COGNITIVE FUNCTION DURING EXERTIONAL HEAT STRESS ASSESSED USING TRADITIONAL AND SERIOUS GAME TECHNOLOGY

By

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ABSTRACT

Firefighting is a physically demanding occupation requiring intermittent bouts of work resulting in increased levels of cardiovascular and thermal strain, while making decisions requiring higher order cognitive abilities e.g. working memory, sustained attention, reaction time, spatial awareness, and information processing. These activities can take place in dangerous conditions with elevated temperatures imposing external stressors on physiological and cognitive function. Previous research has examined the impact of heat stress on cognitive function in general, but the specific influence on firefighters wearing personal protective equipment (PPE) and self-contained breathing apparatus (SCBA) is not well understood. Specific domains of cognitive function can be assessed using computer-based neuropsychological testing batteries, such as the Cambridge Neuropsychological Automated Testing Battery (CANTAB). The CANTAB automatically records the response measures for each test and provides consistent feedback in between trials. Although the CANTAB is well established the cognitive domains it tests may not adequately capture the complexity of the specific decision making required of firefighters while on-duty. The use of serious game technology provides a possible solution to develop a more ecologically valid assessment tool capable of evaluating the specific decision making tasks required of firefighters at an emergency scenario.

Thus, the current thesis aimed to evaluate the effects of exercise-induced heat stress on cognitive function in firefighters using the CANTAB testing battery and a recently developed serious game simulating the decision making tasks required of firefighters in a two-storey residential fire while walking on a treadmill. Additionally, the reliability of repeated CANTAB administrations during treadmill walking was measured and found to have reasonable overall reliability. Decrements in cognitive function (working memory and executive function were observed at a core temperature of 38.5°C and restored following an active cooling recovery protocol. However, when decision making was evaluated using the serious game scenario, task specific performance deficits were not seen during treadmill walking but impairment in memory recall was found following the active cooling recovery protocol. These findings provide fire service personnel with information regarding the cognitive implications of heat stress and the potential use of serious games to evaluate and train cognitive function during exposure to environmental stressors.

Keywords

Occupational physiology, thermophysiology, working memory, attention, firefighting

CO-AUTHORSHIP STATEMENT

Chapter 4: Williams-Bell, F.M., McLellan, T.M., and Murphy, B.A. (2016). The effects of exercise-induced heat stress on cognitive function in firefighters.

Mr. Williams-Bell was involved in developing the experimental protocol, data collection, data analysis and interpretation, and manuscript preparation. Dr. McLellan and Dr. Murphy were involved in the planning of the study including methodological considerations and pilot testing, data interpretation, consultation on statistical analyses, and scientific contributions to the discussion.

Chapter 6: Williams-Bell, F.M., Kapralos, B., Hogue, A., Murphy, B.A., and Weckman, E.J. (2015). Using serious games and virtual simulation for training in the fire service: a review. *Fire Technology, 51*(3), 553-584

Mr. Williams-Bell gathered the information on all of the articles reviewed and provided initial and final manuscript preparation. Dr. Kapralos and Dr. Hogue provided technical assistance in regard to the computer science information described in the articles reviewed as well as technical writing for the article in relation to game development. Dr. Weckman provided technical input for the article as it related to fire engineering and specific physical processes employed by the various fire modeling applications. Dr. Murphy provided assistance with scholarly review and article publication.

Chapter 7: Williams-Bell, F.M., O'Brien, S., Hogue, A., Kapralos, B., Passmore, S.R., McLellan, T.M., and Murphy, B.A. (2016). The use of serious game technology to assess cognitive function in firefighters during exercise-induced heat stress.

Mr. Williams-Bell was involved in developing the experimental protocol, data collection, data analysis and interpretation, content and storyboard for game development, and manuscript preparation. Dr. McLellan and Dr. Murphy were involved in the planning of the study including methodological considerations and pilot testing, data interpretation, consultation on statistical analyses, and scientific contributions to the discussion. Dr. Hogue and Dr. Kapralos provided technical expertise for the development of the serious game. Dr. Passmore provided methodological considerations and content assistance for serious game development. Ms. O’Brien provided assistance with manuscript preparation for the introduction and methods sections.

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LIST OF ABBREVIATIONS

1-RM – One repetition maximum

5RT – 5 choice reaction time

α – Low-frequency waves

β – High-frequency waves

ADMS – Advanced Disaster Management Simulator

ANOVA – Analysis of variance

BF% - Body fat percent

BMI – Body mass index (kg/m^2)

C – Convection

CANTAB – Cambridge Neuropsychological Test Automated Battery

CAVE – Cave Automatic Virtual Environment

CFAST – Consolidated Model of Fire and Smoke Transport

CFD – Computational Fluid Dynamics

Clo – Thermal insulation unit

CNS – Central nervous system

CPAT – Candidate Physical Abilities Test

CRT – Choice reaction time

E_{co} – Condensation of evaporative sweat

EEG - Electroencephalography

EIHS – Exercise-induced heat stress

f_{cl} – Surface area of the clothed body

F_{cl} – Burton’s clothing permeation factor

F_{pcl} – Clothing permeation factor

FCTVE – Fire fighter Command Training Virtual Environment

FDNY – Fire Department of New York

FDS – Fire Dynamics Simulator

FFTL – Firefighter Task Level Serious Game

fMRI – Functional magnetic resonance imaging

GABA – Gamma-aminobutyric acid

GI – Gastrointestinal

GPS – Global positioning receivers

HD – High definition

HMD – Head-Mounted Display

HR – Heart rate (bpm)

HR_{max} – Maximal treadmill heart rate (bpm)

HSP – Heat shock protein

I_a – Resistance of clothing surface

I_{cl} – Intrinsic clothing insulation

i_m – Woodcock vapour permeability factor

I_T – Total insulation

K – Conduction

kJ – Kilojoule

MASCARET – Multi Agents Systems to Simulate Collaborative Adaptive and Realistic Environments for Training

M – Metabolic heat production

mPFC – Medial Prefrontal Cortex

MSA – Mine Safety Appliance

MTS – Match to sample

NBC – Nuclear, Biological, and Chemical clothing

NFIRS – National Fire Incident Reporting System

NIST – National Institute of Standards and Technology

OTS – One touch stocking of Cambridge

PAL – Paired associates learning

PFC – Prefrontal cortex

PPE – Personal protective equipment

PRM – Pattern recognition memory

R - Radiation

RER – Respiratory exchange ratio

RPE – Rating of perceived exertion

RVP – Rapid visual information processing

S – Heat storage

SCBA – Self-contained breathing apparatus

SecureVi – Security and Virtual Reality

SOP – Standard operating procedure

SSP – Spatial span

SSVEP – Steady-state visual evoked potential

STM – Short-term memory

T^{2}eC – Teaching Team Coordination Game

TC – Thermal comfort

T_{core} – Core temperature

TFS – Toronto Fire Service

TS – Thermal sensation

T_{sk} – Skin temperature

UHS – Uncompensable heat stress

USFA – United States Fire Administration

V_E – Minute ventilation

VCO_2 – Carbon dioxide output

VO_2 – Oxygen uptake

VO_{2peak} – Maximal oxygen uptake

W - Watts

W_{ex} – External work

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CHAPTER 1 - Introduction

1.1 Thesis Overview

The physical nature and cardiovascular strain during firefighting has been well documented leading to many recommendations for minimum requirements of aerobic power to gain entry into the occupation (Barnard et al., 1975, Lemon et al., 1977, Sothmann et al., 1991, Gledhill et al., 1992, Sothmann et al., 1992). Firefighting activities, such as victim search and rescue, is extremely physically demanding (Holmer et al., 2007) and requires the firefighter to maintain adequate performance of mental function and acuity while performing tasks under conditions of extreme heat and psychological stress (Smith et al., 2001, Barr et al., 2010, Williams-Bell et al., 2015a). Maintaining high levels of mental function, including attention and retention of important details, is critical not only for the safety of the firefighter but also for the safety of the general public (Morley et al., 2012). Firefighters must be alert, make critical decisions (Smith et al., 2001, Williams-Bell et al., 2015a), and be aware of their surrounding environment in order to determine the safest means of egress, all while working under life-threatening conditions (Barr et al., 2010).

To date, the few studies which have examined cognitive function during exertional heat stress in firefighters have utilized simple mental performance tasks, such as reaction time, to determine any changes with increasing core temperature (T_{core}) (Kivimäki et al., 1994, Smith et al., 1998, Smith et al., 2001, Caldwell et al., 2012, Greenlee et al., 2014). These tests have been reported as not being practical to the firefighting occupation (Barr et al., 2010), not ecologically valid, and capable of withstanding the effects of thermal strain due to their simple nature (Hancock et al., 1998). However, cognitive performance tests that involve dual-tasks (either motor and/or cognitive tasks) or those involving central executive function are more susceptible to decrements from exposure to thermal strain (Hancock et al., 1998, Cian et al., 2000, Cian et al., 2001).

Firefighters are exposed to live fire environments ranging from 38°C to 93.3°C (Faff & Tutak, 1989; Smith, Petruzzello, Kramer, & Misner, 1996) and may even exceed 200°C (Baker, Grice, Roby, & Matthews, 2000). In addition, with fighting fires accounting for only a small portion of their job, firefighters perform other emergency tasks in ambient environments reaching temperatures of 30°C or higher (Selkirk et al., 2004b). With the physical demands of firefighting ranging from light to heavy exercise (Gledhill et al., 1992) increasing T_{core} could potentially cause different responses in cognitive performance (Hancock et al., 1998). In the past decade, with the emerging research in tolerance times for firefighters working in the heat (Selkirk et al., 2004b), improving our understanding of cognitive performance can enhance the published standards for safe working limits in the fire service.

Technological advances have improved the assessment and training techniques in various occupations, including medicine (Kron et al., 2010, Marsh et al., 2010), military (Cox et al., 2010), baseball (Fink et al., 2009), and firefighting (St.Julien et al., 2003, Sowndararajan et al., 2008, Boulet, 2009, Toups et al., 2009). One such technology, termed serious games, refer to video games used for training. Serious games have been shown to improve performance with novice surgeons executing surgical techniques (Derossis et al., 1998, Gallagher et al., 2005). Based on the development and use in medicine, there is potential to train decision making in firefighters in an attempt to counteract the stress imposed on the body through heat exposure and increased T_{core}. Currently, the use of serious games for educational and training purposes in the fire service has focused on incident command with a particular emphasis on strategy and tactical decision making (Backlund et al., 2007, Backlund et al., 2009, Lebram et al., 2009, Larsen et al., 2015). These games do not focus on the individual firefighter's task level activities, which standard operating procedures (SOPs) require that all firefighters know in order to properly function at an emergency scene. The development of a serious game to evaluate decision making at the task level for firefighting will provide a more ecologically valid instrument for assessing cognitive function in firefighters under conditions of exertional heat stress.

This thesis seeks to:

- examine the effects of rising T_{core} on cognitive performance using validated and reliable cognitive tests which are more complex than previous work (Objectives 1 and 2),
- collaborate with game developers to create a serious game module to assess cognitive function under the types of conditions firefighters are likely to encounter (Objective 3), and
- determine whether rising T_{core} affects performance on the serious game (Objective 4).

1.2 Research Objectives and Hypotheses

Objective 1

(1) Determine the effects of exercise-induced heat stress (EIHS) with varying rates of increasing T_{core} on cognitive performance using complex tasks from a computerized neuropsychological testing battery, the Cambridge Neuropsychological Test Automated Battery (CANTAB).

Hypothesis: Dynamic increases in T_{core} *will reveal decrements in cognitive function during exercise-induced heat stress with restoration following active cooling recovery.*

Objective 2

(2) Determine the test-retest reliability and practice effects when utilizing repeated measurements over a short duration with the CANTAB assessment battery.

Hypothesis: The reliability of the CANTAB assessment battery will show consistency with limited practice effects within and between sessions on tests without a strategy component.

Objective 3

(3) Develop a serious game to be used as an assessment tool to evaluate task level activities in firefighting.

Objective 4

(4) Determine if the serious game can measure impairments in cognitive function during EIHS.

Hypothesis: The development of a serious game will reveal decrements in cognitive function with dynamic increases in T_{core} *and be restored following an active cooling recovery protocol.*

CHAPTER 2 - Review of Scientific Literature

This literature review first summarizes the physiology of heat stress, the physiology of thermoregulation and factors affecting heat stress. It then continues to review the nature of injuries suffered by firefighters and the physiological demands of firefighting. Finally, the literature on heat stress and cognitive function as well as the relationship between cognitive function and firefighting is reviewed.

2.1 Physiology of Heat Stress

2.1.1 The Heat Balance Equation

The human body regulates internal temperature around 37°C, which requires the body to balance the processes of heat gain and heat loss. In general, the amount of heat that is produced within and transferred to the body must be balanced through heat loss from the body (Webb et al., 1980). If the amount of heat being generated in the body is greater than the avenue for heat loss, body temperature will increase (Benzinger, 1969). On the other hand, if heat loss is greater than heat production in the body, body temperature will decrease (Magoun et al., 1938). Heat generation within the body results from the metabolic rate which provides energy to perform mechanical work (Benzinger, 1959); however, the body is not 100% efficient with over 70% of energy produced from metabolic reactions converted to heat while the remaining energy is released as heat (Hill, 1938, Barclay, 1996). Heat transfer is generated through conduction, convection, radiation, and evaporation, which when combined with heat generation, results in the level of heat storage (S).

A review by (McLellan et al., 2013) provides the necessary details regarding the heat balance equation and the mechanisms that result in heat gain and heat loss for the individual:

$S = M - W_{ex} \pm (C + K + R) - E_{\text{sk}} + E_{co} - E_{resp} \pm C_{resp}$ (Equation 1.1)

where S (rate of heat storage) is positive for a net heat gain or negative for a net heat loss, and zero ($S = 0$) when the body is in a state of thermal balance. M is the rate of metabolic heat production within the body (representing a source of heat gain) and W_{ex} is energy that has been transformed into external work from some of the total energy produced through metabolism. The heat loss mechanisms provide heat transfer through evaporation of sweat at the skin surface (E_{sk}) and through respiration (E_{resp}). The variables that represent dry heat transfer are convection (C), conduction (K), and radiation (R), which can be avenues for either heat loss or heat gain depending on the magnitude of the temperature in the ambient environment and if contact with surfaces or radiant sources are larger or smaller than the skin temperature. In the case of many emergency service occupations, specifically the focus of the current thesis, firefighting, the addition of personal protective equipment (PPE) can result in heat that has been lost from the evaporation of sweat at the skin surface to become condensed (E_{co}) onto the outer layers of the protective clothing (McLellan et al., 2013).

Heat exchange is expressed in watts, where 1 W = 1 joule per second. Heat production in the human body has been shown to range from 70 to 100 W while resting, 280 to 350 W while walking at a mild pace, and over 1000 W during high intensity exercise (Parsons, 2014). When converted to a relative value taking into account body surface area, the metabolic heat production at rest is approximately 50 $W{\cdot}m^{-2}$ (McLellan et al., 2013).

Dry heat exchange, which refers to radiation, conduction, and convection, is dependent on the thermal gradient within the body as well as between the ambient environment and the body (Hardy, 1934, Hardy et al., 1938). Blood flow is another factor that determines the ability to dissipate heat from the core to the periphery, with greater blow flood increasing the magnitude of conductive and convective heat exchange (Burton, 1939). On the other hand, evaporative heat exchange, referred to as wet heat exchange, transfers approximately 2400 kJ of energy from each litre of sweat evaporated to the environment (Pitts et al., 1944, Dennis et al., 1999). The capacity of evaporative heat loss is determined by the water vapour pressure gradient between the skin surface and the environment (Kerslake, 1972). In order to determine the water vapour pressure of the environment, the ambient air temperature and relative humidity need to be measured. Dry heat exchange is limited in environments where ambient air temperature is close to skin temperature, typically between 35 and 40°C. To maximize evaporative heat exchange, the relative humidity must be low and sweat must be vaporized at the skin due to the negligible heat dissipation from sweat that has dripped or been toweled off from the body (Goldman, 1978, Cheung, 2010). Air flow over the skin surface is another important factor influencing both dry and wet heat transfer, with greater air movement promoting great heat exchange between the body and the surrounding air layer above the skin surface (Nishi, 1981).

Another factor that affects heat balance is clothing; in particular, the thermal resistance and water vapour permeability of the material. Clothing acts as a barrier between the skin and the environment and in the presence of a thermal or water vapour gradient between the two will cause a reduction in heat and moisture transfer. In general, clothing reduces heat loss by trapping air which acts as an insulator. This insulation within the clothing is a measure of thermal resistance, which is the capacity of the clothing layers to prevent heat exchange through conduction and convection. The important properties of the clothing worn by an individual that affects heat and moisture transfer are insulation (i.e. thermal resistance), water vapour and air permeability, surface area of the skin that is covered, number of clothing layers, moisture absorption, condensation, fit, and radiation exchange. These clothing characteristics interact with the environment (temperature, humidity, wind, and solar radiation) as well as human related factors such as sweat gland activity, body position, and body motion (Nunneley, 1989).

When individuals are unclothed, heat exchange can be regulated between the body and the ambient environment directly across the skin. When clothing is worn, air becomes trapped next to the body and provides the primary insulation. The air that becomes trapped next to the body is warmed by the body and consequently reduces conductive and convective heat loss by decreasing the thermal gradient between the skin surface and the environment. The thickness and density of the clothing fabric determines how well air can become trapped between the body and the clothing (McCullough, 1993). Movement of air between the clothing layers impedes thermal insulation when the distance between layers is greater than the dimensions of the boundary layer. This air movement is dependent on wind speed as well as the movement of the individual and local movement of their limbs. Thermal insulation is generally expressed as a single unit, clo, but it is important to note that regional thermal insulation will be different throughout the body based on how much of the specific body part is covered by the clothing as well as the movement of the body part (Wang et al., 2012). Using a thermal manikin, Goldman (1975) has defined the clo value as $1\ \text{clo} = 0.155^{\circ}\text{C}\cdot\text{W}\cdot\text{m}^{-2}$.

When in a clothed state, an air layer is formed directly above the skin and the first layer of clothing forming a microenvironment that now acts as the initial environmental layer for heat exchange from the body to the environment (White et al., 1988, Faff et al., 1989, Sullivan et al., 1992, Holmer et al., 2006). This situation will cause some of the heat exchange through evaporation to occur from the environment and not the individual’s body, further decreasing the ability to maximally lose heat through evaporative processes (Nunneley, 1986, McLellan et al., 1996a). In the presence of multiple clothing layers, as in firefighting, additional microenvironments are formed, each having unique temperature and humidity characteristics, that heat generated by the body’s metabolic functions must pass through before being dissipated and exchanged with the ambient environment (Sullivan et al., 1992). The most effective way to dissipate heat is through evaporation, with maximal evaporative heat dissipation occurring when sweat is directly vapourized at the skin (Nadel et al., 1974). When protective clothing is worn completely, thus encapsulating the individual, the sweat produced on the skin may be absorbed into the clothing layers and become trapped (Kakitsuba et al., 1988). This trapped sweat will cause the clothing layers to become wet and potentially saturated, possibly affecting either the thermal or protective characteristics and altering the rate of heat transfer through the layers (Craig et al., 1974).

Another aspect that can reduce the thermal insulation of clothing is the presence of liquid sweat or water within the clothing layers. This is due to the low thermal resistance (or high thermal conductivity) of water compared to air. The total insulation (I_T) of the protective clothing describes the resistance to the dry heat transfer from the skin to the environment. This value is depicted from the sum of the intrinsic clothing insulation (I_{cl}), which identifies the resistance to heat transfer from the skin to the clothing surface, as well as the resistance of the clothing surface itself (I_a), normalized to the surface area of the body and the additional surface area provided by the clothed body (f_{cl}) (Gonzales, 1987, Gonzalez, 1988).

$I_T = I_{cl} + I_a \,.\, f_{cl}^{-1}$ (equation 1.2)

The ratio of $I_a \cdot I_T^{-1}$ is a dimensionless unit and represents the level of insulation by the clothing garment to impede dry heat transfer from the surface of the skin to the environment, known as Burton's clothing permeation factor, F_{cl} (Nishi, 1981, Gonzalez et al., 1985).

2.1.2 Water Vapour Permeability

The impact of wearing protective clothing includes the ability for the textile materials to transfer water vapour, which is known as water vapour permeability. The measurement of water vapour permeability is a dimensionless value (i_m) utilizing an objective scale ranging from 0 (completely impermeable) to 1 (completely permeable) (Woodcock, 1962). This factor plays a major role in determining heat balance in hot environments due to its impact on evaporative heat loss which is greater than the dry heat loss pathways of radiation, conduction, and convection due to the reduced thermal gradient between the skin and environment. In fact, when air temperature exceeds skin temperature wet heat transfer becomes the only avenue available for heat loss from the body. In addition, a clothing permeation factor, F_{pcl}, defines the level at which clothing reduces evaporative heat loss. It is expressed as a dimensionless ratio that accounts for the water vapour resistance of the air layer around the boundary of the clothing to the water vapour resistance of the entire clothing ensemble (Nishi, 1981, Havenith et al., 1999).

The water vapour permeability (i_m) provides a value for the overall clothing ensemble but a recent investigation by Wang et al. (2012) examined local evaporative resistance using sweating thermal manikins at different air velocities (0.18, 0.48, and 0.78 $m \cdot s^{-1}$) and different walking speeds (0, 0.96 and 1.17 $m \cdot s^{-1}$). The authors reported that walking speed had a more considerable effect on the limbs (thigh and forearm) compared to the torso (back and waist) resulting in different evaporative resistances at localized regions on the body. In addition, the localized boundary air layer should also be taken into account to determine thermal comfort of the individual wearing the clothing ensemble and aid in clothing design (Wang et al., 2012).

2.1.3 Air Permeability

Air permeability is another factor that affects the thermal insulation of PPE through air motion (wind, activity, and natural convection). Previous research has revealed that air permeability is not correlated with the water vapour permeability of the clothing ensemble (Wilbik-Hałgas et al., 2006, Bivainytė et al., 2011). The impact of different wind speeds and movement on thermal insulation has been the focus of many research studies. Gonzalez et al. (2006) exercised participants on a treadmill at a progressive metabolic rate protocol in environmental conditions at a dry bulb temperature of 32°C while wearing five different coveralls. The protocol revealed that air permeability of the clothing was a better predictor of performance when compared with moisture vapour transmission rate. The higher air permeable clothing resulted in higher treadmill speeds and higher metabolic rates compared to the low permeability clothing. Bernard et al. (2010) also demonstrated that an increase in air permeability at ambient dry bulb temperatures of 34°C and 50% relative humidity improved evaporative cooling more so than increasing water vapour permeability. The findings from these studies shed light on the potential for optimizing protective clothing technology to reduce the thermal and cardiovascular strain on the individual and that using the diffusive permeability of a particular fabric will underestimate the level of heat strain experienced (Gonzalez et al., 2006, Bernard et al., 2010). In addition, Havenith et al. (2011) dressed participants in chemical warfare (CW) clothing with differing air permeability characteristics while walking on a treadmill at 4 $km \cdot h^{-1}$ in 36°C, 20% relative humidity, and wind speed of 5 $m \cdot s^{-1}$ and found that with higher air permeability, T_{core}, heart rate (HR), sweat production, and moisture absorption were decreased with a concomitant higher efficiency for sweating. The authors concluded that the lower thermal strain reported reflected the strong correlation between microclimate ventilation from wind speed as well as the pumping effect through bodily movement with air permeability. These data revealed that decreases in thermal strain for military operations was optimally improved through increases in air permeability and not the reduction of material thickness (Havenith et al., 2011).

2.1.4 Multiple Clothing Layers

Many occupations require personnel to wear PPE that reduce heat loss and increase thermal strain. In order to test the thermal properties of PPE, various methods are implemented to determine the prospective heat strain on the individual. The biophysical evaluation of the clothing ensemble is conducted on a guarded hot plate followed by assessment on a thermal manikin (Gonzalez, 1988, Gonzalez et al., 1993). The thermoregulatory model of human skin was developed to measure thermal resistance and water vapour permeability of single and multiple layered textiles (Levine et al., 1998). These textiles are initially placed on a temperature controlled hot plate to simulate the heat transfer between the microclimate, within the layers of the textile, and the external environment. A major advantage of this type of testing is the ability to examine and rank numerous textiles quickly (Endrusick, 1993) but with the limitation that the thermal properties of the textile are not always the same when constructed within a clothing ensemble (Levine et al., 1998). Next, the clothing system is tested using a thermal copper manikin in a controlled ambient environment in order to measure the thermal insulation (clo) and the water vapour permeability (i_m) which provides the heat exchange coefficient (i_m/clo = evaporative resistance) (Levine et al., 1998). Studies involving textiles implement thermal manikins that are capable of simulating a non-sweating or sweating condition (Levine et al., 1998) with the climatic conditions controlled at 27°C and 50% relative humidity (Gagge et al., 1967, ASHRAE, 1993) with at least three different wind speeds (still air, 0.4 to 3 $m \cdot s^{-1}$) to determine the effect of air movement on the thermal properties of the clothing ensemble (Gonzalez et al., 1989).

Research conducted to investigate the effects of clothing insulation and air layers on the body has been performed using an articulated, thermal manikin that can also incorporate body movements and sweating (Bouskill et al., 2002). However, the nature of this testing can be expensive resulting in most manikin testing being conducted on stationary, non-sweating manikins in wind free environments (Bouskill et al., 2002). Measurements in these static conditions may lead to errors as data from moving, articulated, thermal manikins has shown a 50% reduction in thermal insulation from body and wind movement (Holmér et al., 1995) and up to 88% decrease in evaporative resistance (Havenith et al., 1990a) primarily from the increased clothing ventilation.

The clo value provides empirical data to determine the thermal resistance of clothing that supplies information regarding the insulative properties of the material (Watkins, 1984). Gagge et al. (1967) developed the clo value and defined it as the insulation required to maintain comfort and sustain a mean skin temperature of 33°C in room temperature of 21°C, relative humidity less than 50%, wind speed less than 10 $\text{m} \cdot \text{sec}^{-1}$, and metabolic work rate of 50 $\text{kcal} \cdot \text{m}^{-2} \cdot \text{h}^{-1}$. Normal work clothing, which includes light pants and long-sleeved shirt, has a clo value of approximately 1.4 clo (NIOSH, 1986). The outer air layer, bound to the clothing, comprises 0.8 clo of the total value and is reduced through air movement to a value of 0.2 clo (NIOSH, 1986). The number of layers within a clothing ensemble will alter the insulative properties and provide additional air layers which will change the thermal resistance of the clothing.

The multiple clothing layers within the PPE results in sweat that is produced to be transferred between fabric layers that are in close contact, which eventually evaporates from these layers away from the skin's surface (McLellan et al., 1996a, Cain et al., 1998).

The evaporation of sweat from fabric layers reduces the efficiency of the body's cooling process as energy is drawn from the environment in order to evaporate sweat (Cain et al., 1998). The volume of air that is between the skin's surface and the outer layer of protective clothing can be larger than 30 L (Sullivan et al., 1987, Daanen et al., 2005). Havenith (1999) reviewed the dry and wet heat loss associated with wearing protective clothing and indicated that vapour resistance is greater than the insulation of the material only, due to the still air layer that is located between the fabrics and attached to the outer surface. In addition, air movement in the environment will disturb the still air attached to the outer boundary surface as well as potentially penetrate the outer clothing layer affecting the still air within the garment. Movement by the individual wearing the protective equipment can change the thickness of the air layers and also force the exchange of air between the layers and with the environment.

Bouskill et al. (2002) evaluated a one- and three-layer clothing ensemble during various walking (0.37 and 0.77 $m \cdot s^{-1}$) and wind speeds (< 0.2 and 1.0 $m \cdot s^{-1}$) and found that the increases in clothing ventilation reduced intrinsic clothing insulation causing increased heat transfer from the manikin to the external environment. These data have confirmed the previous findings that increases in wind speed and movement in garments increases microclimate ventilation (Nielsen et al., 1985, Lotens et al., 1993) and results in lower T_{core}, skin temperature (T_{sk}), and HR in clothing with higher levels of air permeability (Havenith et al., 2011). The ventilation capacity of clothing varies from zero, in a completely encapsulated ensemble, to 1 $L \cdot min^{-1}$ for low ventilation, to 60 $L \cdot min^{-1}$ for medium ventilation, and upwards of 300 $L \cdot min^{-1}$ at high levels of ventilation (Parsons, 2014). Additional factors that affect insulative properties of the clothing ensemble are fit and body movements. Walking causes the clothing layers to move and creates a wind effect on the outer air layer resulting in a decrease in clothing insulation (Havenith et al., 1990b).

Clothing ensembles with high insulation values are capable of trapping more air within the layers with the resulting intrinsic insulation being affected by movement and wind speed (Havenith et al., 1990b). While exercising in hot environments, air that is completely saturated with water vapour that has been warmed to skin temperature can be transferred from the skin into the ambient air through ventilation in the clothing. Air that is at skin temperature (35°C) and 100% saturated with water vapour contains approximately 140 joules of heat per litre, whereas 1 litre of air in the environment at 30°C and 60% saturated with water vapour contains approximately 80 joules of heat. In terms of the amount of heat exchange that can occur from this mechanism, 60 joules of heat can be lost to the environment from these values (Parsons, 2014). In addition, tight fit clothing shows reductions in insulation of 6 to 31% compared to loose fit clothing (Havenith et al., 1990b). Posture also plays a role in determining clothing insulation with sitting compressing the trapped air layers causing a decrease in intrinsic insulation and a concomitant increase in surface air layer insulation (Havenith et al., 1990b). Under a no wind environment, thermal insulation is maximal when the air gap between the skin and clothing layer is 1 cm thick whereas with wind movement this value decreases to 0.6 cm (Chen et al., 2004).

The thermal insulation of the clothing ensemble is not the only mitigating factor affecting physiological strain on the wearer as the additional weight of the PPE increases metabolism and subsequently increases metabolic heat production (Smolander et al., 1984, Aoyagi et al., 1994). However, the additional weight is not the sole contributor to this increased metabolic rate. Wearing a variety of PPE with different clothing masses and composition of materials has shown an increase in metabolic rate of 2.4 to 20.9% with more than half of the increase being attributed to a factor other than ensemble weight (Patton et al., 1995, Dorman et al., 2009). Teitlebaum et al. (1972) investigated the effect of wearing a five layer clothing ensemble when compared to walking while carrying an equivalent weight (11.2 kg) and found that metabolic rate was increased by 16% primarily due to the increased friction from the clothing. The friction also affects movement creating a hobbling effect and can be attributed to specific characteristics of the clothing including the weight, fabric, and thickness (Teitlebaum et al., 1972).

The development of sweat on the skin's surface may become absorbed into the PPE making the layers wet while altering the thermal and protective characteristics of the PPE and ultimately affecting heat transfer (Craig, 1972, Kakitsuba et al., 1988). Chen et al. (2003) examined twelve garments with differing insulative properties and determined that in a heavy versus low sweating condition (as measured on a thermal manikin), thermal insulation decreases 2 to 8% due to increasing moisture absorption. The sweat absorption appears to increase with the thickness of the clothing layer resulting in the excess moisture to cause a chilling effect following exercise in which the evaporative heat loss is maintained while thermal insulation is reduced (Chen et al., 2003). Maximal evaporative heat dissipation occurs at the skin's surface when sweat is evaporated and heat is extracted from the skin (Nadel, 1978). Evaporation that occurs away from the skin decreases the evaporative heat loss efficiency and results in heat of evaporation being extracted from the environment (McLellan et al., 1996a). Furthermore, Havenith et al.

(2013) clearly demonstrated that the heat of evaporation was significantly lower when the evaporation site is within the clothing layers compared to the assumed value (2.430 $J \cdot g^{-1}$ at 30°C) required for the thermal manikin at the surface of the skin. The heat requirement was shown to be dependent on the distance between the skin and the site of evaporation as well as the number of overlying and underlying layers (Havenith et al., 2013).

The other variable in the heat balance equation that affects the properties of heat exchange is radiation. This type of heat transfer can be absorbed, reflected, and partially transmitted by the clothing materials (Lotens, 1993) with dark colours absorbing more heat than lighter colours (Shkolnik et al., 1980). The peak wavelength of the radiant object varies from 0.5 mu for sunlight (source temperature 5720 K) up to about 10 mu for radiant sources at room temperature (Lotens, 1993). The material absorbing the radiant energy increases its temperature and also increases the radiation that is emitted from the material (Lotens, 1993). Clothing ensembles that include multiple layers absorb part of the radiation in the outer layer and transmit the rest onto the underclothing where it is absorbed and partly reflected. This rebound effect results in heat being stored in various layers within the clothing ensemble (Lotens, 1993). This results in radiation altering the heat loss mechanisms through convection and evaporation and may be affected by the colour of the garment (Lotens, 1993). Nielsen (1990) found that exposure to 742 $W \cdot m^{-2}$ of additional radiation added 90 to 125 W to the heat load while wearing dark or light clothing, respectively. The difference in heat load between the two garments was 35 W accounting for a 0.1°C increase in T_{core} and 0.7°C increase in T_{sk} including 73 $g \cdot h^{-1}$ of sweat evaporation. The most important factors affecting the clothing system are the reflection coefficient for radiation of the outer clothing layer and the wind speed (Lotens, 1993).

2.1.5 Heat Acclimation

The microenvironment within the PPE is hot and wet (McLellan et al., 1996a) reducing the benefits of heat acclimation (Nadel, 1978) when encapsulated (Aoyagi et al., 1994, 1995). Acclimation to a hot and wet environment does not show the same physiological adaptations as observed following hot and dry acclimation with the primary benefit being a lower resting T_{core} (Aoyagi et al., 1995, Buono et al., 1998, Cheung et al., 1998a). Studies utilizing PPE to determine the effects of environment on heat acclimation have shown that acclimation in a hot, humid environment reveal greater benefits than in a hot, dry environment (Aoyagi et al., 1994, 1995, McLellan et al., 1996b). A number of studies have been conducted on the effects of heat acclimation while wearing military nuclear, biological, and chemical (NBC) protective clothing (Aoyagi et al., 1994, 1995, McLellan et al., 1996b). The thermal resistance and water vapour permeability of the military chemical and biological protective equipment has been shown to be 1.90 clo and i_m of 0.27 (McLellan, 2008). These ensembles are similar to firefighting PPE which has been shown to have a thermal insulation value of 1.55 clo and i_m of 0.27 (Selkirk et al., 2004b).

