this dissertation contributes to the growing body of literature describing an association between heat exposure and traumatic injuries. We used more refined methods for assessing environmental heat in both the epidemiologic and field studies. While we provided evidence of an effect of heat on occupational injuries in WA State, we were unable to definitively determine the mechanism by which heat might increase the risk of traumatic injury in a sample of commercial roofing workers. Based on the observed interaction between heat and dehydration in the sample of commercial roofing workers, additional investigation of hydration should be included in future research into the mechanisms mediating the relationship between heat and injury risk a population with both high risk for injuries and heat related illness.

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APPENDIX A

This appendix contains additional methods for the heart rate and core temperature data; descriptive statistics for energy expenditure, area WBGT, and area temperature; and time series plots comparing heat stress and heat strain in a sample of study participants.

Methods—Heat rate and core temperature

The sensors on the Polar chest strap heart rate monitors were moistened prior to being put on the workers and placement was checked during lunch breaks. Participants were asked to arrive at the worksite 30 minutes prior to the start of the work shift and were given the CorTemp sensors with water as soon as they arrived. All pills were checked prior to ingestion to ensure they were active. Both HR and T_{gi} were recorded using the CorTemp Data Recorder (HQInc. Palmetto, LF, USA) attached around participants' waists with the data logger positioned against the lower back.

Data excluded for biological implausibility include HR values above 200 or below 40 bpm and T_{gi} above 42 or below 34 °C as these values would be associated with physiological conditions that would be accompanied by observable symptoms and require medical attention. Missing data, including true missing data not recorded by the data logger and values excluded for biological implausibility, were imputed as the median of the five values immediately before and five values immediately after the missing data point. For consecutive missing values of four or more data points, imputation was not completed due to insufficient available neighboring data.

Table A.1: Number of shifts by pre- and post-shift hydration (U_{sg}) on all days, hot days, and cool days (n all days, n hot days, n cool days).

		Post-shift		
		$U_{sg}<1.025$	$1.025 \geq U_{sg}<1.030$	$U_{sg} \geq 1.030$
Pre-shift	$U_{sg}<1.025$	8, 4, 4	7, 3, 4	3, 3, 0
	$1.025 \geq U_{sg}<1.030$	2, 0, 2	6, 4, 2	3, 1, 2
	$U_{sg} \geq 1.030$	1, 0, 1	2, 1, 1	4, 4, 0

Table A.2: Exposure characteristics of energy expenditure (W), area WBGT (°C-WBGT), and area temperature (°C).

			Energy Expenditure (W)	**Area WBGT (°C-WBGT)**	**Area Ta (°C)**
		n	**Mean (IQR)**	**Mean (IQR)**	**Mean (IQR)**
Full Shift		3241	270 (191, 324)	21.4 (18, 24.8)	21.2 (17.5, 25.2)
Hot		1682	263 (188, 310)	23.9 (22.7, 25.9)	24.4 (21.6, 27.1)
Cool		1559	279 (198, 344)	18.7 (15.8, 21.9)	17.6 (15.6, 20.1)
Pre lunch	1-hour	400	278 (192, 321)	22.5 (19.8, 25.4)	22.1 (18.4, 24.6)
	2-hours	788	281 (192, 328)	22.2 (19.5, 25.3)	21.5 (18, 24.4)
Pre shift end	1-hour	383	247 (177, 311)	24.1 (23.5, 26.1)	25.1 (21.5, 28.6)
	2-hours	771	263 (185, 322)	24.2 (23.5, 25.9)	24.8 (21, 28.2)

n measurements, IQR interquartile range; WBGT wet bulb globe temperature

Table A.3: Effect estimates (Est.), standard error (SE), and 95% confidence intervals (95% CI) for primary exposure (2-hr area ΔREL) and both primary and secondary psychomotor vigilance and balance outcomes. Significant results are in bold.