The physiological benefits of heat acclimation while wearing normal athletic clothing do not provide the same benefits when fully encapsulated in protective clothing. Aoyagi et al. (1994) showed that following eight weeks of aerobic training at 60-80% VO_{2peak} for 30-45-min per day plus six days of heat acclimation (45-55% VO_{2peak} for 60 min per day at 40 °C and 30% relative humidity) pre and post-heat tolerance times were not changed despite the increased sweat rate (0.14 – 0.23 $g \cdot h^{-1}$). However, when implementing a lower work rate (23% of VO_{2peak}) for the heat stress test before and after 6 or 12 days of heat acclimation, Aoyagi et al. (1995) reported a decrease in T_{core}, T_{sk}, and HR while wearing NBC clothing with an increase in tolerance time of 12 to 15-min. In addition, the longer duration (12 days) heat acclimation did not show any additional benefits while wearing NBC clothing mainly due to the hotter and wetter microenvironment within the clothing (Kakitsuba et al., 1988, Sullivan et al., 1992). The increase in tolerance time at the lower work rate may be due to a larger difference between T_{core} and T_{sk} based on the longer tolerance times providing a larger proportion of sweat to be evaporated (Aoyagi et al., 1995). In a follow-up study, McLellan et al. (1996b) examined the effects of heat acclimation in a hot and dry (40°C and 30% relative humidity) compared to a hot and wet (40°C and 30% relative humidity while wearing NBC clothing) environment exercising for 60-min at 45-55% VO_{2peak} for 12 days. The authors reported that it took longer for T_{core} to increase 1.0°C following the hot and wet acclimation protocol during a heat tolerance test in a hot and dry environment (40°C and 30% relative humidity, wind speed < 0.1 $m \cdot s^{-1}$) when compared to a hot and dry acclimation protocol or control group. In addition, the rate of sweat evaporation was increased along with the percent increase in tolerance time following acclimation in a hot and wet environment (McLellan et al., 1996b). Following twelve days of heat acclimation, wearing the NBC clothing increased tolerance times by 27% from 104 to 130 min compared to wearing traditional combat clothing in a hot and dry environment which improved by 11% from 109 to 120 min.

Following up on previous work, Cheung et al. (1998a) sought to determine the effects of aerobic fitness, short term heat acclimation, and hydration on tolerance times while wearing NBC clothing during light exercise in 40°C and 30% relative humidity. The authors reported that the benefits of hot and humid heat acclimation to the microenvironment within the protective clothing were marginal when fluid was administered during the heat-tolerance test (Cheung et al., 1998a). The results from previous studies in this laboratory implemented experimental protocols that utilized fluid restriction, which might typically be encountered in a military environment (Aoyagi et al., 1994, 1995, McLellan et al., 1996b). The addition of fluid intake in heat stress research has been shown to increase tolerance time while wearing protective clothing during exercise in the heat (Cheung et al., 1998b). Therefore, the lack of benefits from acclimation may have been due to the consumption of fluid throughout the heat tolerance test which could have increased tolerance times in the heat during the pre-acclimation test to near maximal levels. This would have caused minimal improvements from the subsequent heat acclimation protocol (McLellan et al., 2013). Overall, this would reinforce the importance of fluid replacement throughout conditions of uncompensable heat stress (UHS) regardless of fitness or acclimation status (McLellan et al., 2013). In these encapsulated clothing conditions, even light or moderate workloads can put an individual in a state of UHS where T_{core} will continue to rise unless the exercise intensity is reduced or seceded and/or the protective clothing ensemble is removed (Cheung et al., 2000, Selkirk et al., 2004a, Selkirk et al., 2004b).

Heat acclimation in a hot and dry environment would appear to provide different physiological adaptations compared to humid heat conditions (Périard et al., 2015). An early investigation by Fox et al. (1967) compared heat acclimation in dry and humid conditions using controlled hyperthermia (T_{core} of approximately 38.2°C) and found that the ability of individuals to maintain higher sweat rates was improved by a reduction of hidromeiosis. Although this adaptation alone may not be sufficient, it is critical that the rate at which sweat evaporates is at an adequate level to achieve thermal balance (Périard et al., 2015).

The mechanisms eliciting substantial evaporative cooling rate in humid conditions requiring the body to overcome the high water vapour pressure of the ambient environment have been suggested in a review by Périard et al. (2015). The authors suggested that this is achieved by maintaining a higher vapour pressure at the skin's surface (through a higher T_{sk}) or larger skin wettedness compared to the requirements in a dry environment. The ability to achieve a higher T_{sk} must be caused by greater blood flow to the skin resulting in greater thermal conductance. Therefore, it can be expected that greater circulatory adaptations, while reducing circulatory strain, will elicit higher skin blood flow in humid compared to dry heat conditions (Périard et al., 2015).

It may also be expected that heat acclimation in hot and humid conditions will result in more efficient sweat evaporation at the level of the skin. Previous research has shown that humid heat acclimation results in an increase in the relative proportion of sweat to be produced at the limbs (Höfler, 1968, Shvartz et al., 1979, Regan et al., 1996). However, Patterson et al. (2004) examined local sweat rates in eleven males acclimated over sixteen exposures with T_{core} maintained at 38.5°C while cycling for 90-min per day. Participants were tested on day one, eight, and twenty-two in 39.8°C and 59.2% relative humidity which revealed that whole body sweat rate increased from 0.87 to 1.16 $L \cdot h^{-1}$

with an increase in local sweat rate at the forearm (117%) exceeding values at the forehead (47%) and thigh (42%). In addition, the increase in local sweat rate at the chest (106%) exceeded the sweat rate at the thigh (Patterson et al., 2004). These results reveal that heat acclimation in a hot and humid environment does not elicit effective sweat redistribution but does alter interregional differences that increase local sweat rate (Patterson et al., 2004).

2.1.6 Physiological Effects of Heat Stress

As reviewed earlier in this chapter, protective clothing is required to shield the individual from the environmental hazards but increases the thermoregulatory challenge through increased metabolic heat production (Givoni et al., 1972, Sköldström, 1987) and decreasing evaporative processes through diminishing water vapour permeability through the clothing layers (Nunneley, 1989). In terms of the brain, Nielsen et al. (2001) examined participants exercising at 60% of aerobic power in 40°C and 19°C environments and found that the ratio of low-frequency (α) to high-frequency (β) waves was increased. This change in brain activity was accompanied by increases in rating of perceived exertion (RPE) with the best predictor of RPE being a reduced electroencephalographic (EEG) frequency in the brain's frontal cortex (Nielsen et al., 2001). Although the specific alterations in EEG and its functional effects are not completely known, these changes may relate to the decrease in cerebral blood flow velocity during long term submaximal exercise (Nybo, 2007). This decrease may be controlled by cerebral vasoconstriction due to a reduction in arterial carbon dioxide through hyperventilation. Nybo (2012) determined that despite this reduction in cerebral blood flow there was approximately a 7% increase in the cerebral metabolic rate of oxygen. Furthermore, exercise in the heat eliciting an increase in T_{core} of 1.5°C produces an approximate increase of 23% in resting metabolic rate including increases in metabolic brain activity in certain areas such as the cerebellum and hypothalamus (Nunneley et al., 2002). These increases in specific regions of the brain are associated with decreases in other areas, which may stress the carbohydrate supply and glycogen depletion of the brain potentially facilitating fatigue during hyperthermia (Nybo, 2007).

One of the key immunological markers that is associated with heat stress is the production of a variety of heat shock proteins (HSPs), which are classified based on their molecular weight (e.g. HSP 70, HSP 90) and have various physiological functions (Kregel, 2002). The role of HSPs has been thoroughly examined to determine their specific functions, regulation, and cellular localization (Lindquist et al., 1988, Welch, 1992, Benjamin et al., 1998). HSPs were first reported by Ritossa (1962) who found that heat shock to *Drosophila* resulted in chromosomal puffs on salivary glands. Despite being given the term based on the response to heat stress, HSPs are synthesized in response to other stressors including light-induced damage to the retina (Barbe et al., 1988), ischemic reperfusion of the heart (Currie et al., 1988, Meerson et al., 1992), liver (Buchman et al., 1990, Bernelli-Zazzera et al., 1992), and kidney (Van Why et al., 1992) in animal models. In addition, they have been shown to be involved in many regulatory pathways and act as molecular chaperones for cellular proteins (Lindquist et al., 1988, Welch, 1992, Moseley, 1997).

The main HSPs are classified depending on their size, ranging from 15 to 110 kDa (Benjamin et al., 1998), and their specific location within the cell (cytosol, nucleus, endoplasmic reticulum, and mitochondria) varies depending on the particular HSP (Schlesinger, 1990, Welch, 1992, Hightower et al., 1997). One of the first physiological functions discovered was the ability to become resistant to heat stress following a prior sublethal exposure to heat, known as thermotolerance (Landry et al., 1982, Li et al., 1983, Mizzen et al., 1988). Although the specific mechanisms of how HSPs manage thermotolerance are not well understood, it appears they play a role in processing stress-denatured proteins (Mizzen et al., 1988), the management of protein fragments resulting from stress-induced translational arrest (Chirico et al., 1988, Palleros et al., 1991), maintaining structural proteins including actin (Lavoie et al., 1993), a chaperone function for cellular proteins across cell membranes (Chirico et al., 1988, Deshaies et al., 1988), and steroid hormone receptor regulation (Bohen et al., 1994). In general, HSPs perform a role in thermotolerance under heat stress and can inhibit programmed cell death, or apoptosis (Garrido et al., 1997, Jones et al., 2004).

In particular, HSP 72 has been shown to improve heat tolerance through cytoprotective effects through intracellular accumulation (Fehrenbach et al., 2000, Kregel, 2002). These cytoprotective effects include reduced incidence of apoptosis (Song et al., 2014) and ischemic-reperfusion injury (Currie et al., 1988, Buchman et al., 1990, Bernelli-Zazzera et al., 1992, Meerson et al., 1992, Van Why et al., 1992) while extracellular HSPs have been associated with mediating immunological functions (Schmitt et al., 2007).

One of the physiological responses to heat stress includes a reduction in splanchnic blood flow (Rowell et al., 1970, Rowell et al., 1971) to provide adequate perfusion of the skin for heat loss (Sakurada et al., 1998) which has been associated with splanchnic region ischemia during whole body heating (Hall et al., 1999). The reduction of blood flow and ischemia to this region has also been associated with the release of HSP 72 into the circulation (Febbraio et al., 2002). Heat stress has been shown to reduce splanchnic blood flow by approximately 40% with a rise in T_{core} from 37 to 41.5°C (Hall et al., 2001) producing cellular hypoxia in the liver and intestine (Hall et al., 1999). This severe heat stress can produce intestinal injury leading to splanchnic endotoxemia (Hall et al., 2001) through intestinal barrier dysfunction increasing the permeability to endotoxin (Lambert, 2008).

Training status has been shown to improve heat tolerance with trained individuals capable of tolerating $T_{core} \leq 40.0$°C during UHS compared to untrained sedentary individuals terminating exercise during exertional heat stress at T_{core} levels close to 39.0°C (Selkirk et al., 2001). Plasma endotoxin concentrations have been reported to be greater in untrained compared to trained individuals at exhaustion following treadmill exercise at 4.5 $km \cdot h^{-1}$ and 2% grade exposed to 40°C and 30% relative humidity at T_{core} values below 40.0°C (Selkirk et al., 2008). The increased heat tolerance in trained individuals may be linked to the maintenance of gastrointestinal integrity through an increase in HSP 72 induction (Moseley et al., 1994) and increased resistance to endotoxin (Ryan et al., 1992).

The rate of heat storage has provided a role for temperature in a rat model to induce an increased accumulation of HSP 70 following a high rate of body heating ($0.166°C \cdot min^{-1}$) compared to a low rate of body heating ($0.045°C \cdot min^{-1}$) in the small intestine, liver, and kidney up to a colonic temperature of 42.0°C (Flanagan et al., 1995). In contrast, human subjects did not show a difference in post-exercise extracellular HSP

72 accumulation following treadmill walking (at approximately 50% VO_{2peak}) to reach a T_{core} of 38.5°C in conditions of 42°C and 30% relative humidity using a high (1.04 ± 0.10 $W \cdot m^{-2}.min^{-1}$) or low (0.54 ± 0.09 $W \cdot m^{-2}.min^{-1}$) rate of heat storage protocol (Amorim et al., 2008). The authors concluded that, for extracellular HSP 72, the increased accumulation following exercise is attributed to the T_{core} attained and not due to the rate of heat storage.

The expression of two HSPs (HSP 27 and HSP 70) are most notable in the brain because they are highly induced in glial cells and neurons and have been reported to be increased in individuals transitioning between normal aging and mild cognitive impairment (Lee et al., 2008, Di Domenico et al., 2010). Previous research has demonstrated the synthesis of HSP 72 from specific cells within the brain when hyperthermia is induced (Walters et al., 1998, Leoni et al., 2000). Lancaster et al. (2004) had participants perform steady-state exercise on a cycle ergometer for 180 min at 60% VO_{2peak} and found that the brain is capable of releasing HSP 72 independent of cell necrosis due to the absence of changes in cerebral blood flow (Lancaster et al., 2004), energy depletion or hypoxia (Nybo et al., 2003). Provided that prolonged exercise at 50% VO_{2peak} for 45 min causes an elevation in brain temperature (Nybo et al., 2002b) with hyperthermia resulting in the synthesis of HSP 72 within specific cells of the brain (Walters et al., 1998, Leoni et al., 2000), the approximately 0.2°C increase in brain temperature compared to T_{core} (Nybo et al., 2002b) may be a factor to explain the increased HSP 72 released from the brain following exercise (Lancaster et al., 2004). In addition, the HSP 72 released from glial cells and taken up by neuronal cells can improve neuronal stress tolerance (Campisi et al., 2003). Increased levels of HSP 70 at rest have been associated with the conversion from normal aging to middle cognitive impairment with specific decrements in language and executive functions (Son et al., 2015). However, the specific role of HSPs during exertional heat stress and their potential cytoprotective effects on cognitive function in healthy individuals has yet to be elucidated.

2.2 Line of duty injuries and casualties in firefighting

Firefighting tasks require firefighters to exert increased levels of cardiovascular strain (Gledhill et al., 1992, Williams-Bell et al., 2010a) with elevated risks of injuries on the fire ground (Duncan et al., 2014). Between 2005 and 2009, there was an estimated annual average of 80,000 injuries in the fire service in the United States (Karter et al., 2010) with 38,660 occurring on the fire ground (Karter, 2012). Of the 38,660 fire ground injuries, 27,920 were classified as minor and 10,740 as being moderate or severe injuries (Karter, 2012). The top four reported injuries classified as minor, on an average annual basis, included strain or sprain (6,880 injuries or 25%), pain only (3,215 injuries or 12%), thermal burns only (2,885 injuries or 10%), and cut or laceration (2,285 injuries or 85) (Karter, 2012). For those injuries classified as moderate or severe, the top three reported included strains or sprain (3,705 injuries or 34%), thermal burn (1,090 injuries or 10%), and pain only (985 injuries or 9%) (Karter, 2012). Activities related to fire suppression accounted for 51% of the minor injuries and 51% of the moderate and severe injuries. Overexertion or strain was determined to account for approximately 2,490 injuries or 23% of all moderate and severe injuries (Karter, 2012). Despite the fact that fires are only a small portion of the calls attended to by firefighters, approximately 23 to 25 firefighters are injured per every 1,000 fires, whereas for every 1,000 non-fire emergencies the incidence is only 0.6 to 0.7 injuries (Karter et al., 2010).

The occurrence of structural fires based on time of day was determined to be 33.5% between noon and 6:00 p.m., 31.2% between 6:00 p.m. and midnight, and 14.9% between midnight and 6:00 a.m (Karter, 2012). When injury rates are taken into consideration, structural fires between noon and 6:00 p.m. accounted for 27.4% of fireground injuries; however, of major interest are the statistics that even though only 14.9% of fires occurred between midnight and 6:00 a.m., this time period accounted for 25.2% of all fire ground injuries, with one of the suspected causes being lowered alertness levels in firefighters during the overnight hours (Karter, 2012). Although not focused entirely on the fire service, Dembe et al. (2005) analyzed 13 years of injury data in the United States and determined that working at least 12 h per day was associated with a 37% increase in hazard rate relative to shorter work days. Despite many fire services implementing 24 h work shifts, research is limited on the incidence of occupational injuries during these extended shifts.

Fatalities in the fire service are also a major concern for firefighters as data has shown that, in 2001, approximately 5.7 firefighters lost their lives per 100,000 structure fires (Fahy et al., 2002), whereas from 2008 to 2012 the incidence was reduced to 2.9 deaths per 100,000 structure fires (Fahy et al., 2014). Of the 1,006 firefighter fatalities between 1995 and 2004, approximately 45% were due to cardiovascular events (Smith, 2011). Based on data from the National Fire Protection Agency (NFPA) between 1990 and 2008, heart attacks greatly outweigh burns and asphyxiations as the major cause of death in the fire service (Smith, 2011). Despite the decrease in the overall number of fire ground injuries in the United States in the past two decades, fire ground injury rates per 1,000 fires has remained consistent from 1981 to 2010 (Karter et al., 2011). This trend has continued to occur despite advancements in equipment design, clothing materials, training, and a greater emphasis on reducing injuries and fatalities (Smith, 2011).

Research examining fatalities related to coronary heart disease has reported associations with various firefighting job tasks including suppressing a fire (32.1%), returning from an alarm (17.4%), responding to an alarm (13.4%), physical training (12.5%), responding to non-fire emergencies (9.4%), and performing non-emergency duties (15.4%) (Kales et al., 2007). The odds of death during emergencies were 12.1 to 136 times greater during fire suppression activities, 2.8 to 14.1 times greater during alarm response, and 2.2 to 10.5 times greater when returning from an alarm compared with the odds during non-emergency related coronary heart disease deaths (Kales et al., 2007).

Firefighters face extreme dangers while performing their job including exposure to toxic fumes, dangerous products of combustion, high radiant heat loads, and situations that result in an extremely chaotic work environment (Smith, 2011). The National Institute for Occupational Safety and Health (NIOSH) released a report in 1992 outlining the death of a firefighter performing wildland firefighting activities in a hot environment in September 1990. The firefighter was wearing full PPE and performing activities which included advancing a booster line and fire suppression for over an hour in an ambient temperature of greater than 35°C. The report concluded that it was possible the firefighter became disoriented and the official cause of death was determined to be heat stroke (Shults et al., 1992).

Although it is difficult to quantify the effects of decision making at a fire scene and the potential adverse incidents that may occur due to incorrect decisions based on exposure to increased thermal strain, the injury data reviewed provides further insight in to the potential injuries and fatalities that may occur from heat exposure.

2.3 Physiological Demands of Firefighting

2.3.1. Metabolic Demands of Firefighting

The ability to quantify the physiological demands of critical firefighting tasks has evolved tremendously over the past four decades. Evaluating these demands requires the capability to measure the primary indicators of physical demand: HR and VO_2. Furthermore, other physiological characteristics have been determined to be predominantly required for firefighting tasks including increased levels of muscular strength and endurance, aerobic and anaerobic power, as well as motor abilities, such as agility, manual dexterity, balance, and flexibility (Gledhill et al., 1992).

Initially, measuring HR responses during live firefighting to predict VO_2 (Sothmann et al., 1991, Sothmann et al., 1992) or using the Douglas bag method (Lemon et al., 1977, Duncan et al., 1979) during fire simulation scenarios were the safest and most practical indicators of the physical demands placed upon firefighters. Studies have shown that within the first minute following a fire alarm, firefighters can increase their heart rate between 47 bpm to 61 bpm from a resting level (Barnard et al., 1975, Kuorinka et al., 1981), up to a level of 195 bpm within the first 5-min of a fire (Barnard et al., 1975) and greater than 160 bpm for 90-min (Barnard et al., 1975).

Other studies have also attempted to determine the average metabolic cost of firefighting while determining a minimum aerobic power. Research examining the average VO_2 of firefighting activities have reported values ranging from 1.9 L/min (Kilbom, 1980), 26.1 $mL\cdot kg\cdot min^{-1}$ (2.2 $L\cdot min^{-1}$) (Lemon et al., 1977), 30.3 mL/kg/min (Sothmann et al., 1990) to 33.9 $mL\cdot kg\cdot min^{-1}$ (2.75 $L\cdot min^{-1}$) (Holmer et al., 2007) with minimum VO_{2peak} requirements of 33.5 $mL\cdot kg\cdot min^{-1}$ (Sothmann et al., 1990), 35.6 – 38.2 $mL\cdot kg\cdot min^{-1}$ (2.8 – 3.0 $L\cdot min^{-1}$) (Kilbom, 1980), greater than 40 $mL\cdot kg\cdot min^{-1}$ (Lemon et al., 1977), 42 $mL\cdot kg\cdot min^{-1}$ (Davis et al., 1982), and 45 $mL\cdot kg\cdot min^{-1}$ (Gledhill et al., 1992).

These previous studies have effectively determined the average VO_2 during simulated firefighting tasks but there are limitations when applying these minimum requirements to the general recruit population. The majority of the studies suggesting a minimum VO_{2peak} analyzed average maximal VO_2 from relatively small sample sizes of all male subjects. As well, controlling the work rate of critical firefighting tasks does not come without major difficulty. The individual’s self-determined working pace may result in a variety of work rates and energy expenditures during simulated firefighting tasks. In the 21st century, more female recruits are being hired representing approximately 3% of the work force in the United States (Hulett et al., 2008) with gender being an important factor related to the epidemiology and task performance of firefighter (Sinden et al., 2012). Previous research has shown that females demonstrate lower performance scores compared to males on physical performance tests (Misner et al., 1987). In addition, studies reveal that females consistently differ on cardio-pulmonary, muscular strength and endurance, and firefighting task performance when compared to males (Sheaff, 2009, Williams-Bell et al., 2009).

Despite the considerable focus on increased HR and VO_2 during actual and simulated firefighting scenarios, work performance during these tasks requires a large amount of anaerobic energy expenditure (Davis et al., 1987, Williams-Bell et al., 2009, Williams-Bell et al., 2010a). Using VO_2 as a measure of energy cost requires the assumption that the majority of energy is being supplied through aerobic sources (Lemon et al., 1977). However, in most firefighting tasks, anaerobic metabolism is a major contributor possibly accounting for more than 50% of the energy required (Lemon et al., 1977). Of the four firefighting tasks (aerial ladder climb, victim rescue, hose drag, ladder raise) examined by Lemon et al. (1977), average respiratory exchange ratio (RER) values ranged from 0.97 to 1.07, possibly indicating a high anaerobic component. Furthermore, Gledhill et al. (1992) collected blood samples 5-min following completion of a series of firefighting tasks and revealed that peak lactate concentrations were in the range of 6 to 13 mmol/L. Furthermore, Williams-Bell et al. (2009) examined the physiological demands of the Candidate Physical Ability Test (CPAT), a pre-employment screening test, and reported average RER values during the 8-min and 32 s circuit of 1.02 in males and 0.97 in females. In addition, stair climbing up to a mean of 20 flights while wearing PPE (9.2 kg), self-contained breathing apparatus (SCBA; 9.5 kg), and carrying a high rise pack (18 kg) revealed an average RER of 1.10 (Williams-Bell et al., 2010a). A subsequent scenario involving a search and rescue simulation on the fifth floor of a high rise building indicated elevated levels of anaerobic metabolism based on an average RER of 1.12 (Williams-Bell et al., 2010a). The metabolic demands reported by earlier studies (Lemon et al., 1977, Davis et al., 1987, Gledhill et al., 1992, Williams-Bell et al., 2009, Williams-Bell et al., 2010a) demonstrate the increased workloads required of firefighters when performing job tasks; however, identifying which factors (protective clothing, SCBA, heat stress) contribute the most to the elevated physical demands has been the focus of numerous research studies over the past 30 years.

2.3.2 Physiological Effects of Personal Protective Equipment

Firefighters are required to wear standard-issue protective clothing (weighing approximately 10 – 15 kg) to mitigate the potential risks to the human body of burns and a SCBA to protect against toxic fumes while being exposed to live fires and burning materials (Prezant et al., 1999, Prezant et al., 2000). Studies have reported ambient temperatures ranging from 38°C to 93.3°C (Faff & Tutak, 1989; Smith, Petruzzello, Kramer, & Misner, 1996) and possibly exceeding 200°C (Baker, Grice, Roby, & Matthews, 2000). As previously reviewed, this clothing ensemble completely covers the firefighter’s body, including encapsulating the head, impairing heat transfer between the body and the ambient environment and prohibiting adequate heat loss (White et al., 1988, Faff et al., 1989, Holmer et al., 2006).

The firefighter PPE also includes the use of a SCBA, typically weighing 10 to 12 kg, predominantly situated on the back of the individual. The total combined weight of the protective clothing and SCBA is approximately 20 – 27 kg; however, at a typical emergency scene, firefighters will also carry various tools or other equipment to perform their activities appropriately which could add an additional 18 kg or more (Williams-Bell et al., 2010a, Williams-Bell et al., 2010b). Current tools and equipment being incorporated by a large urban fire service include chains for stabilizing automobiles during auto extrication tasks (approximately 59 kg), hydraulic generators (approximately 45 kg), tool boxes including various equipment stored inside (approximately 13 to 36 kg), and auto extrication tools (approximately 18 kg). Based on this information regarding the mass of common equipment, it can be seen that some tools and equipment weigh even more than the protective clothing and SCBA ensemble, further increasing the metabolic work associated with performing activities utilizing these tools (Cheung et al., 2010).

Baker et al. (2000) examined the physiological responses of wearing PPE during exercise on a treadmill at 7 $km \cdot h^{-1}$ and reported that HR was increased by 25 bpm (171 bpm vs 146 bpm) and VO_2 was increased to 74% VO_{2peak} (39.9 $mL \cdot kg \cdot min^{-1}$) versus 66% VO_{2peak} (36.1 $mL \cdot kg \cdot min^{-1}$) when compared to wearing a regular sports ensemble in a thermoneutral environment. In addition to wearing PPE, firefighters are required to protect themselves from smoke and other toxins through wearing a SCBA. The SCBA is a pressure-demand respirator that reduces inspired resistance and creates additional protection against toxins in the external environment through the positive pressure properties within the face mask (Raven et al., 1982). Initial research by Davis et al. (1975) found that HR and VO_2 were increased by 33% while wearing PPE and SCBA during treadmill walking when compared to an equivalent work rate in athletic clothing. Additional research has examined the effects of wearing PPE and SCBA on work performance times and reported a decrease of approximately 20% (Raven et al., 1977, Manning et al., 1983). Two decades later, Louhevaara et al. (1995) had twelve participants perform maximal treadmill exercise with and without PPE and SCBA and determined that the decrease in maximal working time and walking speed averaged 25%. At maximal exercise, respiratory (expired ventilation, absolute VO_2, RER) and cardiovascular (HR) measures revealed no differences; however, the full standard issued face mask was not utilized and may account for the lack of differences in gas exchange variables (Louhevaara et al., 1995). The authors concluded that the decrease in performance was attributed to the extra mass of the PPE and SCBA.

Examining the respiratory effects of wearing the SCBA compared to a condition without the use of the SCBA, previous work has shown during light and moderate submaximal exercise, expired ventilation was reduced with an increased VO_2 at the same work intensity (Louhevaara et al., 1984, Louhevaara et al., 1985, Louhevaara et al., 1986, Wilson et al., 1989). In addition, at heavy exercise expired minute ventilation increased by 8.1 L to 10.1 $L \cdot min^{-1}$ with a concomitant increase in VO_2 of 0.54 to 0.8 $L \cdot min^{-1}$ (Louhevaara et al., 1984, Louhevaara et al., 1985, Louhevaara et al., 1986). Tidal volume was decreased while wearing the SCBA during all exercise intensities indicating that the increase in ventilation during heavy exercise was due to an increase in breathing frequency associated with shorter inspiratory and expiratory times (Louhevaara et al., 1985). These changes in breathing pattern may be the result of the shoulder harness of the heavy SCBA impairing efficient thoracic motion and preventing the ability to move freely (Louhevaara et al., 1985).

In contrast, Wilson et al. (1989) observed during heavy and maximal exercise intensities, expired minute ventilation was not different yet there was an increase in VO_2 when compared to the control condition. Furthermore, breathing frequency was decreased in the SCBA condition but was offset by a greater tidal volume resulting in expired ventilation to be maintained at maximal exercise. The authors suggest an increased work of breathing while wearing the SCBA during exercise based on the peak expired pressure accompanied by a decreased expiratory flow (Wilson et al., 1989).

The differences observed by Louhevaara et al. (1985) and Wilson et al. (1989) may be attributed to the different exercise protocols implemented by the researchers. Louhevaara et al. (1985) conducted steady-state exercise with five minute stages at 25, 40, and 57% of the participant's VO_{2peak}, whereas Wilson et al. (1989) utilized an incremental treadmill ramp protocol to exhaustion by increasing grade 0.5% every 12 s. The differences in exercise protocols implemented in these two studies may provide an explanation for the different findings reported in the respiratory variables.

Since the initial research on the physiological responses of wearing PPE and SCBA, manufacturers have modified many aspects of the equipment in order to increase protection and improve performance. Eves et al. (2005) conducted four maximal graded exercise tests on twelve male participants while wearing the full SCBA, the SCBA face mask only, carrying the SCBA but breathing through a low resistance breathing valve, and the low resistance breathing valve only. The data indicated that wearing the SCBA while breathing through a low resistance breathing valve reduced maximal oxygen uptake by 5% while wearing the full SCBA or breathing through the SCBA face mask alone reduced VO_{2peak} by approximately 15% (Eves et al., 2005). These results were different than those of Louhevaara et al. (1985) as submaximal exercise induced no change in ventilation, which may be attributed to the newer, more advanced SCBA model utilized by Eves et al. (2005). The authors concluded that SCBA use reduced VO_{2peak} by limiting expired minute ventilation, but that this observation was secondary to the increased expiratory breathing resistance caused by the use of the SCBA regulator (Eves et al., 2005). However, the authors suggested that these limitations do not appear to be significant below an expired minute ventilation of 110 $L \cdot min^{-1}$ and should not have a significant effect on firefighting operations which are assumed to require an expired minute ventilation of 90 $L \cdot min^{-1}$ to sufficiently perform the tasks (Eves et al., 2005). The ventilatory demands for stair climbing, fifth floor search and rescue, and subway operations have been reported to be 85.3, 90.7, and 53.3 $L \cdot min^{-1}$, respectively (Williams-Bell et al., 2010a, Williams-Bell et al., 2010b). However, individual values for firefighting operations during a fifth floor search and rescue scenario have been reported at levels as high as 118 $L \cdot min^{-1}$ (Williams-Bell et al., 2010a) indicating that some firefighters may experience the respiratory limitations that were previously reported by Eves et al. (2005).

In a follow up study to the work by Eves et al. (2005), Dreger et al. (2006) examined the effects of an updated SCBA model on maximal oxygen uptake while wearing PPE and reported that VO_{2peak} was reduced by 17%. This reduction was related to a decrease in peak ventilation associated with reduced tidal volume but no change in breathing frequency at peak exercise (Dreger et al., 2006).

In order to elicit the effects of the weight of the SCBA or potentially the design of the harness, Bakri et al. (2012) recruited eight male participants to perform treadmill exercise under four conditions: a) 8 kg PPE, b) 8 kg PPE plus 11 kg SCBA with an old harness, c) 8 kg PPE plus 6.4 kg SCBA with an old harness, and d) 8 kg PPE plus 6.4 kg SCBA with a new harness, in ambient conditions of 22 and 32°C. The results showed that wearing an SCBA increased VO_2 by 30 and 50% in the 22 and 32°C conditions, respectively, yet the 4.7 kg lighter SCBA did not show any significant benefits. However, wearing the lighter SCBA and a new harness design utilizing a wide hip strap revealed a reduction in VO_2 compared to the heavier SCBA with an old harness design as well as a non-significant decrease compared to the same SCBA using the old harness (Bakri et al., 2012). These data indicate that functional design of the SCBA may provide beneficial reduction in metabolic demands, although the cardiovascular and thermal strain between SCBA models was not different.

It is evident that wearing PPE and the use of a SCBA results in an increased metabolic work rate and alterations in the respiratory responses to physical activity. The increased work rate has also shown an increase in RER values which could indicate a greater role for anaerobic metabolism during firefighting activities. The impact of these responses on the cognitive performance of firefighters is important to optimize the health and safety of the occupation and civilians.

2.3.3. Heat Stress of Protective Clothing and Firefighting

The nature of firefighting results in exposures to increased temperatures from fire but also to high ambient temperatures from other emergency scenarios while wearing PPE, which does not allow for adequate heat loss during firefighting activities (Duncan et al., 1979). High levels of thermal stress are not necessarily linear to increases in ambient temperature, specifically in situations where protective clothing ensembles are worn, such as firefighting. Many studies have attempted to quantify the rise in T_{core} to firefighting activities as well as heat exposure in a laboratory environment.

Conditions of high ambient temperature and/or relative humidity, or in the case of wearing fully encapsulating clothing ensembles which restrict evaporative heat loss, a thermal steady state may not be possible as the maximal evaporative heat loss possible while wearing the clothing (E_{max}) is potentially less than the maximal amount of heat loss required for thermal balance (E_{req}), defined as UHS (Givoni et al., 1972). Even light or moderate exercise, which may not be thought of as producing large amounts of metabolic heat, may create UHS (Givoni et al., 1972) where the body will continually store heat. The result of increasing body heat storage is a constant rise in body temperature until one of two situations occurs: 1) exhaustion or fatality, or 2) change in the environmental conditions. These environmental changes include: i) removing clothing layers on the individual thereby increasing the efficiency of evaporative heat loss, ii) stopping the work activity or exercise, as well as iii) moving into a shaded location or a place with a cooler ambient temperature (Kamon et al., 1983, Cheung et al., 2000) .

Although performing job activities or exercise in environments of high ambient temperatures and increased metabolic rates increases thermal strain, hyperthermia may not be the limiting factor in these conditions. Lind (1963) conducted an early study on the relationship between ambient temperature and rectal temperature and found that if the ambient temperature is below a critical value then the increases in rectal temperature can plateau and are directly related to metabolic heat production. This determination of a critical value coincides with a compensable heat stress situation where the body is capable of achieving a thermal balance. In contrast, when the ambient temperature surpasses this critical temperature then the subsequent increases in rectal temperature are a product of not only the metabolic heat production but also the ambient air temperature resulting in considerable increases in T_{core}, potentially into dangerous levels (Lind, 1963). As metabolic rate continues to increase to higher levels, the critical point for ambient temperature becomes lower to achieve (Lind, 1963). Exercise in a hot environment will also result in haemoconcentration (Senay, 1972, Wyndham, 1973, Costill et al., 1974).

Barnard and Duncan (1979) were one of the first to measure physiological responses of firefighters while wearing personal protective equipment (PPE) during treadmill exercise at 4.0 $km\cdot h^{-1}$ and 10% grade for 15-min. The authors reported a significant increase in HR and VO_2 during exercise in the laboratory (ambient temperature 16.3 ± 0.2°C; 136.4 ± 4.3 bpm; 10.47 ± 0.75 $mLkg^{-1}\cdot min^{-1}$) or in a sauna (ambient temperature 41.8 ± 0.2°C ; 172.7 ± 3.2 bpm; 10.80 ± 0.59 $mL\cdot kg^{-1}\cdot min^{-1}$) while wearing PPE compared to wearing the normal “blue” uniform (ambient temperature 17.8 ± 0.1°C; 99.2 ± 3.3 bpm, 7.13 ± 0.41 $mLkg^{-1}\cdot min^{-1}$). Mean T_{sk} in the sauna condition increased 5.69 ± 0.2°C. The authors concluded that many of the physiological increases were due to the insulative properties of the PPE and a decrease in the evaporative cooling processes of the body. After 15-min of exercise, rectal temperatures increased 0.06 ± 0.04°C, 0.23 ± 0.04°C, and 0.56 ± 0.1°C for the baseline, PPE in the laboratory, and PPE in the sauna, respectively. Furthermore, following the 15-min exercise protocol, participants in the sauna condition had their rectal temperature continue to increase even during the recovery period. This early study highlighted the importance of the physiological strain imposed on firefighters by wearing PPE while doing work in the heat.

White et al. (1987) had eight men perform moderate and heavy intensity treadmill exercise at 45% and 70% of VO_{2peak} in 28°C and 50% relative humidity wearing full PPE and either a neoprene or GORE-TEX under layer. The authors found that the exercise protocols were associated with HR limits of 90% HR_{max} along with tolerance times close to 30 min and 7-8 min for the 45% and 70% VO_{2peak} conditions, respectively. Despite the moderate and heavy work rates in hot environmental conditions, T_{core} levels were less than 38.5°C after 30-min and even lower following the 7-8-min heavy intensity. These data indicate that for work durations less than 30 min, tolerance times are limited by cardiovascular instead of thermal strain (Cheung et al., 2010). Contrary to these results, when metabolic work rates were kept low, Selkirk et al. (2004b) examined the tolerance times in relation to ambient environments ranging from 25°C to 35°C. The authors found that at these lower work rates, tolerance time was greatly affected by the ambient temperature while wearing full firefighting protective clothing. These data provide insight that with longer tolerance times some evaporative cooling can occur by allowing some water vapour transfer through the clothing layers (Selkirk et al., 2004b).

Faff and Tutak (1989) examined the cardiovascular responses of eighteen male firefighters exercising in firefighter's uniform or in full PPE and SCBA at room temperature (20°C) or in a hot, humid environment (39 ± 1°C, 70% ± 5% relative humidity). The authors reported that, following cycle exercise at 1.5 $W \cdot kg^{-1}$ to volitional fatigue similar to that which cause work to be ceased at a fire scene, VO_2 elevated to 1.65 ± 0.23 $L \cdot min^{-1}$ while wearing firefighter's uniform compared to 1.75 ± 0.15 $L \cdot min^{-1}$ wearing PPE and SCBA, whereas HR increased to 128.5 ± 15.6 bpm and 131.1 ± 10.7 bpm, respectively. During the first 15-min of exercise, there were no differences in rectal temperature in the hot, humid environment between the uniform and PPE conditions. Only three firefighters in the PPE group exercised for longer than 20 minutes and their rectal temperatures were approximately 0.7°C higher than in the uniform condition. The authors reported that T_{core} continued to rise in participants following 10-min of recovery and even exceeded 39°C in some firefighters, indicating that despite volitional termination of exercise most individuals reached the limit of tolerance (Faff et al., 1989).

An initial study by McLellan et al. (1993b) examined the effects of temperature and metabolic rate while wearing three configurations of NBC clothing (combat clothing, combat clothing with partially-opened NBC, and combat clothing with full NBC) on twenty-three unacclimatized male soldiers exercising at either a light (walking at 1.11 $m \cdot s^{-1}$, 0% grade, alternating lifting 10 kg) or heavy metabolic rate (1.33 $m \cdot s^{-1}$, 7.5% grade, alternating lifting 20 kg) at either 18 or 30°C and 50% relative humidity. The data revealed that exercising at a light intensity in 30°C while wearing full NBC reduced tolerance time to 83-min compared to the other two clothing conditions. In comparison, heavy exercise reduced tolerance times to less than one hour in 18°C and 34-min in 30°C. The rate of change in T_{core} was $0.2°C \cdot h^{-1}$ for all three clothing configurations during light exercise in 18°C but reached over $2.5°C \cdot h^{-1}$ for heavy exercise in 30°C. In terms of evaporative efficiency, the full NBC clothing configuration was found to be at 50% efficiency during light exercise in 18°C but was reduced to 20% during heavy exercise in 30°C. The work intensities chosen in this study indicated a metabolic heat production of 250 W and 500 W for light and heavy exercise depicting an oxygen consumption of less than 50% VO_{2peak} during heavy exercise. The authors confirmed at these intensities that thermal strain rather than metabolic strain was exhibited while exercising in NBC clothing.

In a subsequent study, the same exercise intensities, ambient conditions, and clothing configurations were implemented to examine the effects of work to rest schedules and continuous exercise on the tolerance time of eight male soldiers (McLellan et al., 1993a). The authors reported a decreasing hyperbolic function that illustrated the relationship between tolerance time and metabolic rate for the partially-open NBC and fully-encapsulating NBC conditions. For the fully encapsulating NBC condition, an average metabolic rate below 4.7 $mL \cdot kg^{-1} \cdot min^{-1}$ would indicate an infinite tolerance time while performing work at 30°C and 50% relative humidity. Due to cooling of the body occurring during rest periods in this environmental condition, decreasing the metabolic work rate will increase the amount of work completed (McLellan et al., 1993a). The practical example described by the authors suggests that continuous marching at 1.0 $m \cdot s^{-1}$ requiring a VO_2 of 10 $mL \cdot kg^{-1} \cdot min^{-1}$ could be carried out for 112-min for a distance 6.9 km; however, implementing a work to rest schedule of 10-min:20-min (assuming a resting VO_2 of 4 $mL \cdot kg^{-1} \cdot min^{-1}$), the average metabolic rate would be reduced to 6 $mL \cdot kg^{-1} \cdot min^{-1}$ allowing for a 36% increase in work time equating to 152-min. The authors conclude that these benefits in work time will only be observed when the ambient conditions allow for adequate cooling of the body and will be further elevated when the metabolic work rate is close to the level associated with an infinite tolerance time (McLellan et al., 1993a).

Although the previous studies (McLellan et al., 1993a, b) provided information on continuous and intermittent exercise in a hot environment, data was not available on higher ambient temperatures above 40°C. To elicit this information, McLellan (1993) allocated nineteen males into either light intermittent exercise (15-min work to 15-min rest ratio), or light, moderate, or heavy continuous exercise while wearing the same NBC configurations from the previous studies (McLellan et al., 1993b, a). For the heavy exercise and full-NBC clothing, the rate of change in T_{core} was 3.0°$C \cdot h^{-1}$ with each level of NBC clothing associated with a decreasing curvilinear relationship between metabolic rate and tolerance time (McLellan, 1993). The metabolic rate required to elicit an infinite tolerance time was -1.94 $mL{\cdot}kg^{-1}.min^{-1}$, which indicates a clearly unobtainable work rate resulting in positive body heat storage even at a resting rate.

The data collected during exercise while wearing various levels of NBC clothing at 30°C and 50% relative humidity (McLellan et al., 1993a), and 40°C at 50% (McLellan, 1993) and 30% relative humidity (McLellan et al., 1992) indicated that ambient temperature and relative humidity provide a greater influence on tolerance times at low metabolic rates. At tolerance times under 50-min corresponding to metabolic rates above 15 to 20 $mL{\cdot}kg{\cdot}min^{-1}$ the influence of ambient conditions are minimized by the characteristics of the protective clothing. When metabolic rates are less than 15 $mL{\cdot}kg^{-1}{\cdot}min^{-1}$, the ambient environment has a greater impact on the efficiency of sweat evaporation and tolerance time (McLellan et al., 1994). This is illustrated by the evaporative efficiency of sweat increasing from 22 to 40% when relative humidity decreases from 50 to 30% in 40°C corresponding to an increase in tolerance time from 67-min (McLellan, 1993) to 113-min (McLellan et al., 1992), respectively.

As reviewed earlier, any added sweat increase from endurance training or heat acclimation decreases blood volume and increases the sensation of discomfort without any corresponding decrease in T_{core} (Aoyagi et al., 1994) or substantial improvement in heat tolerance while wearing NBC clothing (Aoyagi et al., 1995). In a follow-up study, Cheung et al. (1998a) examined the effects of aerobic fitness, short term heat acclimation, and hypohydration on tolerance times while wearing nuclear, biological, and chemical protective clothing and performing light exercise at 3.5 $km{\cdot}h^{-1}$ and 0% grade. The authors concluded that long term aerobic fitness significantly improves tolerance to EIHS whereas short term heat acclimation did not show any improvements. The primary physiological adaptation that occurs from heat acclimation is an increase in sweat rate, which in an UHS condition while wearing protective clothing with limited water vapour permeability, will not result in an increase in evaporative heat loss and, therefore, not be a beneficial adaptation. The results also further emphasized the importance of hydration during UHS regardless of fitness or acclimation status. The authors suggest that this finding may be due to the fluid replacement provided to participants during the heat stress tolerance test before the heat acclimation protocol resulting in near-maximal tolerance times. The addition of fluid replacement during the UHS protocol can lower HR and increase tolerance time compared to a no fluid replacement condition (Cheung et al., 1998b). In addition, hypohydration resulted in decreased tolerance time with an increased resting T_{core} in the moderately fit participants ($VO_2 < 50$ mL·kg^{-1}·min^{-1}) and an increased rate of rise in T_{core} in the highly fit participants ($VO_2 > 55$ mL·kg^{-1}·min^{-1}) (Cheung et al., 1998a). It appears that fluid replacement during exercise and hydration status prior to exercise during UHS plays a more fundamental role compared to acclimation status for influencing physiological strain.

Selkirk et al. (2001) developed a research design to elicit the effects of different aerobic fitness levels and body fatness on an individual's ability to tolerate exercise in a UHS environment. Participants were matched for aerobic fitness and body fatness in four categories: 1) trained ($VO_{2peak} > 65$ ml·kg lean body mass (LBM)$^{-1}$·min^{-1}, high body fat; 20%), 2) trained (VO_{2peak} 65 ml·kg LBM^{-1}·min^{-1}, low body fat; 11%), 3) untrained (VO_{2peak} 53 ml·kg LBM^{-1}·min^{-1}, high body fat; 20%), and 4) untrained (VO_{2peak} 53 ml·kg LBM^{-1}·min^{-1}, low body fat; 11%). The authors concluded that higher levels of aerobic fitness had a considerable effect on tolerance time in an UHS environment by increasing the T_{core} tolerated (up to approximately 0.9°C) at exhaustion by the individual (Selkirk et al., 2001). In addition, due to the lower heat capacity of adipose tissue compared to skeletal muscle, at a given rate of heat storage (*S*), the rate of rise in T_{core} will be slower for an individual with a lower percent body fat leading to increased tolerance times that are not related to aerobic fitness (Selkirk et al., 2001).

Subsequently, tolerance times for firefighters performing simulated work intensities from very light to heavy on a treadmill at ambient conditions ranging from 25°C to 35°C were determined to be anywhere from 41 to 196 min (Selkirk et al., 2004b). These results were consistent with previous research when NBC protective clothing was worn (McLellan, 1993, McLellan et al., 1993b) concluding that when firefighters wear PPE, ambient temperature and humidity will influence tolerance times at lower metabolic rates while at higher ambient temperatures metabolic rate will be the most prominent factor Indeed, based on these findings, at metabolic rates above 500 W temperature and humidity do not have a major influence on the rate of heat storage while wearing PPE; however, at lower rates of heat storage the evaporative barrier due to PPE will be overcome allowing for evaporative cooling to become proportional to the vapour pressure gradient between the PPE and the external environment. The results from Selkirk et al. (2004b) led to the development of continuous work guidelines for the Toronto Fire Services while performing various activities in the heat (McLellan et al., 2006).

From the growing interest in the literature examining the effects of heat stress on exercise tolerance, a review by Cheung et al. (2010) identified three main factors that determine an individual’s tolerance time during UHS: 1) their initial T_{core} at the start of heat stress trial, 2) the T_{core} that they are able to tolerate before exhaustion, and 3) the rate of increase in T_{core} throughout the duration of the heat stress trial. The understanding of the main factors limiting exercise tolerance in the heat illustrates the need for more approaches to provide adequate countermeasures for practical application. Studies have shown that inducing a drop in T_{core} from 39.5°C to 37.5°C in under 10-min can be accomplished by immersing the entire body into cold water at 2°C (Proulx et al., 2003). Intermittent (10-20°C) or continuous (20°C) water immersion for 15-min during a recovery period can improve work output in a subsequent exercise bout compared to active recovery on a cycle ergometer at 40% VO_{2peak} (Vaile et al., 2008). Despite these beneficial findings the practical implications of whole-body immersion during recovery breaks at fire emergencies is troublesome. This has led to additional research on more practical applications in the field which has shown that hand and forearm immersion, in 17°C water, as a countermeasure can provide 70% of the ensuing heat loss within the first 10-min of cooling (Selkirk et al., 2004a). The practicality of this protocol is very promising in reducing the physiological strain in hot conditions (Cheung et al., 2010) but the possibility of reducing cognitive impairments has not been evaluated.

The large quantity of research that has been conducted on the physiological responses of individuals wearing PPE has provided important information on the various factors that improve or reduce tolerance to working in the heat and have provided safe working guidelines for firefighters exposed to increasing temperatures. The physical limits have been well established but it is also important to quantify how these metabolic and environmental conditions may play a role on cognitive function. The next section will discuss the role of heat stress and its impact on cognitive function.

2.4 Cognitive Function

2.4.1 Relationship between Cognitive Function and Firefighting

As stated earlier, the cognitive processes typically involved in firefighting appear to involve working memory, sustained attention, reaction time, spatial awareness, and information processing (Barr et al., 2010, Morley et al., 2012). These aspects of cognition work together to allow the firefighter to perform their tasks and safely exit the emergency without putting themselves at an increased risk of injury or fatality. The following section discusses the cognitive requirements of firefighting and the cortical areas contributing to these processes.

Working memory retains information for a short duration where it can be manipulated to guide subsequent behaviour when the specific information is not readily available from the environment (D'Esposito et al., 2000). One of the most cited studies in working memory research proposed that the system was comprised of three processes, known as the multicomponent model: 1) visuospatial sketch pad, 2) phonological loop, and 3) central executive (Baddeley et al., 1974b). The three-component system details how the central executive controls the system, with the visuospatial sketch pad storing and manipulating visual and spatial information while the phonological loop plays a role in verbal information (Baddeley et al., 1974b, Baddeley, 2012). The model was capable of explaining how a dual-task (specifically relating to a verbal and visuospatial task combined) involving different domains of information could approach levels of performance similar to single-task conditions (D’Esposito et al., 2015). Research into the precise areas of the brain that undertake working memory is extensive, with Baddeley (2012) stating that in his attempt to write a review on the topic it “ended with more than

50 pages of references”. Both functional magnetic resonance imaging (fMRI) and EEG have demonstrated that the prefrontal cortex (PFC) plays a pivotal role in working memory (Baars et al., 2010). In terms of the involvement of specific locations within the PFC, it appears that the dorso-lateral PFC is involved with information of spatial locations whereas the ventral and lateral PFC have been associated with objects, faces, words, and other non-spatial information (Baars et al., 2010). Human neuroimaging studies have shown that increasing the number of items in working memory (from one to eight items) results in an increase in PFC activation and suggests that it is involved in working memory storage (Cohen et al., 1997) with a link for a role in a large brain network controlling working memory (Baars et al., 2010).

Unlike vision and motor control, working memory does not stem from a discrete neuronal system but includes sensory systems that trigger semantic and episodic memory, and motor systems in order to execute specific behavioural goals (D’Esposito et al., 2015). Although the model proposed by Baddeley and Hitch over four decades ago has been dominant, new frameworks known as state-based models are increasing in prevalence (D’Esposito et al., 2015). Overall, these models assume that information is being held as an internal representation in working memory, whether it is long-term memory, sensory, or motoric, with attention being allocated in order to activate the content. A thorough review of the current state of proposed working memory models can be found in D’Esposito et al. (2015). Current evidence appears to indicate that the PFC stores higher-order information (task rules, goals, or abstract representations) compared to the more stimulus-specific information in extrastriate cortex (Sreenivasan et al., 2014). In particular, the lateral PFC encodes and maintains abstract representations from the object category over representations of visual similarity (Riggall et al., 2012, Lee et al., 2013).

Spatial working memory, a particular part of working memory, is a fundamental aspect of cognition, storing relevant spatial cues for several seconds (Spellman et al., 2015). It is a necessary component of goal-directed action whereby an individual locates a threat or oneself in an evolving and novel environment and relies on the relevant stored spatial information that is constantly being updated and applied to execute a particular behavioral action (Baddeley et al., 1974a). Visuospatial memory has been extensively examined in the literature (de Rover et al., 2011) and shown to engage the hippocampus in associative learning tasks that require memorizing features of objects (Maguire et al., 1998). This notion was developed based on initial work that suggested the hippocampus was the site where processing of spatial and object information converges (Jones et al., 1970). Previous research lends support to the notion that the PFC plays a critical role in successfully executing tasks involving spatial working memory (Curtis et al., 2004). Rodent models have elicited an interaction between the medial prefrontal cortex (mPFC) and the hippocampus for successful spatial working memory tasks (Lee et al., 2003, Jones et al., 2005, Hyman et al., 2010) but the exact mechanisms for encoding, maintenance, and retrieval between the two structures remains unclear (Spellman et al., 2015). Location-specific firing of cells in the ventral hippocampus and the mPFC have been identified (Jung et al., 1998, Kjelstrup et al., 2008, Burton et al., 2009) with damage to the ventral hippocampus impairing goal-related activity in the mPFC (Burton et al., 2009). These findings suggest that the projection of the ventral hippocampus and mPFC may relay important location information during spatial working memory tasks

(Spellman et al., 2015). Recent work by Spellman et al. (2015) has shown that the direct interaction of the ventral hippocampus and mPFC constitutes a pathway that supports encoding of task-relevant spatial cues during spatial working memory performance.

Owen et al. (1995) have shown on a paired associates learning (PAL) task, depicting visual episodic memory and new learning that the frontal and temporal regions along with the hippocampus contribute to performance. In addition, de Rover (2011) confirmed that different neural networks are involved in a PAL test during the encoding and retrieval processes. The authors reported that the PFC, anterior cingulate, temporal-parietal, occipital cortex, and hippocampus were associated with encoding while retrieval consisted of the cuneus, posterior cingulate, and parahippocampal gyrus. However, although the PFC and hippocampus have been shown to contribute to successful spatial working memory together, how they interact and the time course of this interaction is not well understood (Spellman et al., 2015). More recent findings have shifted the notion that lateral PFC controls and maintains information in working memory to a more abstract role whereby the lateral PFC initiates and controls working memory with maintenance occurring in more posterior cortices (Christophel et al., 2012, Riggall et al., 2012). These studies have observed contents of visual working memory being decoded from occipitotemporal (Riggall et al., 2012) and parietal cortices (Christophel et al., 2012) but not lateral PFC, with activation occurring in all regions. In contrast, the lateral PFC does appear to play a role in the maintenance of non-visual content (Romero et al., 2006). Therefore, the role of the PFC is to focus attention on relevant sensory information, select the appropriate representation, and perform executive control necessary to process the information (Postle, 2006) while posterior areas keep content in working memory (Lara et al., 2015). This assumption is reasonable given the reciprocal connections between the PFC and almost all cortices (Pandya et al., 1987).

It is apparent that short-term memory is an important factor in cognition as it relates to firefighting, however further explanation of long-term memory is also warranted. Long-term memory refers to information being retained for days, months, or years and is traditionally split into two categories, declarative (episodic memory and semantic memory) and nondeclarative memory (implicit memory and procedural memory) (Gazzaniga et al., 2014). Long term memory is critical for firefighters to be able to recall standard operating procedures as well as during post-incident debrief sessions where specific information related to the incident will need to be recalled. Many studies have demonstrated significant involvement of the PFC during encoding of information into long-term memory (Ranganath et al., 2004, Ranganath et al., 2005, Blumenfeld et al., 2006). In particular, dorsolateral PFC activation appears to be involved with successful long-term memory encoding of information specifically when encoding or retrieval requires organization (Blumenfeld et al., 2007). In addition, the ventrolateral PFC has been implicated in long-term memory encoding with anterior regions associated with high levels of control for semantic information (Ranganath et al., 2004) and posterior regions linked to tasks requiring less control during selection or selection of phonological information (Fletcher et al., 2003). Overall, it has been suggested that the ventrolateral PFC supports long-term memory through selecting relevant information while the dorsolateral PFC supports long-term memory by building associations with items that are already stored in working memory (Blumenfeld et al., 2007).

Another important aspect of cognition as it relates to firefighting tasks is sustained attention or vigilance. This is referred to as the ability to maintain attention on successive stimuli over a specified duration, typically to detect a correct sequence of infrequently occurring items (Coull et al., 1996). **S**elective attention refers to the ability to focus awareness among relevant inputs, thoughts, and actions while disregarding irrelevant information (Gazzaniga et al., 2014). The system that coordinates attention utilizes subcortical and cortical networks within the brain including the superior colliculus in the midbrain and the pulvinar to control attention, along with areas of the cortex involving the frontal, posterior parietal, posterior superior temporal, anterior cingulate, and posterior cingulate cortices and insula (Gazzaniga et al., 2014). Attention can be shifted in a voluntary or reflexive manner with the former occurring due to our ability to intentionally attend to a stimulus via 'top-down' modulation or through a stimulus-driven response, or 'bottom-up', mechanism (Corbetta et al., 2002, Pessoa et al., 2003). Evidence suggests that spontaneously paying attention to sensory input will also activate the hippocampus, which plays a role in learning (Stark et al., 2003). Neuroimaging studies have indicated the PFC and superior parietal cortices as being associated with sustained attention (Cohen et al., 1988, Pardo et al., 1991). One particular test of sustained attention, rapid visual information processing (RVP), uses rapidly presented numeric digits that the participant must correctly identify in a specific sequence, but also requires selective attention and working memory for successful performance (Coull et al., 1996). Working memory is a component of this task due to the requirement of maintaining two digits at all times in order to accurately identify a correct or false sequence (Coull et al., 1996). A recent study by Neale et al. (2015) established activation of a neural network for performance on an RVP test comprising of the frontal, parietal, cerebellar, and occipital regions in a middle aged cohort. Furthermore, their analyses pointed to the frontal gyri, parietal regions, and cerebellum for their importance in sustained attention for overall processing and phasic aspects of the task (Neale et al., 2015).

The literature on cognitive function is extensive and constantly evolving with technological advances and the ability to uncover, more precisely, the specific roles of different regions of the brain. The studies detailed above have provided insight into the activation patterns and locations involved in various aspects of cognition in order to execute a particular behavioural goal. The next section will describe how the presence of heat stress may alter these aspects of cognitive function and how it can modify performance in firefighters.

2.4.2 Heat Stress and Cognitive Function

Firefighting activities require firefighters to remain alert, maintain high levels of mental function, be aware of their surrounding environment, and make split second decisions all while under conditions of extreme heat and psychological stress (Smith et al., 2001, Barr et al., 2010, Morley et al., 2012, Williams-Bell et al., 2015a). Heat stress, and the associated heat illnesses, can be life-threatening when T_{core} rises above 40°C. This level of hyperthermia can result in dysfunction of the central nervous system (CNS) leading to delirium, convulsion, and coma (Bouchama et al., 2002). In order to determine specific mechanisms involved in CNS abnormalities, a heat stress animal model using rats has been developed by Sharma et al. (1984). Using this model, heat stress without subsequent heat stroke shows an increase in the blood-brain barrier permeability to protein tracers (Sharma et al., 1984) caused by various neurochemical mediators including serotonin (Sharma et al., 1994), prostaglandins (Sharma et al., 1997b), and opioid peptides (Sharma et al., 1997a). Previous work has shown that the region controlling heat production, the frontal cerebral cortex, contains aspartate and glutamate, which is released into extracellular fluid following hyperthermia induced by prostaglandin E1 (Monda et al., 1998). In addition, administration of aspartate and glutamate into the intracerebroventricular region induces hyperthermia in rats (Bligh, 1981) whereas injection of gamma-amino butyric acid (GABA) or taurine into central or systemic circulation results in hypothermia (Sgaragli et al., 1981, Serrano et al., 1985).

Sharma (2006) utilized the heat stress rat model subjected to a biological oxygen demand incubator set at 38°C for 30-min, 1 h, 2 h, 3 h, and 4 h to determine the effects of whole body hyperthermia on glutamate, aspartate, GABA, and glycine. The authors concluded that hyperthermia resulted in increased levels of the excitatory amino acids, glutamate and aspartate, while the inhibitory amino acids, GABA and glycine, decrease in the CNS. This decrease in GABA resulting in impaired inhibitory function during hyperthermia may lead to an increase in excitotoxicity causing cell damage. In addition, glutamate can induce cell death through activation of neural glutamate receptors and calcium influx (Babot et al., 2005) as well as potentially inducing oxidative stress following heat stress (Rössler et al., 2004). An additional important finding by Sharma (2006) was the alteration in the blood-brain barrier resulting in fluid disturbances within the microenvironment potentially contributing to motor and cognitive dysfunction, edema formation, and cell injury. It appears that amino acid neurotransmitters are involved in the molecular mechanism disrupting the blood-brain barrier during heat stress.

The increased exposure to high ambient temperatures along with the heightened levels of cardiorespiratory stress while responding to an emergency cause an increased T_{core} resulting in potential levels of dehydration and psychological stress. These adverse responses have been shown to result in deterioration of cognitive function, especially if the tasks require central executive function (Cian et al., 2000, Cian et al., 2001). Firefighting can impose a situation of profuse sweating for the firefighter with body mass reductions being reported around 2% during simulated victim search and rescue tasks (Rayson et al., 2005). This level of decrease in body mass due to exercise and heat stress has been reported to impact cognitive function, specifically mental concentration and working memory (Sharma et al., 1986). The exact mechanism of this decrease in cognitive function is unclear; however, it is suggested that during these situations of increased stress, firefighters may reallocate their attentional resources to cope with the imposed stress. This reallocation of resources may reduce the individual's capacity to process task-relevant information of the emergency situation (Kahneman, 1973, Hancock, 1986b, 1989, Baars, 1993, Hocking et al., 2001).

Another study conducted by Kivimaki and Lusa (1994) examined cognitive function using a stress choice reaction time test during a single smoke-diving activity; however, environmental heat exposure was not administered. The authors reported that with increasing physical stress during the firefighting activity, task-focused thinking (measured by asking firefighters to think out loud and speak their thoughts) was decreased. The limitation of this study was that no thermoregulatory measurements were taken making it impossible to determine what impact heat stress has on the cognitive function of firefighters while performing a smoke-diving activity (Barr et al., 2010).

Although research has been limited on the effects of heat exposure in firefighters during simulated job tasks, numerous studies have examined the effect of heat stress on cognitive function within the general population. Initial contemporary stress exposure standards were based on the characteristics, response, and limitations of the human physiological system (Hancock et al., 1998). Hancock and Vasmatzidis (1998) challenged this traditional approach to shift the paradigm from examining the physiological limits for occupational exposure limits to understanding the cognitive responses to heat stress. It has been reported that approximately five to ten million workers in the United States may be exposed to the occupational hazard of heat stress (NIOSH, 1986)

Initial documents detailing the heat stress exposure limits for occupational labour were designed to:

> “provide medical criteria which will assure insofar as practicable that no worker will suffer diminished health, functional capacity, or life expectancy as a result of his (or her) work experience” (Millar, 1986, p.iii).

This wording from the NIOSH documents further emphasizes the importance put on heat exposure limits with the view from the medical community to focus, primarily, on physiological limits. Hancock et al. (1998) were not attempting to challenge the limits previously reported, but rather they wanted to shed light that another approach could be a more sensitive tool to help extend the protective effect of exposure limits by focusing on behavioural efficiency. The efficient performance of a task is commonly known to fail before physiological limitations are reached or perturbed beyond the boundaries of steady state (Hancock et al., 1998).

Wing (1965) provided the initial findings on the tolerance limits for mental function after summarizing the results of fifteen publications examining performance on sedentary tasks. Wing’s exposure limits of unimpaired performance to temperature and duration fall well below the physiological limits established by Taylor (1948). A re-evaluation by Hancock (1981) of Wing’s initial summary revealed a limitation in the analysis of one study leading Hancock to conclude that the upper limit of impaired mental function is extremely close to the physiological collapse. Sanders and McCormick (1987) suggested that there was a problem with many of the previous statements with classifying task differentiation in these earlier studies. In particular, Hancock (1998) furthered this by noting the tasks summarized by Wing combined simple mental operations and more complex motor responses into one category.

Initially, Grether (1973) and Ramsey and Morrisey (1978) noted that task differentiation was an important factor in determining heat tolerance for cognitive performance, which a few years later, was furthered by Hancock (1982) in that simple mental operations and more complex motor responses cannot be considered tasks of homogenous cognitive demand. When the tasks were differentiated into heterogeneous categories, the tolerance limit curves are similar in shape but occur at differing absolute tolerance levels (Hancock et al., 1998). These curves representing the various task categorizations are related to the shape of the physiological limits curve presented by Hancock (1998) which are in line with those reported by Meister (1976).

Ramsey and Kwon (1992) reviewed over one hundred and fifty studies examining the impact of heat stress on exposure times while evaluating various types of performance tasks. The tasks were differentiated into simple mental performance and those requiring psychomotor response. Their analysis attempted to determine which tasks revealed significant performance decrement, marginal decrement, no evidence of performance change, or performance enhancement. Their results showed that for the very simple mental performance tasks, there was a lack of evidence that decrement occurred over the spectrum of heat intensities and exposure times with some results actually showing improvements in this category of mental performance specifically during brief exposures (Ramsey et al., 1992). This finding confirmed Hancock's (1981) notion that only a slight mental performance decrement may occur just prior to physiological malfunction. Hancock (1981) also noted that the majority of tasks requiring elements of motor performance are more vulnerable to heat exposure. Hancock (1982) further divided psychomotor performance into more defined categories of single and dual-task demands and found many similarities in a review of the published data.

The original time intensity curves that were developed to illustrate the limits for each cognitive task were substituted by Hancock (1982) to include the different levels of dynamic changes in deep body temperature. Other studies that utilized the wearing of impermeable clothing while manipulating dynamic changes to deep body temperature, without altering the environmental temperature, supported these developed deep body temperature values (Allan et al., 1979b). These initial findings concluded that it is the change in the dynamic thermal state of the individual and not the manipulation of the environmental temperature that influences performance (Hancock, 1982). Therefore, it is the rate of change in deep body temperature that is of critical importance. Hancock (1982) has suggested that the more demanding an information-processing task is, the smaller amount of heat strain that can be tolerated by the individual before performance decrements occur. From the review of the literature, Hancock and Vasmatzidis (1998) proposed new threshold curves for the dynamic rise in deep body temperature for vigilance, dual-task demands, neuro-muscular co-ordination tasks, simple mental performance, and the physiological tolerance limit at 0.055, 0.22, 0.88, 1.32, and $1.65^{\circ}\mathrm{C}{\cdot}\mathrm{h}^{-1}$, respectively. The authors noted that these limits should provide the upper tolerance levels of performance for each of the specified task categories and thought of as the critical failure points relating performance to the intensity of the heat stress. However, these tolerance limits were derived from cognitive tasks performed without substantial increases in muscular or metabolic exertion. The effect of a combination of environmental conditions with increasing levels of metabolic rate on cognitive performance remains unknown and requires considerable further investigation (Mihaly et al., 1988, Hancock et al., 1998).

One of the major limitations in the heat stress literature is the lack of any single theoretical framework that explains the experimental findings to mental performance (Hancock, 1982). Originally, the most common theory cited to explain the changes in cognitive performance during heat stress was behaviour arousal (Provins, 1966), which hypothesized that there is an inverted-U shape relationship (Yerkes et al., 1908) between the arousal level of the individual and the corresponding environmental stress experienced. It has been stated that this theory has been employed by researchers to explain a contradictory data set (Hancock, 1987). Hancock criticized the use of behavioural arousal theory to explain the decrements in cognitive performance due to heat stress (Hancock, 1987) and developed a new dynamic model of stress and sustained attention that implemented a region for maximal adaptability based on the variation of attentional demands under heat stress (Hancock, 1989). In a review of the effects of heat stress on cognitive performance, Hancock et al. (2003) referred to this dynamic model as the Maximal Adaptability Model. This proposed model makes the assumption that heat stress competes for and will drain attentional resources leading to decrements in performance (Kahneman, 1973, Hancock, 1989). The level of input stress that the individual will be able to tolerate will eventually reach an upper limit that defines the region of maximal adaptability (Hancock, 1989). Stress can be from the demanding nature of the cognitive task or from stressors acting upon the individual from the environment, with the cumulative stress affecting both psychological and physiological capabilities (Hancock, 1989). The model identifies that maximal adaptability is greater for physiological compared to psychological functioning. As the input level of stress reaches extremes, an increase in discomfort is experienced followed by a rapid decrease in the psychological capabilities of the individual (Hancock, 1989). As psychological adaptability continues to decrease there will eventually be a similar decrease in the individual’s physiological adaptability.

Another theory that has been used to describe changes attributed to increasing heat stress is the Global Workspace Theory (GWT) proposed by (Baars, 1993). GWT suggests there are numerous subconscious processes required to function simultaneously, such as maintaining body temperature during heat stress or spatial awareness of the body (Gaoua et al., 2012). In contrast, the capacity for conscious processes (i.e. speech, vision, pleasure, pain, excitement, immediate memory, etc.) is limited and is utilized as a coordinator of the unconscious processes (i.e. analyzing visual shapes, mapping body space, maintaining body temperature, etc.) (Baars, 1997). In addition, there is increasing evidence that the effects of an external stimulus result in the ensuing information to be distributed across many neuronal networks throughout the brain (John, 2001). The GWT suggests that consciousness allows the cooperation of multiple neuronal networks to solve problems including retrieval of items from short-term memory (Baars, 1993). According to this theory, external stimuli are constantly competing for conscious access which can impact the capacity to successfully perform each individual cognitive task. Therefore, exposure to heat stress that increases T_{sk} or T_{core} would elicit signals from temperature sensors to the hypothalamus resulting in an efferent response to enhance heat loss and ultimately reduce the neural resources available to complete a cognitive task.

With the emergence of technological advances, it has become increasingly more common to utilize computer-based, touch screen cognitive function testing within the research setting (Fray et al., 1996, Lowe et al., 1998, Robbins et al., 1998, De Luca et al., 2003, Singer et al., 2006, Levaux et al., 2007, Torgersen et al., 2012, Smith et al., 2013). One such application is the CANTAB (Cambridge Neuropsychological Test Automated Battery) (Cambridge Cognition Ltd, Cambridge, UK) testing battery which offers over 25 different cognitive tests assessing various regions of the brain that control visual memory, executive function, attention, semantic/verbal memory, decision making and response control, and social cognition. Since 1987, the use of the CANTAB testing battery has been reported and published in over 1,100 articles, although only a few have examined the effect of body or ambient temperature on cognitive function in emergency service personnel (Rayson et al., 2005, Radakovic et al., 2007).

Research on the cognitive performance of firefighters working in hot environments is limited; however the few studies (Kivimäki et al., 1994, Smith et al., 1998, Smith et al., 2001, Greenlee et al., 2014) that have measured changes in cognitive performance have utilized mental performance tests such as simple reaction time following simulated firefighting tasks. These tests have limited importance during firefighting, which is more reliant on decisions being made correctly rather than at the fastest speed possible, signifying that detrimental consequences are unlikely to occur if the decision requires a few extra milliseconds (Barr et al., 2010). Furthermore, it has been postulated that such tasks may be too simple and not elicit differences between different environmental conditions (Smith et al., 1998). In addition, Kivimäki et al. (1994) reported a decrease in task-focused thinking with increasing levels of physical stress during simulated smoke-diving although environmental heat exposure was not specifically quantified and T_{core} was not measured in the firefighter recruits.

In an attempt to overcome the limited applications from reaction time assessment, more complex neuropsychological assessment batteries, such as CANTAB, have been implemented. One such study examining changes in cognitive function during heat exposure in firefighters was conducted by Rayson et al. (2005) who reported that there was no change in rapid visual information processing, spatial memory span, and choice reaction time using the CANTAB testing battery following a firefighting simulation. The major limitation in this study was the authors conducted the cognitive performance tests thirty minutes following the firefighting simulation activity. The authors acknowledged that the effect of the heat exposure may have been lost during the transition period (Rayson et al., 2005).