		Est.	SE	95% CI	Est.	SE	95% CI	Est.	SE	95% CI	Est.	SE	95% CI
PVT		**Model 1**			**Model 2**			**Model 3**			**Model 4**		
Reaction Time	Intercept	**402.2**	**12.8**	**(376.7, 427.7)**	**443.8**	**56.2**	**(331.4, 556.2)**	**419.4**	**58.0**	**(303.4, 535.4)**	**622.7**	**195.6**	**(231.5, 1013.9)**
	ΔREL	-0.4	1.7	(-3.8, 2.9)	0.0	1.7	(-3.3, 3.4)	0.3	1.5	(-2.7, 3.3)	0.4	1.4	(-2.4, 3.1)
	Time of test				0.0	0.0	(-0.1, 0.0)	0.0	0.0	(-0.1, 0.1)	0.0	0.0	(-0.1, 0.1)
	Delay in test (> 13 min)				-4.2	12.4	(-29.0, 20.6)	-6.5	12.4	(-31.3, 18.4)	-10.1	13.8	(-37.8, 17.5)
	Sleepiness [ref: unlikely abnormally sleepy												
	Average daytime sleepiness							12.9	28.9	(-44.8, 70.7)	2.8	31.1	(-59.4, 65.1)
	May be excessively sleepy							63.3	46.3	(-29.3, 155.8)	76.6	38.8	(-1, 154.2)
	Age (years)										**-3.0**	**1.5**	**(-5.9, 0.0)**
	BMI (kg/m2)										-2.8	6.0	(-14.8, 9.1)
Minor Lapses	Intercept	**5.6**	**1.4**	**(2.9, 8.3)**	6.5	3.9	(-1.2, 14.2)	3.7	3.9	(-4.2, 11.6)	17.9	16.4	(-14.9, 50.7)
	ΔREL	0.0	0.1	(-0.2, 0.3)	0.0	0.1	(-0.3, 0.3)	0.0	0.1	(-0.2, 0.3)	0.0	0.1	(-0.2, 0.3)
	Time of test				0.0	0.0	(0.0, 0.0)	0.0	0.0	(0.0, 0.0)	0.0	0.0	(0.0, 0.0)
	Delay in test (> 13 min)				1.3	1.3	(-1.2, 3.9)	1.0	1.1	(-1.2, 3.2)	0.3	1.1	(-1.9, 2.6)
	Sleepiness [ref: unlikely abnormally sleepy												
	Average daytime sleepiness							0.9	1.8	(-2.7, 4.6)	0.3	2.2	(-4.0, 4.7)
	May be excessively sleepy							**7.3**	**3.4**	**(0.4, 14.2)**	**8.2**	**3.0**	**(2.2, 14.2)**
	Age (years)										**-0.2**	**0.1**	**(-0.4, 0.0)**
	BMI (kg/m2)										-0.3	0.5	(-1.3, 0.8)
Postural sway		**Model 1**			**Model 2**			**Model 3**					
TPL Eyes Open	Intercept	**31.1**	**2.9**	**(25.4, 36.8)**	**34.1**	**3.1**	**(27.8, 40.3)**	18.6	17.0	(-15.3, 52.5)			
	ΔREL	**-1.4**	**0.4**	**(-2.2, -0.6)**	**-1.4**	**0.4**	**(-2.2, -0.6)**	**-1.4**	**0.4**	**(-2.1, -0.6)**			
	Delay in test (> 13 min)				-4.5	2.6	(-9.6, 0.7)	-2.9	2.5	(-7.9, 2)			
	Age (years)							**0.3**	**0.2**	(0, 0.7)			
	BMI (kg/m2)							0.0	0.5	(-1.1, 1)			
TPL Eyes Closed	Intercept	**60.0**	**7.8**	**(44.4, 75.6)**	**72.7**	**8.2**	**(56.3, 89)**	**59.1**	**28.0**	(3, 115.2)			
	ΔREL	0.1	0.7	(-1.4, 1.5)	-0.1	0.5	(-1.1, 0.9)	0.0	0.6	(-1.1, 1.1)			
	Delay in test (> 13 min)				**-20.4**	**6.7**	**(-33.8, -7)**	**-18.3**	**7.1**	(-32.6, -4.1)			
	Age (years)							0.5	0.3	**(-0.1, 1.1)**			
	BMI (kg/m2)							-0.3	0.7	(-1.7, 1)			

VITA

Miriam Calkins was born and raised outside of Boston, MA. She received her Bachelors in Arts and Science (BA/BS) from The Evergreen State College in Olympia, WA with an emphasis in Environmental Studies in 2009. After graduation, Miriam remained in Olympia and became a founding member of a free clinic for acute care needs of un- and underinsured individuals. The Olympia Free Clinic opened its doors in 2011and is still open today. Miriam returned to graduate school in 2012 and in 2014 graduated with her Master of Science (MS) in Exposure Science from the Department of Environmental and Occupational Health Sciences (DEOHS) at the University of Washington in Seattle, WA in 2014. Miriam began working on her doctoral degree in Environmental and Occupational Hygiene from DEOHS at the University of Washington immediately following her MS, where she has continued to develop her expertise in occupational hygiene, heat, and climate science.

In addition to her PhD, Miriam completed a Certificate in Climate Science through the University of Washington Program on Climate Change in which she focused on developing climate communications with labor audiences in King County, WA. Miriam was an Achievement Awards for College Students (ARCS) Fellow and a recipient of the Castner Award during her PhD and she is an active member of the International Society of Exposure Science (ISES), American Industrial Hygiene Association (AIHA), and the American Meteorological Society (AMS) for which she was a student member on the Board of Environment and Health until her graduation.