Radakovic et al. (2007) used the CANTAB tests to investigate the effects of exertional heat stress and acclimation on male soldiers exercising at 5.5 km·h^{-1} in either a cool (20°C) or hot (40°C) environment who were randomly selected into: 1) control group with no acclimation, 2) passive heat acclimation (35°C, 40% relative humidity) for 3 hours over 10 days, or 3) active heat acclimation (35°C, 40% relative humidity) walking for 1 hour at 5.5 km·h^{-1} over 10 days. The authors did not report how they confirmed that heat acclimation was successful. The exertional heat stress protocol included wearing normal combat uniform with a backpack filled with 20 kg of sand to simulate regular weight burden for a maximal duration of 90-min. To assess cognitive performance, the authors implemented three of the CANTAB tests administered before and after the exertional heat stress protocol: 1) motor screening (MOT), reaction time (RTI), and rapid visual information processing (RVP). The authors found that attention performance was lowered in some tasks in the unacclimated soldiers but only in complex tasks (RTI); the simple motor tasks (MOT) were relatively unaffected by heat stress. The authors concluded that exertional heat stress resulted in mild deficits in attention in the unacclimated soldiers and were only significant in complex tasks, whereas simple cognitive tasks were unaffected by the heat stress. The change in tympanic temperature that was reported for each of the groups was approximately 1.7, 1.7, 1.3, and 0.2°C for the unacclimated, passively acclimated, actively acclimated, and control groups, respectively. Furthermore, the passive and actively acclimated soldiers suffered no ill effects of the exertional heat stress on the cognitive tests, even though the authors suggested a similar degree of heat stain as measured by tympanic temperature and HR.

Racinais et al. (2008) examined the effects of passive hyperthermia on cognitive function in subjects who were exposed for two hours in 20°C, 50°C only, and 50°C where cold packs were also applied to the participant's head. Cognitive function was assessed utilizing the match to sample (MTS), choice reaction time (CRT), pattern recognition memory (PRM), RVP, and spatial span (SSP) tests of the CANTAB battery. Baseline T_{core} was not reported although average T_{core} values during the two hours were approximately 37, 38.8, and 38.2°C for the 20°C, 50°C only and 50°C with cold packs, respectively. The authors found that passive hyperthermia without cold packs caused significant decrements in both the memory tests (PRM and SSP) when compared to the 20°C condition, while the more simple attention tests (MTS, CRT, RVP) were not affected by hyperthermia. The authors concluded that the results indicate the existence of frontal lobe activity impairments and that the addition of cold packs to the head during the 50°C passive hyperthermia condition preserved working memory capacity (SSP) but not visual memory (PRM).

Morley et al. (2012) examined the effects of heat stress in non-firefighters while wearing PPE on aspects of cognition including short-term memory, sustained and divided attention, and reaction time before and after exercise. The exercise protocol implemented in this study utilized a work to rest ratio, similar to Selkirk et al. (2004b), with 20-min of exercise at 4.5 $km \cdot h^{-1}$ followed by 10-min of recovery (consisting of 3-min at 2.5 $km \cdot h^{-1}$, 4-min standing rest, and 3-min at 2.5 $km \cdot h^{-1}$) in an environmental temperature of 33 - 35°C up to a total exercise time of 50-min. In a parallel study, the same protocol was conducted but also included cognitive measurements up to 120-min post-exercise. After participants performed 46-min and 48-min of exercise in the two studies, the authors concluded that there were no decrements in neuropsychological testing immediately after exercise but that recall on a memory test was impaired 60 and 120-min post-exercise. These decrements well after termination of exercise were observed for the ten slowest reaction times as these were prolonged at 120-min post-exercise. Measurements of T_{core} were reported only at pre- and post-exercise (increase in T_{core} of approximately 2.0°C) making it unclear whether there was a dynamic increase or decrease in T_{core} during the cognitive testing battery immediately following exercise.

These studies (Rayson et al., 2005, Radakovic et al., 2007, Racinais et al., 2008, Morley et al., 2012) have provided important empirical evidence of the behavioural measures associated with cognitive function while exposed to heat stress, but studies which evaluate brain activity may provide a more in-depth analysis. Hocking et al. (2001) found that following an exercise protocol to increase thermal strain, EEG analysis indicated an increase in steady-state visual evoked potential (SSVEP) amplitude and decrease in latency in the frontal regions of the brain for a spatial working memory task. Other cognitive measures did not show any decrements but revealed increased brain activity. These findings suggest that a cognitive reserve exists which reallocates attentional resources to combat the heat stress and reduces the capacity to perform on the cognitive task once the resources become overloaded (Hart et al., 1990, Wickens, 1991). The draining of attentional resources (Hancock, 1986b) will diminish the cognitive reserve available which, if insufficient, will result in impairments of cognitive function. If performance is maintained, it suggests that an increase in cognitive resources is required to successfully perform on the task (Hocking et al., 2001).

Gaoua et al. (2011a) conducted a passive heat stress study to investigate the specific triggers to cognitive and neuromuscular alterations. Eight participants underwent neuromuscular testing (maximal isometric contraction of the thumb with magnetic stimulation of the motor cortex and electrical stimulation of the motor nerve) and cognitive testing using two tests from CANTAB (One Touch Stocking of Cambridge, OTS 4 and OTS 6). Participants underwent 4 h 30 min of passive heating (wet bulb globe temperature = 38°C) and control (wet bulb globe temperature = 19°C) with cognitive measurements performed every 1 h 30-min with T_{core} maintained at 37.3, 37.8, 38.3, and 38.8°C at each subsequent trial. The authors reported a decline in OTS 6 (a more complex cognitive task compared to OTS 4) immediately upon heat exposure (T_{core} of 37.3°C) and after 4 h 30 m (T_{core} of 38.8°C). Cortical excitability was altered at 3 h of heat exposure (T_{core} 38.3°C) without any change in cognitive function, suggesting different mechanisms involved in physiology and cognition decrements. These data lend support to Hocking's findings based on the decrements observed in a complex cognitive task (OTS 6) which the authors suggest could be the result of interference from the additional attentional load imposed by the dynamic change in T_{core} plus the load from the cognitive task (Gaoua et al., 2011a). Neuroimaging studies corroborate the conclusions of Gaoua et al. (2011a) and Hocking et al. (2001) which have shown a greater use of cognitive resources through increases in electrical activity that lead to maintenance in cognitive performance in a hot environment (Silberstein et al., 1990) until cognitive resources become overloaded (Hocking et al., 2001), potentially with a subsequent decrease in cortical activity (D'Esposito et al., 2000).

An investigation by Caldwell et al. (2012) evaluated the physiological strain and cognitive performance of eight physically active male university students during two hours of low intensity (approximately 30 W) exercise in a control (20°C and 30% relative humidity), and two very hot and dry (48°C and 20% relative humidity) conditions with one also including liquid cooling (15°C water). The aspects of cognitive function that were assessed included attention, verbal working memory, problem solving, and perceptual reaction time. No changes in cognitive function were observed despite maximal T_{core} in the hot condition without liquid cooling of 38.9°C. The authors suggest that the lack of decrements reported in the hot condition may be due to the cognitive tasks implemented not being the most sensitive indices for the particular attributes being evaluated and that the tasks were too simple (Caldwell et al., 2012).

Many studies that have implemented a hyperthermic protocol have utilized an exercise-induced heat stress model, which brings into question the separate effects of exercise and hyperthermia. Previous research has shown that submaximal aerobic activity can improve aspects of cognitive function (Grego et al., 2005, Tomporowski et al., 2007, Coles et al., 2008) for speed of response and reduced errors up to 120-min of exercise (Grego et al., 2005) as well as an exercise-induced arousal for consolidating information into long-term memory with no effect on short-term memory (Coles et al., 2008). In addition, Tomporowski et al. (2007) found an improvement in short-term memory following exercise at 60% of VO_{2max} for 15, 60, or 120-min. However, the addition of substantial heat stress along with exercise removes the potential improvements in cognition (Gopinathan et al., 1988, Cian et al., 2001, Lieberman et al., 2005) but the specific neural mechanisms involved and the alterations in specific brain networks are not well understood (Liu et al., 2013).

Attention is another aspect of cognition that is frequently studied in the literature reflecting a cognitive process that results in selective attention of a particular part of the environment while ignoring irrelevant information (Liu et al., 2013). The attention network has been divided into three separate networks (alerting network, orienting network, and executive attention network), which differ in location and functioning within the brain (Posner et al., 1989). The alerting network maintains sensitivity to incoming stimuli whereas the orienting network selects information from sensory input while the executive attention network resolves conflict (Posner et al., 1989). The alerting network has been shown to include frontal and parietal brain regions including the thalamus (Posner et al., 1989, Fan et al., 2004, Fan et al., 2005) with the orienting network activating prefrontal and parietal areas including the superior parietal cortex and temporal parietal junction (Coull et al., 2000, Coull et al., 2001, Fan et al., 2004) and the executive network activating the frontal lobe, anterior cingulate cortex, and lateral PFC (Carter et al., 1999, MacDonald et al., 2000, Botvinick et al., 2001, Fan et al., 2004). In order to determine the effect of passive heat stress on these particular neural networks, Liu et al. (2013) conducted an fMRI study implementing the attention network test (ANT) following 45-min of passive heat stress in 50°C and 40% relative humidity. For the alerting network, differences in brain regions being activated were observed between the heat stress and temperate control condition with the premotor cortex, middle temporal gyrus, and superior parietal lobule activated during heat stress despite no differences in behavioral data. Similar to the alerting network, the orienting network was not impaired by passive heat stress and other structures were activated (enhanced activity in the temporal lobe with depressed activity in frontal, parietal, and occipital lobes), which is in line with previous work supporting the notion that changes in neuronal activity are observed in order to achieve the same level of performance (Kempton et al., 2011). Moreover, the main finding by Liu et al. (2013) was the impairment of executive function following passive heat stress, which the authors suggest could have arisen due to three possible explanations. First, it is possible that the concentration of 5-HT in plasma may have elevated inhibiting dopamine and altering the executive network. Second, the cognitive impairments in executive control may be task dependent with lower attention tasks being less vulnerable to heat stress than those requiring a higher level of attention (Hancock et al., 2003, Gaoua et al., 2011b). The third explanation describes an insufficient amount of cognitive resources available to maintain performance when they become overloaded by the cognitive task and heat stress (Hancock, 1986b, Hocking et al., 2001, Gaoua et al., 2011b). Overall, the data supported different brain activations in the dorsolateral PFC during passive heat stress (Carter et al., 1999, MacDonald et al., 2000, Botvinick et al., 2001) resulted in an impaired ability to resolve conflict despite no change in the alerting or orienting networks (i.e. monitoring conflict) (Liu et al., 2013).

Although the physiological responses to heat exposure have been well documented and the abundance of literature from cognitive neuroscience, the specific effects on cognitive function are equivocal. In order to explain the lack of consistent findings, previous reviews have illustrated potential inconsistencies in the literature including the level of temperature exposure, the methodology utilized to elicit hyperthermia, the complexity of the cognitive tasks, the duration of heat exposure, and the skill level of the participants (Ramsey et al., 1992, Pilcher et al., 2002, Riniolo et al., 2006). In addition, the definition of hyperthermia has lacked consistency within the literature (Amos et al., 2000, Racinais et al., 2008) leading to a review by Gaoua (2010) suggesting that future studies should interpret data in relation to the dynamic change in T_{core}, the total thermal load as well as the duration of heat exposure but not by merely stating that hyperthermia was induced. Hydration status has also been shown to influence cognitive performance during active and passive hyperthermia (Sharma et al., 1986, Gopinathan et al., 1988, Cian et al., 2000, Cian et al., 2001) although many studies have failed to report the hydration status of their participants. There seems to be consensus that dehydration greater than a 2% loss in body mass does not affect simple cognitive tasks (Tomporowski et al., 2007) but has been shown to decrease speed and accuracy in more complex tasks related to visual motor tracking, short-term memory, and attention (Gopinathan et al., 1988). Simple tasks such as monitoring and choice reaction time have been reported to be impaired when dehydration of a 3 – 5% loss in body mass is induced (Bradley et al., 2003). Choma et al. (1998) reported that rapid weight loss in collegiate athletes of at least 5% body weight resulted in short-term memory impairments potentially due to the hypoglycemic state that was induced. However, tasks demanding sustained attention or visuomotor skills were not impaired (Choma et al., 1998) possibly due to the impact of high motivation eliminating any decrements in cognition resulting from hypoglycemia (Brozek, 1955). In a review by Gaoua (2010), the methodological discrepancies highlighted as the major influences in the inconsistent findings between heat stress and cognitive function include the determination of hyperthermia, active versus passive heating, hydration status, skill level of the participants, and the complexity of the cognitive tasks.

There are still numerous unanswered questions surrounding the effects of heat exposure during dynamic exercise on cognitive function in firefighters. It is unclear if the potential decline in cognitive performance during firefighting activities is the result of increased physiological strain or if heightened anxiety and other psychological aspects play a contributing role (Barr et al., 2010). It is unknown if years of firefighting experience would play a beneficial role for combating the detrimental effects on cognitive function in heat stress as the skill level of the individual appears to play a role (Hancock et al., 2003). One potential explanation is that cognitive performance may be reduced when cerebral blood flow is decreased due to heat stress (Nybo et al., 2001, Wilson et al., 2006) which appears to have an impact on cognitive tasks associated with working memory (Collette et al., 2002). However, despite a reduction in cerebral blood flow, cerebral oxygen extraction and cerebral metabolic rate are both increased (Nybo et al., 2002a, Rasmussen et al., 2010). In a review study by Barr et al. (2010), the authors concluded that future work should focus on performing simulated firefighting tasks, at the intensities and durations that reflect similar energy expenditures encountered by firefighters, while in a climatic chamber using computer-based cognitive function tests that are more realistic to the mental tasks encountered at emergency scenarios.

It is clear from this review of the literature that heat stress presents numerous challenges to physiological and cognitive demands required of firefighters, but very little has been done to assess cognitive function during conditions of heat stress. The CANTAB has been used to explore various aspects of cognitive function but there is little work on its reliability under conditions of repeated testing. An establishment of its use in short duration, repeated measures testing protocols will allow for more accurate conclusions of the particular intervention and its subsequent effects on different aspects of cognition. Another need is for ways to test and train task specific decision making related to firefighting activities. Serious Games offer a potential way to do this.

Serious games and virtual reality-based simulations (or virtual simulations) have grown as a form of teaching in many occupational settings, including medicine (Deutsch, 2009, Fairhurst et al., 2010, Kron et al., 2010, Marsh et al., 2010), rehabilitation (Rand et al., 2009, Cox et al., 2010, Kamper et al., 2010, Lange et al., 2010), baseball (Fink et al., 2009), and firefighting (St.Julien et al., 2003, Sowndararajan et al., 2008, Boulet, 2009, Toups et al., 2009). Using simulations of virtual buildings with virtual fire environments, trainees can interact with a changing environment, simulate various work-related procedures, and/or judge whether a building design is reasonable from a fire safety point of view. Virtual simulation permits trainees to make and correct mistakes while allowing them to experience situations that may not easily be recreated in the real-world due to ethical, cost, and time concerns. In contrast to traditional teaching environments where the teacher controls the learning (e.g., teacher-centred), serious games and virtual simulations present a learner-centred approach to education, so that the player controls the learning through interaction with the situation using an active, critical approach (Stapleton, 2004).   A detailed review of serious games and their use in the fire service is provided in Chapter 6, and Chapter describes the development of a fire fighter task level serious game.

Prior to developing a serious game for firefighter testing, the impact of heat stress on cognitive performance needs to be established with conventional cognitive tests. Experiments testing the effects of heat stress on cognitive function using the CANTAB testing battery be discussed in Chapter 4.

CHAPTER 3 – General Methods

This chapter provides details on the general methods implemented in the experimental designs for the studies described in Chapters 4 and 7. The experimental protocol in Chapter 5 is specific to that study and will be described later. The general methods for the studies in Chapters 4 and 7 include the physiological profile of the participants, physiological and psychophysiological measurements, fluid intake protocol, as well as active cooling recovery regimen.

3.1 Physiological Profile for Chapters 4 and 7

In order to obtain a physiological profile, all participants had their VO_{2peak} evaluated using an incremental treadmill exercise to exhaustion protocol on a motorized treadmill (Full Vision, Inc., Newton, KS) using the Modified Åstrand protocol (Pollock et al., 1978), followed by an evaluation of muscular strength and endurance that has been utilized in previous studies (Williams-Bell et al., 2009, Williams-Bell et al., 2010a, Williams-Bell et al., 2010b). For the incremental exercise test, following a 4 min warm-up at a brisk walking pace (4.8-6.4 $km{\cdot}h^{-1}$), speed was increased to a comfortable running speed for the participant (between 8 and 12.9 $km{\cdot}h^{-1}$) for 2 min followed by 2.5% increases in grade every 2 min thereafter (Pollock et al., 1978). The test was terminated when participants were unable to continue and reached volitional fatigue. VO_{2peak} was taken as the highest 20-s average during the final 2 min of the test. Body fatness was evaluated by four skinfold sites for men (triceps, subscapular, abdomen, and thigh) and then calculated using a specific formula developed by Jackson (1980) to predict percent body fat (%BF).

Muscular strength measures were obtained using a predictive one-repetition maximum (1-RM) protocol, as previously described Kraemer and Fry (Kraemer et al., 2006):

Predicted 1-RM Load Lifted= (1 - 0.025*reps)

Participants completed a warm-up of 5 repetitions with a load of 20.5 kg to become familiar with the test cadence. After a 1-min rest period, they performed the YMCA bench press endurance test lifting 36 kg to a metronome set at 30 repetitions per minute as many times as possible until the subject terminated exercise or could not maintain cadence. Upper body strength was predicted using the YMCA equation, 1-RM = 1.55 x repetitions + 37.9 (Kim et al., 2002). The same warm-up as the YMCA bench press was conducted on the incline leg press followed by determining a load to cause fatigue in fewer than 10 repetitions (Kraemer et al., 2006). A 3–5-min rest period preceded the next 1-RM test. The order of muscle testing was: maximal handgrip dynamometer (Takei Co. Ltd., Tokyo, Japan), flat bench press, seated 45° incline leg press, military shoulder press, and bent bar preacher curls for the biceps. Upper body endurance was assessed using the YMCA bench press protocol described above. Lower body endurance was measured with an absolute load of 123 kg placed on the incline leg press at a cadence of 25 repetitions/min. Subjects were required to lift the load until they were unable to maintain cadence (Williams-Bell et al., 2009, Williams-Bell et al., 2010a, Williams-Bell et al., 2010b).

3.2 Physiological Measurements

3.2.1 Core Temperature

Measurements of T_{core} were obtained using an ingestible telemetric pill (HQ Inc, Palmetto, FL) that sends a radio signal to a data recorder (HQ Inc, Palmetto, FL) connected to a computer, which measures T_{core} every 20s. Throughout the past six decades, technological advances have resulted in the development of a commercially available, small, ingestible, telemetric pill that can pass through the gastrointestinal (GI) tract and has been shown to be an accurate method for measuring T_{core} during dynamic exercise (Edwards et al., 2002, McKenzie et al., 2004, Gant et al., 2006) as well as being more acceptable by research participants (McKenzie et al., 2004). Research has shown that the elapsed time following ingestion of the GI pill will not only affect the location within the body (Gibson et al., 1981), but also how food and drink will affect the temperature measurements when the pill is located in the stomach or upper GI tract (Fox et al., 1962, Stephenson et al., 1992, Kolka et al., 1993, Brake et al., 2002). Wilkinson et al. (2008) examined the effects of cool water consumption (5 - 8°C) on 2 ingestible radio pills, 1 ingested 11.5 hours before the measurement period and the other at the start of the measurement period. The authors concluded that 10 hours following ingestion of the temperature pill, results in good agreement between the telemetry pill and rectal temperature, completely independent of fluid ingestion. Based on this information, in the current thesis, participants were required to ingest a core temperature radio-pill (HQ Inc, Palmetto, FL) approximately 6 to 9 hours prior to attending the heat stress trials.

3.2.2 Skin Temperature

Measurements for T_{sk} were obtained at 4 sites (chest, back, forearm, thigh) every 20s using skin thermistors (ACR Systems, Inc., Surrey, BC) that were taped to each anatomical area and connected to a data recorder. Mean T_{sk} was calculated using the formula [T_{sk} = (0.25 x chest) + (0.25 x back) + (0.2 x forearm) + (0.3 x thigh)] (Ayling, 1986). Data for mean T_{sk} was averaged over the duration of each of the cognitive or serious game trials.

3.2.3 Heart Rate Measurements

HR was monitored using a transmitter (Polar, Kempele, Finland) attached around the chest with a wearable strap. HR was continuously monitored using a receiver attached to the treadmill and recorded every 5 min or recorded every 20s in conjunction with T_{core} (HQ Inc, Palmetto, FL) and displayed on a computer screen, in real-time, during the entire experimental protocol and active cooling recovery phase.

3.2.4 Gas Exchange Measurements

Measurements of open-circuit spirometry were made using the Cosmed $K4b^2$ (Cosmed, Rome, Italy) during the experimental protocol and VO_{2peak} test. Due to the need for participants to wear their SCBA face-piece, during gas analysis the face-piece was removed and the Hans-Rudolph face mask was instrumented so the flowmeter and sample line could be connected to the participant. For the study depicted in Chapter 4, measurements were obtained when the participant mounted the treadmill following recovery after Cog 2 and Cog 3 for a duration of 5-min or until the cognitive assessment trial was completed if the subsequent trial (i.e. Cog 3 or Cog 4) was commenced prior to the completion of the 5-min collection. Data from the final 2-min of collection were averaged and reported. For the study depicted in Chapter 5, measurements were obtained during serious game play at FFTL 2, 3, and 4 for a duration of 5-min. Data from the final 2-min of collection were averaged and reported.

The Cosmed K4b^2 system is a portable unit (170 x 55 x 100 mm, 475 g) until that is affixed to the participant using a chest harness that is connected to a battery pack (170 x 48 x 90 mm, 330 g) strapped to the back of the participant. Measurements of gas volumes are accomplished using a flowmeter comprised of a bi-directional digital turbine and opto-electric reader measuring volumes within a range of 0 – 300 $L{\cdot}min^{-1}$. Within the opto-electric reader, three diodes detect the direction that the turbine is turning. The Cosmed K4b^2 system is equipped with O_2 and CO_2 gas analyzers to determine the metabolic cost of the particular activity. The O_2 analyzer is capable of measuring gas concentrations in the range of 7 – 24% with an accuracy of 0.02% while the CO_2 analyzer can measure in the range of 0 – 8% with an accuracy of 0.01%. The expired gases from the participant are transferred through a semi-permeable Nafion tube to the gas analyzers. The Nafion tube allows water vapour within the sample to be equilibrated with the surrounding environment. The soft, flexible facemask (Hans Rudolph, MO) covers the participant’s mouth and nose and is fastened to a Velcro head piece that is placed over the head. The particular mechanisms regarding how the Cosmed K4b^2 determines inspiratory and expiratory cycles and corresponding volume measurements has been previously described by Pinnington et al. (2001). The Cosmed K4b^2 has been shown to be a reliable gas analysis system (Duffield et al., 2004) with studies revealing a minimal bias

(Eisenmann et al., 2003) or valid measurements compared to the Douglas bag method for V_E, VO_2, VCO_2, and RER (Parr et al., 2001).

3.3 Fluid Replacement

Prior to the start of the experimental protocol, during each rest phase and active cooling recovery protocol, participants were given 5 $mL \cdot kg^{-1}$ (Selkirk et al., 2004b) of warm water (37°C) in order to avoid influencing measurements with the radio pill.

3.4 Subjective Measurements

Participants were asked to provide rating of perceived exertion (RPE) (Borg, 1970) on scale from 6 to 20, as well as thermal sensation (TS), and thermal comfort (TC) (Gagge et al., 1967) on 9-point scales, following the cognitive assessment trials while exercising on the treadmill (Cog 2, Cog 3, and Cog 4) in Chapter 4 and before and after each serious game trial in Chapter 5.

3.5 Active Cooling Recovery

Following completion of the cognitive assessment trial at the end of the treadmill protocol, participants were placed in active cooling recovery by sitting in a cooling chair (DQE, Inc., Fishers, IN) and submerging their hands and forearms in 15-20°C water until their T_{core} returned to 37.8°C, at which time they were presented with the final cognitive assessment trial.

3.6 Specific End-Point Criteria

Specific ethical end-point criteria were utilized for termination of the experimental protocols in Chapter 4 and 5: (1) completion of cog 4 assessment, (2) 4 hours of continuous work, (3) T_{core} reaching 39.5°C, (4) heart rate at or above 95% of maximal heart rate for 3 consecutive minutes, (5) participant volitional termination due to dizziness, nausea, exhaustion or discomfort from the exercise protocol or the PPE and SCBA, or (6) termination by the researcher due to equipment malfunction.

3.7 Cambridge Neuropsychological Test Automated Battery

The CANTAB is an automated cognitive testing battery that was originally designed as a clinical test to diagnose dementia in the elderly population (Fray et al., 1996). The CANTAB battery was administered in the current study to assess various aspects of cognition. The battery was presented using a Motion Computing ® tablet running Windows 7 software and the Intel® Core™ i3 processor. Both visual and auditory feedback were standardized within each testing battery and specific test instructions were provided in accordance with the CANTAB user manual (Cambridge Cognition, 2012). All auditory feedback elicited from the tests was given via the tablet’s speakers with the volume set to a level that was audible by the participant.

1. Spatial Working Memory (SWM)

The SWM test assesses an individual’s capacity to use working memory to recall spatial information and also manipulate items (Owen et al., 1990). It is useful in the evaluation of the frontal lobe and the ability of an individual to use heuristic strategy. Accordingly, the SWM test can be applied to evaluate executive dysfunction.

Display:

The participant is presented with a screen displaying coloured boxes. Within each trial, all boxes remain the same colour and in the same position. However, the colour and positioning used between trials changes to decrease the participant's familiarity with the task and, therefore, lower the chance of strategy acquisition. Initially, only 3 boxes are displayed. Then at each new level, the number of boxes increases and eventually 10 coloured boxes appear on screen.

Task:

In each trial, the participant must click the boxes to discover which one contains a blue 'token'. Once this token is found, the participant must tap the black column to the right of the screen to place them in the 'home space'. Each box will contain 1 token at some point during the exercise and only 1 box will contain a token at any one time. The dependent measures are total errors conducted and a score for strategy.

2. Rapid Visual Information Processing (RVP)

The RVP test is designed to assess an individual's overall performance, and more specifically, to detect any potential issues within the frontal and parietal lobes (Sahakian et al., 1989).

Display:

The participant sees a black screen displaying a white box. Then, in randomized order, digits begin to appear one at a time inside the box at a rate of 100 per minute. A practice phase, lasting 2-min, is included at the beginning of this task. Throughout this practice stage, both visual and auditory feedback are given to help prepare the participant for the subsequent testing phase. The testing phase follows, with no feedback, and lasts 4-min. The last 3-min of the 4-min test are evaluated.

Task:

In the practice level of the test, participants are required to recognize one sequence of three numbers in the order of 3-5-7. To demonstrate recognition of this sequence, they must use the button on the press pad. In the second part of the testing phase, the participant is required to recognize 3 sequences of 3 numbers each. These sequences include: 2-4-6, 3-5-7, and 4-6-8. Throughout the test, these sequences are displayed at the right hand side of the screen as a reminder to the participant. The rate at which these sequences are displayed is 16 sequences per 2-min. Responses are considered successful if they occur no longer than 1800 ms after the last digit in the sequence has appeared on screen. The CANTAB keeps a record of the number of correct and incorrect responses. Incorrect responses are registered when the participant misses a target sequence and also when a participant indicates recognition of a target sequence when the target sequence was, in fact, not displayed. The dependent measures for the RVP test are total correct rejections and response latency (the time between the last digit of a correct 3 digit sequence displayed and when the participant identified it as being correct).

3. Reaction Time (RTI)

The RTI test is designed to evaluate how quickly individuals respond to a visual stimulus. This assessment can evaluate an individual's ability to react to both predictable and unpredictable stimuli (Morris et al., 1987).

Display:

In the initial phase of the RTI test, simple reaction time (SRT), the participant will see the white outline of a circle in the centre of the screen. A yellow spot will then be presented inside the circle. In the second phase of this task, 5 choice reaction time (5RT), 5 circles are shown on screen, and the yellow spot will appear in any one of these circles.

Task:

To successfully complete this task, the participant must press and hold the button on the press pad. They must continue to hold this button until the yellow spot is displayed inside the white circle. Immediately following the appearance of the yellow spot, the participant must release the press pad button to tap the area on the screen where the spot was displayed. Similar to SRT, the 5RT requires the participant to hold the press pad button until a spot appears in one of the 5 circles on screen. Once the spot appears, the participant must select the correct circle as quickly as possible by releasing the press pad button and tapping the precise location on the screen.

4. Paired Associates Learning (PAL)

The PAL test evaluates visual episodic memory and function of the medial temporal region of the brain, which is particularly appropriate in the assessment of an individual’s ability to learn new things and remember visual information (Sahakian et al., 1988).

Display:

In the first 5 levels of the task, 6 white boxes are displayed on screen. In the final level of this task, 8 white boxes are displayed on screen. All boxes open one at a time and, depending on the level, a varying number will contain a pattern. Eventually, as the levels increase, all boxes displayed on screen will contain patterns.

Task:

All of the boxes displayed on screen will open in sequence to show their contents. Initially, only 2 of these boxes will contain patterns. This number will increase by 1 as the level increases. The order in which these boxes are opened is randomized. After all of the white boxes have been opened, the patterns that were displayed inside the boxes will be shown one by one in the centre of the screen. As the patterns appear, the participant must tap the corresponding white box that displayed the particular pattern. If the participant chooses all boxes correctly, they will move to the next level. If a mistake is made, the level will repeat. The test will be aborted if errors are made in 4 consecutive attempts. The dependent measure for this test is total errors on the 8-shape level, adjusted for participants who did not attain this level. This test has been shown to be able to assess memory and new learning in high-functioning individuals (Cambridge Cognition, 2012).

5. Spatial Span (SSP)

The SSP test is a computerized visuospatial analogue of the Corsi Block Tapping Test (Milner, 1971) and assesses visuospatial working memory and the capacity of the frontal lobe.

Display:

Ten white boxes are displayed on screen with a certain number of boxes turning colour, one at a time, depending on the difficulty of the test.

Task:

The level of difficulty for the SSP test ranges from 2 boxes changing colour up to 9 boxes at the most difficult level. At any given level of difficulty, once all boxes in the sequence have changed colour, a tone sounds to prompt the participant to begin the task. The participant must then select the boxes in the same order in which they turned colour. The number, order, and location of the boxes which turn colour vary according to the level of difficulty. In addition, the colour used in each sequence also varies. If the participant completes 3 consecutive trials incorrectly, the test will end. The dependent measure for this test is the total span length successfully achieved.

CHAPTER 4 - The effects of exercise-induced heat stress on cognitive function in firefighters

Preface to Chapter 4

The physiological demands of firefighting have been extensively researched over the past four decades and have been able to quantify the oxygen and respiratory requirements of a variety of job tasks. Involved in these physical job tasks are important decisions that may be the difference between a safe work environment and casualty. It has been suggested that firefighting tasks require firefighters to make critical decisions, remain vigilant and attentive, and have elevated spatial awareness to identify various locations within a structure in order to safely exit (Barr et al., 2010). With this knowledge, firefighters' experiences and knowledge of the critical decisions require at an emergency scenario were examined through qualitative research methods. Interview guides with open-ended questions were developed to obtain information from three firefighters using semi-structured subject matter expert interviews. This information provided valuable feedback to structure the focus group interview guide that was conducted with twelve current career firefighters ranging from the rank of Firefighter to District Chief. The findings indicated that the crucial cognitive tasks required of a firefighter pertain to cognitive domains including sustained attention, working memory, executive function, spatial awareness, and reaction time. The specific details of the qualitative analyses are beyond the scope of this thesis.

Previous research examining cognitive function in firefighters has either employed simple reaction time (Barr et al., 2010), assessed cognition 30-min following heat exposure (Rayson et al., 2005), or use pre- and post-test measurements only (Morley et al., 2012). Few research designs have utilized T_{core} as the independent variable (Selkirk et al., 2008, Wright et al., 2012b); however, cognitive function was not the dependent measure in these studies. In addition, when cognitive function was measured, it was assessed at time points before, immediately after, and at some duration following exercise. Chapter 4 examines the relationship between various aspects of cognitive function and the effect of raising T_{core} in two environmental temperatures: 1) 30°C and 50% relative humidity and 2) 35°C and 50% relative humidity. The aim of this study was to answer research objective 1. Additional results not detailed in this chapter for the physiological profile, HR, gas exchange, and subjective measures can be found in Appendix A.

4.1 Abstract

The aim of this study was to determine the effects of differing rates of increasing T_{core} on cognitive function during EIHS. Nineteen male firefighters were exposed to repeated cognitive assessments, randomized and counter-balanced, in 30°C and 35°C and 50% humidity. Participants performed treadmill walking (4.5 $km{\cdot}h^{-1}$ and 2.5% grade) with cognitive function assessed before exercise (PRE), after mounting the treadmill (Cog 1), at T_{core} of 37.8°C (Cog 2), 38.5°C (Cog 3), and 39.0°C (Cog 4), after dismounting the treadmill (POST), and following an active cooling recovery to a T_{core} of 37.8°C (REC). The cognitive tests implemented at PRE and POST were spatial working memory (SWM), rapid visual information processing (RVP), and reaction time (RTI) while paired associates learning (PAL) and spatial span (SSP) were assessed at Cog 1,

Cog 2, Cog 3, and Cog 4. All five cognitive tests were assessed at REC. Planned contrasts revealed that SSP and PAL were impaired at Cog 3, with SSP also impaired at Cog 4 compared to Cog 1. REC revealed no difference compared to Cog 1, but increased errors compared to Cog 2 for PAL. The decrements in cognitive function observed at a T_{core} of 38.5°C are likely attributed to the cognitive resources required to maintain performance being overloaded due to increasing task complexity and external stimuli from EIHS. The addition of an active cooling recovery restored cognitive function to initial levels.

4.2 Introduction

Firefighting requires tremendous physical and cognitive resources to perform safe and effective operations (Barr et al., 2010). Cognitive demands for firefighters include assessing and executing critical decisions along with situational awareness to determine the safest means of exiting the emergency scene (Barr et al., 2010). Research about the effects of thermal stress on cognitive function for firefighters is limited.

A limitation of previous work using simple cognitive tasks relates to the lack of sensitivity to changes in cognitive function that occur during or following firefighting activities in the heat (Smith et al., 1998). One study addressed this by using a standardized testing battery, the Cambridge Neuropsychological Test Automated Battery (CANTAB), which assesses more complex cognitive tasks, such as sustained attention and working memory capacity, as well as reaction time (Rayson et al., 2005). No impairments in cognitive function were revealed with the live-fire simulation, however, the cognitive tests were administered 30 min after the heat stress protocol, which may have allowed any negative effects of heat stress to dissipate (Rayson et al., 2005).

Despite limited research on firefighters, numerous studies have examined the effect of heat stress on cognitive function within the general population. Early data suggested it was the dynamic change in T_{core} that limited cognitive function and not the absolute T_{core} attained (Allan et al., 1979a). In a review of the literature, Hancock et al. (1998) proposed new threshold curves for the dynamic rise in deep body temperature for vigilance, dual-task demands, neuro-muscular coordination tasks, simple mental performance, and the physiological tolerance limit at 0.055, 0.22, 0.88, 1.32, and $1.65^{\circ}C \cdot h^{-1}$, respectively. Further, it appears that task complexity is a major factor on performance in the heat (Hancock et al., 2003). In a subsequent review, Hancock et al. (2003) suggested that more complex tasks including vigilance, tracking, and multiple tasks conducted simultaneously are more vulnerable to heat stress than simple tasks, such as reaction time and mental transformation. Previous work has shown using a passive heat stress and fMRI model that various regions of brain activation can be affected when compared to a temperate condition, whether or not performance is impaired (Sun et al., 2012, Liu et al., 2013).

This study aimed to examine the effects of EIHS on cognitive function using T_{core}, rather than time of exposure, as the independent variable (Wright et al., 2012a). The impact of differing rates of increase in T_{core} were studied together with an active cooling recovery similar to that performed on the fire ground (Selkirk et al., 2004a). We hypothesized that aspects of cognitive function relevant to firefighting would be impaired with increasing levels of T_{core} and subsequently restored following active cooling recovery.

4.3 Methods

The research protocol was approved by the Office of Research Ethics at the University of Ontario Institute of Technology (REB #13-076) and informed written consent was obtained prior to participation in the study. Nineteen male firefighters were recruited to take part in each phase of testing. Participants were requested to refrain from vigorous exercise, alcohol, non-steroidal anti-inflammatories, and sleep medication in the 24 hours prior to testing and to refrain from consuming alcohol or nicotine 12 hours prior to arrival. Inclusion criteria were (1) incumbent firefighter, (2) age less than 50 years, (3) not currently taking medication, and (4) urine specific gravity (USG) less than 1.030, (values higher indicate serious dehydration (Casa et al., 2000)), prior to the EIHS protocol.

Testing was conducted on 3 separate days, 1 day for familiarization of the CANTAB battery, and 2 days for the EIHS and cognitive function protocols. All EIHS trials were conducted at the University of Ontario Institute of Technology's ACE climate chamber at 30°C or 35°C and 50% relative humidity, with wind speed maintained at ≤ 0.1 $m{\cdot}s^{-1}$. The EIHS trials were randomized and at least 28 days apart during the winter months (January through April) to limit any potential effects of acute heat acclimation by the firefighters (Selkirk et al., 2004b).

Nine participants attended the climate chamber at 0800 h and 10 participants began testing at 1200 h on both testing days after ingesting a T_{core} radio-pill (HQ Inc, Palmetto, FL) approximately 6 to 9 hours prior to attending the EIHS trials. Upon arrival, each participant had their nude body mass measured on a digital scale (Tanita, Arlington Heights, IL) to 0.1 kg and USG analyzed (Atago Co., LTD., Tokyo, Japan). Physiological measurements included T_{core}, heart rate (HR) using a transmitter (Polar, Kempele, Finland) attached around the chest with a wearable strap, and percent body fat was evaluated by four skinfold sites (triceps, subscapular, abdomen, and thigh) and then calculated using a specific formula developed by Jackson et al. (1980). Subjective measures of thermal sensation (Gagge et al., 1967) and RPE (Borg, 1970) were recorded immediately following cognitive tests (Cog, 2,3 and 4).

Once instrumented, participants (wearing station gear consisting of pants and short-sleeved t-shirt) donned their bunker pants (PPE1) and completed the pre-test (PRE) cognitive assessment. Then, participants donned their jacket, flash hood, gloves, helmet, and self-contained breathing apparatus (SCBA) with face-piece (PPE2). Participants began treadmill walking at 4.5 $km \cdot h^{-1}$ and 2.5% grade while performing Cog 1. Treadmill walking continued until they either completed: (i) 30 min of exercise, at which time they would receive a 5-min rest break and wear PPE1and jacket or (ii) reached a level of 37.8°C where they would then complete Cog 2. Following Cog 2, participants were seated for 10-min wearing only PPE1 and jacket. After, participants donned PPE2 and completed the same work to rest ratio until T_{core} reached levels of 38.5°C (Cog 3) and 39.0°C or declaring 10-min of exercise remaining until volitional fatigue (Cog 4). Participants removed PPE2 and performed the post-test (POST) while seated. Next, participants were placed in active cooling recovery by sitting in a chair (DQE, Inc., Fishers, IN) and submerging their hands and forearms in 15-20°C water until their T_{core}

returned to 37.8°C and then completed the recovery (REC) cognitive assessment trial. Previous work has suggested that the final T_{core} of firefighters in similar ambient conditions is approximately 39.0°C (Selkirk et al., 2004b). This study utilized T_{core} as the independent variable rather than time of exposure (Wright et al., 2012a) with similar targets of T_{core} as investigated by Gaoua et al. (2011a).

Due to volitional fatigue, only 13 and 12 participants were able to reach Cog 4 in the 30°C and 35°C conditions, respectively. To mitigate the potential for dehydration, participants were given 5 $mL \cdot kg^{-1}$ (Selkirk et al., 2004b) of warm water (37°C) before PRE and following Cog 2, 3, 4, and active cooling recovery to avoid influencing measurements with the radio-pill. Upon completion of REC, participants removed their PPE within 5-min and toweled off any remaining sweat to determine final nude mass.

Cognitive function was assessed using the CANTAB battery (Cambridge Cognition, Cambridge, UK), specifically (i) visual episodic memory, PAL, ii) processing and psychomotor speed, RTI, (iii) visuospatial working memory, SSP, iv) working memory and strategy, SWM, and v) sustained attention, RVP. During exercise (Cog 1, 2, 3, 4) only PAL and SSP were assessed, whereas before (PRE) and after exercise (POST and REC) the complete CANTAB battery was performed. A detailed description of the 5 cognitive tests can be found in Chapter 3.

There was no main effect of time of day on the performance of cognitive function. As a result, all participants were grouped together for subsequent analyses. Normality for each of the dependent variables was confirmed using the Shapiro-Wilks test. A two-within (cognitive trial x condition) repeated measures ANOVA was conducted on dependent measures for RTI, SWM, RVP, TS, RPE, and overall ΔT_{core}. Simple effects analysis using a Bonferroni correction was conducted when a significant interaction effect was found. Linear mixed model (LMM) analyses were performed for PAL, SSP, PSI, and ΔT_{core} during each cognitive trial. Condition and cognitive trial were entered into the model as fixed factors, with subjects entered as a random factor for the PAL, SSP, and PSI analysis, whereas condition and time were entered as fixed factors for ΔT_{core}. The covariance structure for repeated measures was auto-regressive (AR1) with the interaction removed from the final model when nonsignificant. *A-priori* planned contrasts were analyzed compared to PRE (for SWM, RVP, RTI) or Cog 1 (for PAL, SSP) for each cognitive assessment trial and Cog 2 for all trials to determine effects of active cooling recovery.

The dynamic change in core temperature (ΔT_{core}), the initial T_{core}, the final T_{core}, pre-nude body mass, percent change in body mass, hydration, USG, and end-point HR were each compared between conditions using paired t-tests. Statistical significance for all analyses was set at an alpha level of ≤ 0.05. Data are presented as the mean ± standard error of the mean.

4.4 Results

Mean vales for age, years of firefighting service, body mass, height, body mass index (BMI), and percent body fat were 35.6 ± 2.0 years, 10.0 ± 2.1 years, 85.1 ± 2.9 kg, 1.76 ± 0.07 m, 27.3 ± 0.7 $kg \cdot m^{-2}$, and 16.7 ± 1.3%, respectively. Data for initial and final T_{core}, ΔT_{core}, T_{core} at the start of each cognitive trial, exposure time, work duration, end-point HR, change in body mass, and fluid intake are depicted in Table 1. Final T_{core}, ΔT_{core}, exposure time, and work duration were all significantly greater in 35°C ($p \leq 0.05$).

Figure 4.1 reveals data for ΔT_{core} (normalized to the percent of the protocol completed to account for varying exposure times between participants) over the duration of heat exposure (Figure 4.1A) and during the individual cognitive trials (Figure 4.1B). ΔT_{core} over the duration of heat exposure revealed an interaction effect (condition x cognitive trial) with simple effects revealing 35°C was elevated at 40, 50, 60, and 70% of the protocol completed ($p \leq 0.05$). Individual LMMs of ΔT_{core} at each cognitive trial revealed a main effect of condition with 35°C greater at Cog 2, 3, 4, and POST ($p \leq 0.05$).

Simple reaction time (Figure 4.2A) revealed a main effect of cognitive trial ($p \leq 0.05$) with planned contrasts revealing a faster reaction time at POST ($p \leq 0.05$). SWM token search time (Figure 4.2B) revealed a main effect of cognitive trial ($p \leq .05$). Total correct rejections (Figure 4.2C) for the RVP test revealed a main effect of cognitive trial ($p \leq 0.05$) with planned contrasts showing increases in correct rejections at POST ($p \leq 0.05$) compared to PRE. RVP latency (Figure 4.2D), indicating the time to respond following a correctly identified three-digit sequence, revealed a main effect of cognitive trial ($p \leq 0.05$) with planned contrasts indicating a faster latency at POST ($p \leq 0.05$) compared to PRE.

PAL total errors at the 8-object level, adjusted for test termination prior to this level, (Figure 4.2E) revealed a main effect of cognitive trial ($p \leq 0.05$) with planned contrasts indicating at Cog 3 there were significantly more errors compared to Cog 1 ($p \leq 0.05$). Planned contrasts revealed a difference between Cog 2 and REC ($p \leq 0.05$) with no difference between Cog 1 and REC. Span length (Figure 4.2F) observed during the SSP test revealed a main effect of cognitive trial ($p \leq 0.05$) with planned contrasts indicating a significantly shorter length achieved at Cog 3 and Cog 4 ($p \leq 0.05$) compared to Cog 1. All other cognitive variables revealed no main effects.

TS revealed a main effect of time ($p \leq 0.05$) with post-hoc analysis indicating that participants reported feeling hotter at Cog 3 (3.2 ± 0.2, 3.4 ± 0.1) and Cog 4 (3.4 ± 0.2, 3.6 ± 0.1) compared to Cog 2 (2.5 ± 0.2, 2.8 ± 0.2) in the 30°C and 35°C conditions, respectively ($p \leq 0.05$). RPE revealed a main effect of condition, time, and interaction ($p \leq .05$) with values in the 30°C condition of 12.2 ± 0.3, 15.4 ± 0.6, 16.4 ± 0.7 and in the 35°C condition of 13.6 ± 0.6, 15.5 ± 0.6, 16.4 ± 0.7 for Cog 2, Cog 3, and Cog 4, respectively. Simple effects analysis between conditions revealed a significantly lower RPE at Cog 2 in the 30°C condition, while within-group analysis indicated that Cog 2 was significantly lower than both Cog 3 and Cog 4 ($p \leq 0.05$) for both conditions.

Table 4.1: Data for T_{core}, starting T_{core} at each cognitive trial, total exposure time, work duration, end-point HR, Δbody mass, and fluid intake.

Measurement	30°C & 50% Humidity	35°C & 50% Humidity
Initial T_{core} (°C)	37.2 ± 0.1	37.1 ± 0.1
Final T_{core} (°C)	38.8 ± 0.1	39.1 ± 0.1[a]
ΔT_{core} (°C·hr^{-1})	0.85 ± 0.1	1.40 ± 0.1 [a]
PRE (°C)	37.2 ± 0.1	37.2 ± 0.1
COG 1 (°C)	37.2 ± 0.1	37.1 ± 0.1
COG 2 (°C)	37.8 ± 0.01	37.8 ± 0.01
COG 3 (°C)	38.5 ± 0.02	38.5 ± 0.03
COG 4 (°C)	38.8 ± 0.1	39.0 ± 0.03
POST (°C)	38.8 ± 0.1	39.1 ± 0.1
REC (°C)	37.8 ± 0.04	37.8 ± 0.03
Exposure time (min)	122.3 ± 6.0	85.2 ± 3.8[a]
Work duration (min)	84.3 ± 3.2	62.0 ± 3.5[a]
End-point HR (bpm)	156 ± 4	163 ± 4
Δbody mass (%)	-1.1 ± 0.2	-1.1 ± 0.3
Fluid Intake (%)	94.4 ± 2.9	92.9 ± 3.9

[a]denotes significantly different from 30°C & 50% humidity condition ($p \leq 0.05$)
T_{core} = core temperature

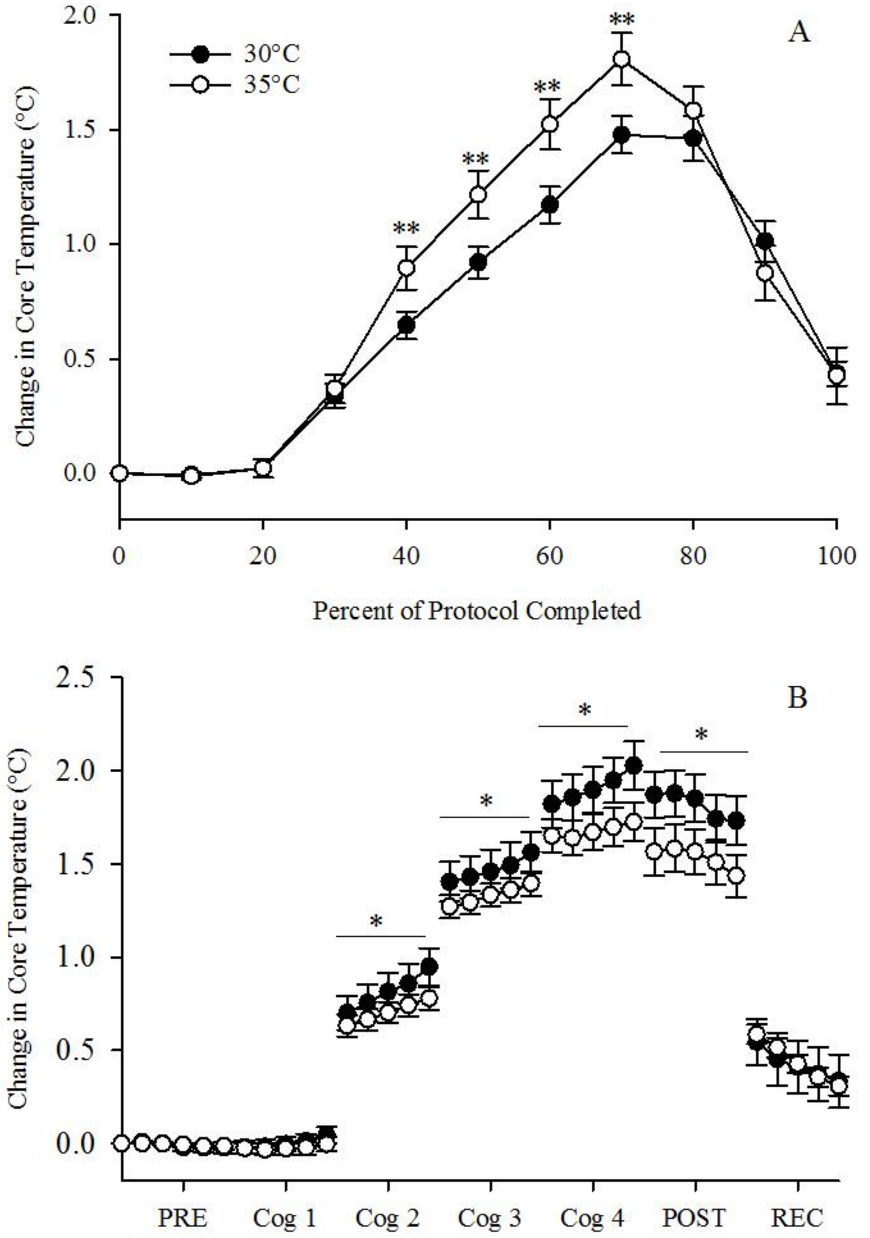

Figure 4.1: Physiological data for ΔTcore (A; normalized to percent of protocol completed) and ΔTcore (B) during each of the cognitive assessment trials (normalized from 0 – 100% of trial completed).
*indicates different from 30°C ($p \leq 0.05$)
**indicates main effect of condition ($p \leq 0.05$).

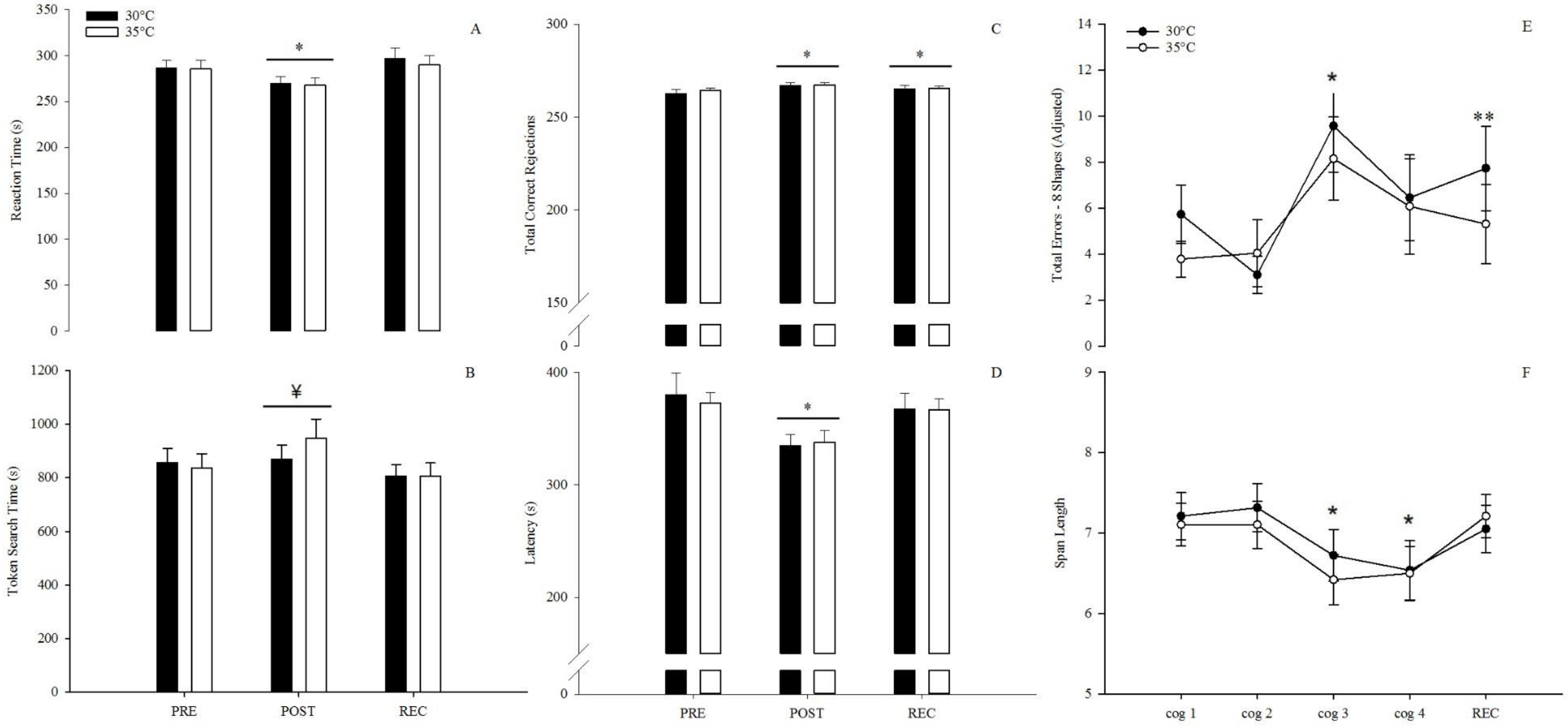

Figure 4.2: Data from the simple reaction time (RTI) test (A), spatial working memory (SWM) test (B), rapid visual information processing (RVP) test (C and D), PAL test (E), and SSP test (F) for the 30°C (closed circles) and 35°C (open circles) conditions.

*indicates main effect of cognitive trial ($p \leq 0.05$) with planned contrasts revealing different from PRE or Cog 1 ($p \leq 0.05$).

¥indicates main effect of cognitive trial ($p \leq 0.05$)

**indicates planned contrasts different from Cog 2 ($p \leq 0.05$)

4.5 Discussion

This study found impairments in visuospatial working memory, visual episodic memory, and executive function once a T_{core} of 38.5°C was attained at two different rates of increasing T_{core} (0.85 and 1.40°C$\cdot$hr^{-1}), with accompanying elevations in HR and psychophysiological indices. The implementation of an active cooling recovery restored cognitive function to initial levels. Firefighters performing moderate-intensity activities at an emergency scene in a hot, humid environment will be challenged with increased metabolic rate, impaired thermoregulation due to PPE, as well as elevated T_{sk} and HR. The current data reveal that reaching a T_{core} of 38.5°C may impair aspects of cognitive function.

One explanation for the impairments observed in cognitive function is the Global Workplace Theory (GWT) suggested by Baars (1993). The GWT suggests that the cognitive capacity of humans is limited by the various external stimuli constantly competing for the limited conscious processes available to successfully execute the proper outcome of a task (Baars, 1993, Baars, 2005). Similarly, the inclusion of a motor task (treadmill walking) during the SSP and PAL tests resulted in a motor plus cognitive task. Dietrich (2006) proposed the transient hypofrontality theory, stating that dynamic movements of the body require an increase in brain activation, which appears to specifically affect the prefrontal cortex by reallocating neural resources to perform cognitive tasks. Previous studies have shown that the Corsi Block Test, analogous to the SSP test, generates significant activation in the ventro-lateral prefrontal cortex (Qian et al., 2014) as well as a neural network encompassing the visual occipital, posterior parietal, and dorsolateral prefrontal cortices (Nybo et al., 2002a), and the hippocampus during encoding of spatial locations (Morley et al., 2012). The potential reallocation of neural resources from the prefrontal cortex may provide an explanation for the impaired performance in the SSP test.

In addition, the PAL test has been shown to increase activity in the hippocampus (during encoding of a newly shown object) and parahippocampal gyrus (during retrieval of the location of the object) with increasing task complexity (Robinson et al., 2013). Previous research has found that exercise and hyperthermia resulted in reduced middle cerebral blood flow (Nybo et al., 2001) with regional decreases in the hippocampus and prefrontal cortex (Qian et al., 2014). However, subsequent research showed that the reduction in global cerebral blood flow (gCBF) during exercise, producing an increase in T_{core} of 1.6°C, resulted in a 7% increase in cerebral oxygen uptake, likely attributed to a Q_{10} effect of higher tissue temperature (Nybo et al., 2002a). In addition, Qian et al. (2014) found regional blood flow decreases in the hippocampus and prefrontal cortex following passive heat stress in 50°C. The current findings suggest the increase in cognitive resources required to perform the SSP and PAL tests at a T_{core} of 38.5°C combined with exercise resulted in impaired cognition.

Active cooling recovery to a T_{core} of 37.8°C resulted in restoration of visuospatial memory and visual episodic memory to initial levels. Previous work has reported decrements in memory recall 60 and 120-min following treadmill exercise at 33-35°C (Morley et al., 2012) as well as impairments in visual declarative memory immediately following a simulated fire emergency with reductions in working memory 20-min post simulation (Robinson et al., 2013). Cognitive impairments following an emergency scenario can put firefighters in increased danger upon performing additional duties, reexposure at the scene, or emergency calls later in their shift. The data from the current study reveal the importance of an active cooling recovery protocol not only to reduce physiological strain but also improve cognitive function to perform duties within the same work shift.

The direction of T_{core} declined during the POST and REC cognitive assessments, which may explain the lack of observed impairments. Allan and Gibson (Allan et al., 1979a) have shown that the direction of ΔT_{core} may have a substantial impact on cognitive function, with greater impairments observed when T_{core} is rising compared to falling between T_{core} of 37.9 and 38.5°C. The cognitive task implemented took 60s to complete, and, although not specifically stated by the authors, T_{core} would have been falling up to 0.3°C during each assessment, similar to the changes in the current study. Hancock (1986b) has also suggested that achieving heat balance, separate from the degree of T_{core} increases, can result in restoration of cognitive function. In contrast, similar to previous findings, simple reaction time (Smith et al., 1998) and latency reaction time on the RVP test (Schlader et al., 2015) were faster immediately post-heat stress and then returned to initial levels following active cooling recovery. In addition, recent studies have shown changes in brain activation during passive heat stress despite no change in task performance (Hocking et al., 2001, Liu et al., 2013) suggesting that participants in the current study may have executed varying levels of neuronal activity to produce the same level of task performance (Kempton et al., 2011).

The findings in this study have potential applications for Incident Commanders who are in charge of strategic and tactical planning while at an emergency scenario. Based on the “Incident Commander’s Guide” developed by McLellan et al. (2006), firefighters performing moderate-intensity work (such as primary search, overhaul, ladder setup, and vehicle extrication) at 35°C and 50% humidity would attain a T_{core} of 38.5°C in 53-min. Firefighters in the current study required 58.2 ± 4.5-min to reach a T_{core} of 38.5°C. These findings suggest that aspects of cognitive function are impaired after performing specific job tasks in this condition for approximately 50 to 60-min. With this knowledge, Incident Commanders will be able to move firefighters to an active cooling recovery station before sending them back into the emergency scenario. Furthermore, this is the first study to show that cognitive function appears to be restored to initial levels after an active cooling recovery following EIHS, emphasizing the need for active cooling recovery during firefighting job tasks in hot environmental conditions (Selkirk et al., 2004a).

4.6 Conclusion

This study found that at two different rates of increasing T_{core} visuospatial working memory, visual episodic memory, and executive function, were impaired when T_{core} reached a level of 38.5°C, with continued impairments in visuospatial working memory and executive function at T_{core} of 39.0°C. These data, combined with previous findings, can be applied to any emergency scenario while working in the heat to provide the fire service with information regarding the length of time firefighters can perform job tasks before reaching levels that may result in impaired cognition. This study confirms the necessity of an active cooling protocol following work in the heat to not only reduce T_{core} but to simultaneously reduce the impact on cognitive function before performing further job tasks.

4.7 Practical Implications

- Impairments in certain aspects of cognition may occur as early as a T_{core} of 38.5°C given that the dynamic rate of increase is at least $0.85°C \cdot hr^{-1}$.
- Performing moderate intensity work can elicit this level of T_{core} in under one hour.
- Implementing an active cooling recovery protocol using forearm submersion in a water bath can return cognitive function to pre-exercise levels.

CHAPTER 5: Reliability and practice effects of the CANTAB cognitive assessment battery during treadmill walking

Preface to Chapter 5

The results from Chapter 4 provide a better understanding of the T_{core} value during moderate intensity firefighting tasks when cognitive function may become impaired. Through combining these findings with previous research (McLellan et al., 2006) the fire service can determine the safe work duration of their personnel before attaining a T_{core} of 38.5°C and can minimize the potential risk of impaired cognition. However, the specific research design of implementing repeated measures cognitive testing with dynamic exercise highlights the need to further understand the limitations of the CANTAB battery and the potential practice effects that may result.

The use of repeated measurements to assess cognitive function requires the examination of the test-retest reliability of the assessment battery to determine the direct effects of a specific protocol or intervention. In parallel to the study conducted in Chapter 4, a research design was developed to determine the feasibility of administering the CANTAB testing battery during treadmill walking as well as determine the effects of repeated cognitive measurements. Despite the use of CANTAB in thousands of research studies, only one study has examined the test-retest effects of specific assessments from the cognitive battery (Lowe et al., 1998). In addition, the retest session occurred 4 weeks after the initial test, which does not provide adequate information on the potential practice effects that may arise within a single session. Being able to determine the reliability of the various tests employed by CANTAB can help identify the cause of any decrements that occur due to EIHS. The aim of this chapter was to answer research objective 2.

5.1 Abstract

There is growing interest in the role of exercise on neural function. The Cambridge Neuropsychological Test Automated Battery (CANTAB) provides an easy to administer cognitive testing battery that provides standard administration of each test and could potentially be used to assess changes in cognitive function during acute exercise. However, there is limited information on its test-retest reliability or practice effects of the CANTAB and none on its reliability when administered during exercise. The aim of this study was to determine the test-retest reliability and identify potential practice effects from repeated measures cognitive testing within and between two sessions separated by at least five days. A secondary aim was to determine the feasibility of administering the CANTAB during treadmill walking. Twenty-three male university aged participants were randomly assigned to either the exercise (20.8 ± 0.9 years) or control (21.8 ± 1.9 years) groups. Both groups had their cognitive function assessed using 5 CANTAB tests (SWM, RVP, RTI, PAL, SSP) before and after the protocol. In addition, 2 of the tests (spatial span and paired associates learning) were evaluated following 10-min of light intensity exercise while walking on a motorized treadmill (4.5 km.h-1, 0% grade) followed by 5-min of seated rest. This work to rest ratio was continued until 5 serial measures were completed. The control group was assessed at the same time points following seated rest. Intraclass correlation coefficients (ICCs) were calculated for each dependent measure (28 measures per group). ICCs were similar for both exercise and control groups with 17 of 28 for the non-exercise group and 16 of 28 had ICCs greater than 0.60, which is

considered “good” reliability (Cicchetti et al., 1981). In addition, practice effects were noted on dependent measures for the spatial working memory and rapid visual information processing tests, with an improvement in paired associates learning only observed in session 1. The CANTAB is a feasible testing battery to be incorporated into treadmill walking experimental designs with no impact on cognitive function when compared to a seated rest control group. However, familiarization with 2 to 5 trials may provide additional experimental design benefits to help reduce any effect of practice on repeated cognitive measurements.

5.2 Introduction

Due to the efficiency and accuracy of modern technology, computer-based systems have become extensively used in research and clinical settings. Over the last thirty years, automated testing batteries, designed to assess various aspects of cognitive function, have become more common (Smith et al., 2013). These computerized testing batteries can simultaneously record several aspects of the participant’s test performance such as response time, number of correct responses, and strategy in a much more efficient way which would not be possible with traditional pen and paper tests (Schatz et al., 2002)**.** In addition, all feedback given to the participant when using a computerized battery is consistent between trials (Fray et al., 1996). The ability to provide multiple cognitive testing trials over a specified period of time can assist in determining changes due to a particular intervention or condition (Lowe et al., 1998). However, the use of repeated measures in cognitive testing relies greatly on the assumption that each individual assessment has a high test-retest reliability, which is not commonly found for the majority of neuropsychological testing batteries (Lowe et al., 1998).

One of the computerized cognitive assessment batteries that is commonly used was designed at the University of Cambridge and is known as the Cambridge Neuropsychological Test Automated Battery, or CANTAB (Levaux et al., 2007). The CANTAB has been used for assessment of cognitive function in several clinical populations, which include individuals living with psychiatric disorders (Potvin et al., 2005) and neurodegenerative diseases (O'Connell et al., 2004, Égerházi et al., 2007), as well as those who have undergone neurosurgery (Fray et al., 1996). Under certain conditions, such as monitoring cognitive function over a longer period of time, a single battery must be completed multiple times in a repeated measures design. When employing repeated measures in research, the potential increase in performance based solely on practice effects must be determined and controlled for.

Research regarding the test-retest reliability of the CANTAB has been limited with only one known publication, which utilized participants between 60 and 80 years of age (Lowe et al., 1998). Lowe et al. (1998) considered test-retest reliability to be acceptable if the intraclass correlation (ICC) coefficient was higher than 0.75 to 0.80. For total errors on the spatial working memory test (0.68) and spatial span length (0.64), ICC reliability values were lower than expected. However, the average trials to success on the paired associate memory test had a higher reliability coefficient (0.86). The authors concluded that a test-retest interval of approximately 4 weeks reveals a high potential to yield inaccurate results. This suggests practice effects could impact test scores and make the CANTAB less than ideal for use in research that requires repetitive administration of the same battery. However, that study did not test reliability during repeated measures within a single session over a short duration repeated measures design.

One reason that certain batteries have lower test-retest reliability than others is due to the potential of acquiring a particular strategy for performance, which can occur once an adequate number of trials have been completed (Lowe et al., 1998). Uncovering an optimal strategy leads to improved test performance; however, decreased test performance will result if an ineffective strategy is utilized (Lowe et al., 1998). It has been shown that tests which are most significantly impacted by strategy development are those which involve the frontal lobe (Lowe et al., 1998).

The CANTAB is utilized to assess cognitive function across several domains: 1) memory, 2) executive function, 3) attention, 4) decision making, and 5) social cognition. The information gathered from the aforementioned studies (Lowe et al., 1998, Falleti et al., 2006) is useful in understanding the limitations of computerized cognitive testing and is, therefore, very important to consider when designing short-interval repeated measures protocols involving the CANTAB battery.

One previous study assessed reliability of a computerized cognitive assessment tool known as the CogState battery and found that with short test-retest intervals of only 10-min, practice led to notably improved performance between the first and second trials with no further improvement subsequent trials completed within the same session (Falleti et al., 2006). Similar research to the Falleti et al. (2006) study is required to evaluate the use of repeated testing with the CANTAB.

There is continued interest in the effect of acute exercise on brain function due to the equivocal findings in the literature. A recent meta-analysis suggested that there was a small, positive effect of acute exercise on cognition when assessed during exercise, immediately after exercise, and after a delay (Chang et al., 2012). However, a number of initial reviews concluded that there is little support that acute exercise significantly influences cognition (Tomporowski et al., 1986, Etnier et al., 1997, McMorris et al., 2000). In a practical context, when assessing cognitive function in relation to exercise, testing would need to be administered before, during, and after performing an activity. The CANTAB could be a useful testing battery for applied occupational and exercise research, however there is no data available on its reliability where participants complete the tests while performing a physical task.

Therefore the goal of the current study was to determine 1) whether there are practice effects for the CANTAB assessment battery over short duration repeated measurements, 2) determine the reliability of CANTAB outcome measures when administered repeated times both on the same day and one week apart, and 3) to determine the feasibility of administering the CANTAB during dynamic movement through treadmill walking. The reliability of 5 different tests from the CANTAB battery, which covered a range of different cognitive abilities was assessed. These tests included Spatial Working Memory (SWM), Rapid Visual Information Processing (RVP), Reaction Time (RTI), Paired Associates Learning (PAL), and Spatial Span (SSP).

5.3 Methods

5.3.1 Participants

Two groups (exercise and non-exercise) of individuals took part in this study with the first group being examined while conducting treadmill walking and the second group being tested without exercise. Participants were recruited from the University of Ontario Institute of Technology community and informed written consent was obtained prior to participating in the study. The research protocol was approved by the Office of Research Ethics at the University of Ontario Institute of Technology (REB# 12-076). Twenty-three male participants were recruited from an undergraduate university population and designated into either the non-exercise (N = 12; 21.8 ± 1.9 years) or exercise (N = 11; 20.8 ± 0.9 years) groups. Males were utilized to control for gender effects and provide information on practice effects when using the CANTAB in a similar experimental protocol in our laboratory (Williams-Bell et al., 2015b).

5.3.2 CANTAB Cognitive Testing Battery

The specific testing protocol consisted of 5 tests from the CANTAB assessment battery, which included SWM, RTI, RVP, SSP, and PAL. These 5 tests were selected based on their inclusion in a parallel study that represented the cognitive tasks required of firefighters (see Chapter 4; Williams-Bell et al., 2015b) and cover many of the cognitive domains that are critical to firefighter safety at an emergency scene (i.e. working memory, sustained attention, and reaction time) (Morley et al., 2012, Williams-Bell et al., 2015a). Because each test assesses a different aspect of cognitive function, they differ with regards to presentation, task, and feedback. However, these components are standardized within each individual test. Specific details of each test are described in Chapter 3.

5.3.3 Experimental Protocol

Participants were asked to attend 2 sessions each lasting approximately 2 h. These sessions were separated by a minimum of 7 and no more than 10 days. The experimental protocol included 5 cognitive testing time points. The initial and final trials, Trials 1 and 5, included all 5 of the tests described previously – SWM, RVP, RTI, SSP, and PAL. Trials 2 to 4 included only SSP and PAL in order to reduce test duration while walking on the treadmill. Within each cognitive trial, the order of the individual CANTAB tests were randomized to avoid any potential carry-over effects.

Each CANTAB test included a practice level to orient the participant to the procedures required for that particular test. Practice levels were included for all tests in Trial 1 to allow participants to become familiar with each task before their scores were recorded. For Trials 2 to 5, the practice levels were not included to reduce the amount of time required to complete the entire testing battery at that particular cognitive trial.

5.3.4 Exercise Group

Participants in the exercise group completed the 5 CANTAB tests with the addition of intermittent bouts of exercise by walking on a motorized treadmill at 4.5 $km \cdot h^{-1}$ and 0% grade. This exercise intensity was chosen to elicit physical activity that would be representative of the workload required of various occupations while performing cognitive tasks, such as firefighting (Selkirk et al., 2004b).

Trials 1 and 5 were each divided into two parts. In Trial 1, the SWM, RVP, and RTI tests were conducted while the participant was seated. The SSP and PAL tests were completed while the participant walked on a treadmill at the prescribed exercise intensity.

For Trial 5, the SSP and PAL tests were performed on the treadmill, immediately followed by the participant becoming seated and completing the SWM, RVP, and RTI tests.

After completing Trial 1 while walking on the treadmill, the participant continued for an additional 10-min at the same workload. Immediately after, participants completed Trial 2 while still walking on the treadmill, followed by seated rest for 5-min. Then, the participants re-mounted the treadmill and began walking for 10-min before completing Trial 3. The same work to rest ratio was conducted until participants completed the SSP and PAL tests of Trial 5. Upon completion, participants were immediately seated and completed the SWM, RTI, and RVP tests.

5.3.5 Non-Exercise Group

No physical activity was conducted for participants of the non-exercise group with all tests completed while seated. Upon completion of Trial 1, participants were asked to rest and remain seated for 10-min. After, they completed Trial 2 followed by 15-min of seated rest. All subsequent trials, which included Trials 3, 4, and 5, were also separated by 15-min periods of inactivity. The session concluded upon completion of Trial 5.

5.4 Statistical Analysis

Violations of normality were tested using the Shapiro-Wilks test. The outcome measure for the PAL test (total errors at the 8-shapes level) was log transformed to conform to the assumption of normality. ICC coefficients were calculated using the method described by Hopkins (2015). The ICC reliability coefficients were determined based on the guidelines described by Cicchetti et al. (1981) who indicated levels of clinical significance to be poor (below .40), fair (.40 and .59), good (.60 and .74), and excellent (.75 and 1.00). The ICC values were determined for consecutive tests (i.e. Trials 1 to 2, 2 to 3, etc.) for PAL and SSP while ICCs for RVP, RTI, and SWM were determined for Trials 1 to 2 within each session. A two-way ANOVA (trials x session) was performed on all cognitive measures for the exercise and non-exercising groups. Previous research has recommended that changes in performance be expressed as an estimate of effect size, therefore Cohen's d (Cohen, 1988) was calculated for performance change between the first and last trial of session 1 and the first trial of session 1 and last trial of session 2 (approximate 1 week interval). A one-way (trial) analysis of variance (ANOVA) was performed on all cognitive measurements at these assessment points. Raw difference scores were also calculated to provide the amount of change observed for each cognitive measurement. Furthermore, due to the number of statistical tests performed on the cognitive measures and similar to the test-retest analyses conducted by Falleti et al. (2006), significance was set at $p \leq 0.01$. Data is presented as mean ± standard deviation.

5.5 Results

5.5.1 Test-Retest Reliability

The ICC coefficients for the dependent variables from the SWM, RTI, and RVP tests are depicted in Table 5.1 and the PAL and SSP tests in Table 5.2 the exercise and non-exercise groups. Seventeen of the 28 ICC values for the non-exercise group and 16 of 28 for the exercise group were greater than 0.60 with some improving during session 2. For the non-exercise group, of the serial measures obtained over 5 trials, the lowest reliability coefficients (0.22) were observed between Trials 2 and 3 on the PAL test for total number of errors made at the 8-object level and between Trials 1 and 2 for SSP span length (0.23). For the exercise group, the lowest ICC coefficients were observed between Trials 1 and 2 for SSP spatial span (-0.42) and Trials 4 and 5 for PAL total errors at the 8-shape level (-0.07). In addition, the RTI test revealed consistent results for both groups with all but one ICC value being greater than 0.70. In contrast, the SWM test showed an improvement in ICC values during session 2 for total number of errors performed while total number of rejections on the RVP test remained consistent above 0.67.

Table 5.1: Intraclass correlations for the SWM, RVP, and RTI tests for the non-exercise and exercise groups. ICC values classified as poor (below .40), fair (.40 and .59), good (.60 and .74), and excellent (.75 and 1.00) based on Cicchetti et al. (1981).

Non-Exercise Group	**Session 1**	**Session 2**
Task	**Trials 1 to 2**	**Trials 1 to 2**
SWM		
Errors	0.45	0.74
Latency	0.39	0.32
RVP		
Rejections	0.72	0.72
Latency	0.76	0.72
RTI		
SRT	0.92	0.90
CRT	0.88	0.85
Exercise Group		
SWM		
Errors	0.18	0.45
Latency	0.90	0.82
RVP		
Rejections	0.67	0.70
Latency	0.46	0.98
RTI		
SRT	0.62	0.82
CRT	0.86	0.71

SWM = spatial working memory; RVP = Rapid visual information processing; RTI = Reaction time; SRT = Simple reaction time; CRT = Five choice reaction time.

Table 5.2: Intraclass correlations for the PAL and SSP tests in the non-exercise and exercise groups. ICC values classified as poor (below .40), fair (.40 and .59), good (.60 and .74), and excellent (.75 and 1.00) based on Cicchetti et al. (1981).

Non-Exercise Group	**Session 1**				**Session 2**			
Task	**Trials 1 to 2**	**Trials 2 to 3**	**Trials 3 to 4**	**Trials 4 to 5**	**Trials 1 to 2**	**Trials 2 to 3**	**Trials 3 to 4**	**Trials 4 to 5**
PAL								
Errors, 8 shapes	0.77	0.22	0.71	0.50	0.19	0.47	0.67	0.76
SSP								
Span Length	0.23	0.65	0.66	0.61	0.52	0.39	0.62	0.39
Exercise Group								
PAL								
Errors, 8 shapes	0.31	0.27	0.65	-0.07	0.85	0.70	0.80	0.85
SSP								
Span Length	-0.42	0.46	0.62	0.19	0.46	0.50	0.62	0.43

PAL = Paired associates learning; SSP = Spatial span.

5.5.2 PAL and SSP

The mean data for the PAL and SSP tests in the exercise and non-exercise groups are depicted in Table 5.3 along with the two-way repeated measures ANOVA statistics. One-way repeated measures ANOVA results, Cohen's d, and the raw difference between means is reported comparing Trials 1 and 5 (within session 1) as well as Trials 1 and 10 (first and last trials between sessions 1 and 2) are shown in Table 5.4 for both groups. Although the two-way repeated measures ANOVA did not reveal a significant main effect of trial or session, the one-way repeated measures ANOVA showed an improvement within session 1 for total errors at the 8-object level corresponding with a large effect size (d = 1.10). However, between sessions (Trials 1 to 10), there was no difference in total errors resulting in a small effect size (d = 0.09). Furthermore, span length on the SSP test revealed no differences between Trials 1 and 5 or Trials 1 and 10, although there was a moderate effect size (d = -0.74) for the longer span length at Trial 10 compared to Trial 1.

For the exercise group, neither test revealed an improvement across the five trials within or between sessions. When comparing data from Trials 1 and 5 and Trials 1 and 10, there were no differences and the effect sizes were small for the PAL and SSP tests.

5.5.3 SWM, RTI, and RVP

For the tests conducted pre and post-exercise (SWM, RTI, RVP), two-way repeated measures ANOVA analyses are depicted in Table 5.5 for the exercise and non-exercise groups. For the non-exercise group, the data revealed an improvement for total

Table 5.3: Mean values for all tests within and between each day including the two-way ANOVA values for the both groups.

Non-Exercise Group	**Session 1**					**Session 2**					**Session**		**Trial**	
Task	**Trial 1**	**Trial 2**	**Trial 3**	**Trial 4**	**Trial 5**	**Trial 1**	**Trial 2**	**Trial 3**	**Trial 4**	**Trial 5**	**F**	**p**	**F**	**p**
PAL														
Errors (#)	5.4 ± 4.3	2.3 ± 2.9	4.3 ± 5.3	6.7 ± 11.6	2.3 ± 3.7	2.0 ± 2.9	2.7 ± 4.2	4.3 ± 5.2	5.2 ± 7.4	5.0 ± 8.0	.094	.765	1.263	.302
SSP														
Span Length	7.3 ± 0.9	6.8 ± 1.2	7.2 ± 1.0	7.7 ± 0.8	7.3 ± 0.9	7.8 ± 0.8	7.4 ± 1.2	7.4 ± 1.0	7.5 ± 1.2	7.8 ± 1.0	3.957	.072	1.486	.223
Exercise Group														
PAL														
Errors (#)	6.5 ± 7.9	1.9 ± 2.1	3.4 ± 5.9	3.5 ± 4.6	5.6 ± 8.4	3.5 ± 4.7	2.9 ± 4.4	4.3 ± 6.2	6.0 ± 12.3	5.9 ± 8.2	.048	.831	1.507	.241
SSP														
Span Length	7.7 ± 0.9	7.5 ±1.2	6.9 ± 1.3	7.5 ± 1.1	7.6 ± 0.9	7.8 ± 0.9	7.8 ± 1.0	7.1 ± 1.1	7.3 ± 1.2	7.4 ± 1.3	.011	.918	2.487	.059

PAL = Paired associates learning; SSP = Spatial span; Session = Two-Way ANOVA results for Session as a factor; Trial = Two-Way ANOVA results for Trial as a factor.

Table 5.4: One-way ANOVA values, Cohen's d, and raw difference in scores between Trials 1 to 5 and Trials 1 to 10 in both groups for the PAL and SSP tests.

Non-Exercise Group	**Trials 1 and 5**				**Trial 1 and 10**			
	F	p	d	Raw Difference	F	p	d	Raw Difference
PAL								
Errors	10.209	0.009	1.10	-3.1	0.020	0.89	0.09	-0.4
SSP								
Span Length	0.103	0.75	0.00	0.0	3.000	0.11	-0.74	0.5
Exercise Group								
PAL								
Errors	0.041	0.84	0.16	-0.9	0.057	0.82	0.11	-0.6
SSP								
Span Length	0.070	0.796	0.16	-0.1	1.379	0.27	0.39	-0.3

PAL = Paired associates learning; SSP = Spatial span;

errors on the SWM test and RVP total correct rejections at Trial 2 ($p \leq 0.01$). When comparing data from Trials 1 and 2 (first and last trials in session 1) as well as Trials 1 and 4 (first trial of session 1 and last trial of session 2; Table 5.6), there was an improvement in total errors on the SWM test. However, despite the other tests not revealing differences based on the corrected probability value ($p \leq 0.01$), 3 measures indicated large effect sizes ($d > 0.80$), with an additional 2 measures showing moderate effect sizes. None of the measures were different between testing sessions.

For the exercise group, two-way repeated measures ANOVA analysis revealed an improvement in SWM latency between Trials 1 and 2 with a moderate effect size ($d = 0.65$). In addition, the effect size for SWM latency between Trials 1 and 4 was high ($d = 1.48$) indicating a large decrease in SWM latency. None of the remaining measures revealed differences between Trials 1 to 2 and Trials 1 to 4. However, for Trials 1 to 2, one measure revealed a large effect size (RVP correct rejections) and two others indicated moderate effect sizes (SWM total errors, RVP latency). In addition, none of the tests showed differences in mean scores between Trials 1 and 4, despite one additional measure revealing a large effect size (RVP correct rejections) and one moderate effect size (simple reaction time). The remaining measures all indicated small effect sizes between Trials 1 to 2 and Trials 1 to 4.

Table 5.5: Mean values for all tests within and between each session including two-way ANOVA values for the exercise and non-exercise groups.

Non-Exercise Group	**Session 1**		**Session 2**		**Session**		**Trial**	
Task	**Trial 1**	**Trial 2**	**Trial 1**	**Trial 2**	***F***	**p**	***F***	**p**
SWM								
Errors (#)	28.5 ± 8.9	26.5 ± 12.9	27.6 ± 17.5	18.2 ± 16.9	2.241	.163	10.869	.007*
Latency (ms)	830.7 ± 212.2	699.9 ± 114.3	784.3 ± 161.9	795.3 ± 401.1	.156	.701	1.967	.188
RVP								
Rejections (#)	251.9 ± 13.2	259.0 ± 8.3	256.6 ± 11.6	260.7 ± 9.6	.996	.340	9.542	.010*
Latency (ms)	412.7 ± 106.8	366.2 ± 84.0	415.8 ± 86.1	398.8 ± 101.6	1.673	.222	5.875	.034
RTI								
SRT (ms)	289.4 ± 39.7	277.1 ± 37.2	291.5(51.0)	302.3 ± 73.5	1.248	.288	.015	.904
CRT (ms)	312.2 ± 54.8	310.9 ± 60.4	322.1(56.4)	337.9 ± 79.5	2.953	.114	.888	.366
Exercise Group								
SWM								
Errors (#)	32.6 ± 18.1	26.3 ± 9.4	30.3 ± 12.9	26.7 ± 21.4	.051	.826	1.557	.240
Latency (ms)	910.4 ± 356.3	771.8 ± 238.5	736.3 ± 198.7	658.6 ± 124.3	6.041	.034	8.850	.014*
RVP								
Rejections (#)	256.8 ± 8.6	263.2 ± 9.2	262.0 ± 5.9	262.9 ± 7.8	1.371	.272	7.940	.020
Latency (ms)	372.6 ± 47.2	354.3 ± 38.5	387.2 ± 119.8	373.8 ± 109.0	.489	.502	3.655	.088
RTI								
SRT (ms)	272.9 ± 25.9	280.9 ± 31.2	280.2 ± 48.7	283.9 ± 35.4	.224	.646	.970	.348
CRT (ms)	289.4 ± 27.6	291.5 ± 28.2	305.7 ± 39.2	301.7 ± 46.5	3.601	.087	.023	.881

SWM = spatial working memory; RVP = Rapid visual information processing; RTI = Reaction time; SRT = Simple reaction time; CRT = Five choice reaction time; Day = Two-Way ANOVA results for Session as a factor; Trial = Two-Way ANOVA results for Trial as a factor.

Table 5.6: ANOVA values, Cohen's d, and raw difference in scores between Trials 1 and 2 and Trials 1 and 4 in both groups for the SWM, RVP, and RTI tests.

Non-Exercise Group	**Trials 1 and 2**				**Trials 1 and 4**			
	F	p	d	Raw Difference	F	p	d	Raw Difference
SWM								
Errors	0.335	0.58	0.26	-2.0	9.305	0.01	1.13	-10.3
Latency (ms)	5.520	0.04	1.13	130.8	0.270	0.61	0.16	-35.4
RVP								
Rejections	7.640	0.02	-0.93	8.1	5.341	0.04	-1.09	8.8
Latency (ms)	5.154	0.04	0.69	-46.5	0.717	0.42	0.19	-13.9
RTI								
SRT (ms)	6.130	0.03	0.45	-12.3	0.674	0.43	-0.32	12.9
CRT (ms)	0.021	0.89	0.03	-1.3	2.888	0.12	-0.54	25.7
Exercise Group								
SWM								
Errors	1.277	0.29	0.65	-6.3	0.622	0.45	0.42	-5.9
Latency (ms)	9.104	0.01	0.66	-138.6	7.601	0.02	1.48	-251.8
RVP								
Rejections (# correct)	7.799	0.02	-1.02	6.4	4.412	0.06	-1.05	6.1
Latency (ms)	2.206	0.17	0.70	-18.3	0.002	0.96	-0.02	1.2
RTI								
SRT (ms)	1.019	0.34	-0.40	8.0	2.113	0.18	-0.51	11.0
CRT (ms)	0.182	0.68	-0.11	2.1	1.921	0.20	-0.47	12.3

SWM = spatial working memory; RVP = Rapid visual information processing; RTI = Reaction time; SRT = Simple reaction time; CRT = Five choice reaction time.

5.6 Discussion

Over half of the dependent CANTAB measures were found to have good or excellent reliability. The reliability for the exercise group was similar, overall, indicating that it is feasible to administer the CANTAB during treadmill walking. Another important finding from the current study was the general lack of practice effects observed in 5 tests from the CANTAB battery. Improvements were found in the SWM and RVP tests indicating the presence of practice effects, which should be taken into account for repeated measures designs. However, no decreases in performance were identified in any of the tests, which is important as any decrements in performance may indicate fatigue or a lack of motivation over the course or at the end of the testing protocol. (Falleti et al., 2006).

5.6.1 Reliability

The ICC values for the various dependent measures revealed a range from poor (below .40) to excellent (.75 to 1.00) reliability for the PAL and poor (below .40) to good (.60 to .74) on the SSP tests in the exercise and non-exercise groups. During session 2 in the exercise group, the PAL test revealed ICC values from good to excellent while in the non-exercise group ICC values improved across each of the 5 trials. This suggests that familiarizing a participant with at least 5 trials on a day prior to the experimental protocol may improve the test-retest reliability during subsequent sessions administered within a week.

The RVP values in both groups revealed good to excellent ICC coefficients in each session with SRT and 5RT showing the highest overall ICC values within and between sessions. In contrast, the SWM test revealed poor ICC values in the non-exercise group with excellent ICCs for search time in the exercise group. This finding is consistent with previous work that has shown tests which involve strategy (as is required for the SWM test) reveal the largest practice effects due to participants potentially finding an optimal strategy for performance (Lowe et al., 1998) which would relate to poor test-retest correlations.

5.6.2 The Presence of Practice Effects

This study revealed practice effects on 3 tests within each session associated with the CANTAB battery, occurring between Trials 1 and 2 (SWM and RVP) with only one test showing improvement for the serial measurements at Trial 5 (PAL). Within session analyses, based on effect size, revealed moderate improvements in the non-exercise group for RVP latency, 5RT, and SWM total errors, while between sessions moderate improvements in SSP span length were observed, although none of these measurements reached statistical significance at the corrected level of $p \leq 0.01$. In addition, within session analyses for the exercise group revealed a significant improvement in SWM search time at Trial 2 with between session analyses indicating large effect sizes for SWM search time between Trials 1 and 4 ($p \leq 0.01$). In addition, RVP correct rejections revealed large effect sizes between Trials 1 and 2 as well as Trials 1 and 4. Moderate improvements based on effect size were seen in SWM search time from Trials 1 to 2, RVP latency from Trials 1 to 2, and 5RT from Trials 1 to 4. Furthermore, two-way ANOVA analyses revealed a main effect of trial for SWM search time indicating a faster search to completion at post-test (Trials 2 or 4) within each session ($p \leq 0.01$).

Further analysis of the effect size data reveals that the differences in the RTI reaction time and RVP response latency data are all less than 30 ms, which would likely not be considered ‘practically significant’ as it is less than 100 ms (Walker et al., 2004). Based on this information, strictly interpreting the data based on the effect sizes would provide a very different explanation without examining what the raw mean differences reveal. The observation of practice effects on some of the measurements examined in this study are consistent with previous work. These studies have shown that cognitive function tasks associated with detection, memory, matching, and learning appear to be affected with repeated presentations of the task (McCaffrey et al., 1993, Feinstein et al., 1994, Versavel et al., 1997, Benedict et al., 1998). It appears that most neuropsychological tests show practice effects when they are given twice (McCaffrey et al., 1993, McCaffrey et al., 2001), although the test-retest intervals in previous studies have not been standardized and range from a few days, to one week, and upwards of two years (Falleti et al., 2006). Falleti et al. (2006) suggested that the presence of practice effects may be dependent on how many times an individual is required to complete specific cognitive tests.

From the current results, it would appear that individuals who do not have prior experience on a particular cognitive battery may improve their performance following repeated testing on certain tests (SWM, RVP, PAL). If this is the case, these tests would become problematic if administered only at a single occurrence to determine clinical significance. Therefore, individuals should be assessed at least twice before any valid conclusions can be drawn from the data (Falleti et al., 2006).

5.6.3 The Absence of Practice Effects

Two-way ANOVA analyses revealed that thirteen of the sixteen variables measured in this study did not reveal a main effect of trial. Other than total errors at the 8-object level in the PAL test between Trials 1 to 5, none of the other serial measurements for SSP or PAL revealed practice effects. None of the cognitive measurers revealed a main effect of session indicating that performance was not significantly improved at session 2. These findings are in contrast to those observed by Falleti et al. (2006) who found that when the CogState battery (assessing reaction time, attention, working memory, and learning) was completed following a test-retest interval of 1 week, practice effects were, in fact, notable for certain tests. A new protocol was then designed in which participants first completed two initial assessments separated by a 10-min interval and then completed the same assessment following a one month test-retest interval (Falleti et al., 2006). The results of the new protocol provided evidence that practice effects did not influence the data following the 1 month interval (Falleti et al., 2006).

It is possible that the lack of improvements in the PAL and SSP tests were due to the presence of mental fatigue especially since the last assessment was approximately 2 hours following the beginning of the protocol (Falleti et al., 2006). Based on this notion, it is conceivable that practice effects did occur following the first assessment but were counteracted by mental fatigue or boredom, resulting in no improvement in performance (Falleti et al., 2006).

In summary, it appears that in order to reduce practice effects in the cognitive tests employed in this study, a double baseline protocol should be implemented when changes in cognitive function over time are being examined (Collie et al., 2003). Furthermore, the addition of a non-intervention group to act as a control will allow researchers and clinicians to distinguish the difference between observed practice effects and changes due to the specific treatment imposed (Collie et al., 2002).

5.7 Implications

Over the past thirty years, the use of automated cognitive testing batteries has grown specifically for use in a clinical and research setting (Smith et al., 2013). The CANTAB offers an easy to administer testing battery that provides standard administration of each test across a number of test-retest intervals (Levaux et al., 2007). The data in the current study reveal that search time in the SWM test is improved with repeated presentations over a short term interval. This finding is consistent with previous research that has reported cognitive assessments requiring a particular strategy for performance show greater practice effects (Basso et al., 1999). Clinical examinations or research studies utilizing tests involving strategy should implement, at minimum, a double baseline to stabilize practice effects. Further research needs to be conducted to determine the short term practice effects on the SWM test when more than two repeated measurements are observed along with the longitudinal effects spanning over weeks and months. Despite the significant improvements in RVP total correct rejections, a raw change of 4 to 8 correct rejections relates to a 1.6 to 2.8% improvement. These percentage improvements have previously been classified as constituting small practice effects and, therefore, may not be practically significant (Versavel et al., 1997).

Another important finding from the current study is the lack of practice effects observed during treadmill walking for the exercise group as well as the non-exercise group. The importance of this observation is the ability to utilize the CANTAB testing battery during dynamic movements such as treadmill walking. The implementation of dynamic exercise implies that the participant is performing a dual task, which is classified as carrying out a mechanical work task with a corresponding cognitive task (Brisswalter et al., 2002). With the addition of the imposed physical task, the participant's attention may become focused towards control of the mechanical task resulting in coordination mechanisms draining attentional resources and potentially reducing cognitive performance (Lambourne et al., 2010). Pesce et al. (2003) have suggested that the skill level of the participant will play a role, indicating that those who are less skilled will require greater allocation of attentional resources towards the physical task ultimately reducing the availability for the cognitive task. However, it can be implied that treadmill walking in the current study does not require a high skill level and therefore should not require substantial attentional resources in order to perform the task.

In addition, the exercise implemented has been previously reported as being light intensity for firefighters exercising while wearing protective clothing (Selkirk et al., 2004b). Meta-analyses have shown that when cognitive measurements are taken during exercise, decrements in performance are observed whereas when measurements are taken immediately following exercise improvements are reported (Lambourne et al., 2010). However, the results in the current study did not show a decline in cognitive measures during exercise or at rest. This is in agreement with the cognitive energetic models described by Sanders (1983) and Kahneman (1973) that indicate an inverted-U response to exercise intensity suggesting that at rest and lower levels of exercise, poor cognitive performance would result when compared with intermediate exercise intensity, which would elicit optimal arousal and thus, maximal performance (Chmura et al., 1997, Arent et al., 2003, McMorris et al., 2011). In addition, multiple meta-analytic reviews have determined that exercise lasting between 11 to 20-min does not affect cognitive performance (Lambourne et al., 2010, Chang et al., 2012) with at least 20-min of exercise required for performance improvements to be observed (Brisswalter et al., 2002, Lambourne et al., 2010). A recent study by Chang et al. (2015) found that moderate intensity exercise (approximately 65% of HR reserve) over a 20-min duration resulted in improved accuracy and shorter response times on the Stroop test, whereas exercise durations of 10 and 45-min had negligible benefits. The exercise protocol implemented in the current study included continuous exercise durations of approximately 20-min or less followed by a 5-min rest period, which may provide an additional explanation for the lack of improvements in the exercise group.

Based on the ICC values, it appears that the PAL test should be familiarized with up to 5 trials prior to data collection. In addition, SRT and 5RT have relatively high reliability indicating that these measures are reliable in test-retest comparisons of clinical and research designs. The SSP test provided an overall good reliability while the SWM test should include a number of baseline trials until participants determine an optimal strategy in order to minimize practice effects before changes over time or due to an intervention are determined.

Conclusion

The administration of the CANTAB testing battery during a physical task of treadmill walking did not alter cognitive performance when compared to a non-exercise group. There was no evidence of practice effects for 2 tests of cognitive function, which assess an individual’s visuospatial memory, visual episodic memory, and executive function (SSP and PAL), when measured during 5 repeated trials over 2 sessions, separated by 1 week. However, 2 of the tests administered before and immediately after exercise (SWM, RVP) showed improvements in performance indicating the presence of practice effects from repeated testing. Test-retest reliability of all 5 tests appeared to improve during the second session indicating that 2 to 5 familiarization trials may be required prior to baseline testing when measuring changes in cognitive function in response to a particular experimental protocol or intervention.

CHAPTER 6: A Review of Serious Games in the Fire Service

Adapted from:

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Preface to Chapter 6

The main results from Chapters 4 and 5 provided insight into the impact of heat stress on cognitive function using computer-based neuropsychological testing. The next step in this research was to develop a more realistic assessment tool that simulates the nature of decision making tasks that are encountered by firefighters at a fire scene using serious game technology. Prior to commencing with the development of the serious game, the current practices and technology being used by the fire service needed to be established. The following chapter details the various video games, serious games, and virtual simulations that have been created either for or with the fire service as the main theme and the main training objective for each technology.

6.1 Abstract

Firefighting is an extremely physically and physiologically demanding occupation, requiring tremendous resources for training personnel as well as incurring significant workplace safety and insurance board (WSIB) costs. Approximately 33% of firefighter injuries result from exposure to fire leading to the possibility of reducing these injuries through training firefighters to make better decisions, particularly when under stress. Simulation (and virtual simulation in particular) offers a safe and cost-effective alternative to practice with real fire, offering entry level training to aid firefighters to reach a specific competency level. With the ubiquity of video-game play and advent of new consumer-level physical interfaces for video-games (e.g., the Nintendo Wii Fit balance-board and the Microsoft Kinect), serious games (games whose primary purpose is education and training), are able to provide users with innovative interactive techniques that are highly engaging and immersive. This paper reviews the development of serious games and virtual simulation applications that may be utilized for training in the fire service. Current technology allows for the simulation of fire spread and smoke movement along with training certain firefighting skills and incident command coordination. To date, gaming technology is not capable of providing a real world scenario that is completely and faithfully accurate in a dynamic virtual environment. Although additional work remains to overcome current issues associated with serious games and virtual simulations, future work should focus on utilizing the benefits of gaming environments and virtual simulations to recreate the decision making processes and physical task requirements that individual firefighters encounter in an emergency situation and incorporate them into a simulation environment where the physical and psychological stresses are analogous to live firefighting situations.

6.2 Introduction

Firefighting is a rigorous and physically demanding occupation involving heavy lifting, bending, twisting, and awkward postures, with only a small amount of time actually spent fighting fires (Duncan et al., 1979, Lusa et al., 1994, Baker et al., 2000, Austin et al., 2001). However, while fighting fires, firefighters must make many decisions in potentially life-threatening situations, most of which involve protecting the safety of civilians and the firefighters themselves. Outside of fighting fire, the majority of work-related time involves responding to medical emergencies, motor vehicle collisions, and industrial accidents in addition to maintaining and storing equipment in the fire hall (Baker et al., 2000, Selkirk et al., 2004b). Nearly one-third of firefighter injuries result from exposure to fire (including smoke inhalation), with many of these injuries thought to be preventable through better decision making under conditions of increased physiological strain (Hancock et al., 2003). According to data from the International Association of Firefighters (IAFF), the incidence of injury in the fire service is four times greater than in private industry, with one in every three firefighters being injured in the line of duty (Walton et al., 2003). Due to the combined physiological and psychological demands of fighting fires, firefighters go through extensive training which typically takes place in the "classroom" with the implementation of the standard operating guidelines taking place during live fire training scenarios. These scenarios require tremendous resources including training personnel, specialized training facilities and carefully planned live fire evolutions, as well as new training models for each subsequent training activity (Backlund et al., 2007).

Simulation (and virtual simulation in particular) offers a safe, ethical, and cost-effective alternative to practice in certain real fire scenarios, offering trainees the opportunity to train until they reach a specific competency level. Using simulations of virtual buildings with virtual fire environments, trainees can interact with a changing environment, simulate various work-related procedures, and/or judge whether a building design is reasonable from a fire safety point of view. Virtual simulation permits trainees to make and correct mistakes while allowing them to experience situations that may not easily be recreated in the real-world due to ethical, cost, and time concerns. The rising popularity of video games has seen a recent push towards the application of video game-based technologies to teaching and learning. Serious games (games that are used for training, advertising, simulation, or education (Susi et al., 2007)), provide a high level of interactivity and engagement not easily captured in traditional teaching and learning environments. In contrast to traditional teaching environments where the teacher controls the learning (e.g., teacher-centred), serious games and virtual simulations present a learner-centred approach to education, so that the player controls the learning through interaction with the situation using an active, critical approach (Stapleton, 2004).

Serious games and virtual reality-based simulations (or virtual simulations) have grown as a form of teaching in many occupational settings, including medicine (Deutsch, 2009, Fairhurst et al., 2010, Kron et al., 2010, Marsh et al., 2010), rehabilitation (Rand et al., 2009, Cox et al., 2010, Kamper et al., 2010, Lange et al., 2010), baseball (Fink et al., 2009), and firefighting (St.Julien et al., 2003, Sowndararajan et al., 2008, Boulet, 2009, Toups et al., 2009). Current gaming technologies implemented in the fire service focus on training those involved at the strategic and tactical levels of firefighting and not at the task or individual level. While there may be some debate over definitions, the strategy is generally comprised of elements of what needs to be done, what is to be done and who is to do it, whereas the tactical plan relates to how it will be done given the particular strategy that is adopted and situation in which it is being applied (Clark, 1991, Coleman, 2002). Firefighter education at the task level (e.g., selection and use of tools, ventilation, hose line selection and operation, right or left hand room search), typically occurs at the fire academy, through early recruit training programs and learning on the job while working with senior firefighters. With the advancement in the use of computer games for educational purposes, appropriate firefighter training at the task level can be implemented, particularly as related to reduction of injuries from musculoskeletal disorders, as well as to improvement of decision making under stress.

Educators, researchers, and game developers have recognized that console-based video and computer games are capable of providing enhanced learning experiences (Norman, 2001, Gee, 2003, Prensky, 2003, Stapleton, 2004). Current literature on the use of games and virtual reality for firefighting has primarily focused on improving team communication and incident command decision making (St.Julien et al., 2003, Sowndararajan et al., 2008, Boulet, 2009, Toups et al., 2009), but has generally ignored skills training, such as in appropriate materials-handling techniques or training with respect to decision making. Involving firefighters in problem solving and training exercises related to materials handling, for example, requires an appreciation of the conditions and specific attributes that may contribute to or maintain musculoskeletal disorders in their work environment. One study reported 40% of injuries were caused by physical training, followed by on-duty emergency and fire hall activities at 25% and 14%, respectively (Staal et al., 2005).

With the advent of new physical interfaces for video games, (e.g., the Nintendo Wii Fit balance-board and the Microsoft Kinect), video games are able to provide users with innovative interaction techniques that are highly engaging and immersive. Furthermore, such technologies allow video games to easily monitor the user's physical activity with minimal barriers to entry, enabling a host of new applications to be developed at reasonable cost. For example, the Microsoft Kinect camera-based sensor enables accurate measurement of up to twenty locations on the human body, can track the pose of the user's joint structure, recognize trained gestures, and perform all of this processing in real-time for multiple users simultaneously. It does not require the user to wear special tracking markers, allowing for fast and reliable setup. Thus, this platform provides serious games developers and educators the opportunity to develop highly engaging, interactive, and entertaining physical training programs at relatively low cost.

Given the potential afforded by the use of game-based technologies for firefighter training, here we present a thorough overview of the existing literature pertaining to serious gaming and virtual simulation as it might be applied for training purposes in the fire service. In the process of doing so, we outline existing serious games and virtual simulations that have been applied to firefighter training and discuss their benefits and limitations. We also discuss what we believe are some open problems that must be addressed in order to capitalize on these technologies for advanced firefighter training applications.

To guide the discussion, Table 6.1 provides a complete summary of all the video games, serious games, and other relevant computer-based software reviewed in this article. For each game or software reviewed, the specific focus is categorized into the following classes: i) entertainment, ii) education, and iii) training. Within the training category, the primary focus of the game or software has been further divided into whether it relates to training in: i) incident response, ii) decision making, iii) team coordination, or iv) task level skills. Those items which relate to multiple categories or foci have been identified and are illustrated with an “X” to represent the various aspects of their applicability. Items in each category are reviewed in further detail in the following sections. Furthermore, Table 6.2 represents which major aspects of fire safety were addressed by each gaming or simulation technology, based on whether it primarily dealt with: i) fire dynamics, ii) people dynamics, iii) firefighting skills, iv) building evacuation, or v) fire safety education.

6.3 Firefighting Video Games

Given the rising popularity of video games in addition to their many benefits when used for educational purposes, there have been numerous attempts to create fun, firefighting themed games for entertainment purposes. In 1982, one of the first firefighting themed video games, *Fire Fighter*, was released for the Atari 2600 gaming console. In *Fire Fighter*, players take on the role of a firefighter attempting to save a panicked man from a burning warehouse. The player’s goal is rather simple: rescue the panicked man in the minimum amount of time. Since the release of *Fire Fighter,* there have been additional attempts to create entertaining firefighting games: *Fire fighter FD* (Konami, 2004) for the Sony PlayStation 2, *Fire fighter Command: Raging Inferno* (Kudosoft Interactive, 2005) for the PC, *Real Heroes: Fire fighter* (Conspiracy Entertainment Corp., 2006) for the Nintendo Wii, and the *Emergency* series of six games (Sixteen Tons Entertainment, 1998-2013) for the PC (Figure 6.1). These games were developed explicitly for the purpose of entertainment using home entertainment systems and generally lack the appropriate instructional design and clear learning objectives that are required for effective firefighter training and educational purposes. Their content and game play is not necessarily accurate to standard operating guidelines of structural firefighting services nor will they require the user to have the same experience or expertise for decision making or incident command organization as would be essential for an actual firefighter.

6.4 Serious Games, Virtual Simulations and Firefighting

With the emergence of serious games, researchers and training personnel involved in firefighter educational development have attempted to employ gaming methods to train recruit and incumbent firefighters (Backlund et al., 2007, Houtkamp et al., 2007, Backlund et al., 2009, Lebram et al., 2009). Many of the firefighting simulations and serious games currently employed focus primarily on training for breathing apparatus entry, systematic search of a smoke filled building, or fire suppression (Pietrzak et al., 1986, Backlund et al., 2007, Backlund et al., 2009, Lebram et al., 2009), communication and leadership on the fire ground (St.Julien et al., 2002, Querrec et al., 2003, St.Julien et al., 2003, Houtkamp et al., 2007), and fire safety education (Walker et al., 1992, DeChamplain et al., 2012, Tawadrous et al., 2013), while other simulation platforms have also been developed for visualization of structural fires for applications related to fire safety engineering and design (Peacock et al., 1993, Bukowski et al., 1997). Though these latter simulations and serious games were not developed with any objective related to firefighter training, the underlying software that predicts fire behaviour in buildings forms one key element necessary in any integrated gaming platform for advanced fire training applications.

One of the initial applications of simulating fire behaviour in structures was developed by Bukowski et al. (1997) for such an engineering application (see Figure 6.2 revealing how a pool fire scenario could be previewed and destructive experiments performed to evaluate fire safety studies). They coupled the real-time, interactive, Walkthru visualization system to the CFAST (Consolidated Model of Fire and Smoke Transport) model for fire behaviour developed at the National Institute of Standards and Technology (NIST) (Peacock et al., 1993). The CFAST model was used to simulate the gas concentrations, temperatures, and the height of the smoke layer that developed during a fire in a dwelling with multiple rooms (Peacock et al., 1993). The predicted data were passed through the Walkthru visualization system which was configured to present the information to the user in various modes depending on the intent of the exercise. The calculation speed of CFAST is relatively fast which makes the software amenable to this kind of application; however, speed comes at the expense of significant simplification of the fire physics, as well as limitations in the complexity of compartment geometries that can be modelled.

Table 6.2: Overview of the nature of the video games, serious games, and virtual simulations reviewed

Authors	**Entertainment**	**Education**	**Training**			
			Incident Response	*Decision Making*	*Team Coordination*	*Task Level Skills*
Backlund et al. (2007), (2009)						X
Bukowski et al. (1997)		X				
Carnegie Mellon University			X	X		
Cha et al. (2012)			X	X	X	
Chittaro et al. (2009)		X				
DeChamplain et al. (2012)		X				
Digital Combustion			X	X	X	
Dugdale et al. (2004)			X	X	X	
Emergency by Sixteen Tons Entertainment	X					
Environmental Tectonics Corportation (2012)			X	X	X	
Fire fighter by Atari	X					
Fire fighter Command: Raging Inferno by Kudosoft Interactive	X					
Fire fighter FD by Konami	X					
Gamberini et al. (2003)		X				
Li et al. (2004)				X	X	
Querrec et al. (2004)			X	X	X	
Real Heroes: Fire fighter by Conspiracy Entertainment Corp.	X					
Ren et al. (2008)		X				
Smith et al. (2009)		X				
St.Julien et al. (2003)			X			
Tate (1997)			X			
TEEX Emergency Services Training Institute				X		
Toups et al. (2007b)		X			X	
Toups et al. (2011)		X			X	
VectorCommand Ltd.			X	X		

Table 6.3: Overview of the main characteristics of the serious games and virtual simulations reviewed in this paper based on the goals of the developed model.

Authors	**Fire Dynamics**		**People Dynamics**		**Firefighter Skills Training**	**Building Evacuation**	**Fire Safety Education**
	Fire Development	*Smoke Movement*	*User Coordination*	*Virtual Agent Coordination*			
Backlund et al. (2007), (2009)					X		
Bukowski et al. (1997)	X	X					
Carnegie Mellon University			X				
Cha et al. (2012)	X	X	X		X		
Chittaro et al. (2009)						X	
DeChamplain et al. (2012)							X
Digital Combustion			X				
Dugdale et al. (2004)			X	X			
Environmental Tectonics Corportation (2012)			X				
Gamberini et al. (2003)						X	
Li et al. (2004)			X		X		
Querrec et al. (2004)		X		X			
Ren et al. (2008)	X	X			X		
Smith et al. (2009)						X	
St.Julien et al. (2003)	X	X		X			
Tate (1997)					X		
Tawadrous et al. (2013)							X
TEEX Emergency Services Training Institute					X		
Toups et al. (2007b)			X				
Toups et al. (2011)			X				
VectorCommand Ltd.			X				

Figure 6.1: Screenshot of Emergency: 2013 developed by Deep Silver in 2012 for PC. Reprinted with permission.

Figure 6.2: An intense pool fire in a student office; 100 seconds after ignition, the room is nearly filled with smoke. Reprinted with permission.

Nonetheless, the Walkthru-CFAST model was deemed useful to provide fire safety engineers with a simulation based design environment in which to assess building fire hazards and safety systems, as well as to evaluate the fire performance of different building designs. While the CFAST zone modeling software is still widely used by the engineering community for computer based prediction of fire behaviour, the visualization and graphic technology that was utilized has become outdated.

Research to evaluate the use of serious games directly for rescue services training has been undertaken in Sweden over the past decade (Backlund et al., 2007, Backlund et al., 2009, Lebram et al., 2009). This led to the development of Sidh (see Figure 6.3 depicting the users point of view in the simulation model while in a standing position), a game-based firefighter training system which employs a CAVE (Cave Automatic Virtual Environment) immersive virtual reality environment (Cruz-Neira et al., 1992) to simulate thirteen realistic situational environments for training students in search and rescue while wearing a breathing apparatus. In the CAVE, the firefighter trainee is surrounded by four fixed position screens that deliver stereoscopic 3D visualization of the scenario while they move around, pointing their firefighting nozzle as they search for victims. The ‘hot, stressful’ interactive audio-visual environment is intended to simulate the physical and psychological demands of the search and rescue task in a smoke-filled environment. As such, the health of the firefighter is adapted during the game depending on time taken to fulfil a task and whether the player is in an upright or crouched position, etc. After the game was developed, thirty-one firefighting students were recruited to play. The participants were divided into two groups, with the first group (experimental group) being given two, 30-min sessions playing Sidh, followed by a search mission at a training

Figure 6.3: In-game visual of the Sidh fire fighter training simulation with the fire fighter in a standing position dealing with a smoke filled room. (Backlund et al., 2007, Backlund et al., 2009, Lebram et al., 2009). Reprinted with permission.

Figure 6.4: Snapshot of the single family home used in St. Julien and Shaw's virtual environment fire fighter training simulation (St.Julien et al., 2002). Reprinted with permission.

centre. The other group (control group) started with the search mission followed by a single session playing Sidh. Student performance was monitored during the game by a camera hung from the ceiling, as well as data automatically collected by the software. Student self-reflections were also collected after each session. Comparison of data from the experimental versus the control group revealed that the simulation provided an enjoyable experience and successfully complemented traditional learning as shown by a decrease in the number of times a victim was missed as well as through student responses to the self-reported learning questionnaires (Backlund et al., 2007, Backlund et al., 2009).

Furthermore, Tate (1997) examined the effects of using a virtual environment to train shipboard firefighters compared to traditional mission preparation. A full-scale virtual model of the USS Shadwell was created with Corypheus’ Designers Workbench and trainees interacted with their environment using a Virtual Research VR4 head-mounted display (HMD) and joystick interactive controls. The fire was simulated using video images of a real fire capturing the dynamic nature of the fire growth and smoke movement through each compartment. A selection of Navy firefighters was tasked to perform a familiarization exercise in the smoke filled ship with no fire, in addition to a full firefighting and suppression operation. Although the sample size was statistically limited, it was found that those firefighters who trained using the virtual environment completed a 2-min long real-life firefighting mission, on average, 30 s faster than the control group. Clearly both of the above studies point to the potential to develop new firefighting training methods using game-based immersive virtual environments.

In the area of training for incident command, St. Julien and Shaw (2002) developed the Fire fighter Command Training Virtual Environment (FCTVE) to train commanding officers how to conduct and lead a fire team on the fire ground (see Figure 6.4 depicting the characters and single family home in the virtual environment). Visuals of fire trucks and fire hydrants are added to the fire ground as appropriate. A database of animated characters allows simulation of the team of firefighters as they engage in various walking, crawling, climbing, cutting, chopping, rescue, carrying and firefighting/suppression operations. The house fire scenarios themselves are modelled offline using the Fire Dynamics Simulator (FDS) computational fluid dynamics software developed at NIST (McGrattan et al., 2008). FDS is a large eddy fire simulation model that numerically solves the Navier Stokes equations for low speed, buoyancy driven flows to predict time and spatially resolved temperatures, concentrations and smoke distributions throughout an entire burning structure[1]. Each house fire situation is pre-computed in FDS with data output at 1 s intervals. Different related scenarios must be run to model the impacts of each firefighter action on the base fire scenario. The spatial and temporally resolved data is rendered onto volumes to visualize smoke distribution throughout the space, and coupled with decision trees to pass appropriate information to the virtual environment in order to visualize and animate the fire and smoke movement in the single family house fire of interest. Based on the evolution of the fire, the FCTVE system then allows commanding officer trainees to instruct the virtual firefighters

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[1] "Smokeview is a software tool designed to visualize numerical calculations generated by fire models such as the Fire Dynamics Simulator (FDS), a computational fluid dynamics (CFD) model of fire-driven fluid flow or CFAST, a zone fire model. Smokeview visualizes smoke and other attributes of the fire using traditional scientific models such as displaying tracer particle flow, 2D or 3D shaded contours of gas flow data such as temperature and flow vectors showing flow direction and magnitude" Forney, G. P. and McGrattan, K. B. (2008). User's guide for smokeview version 5-a tool for visualizing fire dynamics simulation data. *National Institutes of Standards and Technology Special Publication*, 1017..

(avatars) to perform various tasks to extinguish the fire. During the training exercise, the trainee navigates within and around the environment, viewing the fire scene from any angle, and commands and instructs the firefighter avatars to perform specific duties. Through incorporation of the precomputed FDS data, users experience dynamic fire situations with changing fire and smoke behaviour based on changes to the environment brought about by firefighter actions. This system has been classified as the first to incorporate data from a three-dimensional computational fluid dynamics (CFD) model into a fire training simulator (Cha et al., 2012).

Again using the FDS software to predict fire development and smoke movement, Ren et al. (2008) created a virtual reality system intended for training of personnel in fire and emergency evacuation drills (Figure 6.5). As in the FCTVE simulator discussed above, a three-dimensional building model is created and FDS is used to precompute detailed time and spatially resolved data from a variety of plausible fire and evacuation scenarios. The FDS output data is stored and instead of being volume rendered, it is instead reprocessed using a multi-grid, multi-base state amendment model so that fire and smoke movement information can be passed in compressed form and thus in real time to the Vega visualization system. This system employs video images of real fire plumes and smoke to create textured images which are mapped to particle systems to provide very fast and realistic animations of fire and smoke movement. The trainee interacts with the fire scenario via a head-mounted display and mouse with functions that allow the user to navigate through the scenario and pick up and use firefighting tools. Evacuation paths and human animations can also be added to simulate evacuation during the fire. Once developed, the system was tested for evacuation training using a simulated scenario that involved a fire in a below-grade subway station. It was determined that the system could be used to safely and effectively simulate and evaluate emergency evacuation procedures as well as to conduct fire response and evacuation drills in a virtual environment.

Cha et al. (2012) further developed a virtual reality based fire simulator that was intended to allow members of the general public to experience ‘real’ fire situations, to allow firefighters to train at an entry level, and to aid firefighting commanders in the assessment of different fire scenarios and in making appropriate fire ground plans and safe command decisions (see Figure 6.6 of the fire development and smoke spread of an automobile accident in a tunnel). To accomplish this, FDS was again employed to precompute detailed time and spatially resolved smoke, gas concentration and temperature data related to the fire and evacuation scenarios of interest. The large quantities of FDS output data were then reprocessed using Octree space partitioning (Foley et al., 1997) and multiple-resolution based, level of detail selection methods (Foley et al., 1997) to optimize data transfer and facilitate real time simulation of a changing environment. In this simulation, normalized soot density data was used for visualization of general smoke propagation, while other output variables such as temperature, heat release rates, CO, CO_2, and O_2 concentrations were normalized based on threshold values representing safe versus hazardous exposure conditions. Since these variables are not generally related to optical signatures, an appropriate colour-based transfer function was developed to incorporate their hazard information (red for most noxious gas; blue for less noxious gas, for example) into the virtual scene as well.

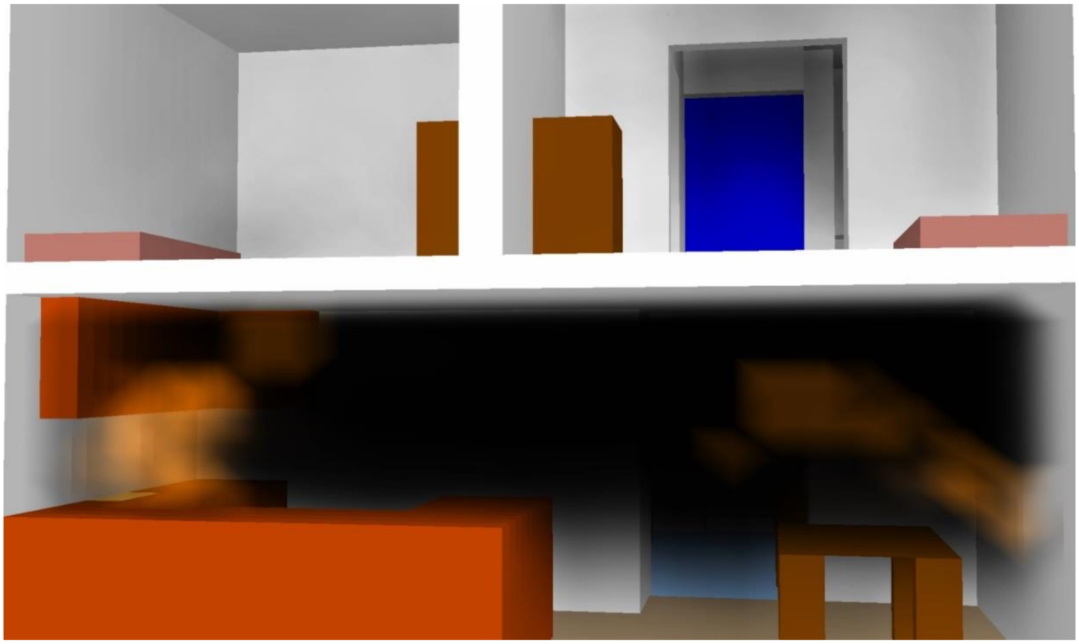


Figure 6.5: A depiction of fire development and smoke spread using Smokeview for visualizing Fire Dynamics Simulation data from (Forney et al., 2008). Reprinted with permission.

Figure 6.6: Fire training scenario of an automobile accident and fire in a tunnel using the virtual reality based fire training simulator developed by Cha et al. (Cha et al., 2012). Reprinted with permission.

Based on the combined information, multiple measures of safety could be included in an operational simulation. The system was tested using the scenario of a vehicle fire in the Jukryeong Tunnel in Korea. While the basic fire situation and individual hazards were represented in their simulation, extension is required to further optimize data transfer so that multiple hazards can be visualized and more complex environments can be simulated. In addition, interaction between the simulation and the trainee can be improved through inclusion of multi-sensory interfaces and through precomputed or real-time adaptation of the simulated environment as avatars or trainees undertake firefighting tasks.

The Environmental Tectonics Corporation developed the Advanced Disaster Management Simulator (ADMS) (see Figure 6.7 depicting the visualization of fire fighters suppressing a fire on a city block) as a virtual reality training solution to train emergency response commanders how to properly respond to terrorism, fire threats and other emergencies (Environmental Tectonics Corportation, 2012). ADMS is commercially available and allows emergency coordination centre staff, incident commanders and crews to setup appropriate protocols and chain of command, make important fire ground decisions, allocate firefighting resources, such as equipment and personnel, and apply response tactics for various emergency and fire incidents. Despite the apparent breadth of this system over other existing simulators, it does not provide trainees with very realistic experience in fighting fires due to the simple, planar graphics technology that it employs, thus limiting visualization of fire progression and precluding realistic immersion of the user into the scenario at hand (Cha et al., 2012).

The concept of faithfully representing real life situations via virtual interaction with an environment can present interesting issues when considering training via virtual reality simulation. Although the situation is improving, given recent technological advances and the availability of innovative consumer level hardware such as the Microsoft Kinect, mapping real-world interactions to the virtual world can still be challenging (Dugdale et al., 2004). Dugdale and Pavard (2002) developed a serious game intended to train incident commanders to properly supervise a rescue operation by coordinating their unit's actions including the safety of the crew and civilians, and appropriately establishing the chain of command to report information back to the control centre and request reinforcements or further information as necessary. Due to the objective of the game, they attempted to include real-world interactions between characters in the virtual training environment. Furthermore, since human communication relies heavily on gestures, this included determination of appropriate gestures for the virtual characters. In order to collect the necessary background data, they utilized observational field studies with on-site video capture of real fire scenarios, including an analysis of operating procedures and other formal documents related to each situation. In addition, they conducted interviews with firefighters and training personnel and participated in debriefing sessions with the trainees (Dugdale et al., 2002). The on-site field data were then analyzed to determine the appropriate design for realistic interactions amongst various members of the teams, including gestures (McNeill, 1996, Cassell et al., 1999). An analysis of the data revealed that there was a series of generic gestures that individuals perform during conversations; a finding that led to the development of a set of rules outlining when and how each gesture is commonly executed. As a result, the virtual characters developed in the simulation were generally considered to be realistic, except in some aspects of their facial appearance. This, as suggested by the authors, can be overcome by employing texture-based photographs and mapping them to the face of each avatar. Furthermore, due to the real-life situational data used in the game design, the virtual training environment appeared to initiate similar decision making processes for the trainees as they would encounter in real world situations.

Another interesting approach in firefighting simulation was employed by Querrec et al. (2004) in their SecureVi (Security and Virtual Reality) system which allows developers to create various training environments and offers mechanisms by which these environments can also be improved as they are run (see Figure 6.8 depicting a gas leaking scenario at a factory site and the development of a gas cloud in the simulation). Using the MASCARET concept (Multi Agents Systems to simulate Collaborative Adaptive and Realistic Environments for Training), they incorporated non-player controlled ‘agents’ into a physical simulation of a real scenario and programmed these ‘agents’ with human characteristics to act realistically in terms of transfer of information amongst, for example, members of a response team. Through the use of artificial intelligence techniques, these programmed agents reacted to the actions of a user and adapted their actions based on the evolving situation so that users became immersed in specific operational situations or environments that were too dangerous to conduct, or were inaccessible, in the real world.

Figure 6.7: Firefighters performing fire suppression within the Advanced Disaster Management Simulator (Environmental Tectonics Corportation, 2012). Reprinted with permission.

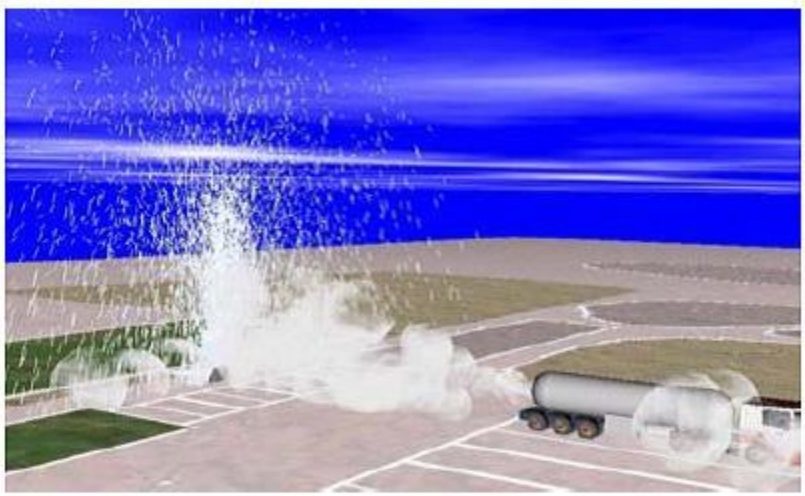


Figure 6.8: Example of the 3D environment from the SecureVi virtual environment fire fighter training simulation from Querrec et al (Querrec et al., 2004). Reprinted with permission.

The simulation system included an organizational model with interacting physical and social environments and appropriate rules, behaviour and constraints configured to train incident commanders in operational management and control of larger emergency scenarios, such as a major toxic gas leak at a factory site. The main incident in this example dealt with development and propagation of a gas cloud due to the leak and was dependent on the environmental conditions, as well as the behaviour of team members. It was of interest to assess the impact of the leaked gas on firefighters and civilians so that the objective of the scenario was to efficiently secure the civilians, to reduce the spread of the gas leak and minimize its effect on emergency responders, and to protect any additional gas tanks on the site by minimizing the possibility of ignition of the gas cloud. A series of source and target agents were established through which information related to the situation was passed (from source to target) with a recruiter whose role it was to track the source-target interactions at the organizational level. In the course of the simulation, three different networks interacted, including i) a mobility network in which the wind (source and recruiter) acted on toxic gas particles (target) to predict dispersion, ii) a toxicity network where effects of the gas cloud and leak were determined so that humans play the role of both recruiter and target, and iii) a collision network where the water walls which were being used to slow down the progression of the gas cloud acted as source and recruiter. The use of the autonomous multi-agents allowed the characters in the scenario to adapt to their dynamic environment and to calculate implicit plans to carry out specific actions that may not have been instructed by the user to that point in the exercise. If these autonomous characters were not able to fulfill a particular action, they could deem the action to be a failure and the agent would then ask the user for supplementary orders. This model required three roles (expert, trainer, and learner) based on four phases within the teaching use of SecureVi: i) design of elements, ii) describing scenarios and assigning roles to agents, iii) simulation, and iv) debriefing. The intended use of this model requires an expert or group of experts with expertise in MASCARET to program the specific physical characteristics of the simulation. Once the simulation is performed, the model is capable of recording all actions and messages entered by the users that can be used by firefighter training personnel during the debriefing stage. However, the effectiveness of the model to efficiently train incumbent or recruit firefighters was not reported using quantitative measures.

Toups and Kerne (Toups et al., 2007a) sought to develop principles for design of games that promoted collaboration and team work amongst users based on examination of practices and information transfer processes experienced by firefighter trainees during the actual process of communicating, processing, and integrating emergency information at an incident scene (in the workplace). Based on the results, the authors note that firefighters make use of their cognitive resources more efficiently through implicit coordination, which is typically learned from live fire training exercises and/or responding to actual emergencies. They concluded, then, that interactive simulations could aid in the training process by allowing development and implementation of particular attributes that are based on the proper information acquisition and communication needed to work together to build the ‘information picture’.

Following up on their analysis of the potential for implicit coordination training in firefighter trainees, Toups and Kerne (Toups et al., 2007b) developed an augmented reality game, called *Rogue Signals,* with the purpose to enhance training of team coordination skills. As such, a user must coordinate their actions effectively to be successful in the game. Utilizing head-mounted displays, global positioning receivers (GPS), speakers, radio, and a backpack-mounted computer, the player is provided with differential information, mixed communication modes and audible cues related to the training scenario while immersed in the game environment. Firefighter trainees (*seekers)* work together with an external viewer (*coordinator)* to find hidden artifacts in the real world while attempting to avoid computer-controlled enemies in the virtual world. The *coordinator* has access to the virtual world view and must guide the *seekers* around virtual obstacles toward their intended goals. In a later evolution of the game, work practices of fire emergency personnel were also incorporated to teach response coordination skills (Toups et al., 2009) without the fire and smoke inherent in an actual incident. The game creates a distributed cognition environment where team members need to rely on each other to communicate rapidly-changing information, while also being subjected to a realistic level of stress that might be encountered during performance in a real emergency response.

Most recently, Toups et al. (2011) developed a zero-fidelity simulation (defined as a simulation “in which human- and information-centric elements of a target environment are abstracted”), called *Teaching Team Coordination Game* (*T^2eC*), to supplement the preparation of fire emergency response students for live burn training. According to the authors, the zero-fidelity approach reduces the cost of the simulation whilst increasing the focus on the desired elements of education. In order to test whether the game improved coordination, 28 firefighter students played the game over four sessions, separated by one-week intervals. In each session, team members played the game under two conditions, with all the seekers co-located in one room and the *coordinator* in a separate room or with all seekers and coordinator distributed in separate rooms. It was concluded that the team coordination amongst students had improved through a shift to implicit coordination and that this also enhanced their ability to connect the game play to real practice during live fire burn training. As such, this study provided further evidence that zero-fidelity simulation is an effective approach to firefighter education.

Many urban fire departments are currently using serious games and virtual simulations to aid in training incident commanders how to respond in various emergency scenarios. A large metropolitan fire department in Canada has used two of the available training products, *Fire Studio* (Digital Combustion, California) and *VECTOR Tactical Command Trainer* (VectorCommand Ltd, United Kingdom) to develop educational programs for their personnel. Custom digital photographs are imported into *Fire Studio* and used to create relevant emergency scenarios for a given training exercise. This, coupled to a flexible incident command trainer, allows fire departments to create their own custom scenarios and to train firefighters and incident commanders on appropriate coordination and management of emergency situations according to their own departmental guidelines.

VECTOR, launched in 1997 in the United Kingdom, is a flexible command trainer that combines artificial intelligence, virtual reality, and 3D training methods into a training tool for incident commanders in the fire service. Fire departments can again customize emergency scenarios by changing multiple variables (type and location of fire, different building skins, time of day, and wind direction), in an attempt to challenge the trainees’ incident command knowledge and decision making skills. The trainee has the capacity to use the visual information for their initial observations of the scene after which they provide radio or face-to-face communication with a system facilitator to issue orders or to call in additional support. All participants within the training system have their own virtual characters (avatars) so that the command trainee is able to view where all team members are located within the scenario.

In addition to workplace coordination and command skills, one of the other major skills required in the fire service is the ability to safely and effective drive a fire truck. Texas A & M Engineering Extension Service developed the MPRI FireSim driving simulator to augment on-board training of vehicle operation across Texas. The simulator utilizes computers, various driving scenarios, and three high definition (HD) display screens to enhance the decision making power and driving behaviour of vehicle operators over a broad spectrum of maneuvers.

Another relevant serious game that has been implemented for training purposes within the fire service was originally designed for use by the Fire Department of New York (FDNY). This game was developed under the project name: HazMat Hotzone (Carnegie Mellon University, 2002). It was created to assist firefighters in training for hazardous and chemical emergencies using video gaming technology. For the firefighters participating in the simulation, the main objective is to teach communication, observation, and critical decision making to the first responders. One of the key benefits of this particular serious game over many of the others are that the training instructor has full reign over what aspects of the simulation are involved for a particular scenario (i.e., location of the hazard, the specific effects, weather conditions, and where the victims are located in addition to their particular symptoms). The training instructor can also implement any secondary scenarios within the game at any time to further incorporate new elements into the original emergency situation while firefighters are participating in the game.

The serious games and virtual simulations discussed here have implemented various models to simulate the physical characteristics of a fire situation to provide a training environment for firefighters. Many of these models have focused primarily on the development and programming of a set of realistic characteristics for the fire scenario, whereas others were more concerned with the interaction of the users and their ability to accurately coordinate a team of firefighters. The difficult yet important integration of these two facets onto a single platform will provide advancement in the use of serious games and virtual simulations for training in the fire service.

6.5 Fire Education Using Serious Games and Virtual Simulations

It is clear from the above discussion that many of the elements required for simulation of different training scenarios for firefighters are currently in use or under development. Despite this, it is important to step back and ask whether games are a most appropriate platform for the conduct of this training. Along these lines, virtual reality has gained considerable interest, since its inception, as an application under which to study various features of spatial cognition (Wilson et al., 1997, Péruch et al., 1998, Waller, 1999), memory (Gamberini, 2000), and learning (Wilson et al., 1997), based on the conclusion that the cognitive mechanisms that exist within real environments and virtual environments appear to be analogous (Richardson et al., 1999).

One of the initial studies in this area was conducted by Witmer et al. (1996) where the authors concluded that virtual environments were able to effectively train users to determine a navigational route through a situation without the need to receive verbal directions and photographs. They also showed that learning a specific route within a real building can be accomplished using a virtual environment where the users are able to interact with the environment possibly through a head-mounted display. Furthermore, Witmer and Sadowski, Jr. (1998) found that virtual environments can be configured to depict real world complexities and, as such, can be employed to effectively train users how to undertake cognitive spatial tasks. Conversely, some of the literature reveals that a virtual environment may not be as effective for the acquisition of spatial knowledge so that learning a specific spatial layout by use of a virtual simulation may take individuals significantly longer (Arthur et al., 2001) or equal time (Waller et al., 1998) when compared to obtaining the same knowledge by way of a map, in a static or dynamic virtual environment. Impediments to these studies revolve around the limitations of the software technology employed (Arthur et al., 2001) or the expertise of the participants in using a virtual environment system (Waller et al., 1998). Based on this earlier work, Gamberini et al. (2003) developed a virtual environment through which to study participants' responses to the appearance of a fire and to the resulting emergency within a library structure. Eighty-four participants were provided the opportunity to explore the library environment without any hazards present to orient themselves with the environment. Following this, participants were asked to reach a pre-determined point in the virtual environment where a fire emergency would be enacted via one of two possible situations, a fire closer to the participant and the other further away from the participant.

Participants themselves were subjected to three different surrounding environments based on the intensity of the situation. In all cases, they were asked to act as naturally as possible to find their way to the exit. Results indicated that individuals recognized and responded to complex situations within a virtual environment in a manner similar to how they react in a real environment. The authors concluded that their data support the use of virtual environments to simulate emergency scenarios for training based on the fact that participants in these tests produced adaptive responses to their virtual environment, again in an analogous fashion to what would be expected in a real world situation.

Smith et al. (2009) note that conducting live fire evacuation drills in buildings with realistic conditions is difficult and, no matter how well planned, they cannot feature dynamically changing environments such as smoked filled corridors, blocked exits, and fires in unexpected locations; just those situations that require immediate decisions and action by firefighting personnel. To overcome these limitations, they developed a 3D gaming environment to aid in virtual fire drill evaluations. By re-using existing gaming technologies and assets, over a three week period, a single developer was able to create a virtual real-world environment to aid in fire drill evaluations. The authors concluded that users perceive the virtual environment to be realistic, but performance during the evaluations is also correlated with the previous gaming experience of each trainee.

Chittaro and Ranon (Chittaro et al., 2009) also developed a serious game to educate individuals on the proper evacuation procedures during a building fire scenario. The game allows the user to gain navigational knowledge of the building and to learn appropriate techniques to properly evacuate the building under various fire conditions and scenarios. The authors concluded that the initial prototype of the game has advantages in that it is capable of acquiring actions of the players and determining behaviours of the users. Furthermore, analysis of the player's actions may lead to revealing deficiencies in the architecture or layout of the real building. However, future work is needed to increase the realism of the fire and fire room environment, to implement more robust physiological feedback to the user, and to create a multi-user environment that can more realistically simulate multiple person evacuation from larger structures.

Not all simulations and serious games have been created specifically for the fire service; some have been produced to train and educate the general public in fire safety. *Blaze* (DeChamplain et al., 2012), a serious game developed to improve and educate on household (kitchen) fire safety, allows the user to experience and deal with dangerous and potentially life-threatening fire-based events in a safe, fun, and engaging manner (see Figure 6.9a depicting a stove top fire in the kitchen of a home). The game was developed to educate a participant on how a fire should properly be extinguished, and to recognize that, depending on how big the fire is, they should either call the fire department or evacuate their home. As the game starts the user's avatar body is not visible in the scenario, so the game participant begins by seeing a stove top cooking fire in the kitchen. The goal is to choose the appropriate instrument or method by which to respond to the fire and to extinguish the fire should that be a viable option. When the appropriate response is to extinguish the fire, the user must recognize the type of fire and choose whether to use baking soda, water, or a fire extinguisher to extinguish the fire. For example, choosing to pour water over a grease fire will cause the fire to continue to burn. If a user continually makes incorrect choices, their progress in the game ceases and their avatar will come into view, pass out due to smoke inhalation or prolonged exposure to the fire. This approach allows players to gain knowledge in the potential positive and negative effects of using products in a house on a stove top fire without the use of an actual fire. The use of feedback following a decision or action being made along with the simulation training model appears to provide a strong platform for the training of civilians during kitchen fires.

More recently a serious game was developed by Tawadrous et al. (2013) to train individuals (employees of a large institution such as a university) to react appropriately to a given type of threat (bomb threat, gas leak, or explosion and fire, amongst others) (see Figure 6.9b depicting a chemistry lab in a university environment within the serious game). The authors describe a gaming platform in which the trainee is faced with a toxic fire scenario within a typical university biology laboratory. Based on the sequence of events that ensue, the user must make correct responses and decisions in order to handle the emergency scenario present and proceed through the game. A specific fire extinguisher technique known as the Pull, Aim, Squeeze, and Sweep method is implemented and must be used to put out a fire (see Figure 6.10).

Thus, if the user does not employ this method or if they make an incorrect decision, they will not be able to proceed and instead will be given on-screen information as to why the proper response was not achieved. Again the combination of scenario based training and active feedback included in the game is thought to provide an effective platform upon which to train employees with a wide variety of skill sets on appropriate decision making, safety precautions and fire extinguishing methods to employ should a fire actually occur in their institution.

Figure 6.9: (top) screenshot depicting a stove top fire that has started to spread out of control. Reprinted with permission from DeChamplain et al. (2012), (bottom) sample screenshot illustrating the area of the chemistry laboratory where the simulation is based. Reprinted with permission from Tawadrous et al. (2013).

6.6 Forest Firefighting Simulations

The work by Li et al. (2004) developed a virtual reality simulator suitable for training fire fighters on how to battle forest fires. Their system employed a virtual reality and Distributed Interactive Simulation (DIS) technique to render and model a virtual forest fire environment such that participants could be asked to establish the organizational flow required in collaborative forest firefighting using ground and air firefighting units to efficiently fight the fire. To represent the many complexities associated with forest fires (wind, nature of the wood, slope of the forest area, slope direction, vegetation, climate, and terrain), the authors based the physical fire simulation on the Rothermel (1972) models for behaviour of surface fires and the improved model (Rothermel, 1991) for crown fires. The original model proposed by Rothermel in 1972 was very suitable for this purpose as it required no prior knowledge of the burning characteristics of a particular fuel source. The only variables that were required were the physical and chemical composition of the fuel source and the environment where it would burn (Rothermel, 1972). The spreading rate and the boundary of the forest fire were determined using the FARSITE (Finney, 1994) fire spread model (based on Huygen's principle to describe the movement of a wavefront) (Born et al., 1999), allowing wind speed, slope, and additional aspects to influence how the fire spreads during the simulation. Based on the overall functionality of the models for smoke and spread of the forest fire, as well as the demonstrated effectiveness of the air and ground firefighting units to coordinate fighting the fire, the authors concluded that the simulation system met the need in terms of training wildland firefighters for forest firefighting. However, the authors did not report

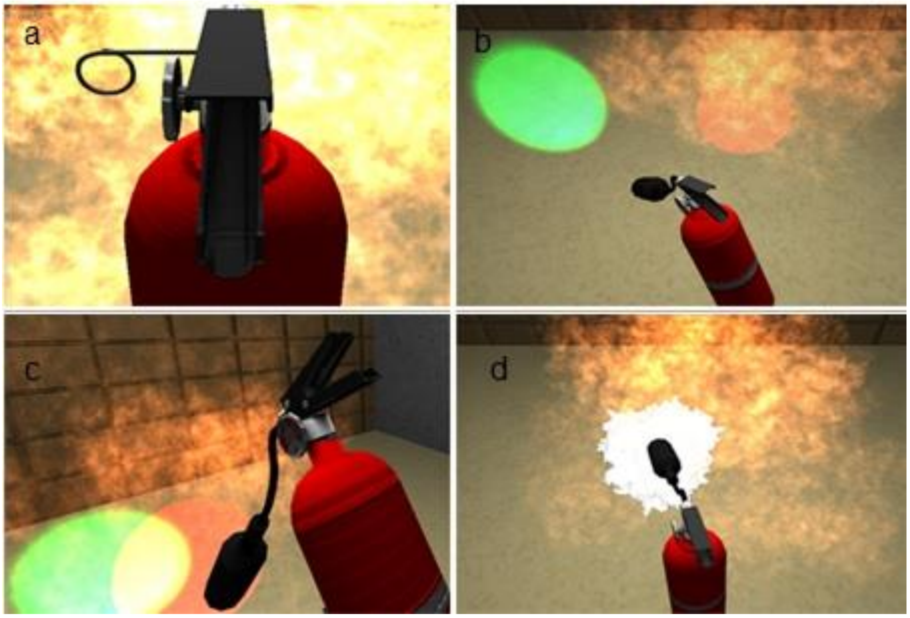


Figure 6.10: Screenshot from the Tawadrous et al. (2013) game depicting the Pull, Aim, Squeeze, and Sweep (P.A.S.S.) method. a) prompts user to pull pin, b) prompts user to aim, c) prompts user to squeeze handle, and d) Prompts user to maneuver sweeping motion). Reprinted with permission.

any quantitative data on how this particular simulation was determined to be a useful aid in the training process.

6.7 Open Problems

The firefighting occupation has been well established as a physically and psychologically demanding job which can put the firefighter in extremely hazardous situations that include thermal stress, exposure to chemical substances, and impacted by numerous psychological factors (Gledhill et al., 1992, Selkirk et al., 2004b, Williams-Bell et al., 2009, Williams-Bell et al., 2010a, Williams-Bell et al., 2010b). Due to the nature of the job, performing live training simulations places the firefighter at risk even if all safety precautions are taken. Additionally, real-life simulations of realistic fire situations are expensive and take a long time to set-up and run. With the continuing development of new technology and methods, substantial benefit may accrue to the fire service with increasing the use of serious games to aid in the education and training of firefighters. Such technology may be used to minimize exposure of firefighter trainees to hazardous fire conditions during training and to supplement the ever waning live firefighting experience that they obtain in the course of their daily jobs. With the current ubiquity of video game play, particularly with the current generation of learners, and the inherent engagement, interaction, and motivation of video games, the use of video game-based technologies for educational purposes (i.e., serious games), are being applied in a variety of applications including firefighter training. Serious games applied to firefighter education and training minimize the hazardous conditions that firefighters are often subjected to during training simulations. Although serious games cannot completely replace hands-on training sessions, their incorporation into a comprehensive training package can mediate the high costs of running certain training scenarios and can provide a more convenient training environment for particular tasks and critical decision making that is required of the job.

Serious games can also be used as a precursor to live simulations offering trainees the opportunity to train until they reach a specific competency level, thereby ensuring they optimize their time and learning potential when exposed to live simulation training exercises that are resource intensive and expensive to run.

In this paper, we presented a thorough review of the use of serious gaming and virtual simulation for the education and training of fire fighters. The majority of these serious games and virtual simulations have focused primarily on decision making and strategic command of firefighting crews on the fire ground required by incident commanders (Tate et al., 1997, St.Julien et al., 2003). Although the decisions and actions of incident commanders at a fire scene are critical to the tactics used in fire suppression and for the safety of the firefighter and civilians, there appears to be a void in the development of serious games for task level job activities of the individual firefighter. These task level activities can range from task specific movements based on safe biomechanical techniques to accurate decisions being made by the firefighter within the fire scenario itself. Typically, the average firefighter will not have the same experience or expertise as a captain or incident commander. Therefore serious games and simulations provide an optimal opportunity for firefighters to gain experience that would otherwise take years to achieve through virtual simulations of potential fire ground incidents and benefit from their development. Further research into the development of serious games and simulations to be utilized for the fire service should focus on the physical tasks (e.g., fire suppression, victim search and rescue) and the decision making that the individual firefighter entering the fire will undergo. None of the previous work presented here has focused on a game or simulation that both educates on proper procedure of firefighting tasks while accurately monitoring certain physiological variables (i.e., decision making, body position, technique). This may in part be due to the lack, until very recently, of consumer-level (cost-effective) sensors that could be used to monitor physiological progress of the trainee. With the advent of new sensing technologies and strategies initially developed for gaming purposes, it is now possible to accurately monitor physical attributes of motion using a variety of hardware mechanisms while allowing for novel interaction techniques that increase engagement and lead to a better overall educational experience. For instance, the main sensing modality of the Nintendo Wii (the Wii Remote), contains accelerometers and gyroscopes (Wii Motion Plus), that provide enough sensing capability to track the orientation of a single joint in a kinematic chain; the Nintendo Wii Fit balance board provides estimation of the centre of gravity and leg lifts; Microsoft's Kinect tracks an entire skeletal model of the player's body by measuring 20 of the player's joints to estimate full-body motion as well as body-type characteristics. The Kinect allows users to interact with their application using a natural user interface that employs gestures thus eliminating the game controller and the typically non-natural and potentially limiting interaction it affords. In surgical training for example, using the Kinect within a virtual operating room, surgery trainees are able to perform their required tasks in a more intuitive manner that is better representative of the real world (Robison et al., 2011).

That being said, although the popularity of serious games is growing and they are becoming more widely used, before their use becomes more widespread, a number of open problems must be addressed. Tashiro et al. (2007) developed a typology of serious games for healthcare education and identified seven areas that require research and improvements for the effective development of serious games: i) disposition to engage in learning, ii) impact of realism/fidelity on learning, iii) threshold for learning, iv) process of cognitive development during knowledge gain, v) stability of knowledge gain (retention), vi) capacity for knowledge transfer to related problems, and viii) disposition toward sensible action within clinical settings. Although they focused on serious games for healthcare education, the problems they outline are universally applicable. Of particular importance is the question regarding the impact of realism/fidelity (i.e., the extent to which the appearance and/or the behavior of the simulation matches the appearance and behavior of the real system) on learning (Farmer et al., 1999). Despite the great computing hardware and computational advances we have experienced, real-time high fidelity rendering of complex environments across all modalities is still not feasible (Hulusic et al., 2012). Designers and developers of serious games, and virtual simulations in general, typically strive for high fidelity environments, particularly with respect to the visual (graphical) scene. However, evidence suggests high fidelity simulation does not always lead to greater learning (Norman et al., 2012), and striving for high fidelity can burden our computational resources (particularly when the simulation is intended to be used on portable computing devices), increase the probability of lag and subsequent discomfort and simulator sickness (Blascovich et al., 2011), and lead to increased development costs. Greater work that examines the relationship between fidelity and learning still remains.

A further issue revolves around the effectiveness of serious games. In other words, for serious games to be considered a viable educational tool, they must provide some means of testing and progress tracking and the testing must be recognizable within the context of the education or training they are attempting to impart (Chen et al., 2005). Although various methods and techniques have been used to assess learning via serious games and simulations in general, assessment is commonly accomplished with the use of pre- and post-testing, a common approach in educational research which itself is not perfect (Becker et al., 2011). However, serious games (and games in general) do contain in-game tests of effectiveness where, as players progress through the game, they accumulate points and experience which make the next stages and levels of the game easier and thus the user should score higher if any learning has been imparted. Recently there has been plenty of effort placed on the use of such in-game assessments for evaluation of user learning, moving assessments away from the predominant, classic form comprised of questionnaires, questions and answers, etcetera. This provides the opportunity to take advantage of the medium itself to employ alternative, less intrusive, and less obvious forms of assessment which could (and should) become a game element itself (Bente et al., 2009). Integrating the assessment, such that the player is unaware of it, forms the basis of what Shute et al. (2009) describe as stealth assessment (see Bellotti et al. (2013) for a thorough discussion on serious games assessment).

Realistically representing the complexity of a developing fire and faithfully simulating the impact of numerous firefighter response procedures on that fire also currently represents a limitation in the application of serious games and virtual simulations to impart ‘real-life experience’ for the firefighter. As previously mentioned, one of the limitations of serious games and virtual simulations is the lack of providing real-life experience of actual fire situations for firefighters. In a non-traditional sense, the inside of a burning structure can be considered the firefighter’s workplace. Thus, any fire development and response simulation in a serious game must not only be credible but also sufficiently realistic to afford the necessary level of training, a requirement that becomes increasingly difficult to meet as firefighting techniques become more sophisticated. Simulating fire suppression, for example, involves not only representation of fire development, already shown to be a limitation in work discussed above (St.Julien et al., 2002, Ren et al., 2008, Cha et al., 2012), but also involves simulating the complex physics involved in initial attack of the fire, allowing the firefighters to advance into the structure. For a realistic simulation to proceed, the nozzle stream would have to be altered at the appropriate point in the simulation with the physics modified to model interactions of the hose stream with the seat of the fire. To properly train such complicated techniques in a virtual environment requires not only accurate prediction of complex physical interactions that lead to fire development under multiple possible actions of the firefighter, but also necessitates an accurate feedback system be in place for assessing and monitoring those actions as well. The level of complexity can be understood by looking at two examples. In the first instance, spraying an insufficient amount of water on the fire will lead to an increase in radiation, temperature, and eventually a flashover scenario (Liu et al., 2002), yet the physics involved with transition to flashover is very much an active area of research in fire science so appropriate models of this phenomena would need to be developed. Alternately, if too much water is applied to the fire clouds of steam can be produced, posing significant hazards to both the firefighter and any potential victim being rescued (Liu et al., 2002). Again, this situation would somehow have to be incorporated into a comprehensive tool for firefighter education. In order for serious games and virtual simulations to complement real-life experiences, then more sophisticated models and techniques must be incorporated and properly assessed and feedback provided so the firefighter can understand and learn from the scenario that they are immersed in.

Whilst incorporating the full complexity of a fire situation into a serious game or virtual simulation may currently be out of reach, incorporation of specific key elements of firefighting training might well be a viable proposition. Based on current training problems and needs in the fire service, for example, it is recognized that increasing the experience of the firefighter in hose stream application and the ability to maneuver in a very low body position within the lower cool gas layer to advance into a structure are critical training procedures that can mean the difference between suppressing a fire or creating a situation of immediate danger to life and health (Scheffey et al., 1997, Grimwood, 2000, Liu et al., 2002). These two methods are extremely important in the safe and appropriate training of air management, which has previously been reported as being of central importance in the fire service (Williams-Bell et al., 2010a, Williams-Bell et al., 2010b). At the same time, it has been shown to be possible to simulate some aspects of these in a virtual environment (Backlund et al., 2007, Backlund et al., 2009, Lebram et al., 2009). Therefore, if game developers and researchers are able to develop simulations and serious games that can effectively address even these elements, it may be possible to increase the experience of firefighters in these critical operational techniques in a safe and cost-effective manner.

6.8 Discussion

The application of virtual simulations and serious games is becoming more widespread within firefighter education and training. In addition to their inherent interaction, motivation, and engagement, the application of virtual simulations and serious games to firefighter education and training can provide a safer and cost effective training environment. The majority of these tools that have been developed to date focus on fire education (Bukowski et al., 1997, Gamberini et al., 2003, Forney, 2007, Toups et al., 2007b, Ren et al., 2008, Chittaro et al., 2009, Smith et al., 2009, Toups et al., 2011, DeChamplain et al., 2012, Tawadrous et al., 2013) incident command level decision making and team coordination (Tate, 1997, St.Julien et al., 2003, Dugdale et al., 2004, Querrec et al., 2004, Cha et al., 2012, Environmental Tectonics Corportation, 2012), and building evacuations (Korhonen et al., 2007, Kuligowski, 2013). Importantly, very few have been developed at the individual task level duties of the fire fighter (Backlund et al., 2009). One of the major limitations of virtual simulations and serious games has been the limited use and reporting of quantitative measures to accurately assess the effectiveness and efficacy of the simulation along with the ecological validity. For serious games to be accepted as a viable educational tool, they must provide some means of testing and progress-tracking and the testing must be recognizable within the context of the education or training they are attempting to impart (Chen et al., 2005). A number of studies have employed various methods and techniques to assess the effectiveness of serious games and various comprehensive reviews have been conducted to examine the overall validity of game-based learning in general. Results of these studies and reviews seem to suggest that game-based learning is effective for motivating and for achieving learning goals at the lower levels in the Bloom's taxonomy (Connolly et al., 2012). The assessment of user learning within a serious game is not a trivial matter and greater work is required. However, with the advent of recent technological advancements, it is now possible to extend and enhance assessment by recording game-play sessions, and keeping track of players' in-game performance. In-game assessment is particularly useful given that it is integrated into the game logic without breaking the player's game experience and it enables immediate provision of feedback and implementation of adaptability (Bellotti et al., 2013).

Another major criticism of virtual simulations and serious games has been their ability to provide a realistic educational and training environment. Fully recreating a complex interactive, and dynamic real-world fire environment across all of the senses is still beyond our computational reach (Hulusic et al., 2012). That being said, recent hardware and computational advancements are providing designers and developers of serious games the opportunity to develop applications that employ high levels of fidelity/realism and novel interaction techniques using off-the-shelf consumer level hardware and devices; as technology continues to improve, even higher fidelity/realism will follow. However, despite striving for high fidelity, recent work has suggested that high fidelity does not always lead to greater learning (Norman et al., 2012) and therefore, greater work remains to examine the intricate relationship between the level of fidelity and effectiveness of learning.

With respect to firefighting, one of the most important factors for health and safety in the fire service that has received limited attention in the scientific literature is cognitive function, and primarily how it relates to thermal stress. Similarly, it has been incorporated at only a cursory level, with no consideration of the impact of thermal stress, into the serious games and virtual simulations discussed above. To date, the few studies which have examined cognitive function during exertional heat stress in fire fighters have utilized simple mental performance tasks, such as reaction time, to determine any changes in cognition with increasing T_{core}. These tests have been reported as being capable of withstanding the effects of thermal strain due to their simple nature (Hancock et al., 1998), and therefore as not being practical to the firefighting occupation (Barr et al., 2010), nor ecologically valid. On the other hand, cognitive performance tests that involve dual-tasks (either motor and/or cognitive tasks) or those involving central executive function are more susceptible to decrements from exposure to thermal strain (Hancock et al., 1998, Cian et al., 2000, Cian et al., 2001). In a review study by Barr et al. (2010), the authors concluded that future work should focus on performing simulated firefighting tasks, at the intensities and durations that reflect similar energy expenditures as those encountered by fire fighters, while in a climatic chamber using computer-based cognitive function tests that are more realistic to the mental tasks encountered at emergency scenarios. This idea points to yet another open opportunity for the use of serious games and virtual simulation in an application with direct impact to the fire service.

6.9 Conclusion

In this paper we have reviewed the use of virtual simulation and serious games for the education and training of firefighting. The advances in technology have allowed for game developers to depict emergency scenarios in a semi-realistic fashion that can greatly benefit firefighter education; however, the ability to completely recreate real world dynamic fire simulations that are precisely accurate are still beyond the technological capacities currently available. Although greater work remains to overcome the open problems associated with use of serious games and virtual simulations in universal fire training applications, the next step in the process will be to utilize the benefits of the gaming environments in recreating the decision making processes that firefighters must encounter in an emergency situation and incorporate and monitor them in an environment where the physical and psychological stresses are analogous to a live situation.

CHAPTER 7 - The use of serious game technology to assess cognitive function in firefighters during exercise-induced heat stress

Preface to Chapter 7

The results from Chapters 4 and 5 provide further insight for the appropriate use of the CANTAB cognitive assessment battery for repeated measures testing within a short duration research design. However, the findings indicate that certain precautions should be taken when interpreting the data for particular tests within the battery and to alleviate these shortcomings, at minimum, a double baseline familiarization should be implemented. Despite these recommendations for future research utilizing CANTAB, the specific tests that formed the main findings of Chapter 4 did not show any signs of practice effects in the results detailed in Chapter 5.

Neuropsychological assessment batteries have been extensively researched and determined to be valid and reliable measurement tools. However, the ecological validity of using such assessment tools may not equate to the actual decision making tasks required of individuals working in particular occupations, such as firefighting. The novel tasks performed on the CANTAB assessment battery would classify the participant's skill level as novice when they would be considered an expert in terms of the cognitive abilities related to firefighting. Hancock et al. (2003) has suggested that the skill level of the individual can play a factor in how susceptible they are to the impact of heat stress on cognitive function.

Serious game technology has been utilized in numerous occupational settings for training (St.Julien et al., 2003, Sowndararajan et al., 2008, Boulet, 2009, Toups et al.,

2011) or rehabilitation (Rand et al., 2009, Cox et al., 2010, Kamper et al., 2010, Lange et al., 2010). The ability of serious games to be a high fidelity simulation of an actual environment may not be entirely necessary for learning (Norman et al., 2012), but it is essential that they assess participant activity (Bellotti et al., 2013) in order to provide it as a potential tool to assess the cognitive abilities of firefighters in a more ecologically valid measure (Barr et al., 2010). This approach can provide more realistic decision making tasks and determine if the changes identified in Chapter 4 could potentially be due to performing novel cognitive tasks compared to decision making tasks that they have been extensively trained for in the field.

The development of a serious game that could be utilized as an assessment tool for the fire service took over two years from the initial planning stages until completing the final product. Initially, 3 subject matter expert interviews were conducted with 2 training officers and 1 firefighter. These semi-structured interviews were recorded to develop the progression of questions to be utilized during focus groups. Upon completion of the analysis, a focus group was conducted with 12 fire service personnel from various fire halls ranging in experience from a first year firefighter to Training Officers and a District Chief. The focus group was conducted to gain further insight into the specific experiences of firefighters while at fire emergencies. Specific interview guides were created, based on the subject matter expert interviews and fire hall observations, with open-ended questions to guide the facilitators in eliciting responses. All focus groups were recorded using a digital recorder to be transcribed verbatim. The main findings from the focus groups included the necessary tasks required of an individual firefighter while at a fire scene. These included proper radio communication, acknowledging improper hose lengths, spatial awareness, victim locations, fire alarms sounding, preliminary search of the premises, and communication with members of the immediate family or bystanders. This information was then utilized to develop a storyboard for the serious game simulating a two-storey residential fire where only one apparatus (i.e. fire truck) is deployed.

The next task was to observe firefighters during active drills and routine fire hall activities at an urban fire hall. Tasks within the fire hall were observed as well as active fire suppression tasks and post-fire equipment maintenance were characterized and recorded. All observations were digitally captured using still images and video. During the fire hall observation, observation data was collected at a two-storey fire scenario classified as a 2-alarm fire. Following the active fire suppression activities, informal conversations were conducted with the firefighters who were engaged in the emergency to elicit any additional information from the specific tasks that were conducted within the fire scene.

The serious game storyboard was developed with assistance from Training Officers and translated to the game development team. The game development team acquired the information and began to implement particular placeholders into the serious game prototype to develop a blueprint of the scenario. The interdisciplinary nature of the research team made it necessary to setup particular communication strategies to manage project development. Following the creation of the storyboard for game developers, weekly meetings were established with the game development team. These weekly meetings were conducted to review progress on game development and determine next steps to be included for each subsequent week. In addition, the research team liaised with fire personnel on a monthly basis to provide prototypes of game development and receive feedback from experts in the field. This information was then relayed to the game development team at the weekly meetings. Following 4 months of game development, a focus group was scheduled with fire personnel to elicit feedback on the prototype of the serious game. Comments and feedback were recorded and reviewed by the research and game development teams. Bi-weekly meetings were established to implement the modifications suggested by fire personnel experts. In January 2015, a second focus group was established to determine if game development had reached a level for research purposes. In June 2015, a third focus group was organized with a second urban fire service to determine the transferability of the serious game. This process provided valuable information for future research in that project management between interdisciplinary teams is critical for the effective and efficient development of a serious game.

This chapter aimed to determine the effects of EIHS on cognitive function using serious game technology and answer research objective 4. Additional data not detailed in this chapter for the physiological profile of participants, HR, gas exchange, and subjective measures can be found in Appendix B.

7.1 Abstract

The purpose of this study was to assess cognitive function in firefighters while exposed to EIHS using a Firefighter Task Level (FFTL) serious game that simulates the cognitive demands of an individual firefighter. Cognitive performance was tested at repeated intervals while 10 male firefighters exercised in 35°C and 50% humidity while performing a game-based simulation. Participants performed treadmill walking ($4.5\ km \cdot h^{-1}$ and 2.5% grade) with cognitive function assessed at the start of exercise (FFTL 1), at T_{core} of 37.8°C (FFTL 2), 38.3°C (FFTL 3), and 38.5°C (FFTL 4), and following an active cooling recovery protocol to reduce T_{core} to 37.8°C (FFTL 5). Cognitive Function was assessed using a FFTL serious game developed to represent tasks (search and rescue, spatial awareness, memory recall) required during a two-storey residential fire. Planned contrasts revealed that the percent change of tasks completed was impaired at FFTL 5 compared to FFTL 1. Room search time for bedroom 3 and 4 searched in FFTL 3 was significantly longer than bedroom 2 in FFTL 2. This study revealed that the percent of correct decisions was not impaired during an EIHS protocol assessed using a serious game but room search time was prolonged at 38.3°C (FFTL 3). However, following an active cooling recovery regimen, memory recall was impaired compared to initial performance. The presence of long-term memory impairments may be troubling for subsequent incidents or during fire scene investigation following an emergency.

7.2 Introduction

Firefighting is a physically demanding occupation largely comprised of low intensity work rates for a long duration, interspersed by moderate to high workloads (Barr et al., 2010). This physical work is magnified by the effects of heat stress, PPE, and the SCBA. Although the physiological impact of firefighting has been well documented, less emphasis has been placed on cognitive function (Morley et al., 2012). Barr et al. (2010) stated that maintaining adequate cognitive function under heat stress is essential to accurately make decisions, remain vigilant, and remember important geographical locations within a fire scene. To date, studies examining the effects of heat stress on cognitive function have primarily utilized simple tasks, such as reaction time (Barr et al., 2010), which do not reflect realistic firefighting scenarios (Morley et al., 2012).

Emerging advancements in game technology provide the potential to implement interactive and engaging assessment and training tools using game-based simulations. These simulations, termed serious games (Susi et al., 2007), provide a safe and cost-effective means of training (Williams-Bell et al., 2015a). Serious games have been introduced to the fire service in the past decade, where they have primarily been utilized in the training of officers and incident commanders in strategic and tactical decisions at an emergency scene (Williams-Bell et al., 2015a). To our knowledge, serious games, whose focus is on task level activities of the individual firefighter (e.g. hose line operation, search and rescue, points of egress), have not been developed and employed on a wide-scale despite the fact that task level activities play a major factor in the successful management of an emergency scene (Williams-Bell et al., 2015a). Currently, task level education for firefighters occurs at the fire academy during recruit training and on the job working alongside senior firefighters and officers (Williams-Bell et al., 2015a). Therefore, the development of a firefighter-based serious game should focus on cognitive tasks related to appropriate decision-making, reaction time, working memory, spatial awareness, and memory recall. In addition, virtual reality simulations have been implemented in numerous contexts to assess various features of spatial cognition (Waller, 1999), memory (Waller, 1999), and learning (Wilson et al., 1997), based on the concept that real environments and virtual environments need to share similar cognitive mechanisms (Richardson et al., 1999). Integrating assessments throughout each scenario allows for the examination of how and when the subject makes each choice, allowing for a more valid assessment of cognitive function (Bellotti et al., 2013). The immersive nature of serious games allows for situation-specific assessment of cognitive function, compared to standard cognitive testing batteries (Shute et al., 2009).

The purpose of this study was to utilize a serious game that simulates the task level activities of an individual firefighter on the fire ground and use it to assess aspects of cognitive function while exposed to EIHS. We hypothesized that performance on the serious game would be reduced with increasing levels of T_{core}.

7.3 Methods

Ten male career firefighters were recruited as participants to take part in testing. Participants were requested to refrain from vigorous exercise, alcohol, non-steroidal anti-inflammatories, and sleep medication in the 24 hours prior to testing. Participants were also requested to refrain from consuming caffeine or nicotine in the 12 hours prior to any experimental testing. The research protocol was approved by the Office of Research Ethics at the University of Ontario Institute of Technology (REB# 12-076) and written informed consent was obtained prior to participation in the study.

The EIHS trials were conducted at the University of Ontario Institute of Technology's ACE environmental chamber. Ambient temperature and relative humidity were controlled to 35°C and 50% with wind speed maintained at < 0.1 $m \cdot s^{-1}$. The EIHS trials were conducted during the spring months (March and April, 2015) to limit any potential effects of acute heat acclimation (Selkirk et al., 2004b). Five participants attended the environmental chamber at 0830 h and 5 participants began testing at 1200 h to counter balance the effects of circadian rhythm on T_{core}. Participants were required to ingest a radio-pill (HQ Inc, Palmetto, FL) approximately 6 to 9 hours prior to starting the protocol. Upon arriving at the climate chamber, each participant had their nude body mass measured on a digital scale (Tanita, Arlington Heights, IL) to 0.1kg and urine specific gravity (USG) analyzed (Atago Co., LTD., Tokyo, Japan).

The FFTL serious game is a computerized simulation of a two-storey residential house fire created using the Unity game development engine software. The FFTL is a first-person simulation displayed on a 46" screen placed approximately 1 m directly in front of the participant while standing on the treadmill. The participant controls the progress of the serious game using a Microsoft Xbox® controller plugged into the computer.

The FFTL simulates a single apparatus arrival at a two-storey residential fire, with 2 civilians trapped inside and 2 fires burning on the first floor the house. The FFTL scenario was created to simulate the specific tasks required that an individual firefighter would typically encounter at a fire. The FFTL consists of 5 scenes that represent the different stages of a fire emergency. The floorplan for the two-storey residence in the FFTL is depicted in Figure 7.1A. The first stage, FFTL 1, involves the fire crew arriving at the emergency scene and determining the best way to enter the residence. Once inside the residence, the participant must search the main floor, put out 2 fires, and determine if there are any victims (total of 6 tasks). FFTL 2 begins on the second floor of the residence where the player is required to search 3 of the 5 rooms and find 1 of the 2 victims (total of 17 tasks). FFTL 3 requires the player to search the remaining 2 rooms on the second floor and find the second victim (total of 17 tasks). The participant is instructed to search 3 rooms (bedroom 1, study, and bedroom 2 in Figure 7.1A) on the second floor of the structure during FFTL 2 and the remaining 2 rooms (bedroom 3 and bedroom 4 in Figure 7.1A) during FFTL 3. Four of the rooms on the second floor, (bedroom 1, study, bedroom 2, and 3) involved 5 tasks while bedroom 4 involved 6 tasks due to the second victim being discovered at this location. FFTL 4 begins with the primary egress (main staircase) blocked due to roof collapse with the participant being required to find a new exit from the emergency scene (total of 4 tasks). FFTL 5 simulates the post-emergency tasks of being interviewed by the Fire Marshall requesting specific information of major events (audible smoke alarms, locations of fires and victims) occurring in FFTL 1, 2, and 3 (total of 10 tasks). The difficulty of each FFTL stage within the burning residence was maintained by having similar levels of decreased visibility, due to smoke and minimal light, throughout the scenario. The final version of the FFTL serious game was viewed by subject matter experts, Fire Commanders, Captains, and Training personnel and was deemed to represent the nature of tasks that would be required of a firefighter at a single apparatus fire emergency.

The participant was evaluated on proper administering of their SCBA, the direction of room search that was conducted (left or right hand search), fires extinguished, radio communications, appropriate maydays, and whether all potential locations of a victim were searched. In addition, spatial awareness was evaluated through questions following FFTL 2 and FFTL 3 to determine the location and number of windows and rooms located during the particular stage. Game play within each scene was recorded to determine (post-process) the participant’s percent change of tasks completed, and the time to conduct a search and rescue to locate civilians in each of the 5 rooms on the second floor (encountered during FFTL 2 and 3).

Approximately 1 week prior to the EIHS protocol, participants were given a familiarization session with game play of the FFTL. This session included playing through the tutorial level once, which incorporated training of all game and controller functionality. Afterward, the participants were asked to complete the tutorial level within a 3-min timeframe. On day 2 prior to the EIHS trial, participants were again requested to play the tutorial level until they achieved a completion time under 3-min. The 3-min completion time ensured that all participants had basic competency in game play.

Once instrumented, participants (wearing station issued pants and short-sleeved t-shirt) donned their PPE including bunker pants, jacket, flash hood, gloves, helmet, SCBA with face-piece (PPE 1). Participants mounted the treadmill and began walking at 4.5 $km \cdot h^{-1}$ and 2.5% grade while performing FFTL 1 of the serious game. This specific speed and grade implemented has been previously compared to moderate intensity firefighting activities (e.g. primary search) (McLellan et al., 2006). Participants were allowed to remove their gloves while playing FFTL on the treadmill. Participants continued to perform treadmill walking until they either completed: (i) 30-min of exercise, at which time they would receive a 5-min rest break and remove their SCBA, face-piece, flash hood, helmet, and gloves (PPE 2), or (ii) reached the next T_{core} value and completed the corresponding scene. Following FFTL 2 at a T_{core} of 37.8°C, participants were seated for 10-min wearing PPE 2. After, participants donned PPE 1, remounted the treadmill and completed the same work to rest ratio until their T_{core} reached levels of 38.3°C (FFTL 3) and 38.5°C (FFTL 4). These levels of T_{core} were chosen as previous work has shown volitional fatigue in firefighters while performing moderate exercise at 35°C at a T_{core} of 38.9°C (Selkirk et al., 2004b). Upon completing FFTL 4, participants removed their PPE, excluding bunker pants, and were placed in active cooling recovery by sitting in a chair (DQE, Inc., Fishers, IN) while submerging their hands and forearms in 15-20°C water until T_{core} returned to 37.8°C and then completed Cog 5. Participants were given 5 $mL \cdot kg^{-1}$ of warm water (37°C) to avoid influencing measurements with the radio-pill before FFTL 1 and following FFTL 2, 3, 4, and during active cooling recovery. Following FFTL 5, participants toweled off any remaining sweat to have their final nude mass measured.

Core temperature was measured using an ingestible radio-pill (HQ Inc, Palmetto, FL) that sends a telemetric signal to a data recorder (HQ Inc, Palmetto, FL) connected to a computer, which measures T_{core} every 20s and calculates an average each minute. Skin temperature was measured at 4 sites (chest, back, forearm, thigh) every 20s using skin thermistors that were taped to each anatomical area and connected to a data recorder. Mean skin temperature calculated using the formula [T_{sk} = (0.25 x chest) + (0.25 x back) + (0.2 x forearm) + (0.3 x thigh] (Ayling, 1986).

Heart rate was measured using a transmitter (Polar, Kempele, Finland) attached around the participant’s chest with a wearable strap. Heart rate was continuously monitored using a receiver attached to the treadmill and recorded every 20s in conjunction with T_{core} (HQ Inc, Palmetto, FL) and averaged each minute. Percent body fat was evaluated by 4 skinfold sites (triceps, subscapular, abdomen, and thigh) and then calculated using a specific formula developed by Jackson et al. (1980)

Normality for each of the dependent variables was confirmed using the Shapiro-Wilks test. TS data was not normally distributed and hence the Friedman’s test with

Wilcoxon Rank post-hoc analysis with a Bonferroni correction was used. A repeated measures analysis of variance (ANOVA) was conducted on all serious game play measures (percent change of tasks completed, room search time). *A priori* planned contrasts for percent change of tasks completed were analyzed compared to FFTL 1. Post-hoc analysis using a Bonferroni correction was performed for all other variables. Violations of sphericity were analyzed using the Huynh-Felt correction.

Statistical significance was set at an alpha level of ≤ 0.05. Data are presented as the mean ± standard error of the mean.

7.4 Results

Participants in this study were 40.0 ± 2.7 years with 15.4 ± 1.8 years of service as a firefighter. Anthropometric characteristics for height, body mass, body mass index (BMI), and percent body fat were 1.78 ± 0.04 m, 89.8 ± 2.3 kg, 28.4 ± 0.7 $kg \cdot m^{-2}$, and 19.0 ± 1.4%.

Participants were exposed to the EIHS protocol for 73.4 ± 5.0-min including a total exercise duration of 48.1 ± 4.3-min. Data for the cognitive measurements recorded during the FFTL game are depicted in Figure 7.2. Percent change of tasks completed (Figure 7.2A) relative to FFTL 1 revealed a main effect of cognitive trial ($p \leq 0.05$) with planned contrasts indicating a significant decline at FFTL 5. Search and rescue for the individual rooms searched in FFTL 2 (bedroom 1, study, bedroom 2) and FFTL 3 (bedroom 3 and 4) revealed a main effect of room search time (Figure 7.2B). Post-hoc analysis indicated that the time to search bedroom 4 and bedroom 5 (during FFTL 3) was longer than bedroom 2 ($p \leq 0.05$) but not bedroom 1 or the study.

Physiological data for T_{core}, and T_{sk} are depicted in Figure 7.3 while HR (normalized to percent of protocol completed) and TS are presented in Figure 7.4. Core temperature was 37.2 ± 0.1, 37.9 ± 0.1, 38.3 ± 0.04, 38.5 ± 0.04, and 37.8 ± 0.02°C, at the start of FFTL 1, 2, 3, 4, and 5, respectively. TS revealed a main effect of cognitive trial with post hot analysis indicating that participants perceived they were significantly hotter at FFTL 2, 3, and 4 compared to Cog 1 and 5 ($p \leq 0.05$).

Pre and post-nude body mass was not different (92.3 ± 2.5 vs 91.8 ± 2.5 kg) revealing a percent change of body mass of -0.5 ± 0.5%. Participants consumed 95.0 ± 3.3% of the fluid provided, while pre and post-USG values were not different (1.013 ± 0.003 vs 1.016 ± 0.003) indicating that participants were hydrated (≤ 1.020) before and after the experimental protocol (Sawka et al., 2007).

Figure 7.1: Floorplan of the Firefighter Task Level (FFTL) serious game (A), screenshots of the FFTL depicting the front of the two-storey house with one of the family members out front (B; FFTL 1), the firefighter (participant) suppressing a couch fire (C; FFTL 1), location of the first victim (D; FFTL 2), collapse of the main stairwell (E; FFTL 3), bedroom view searching for window exit (F; FFTL 4), and Fire Marshall question screen (G; FFTL 5).

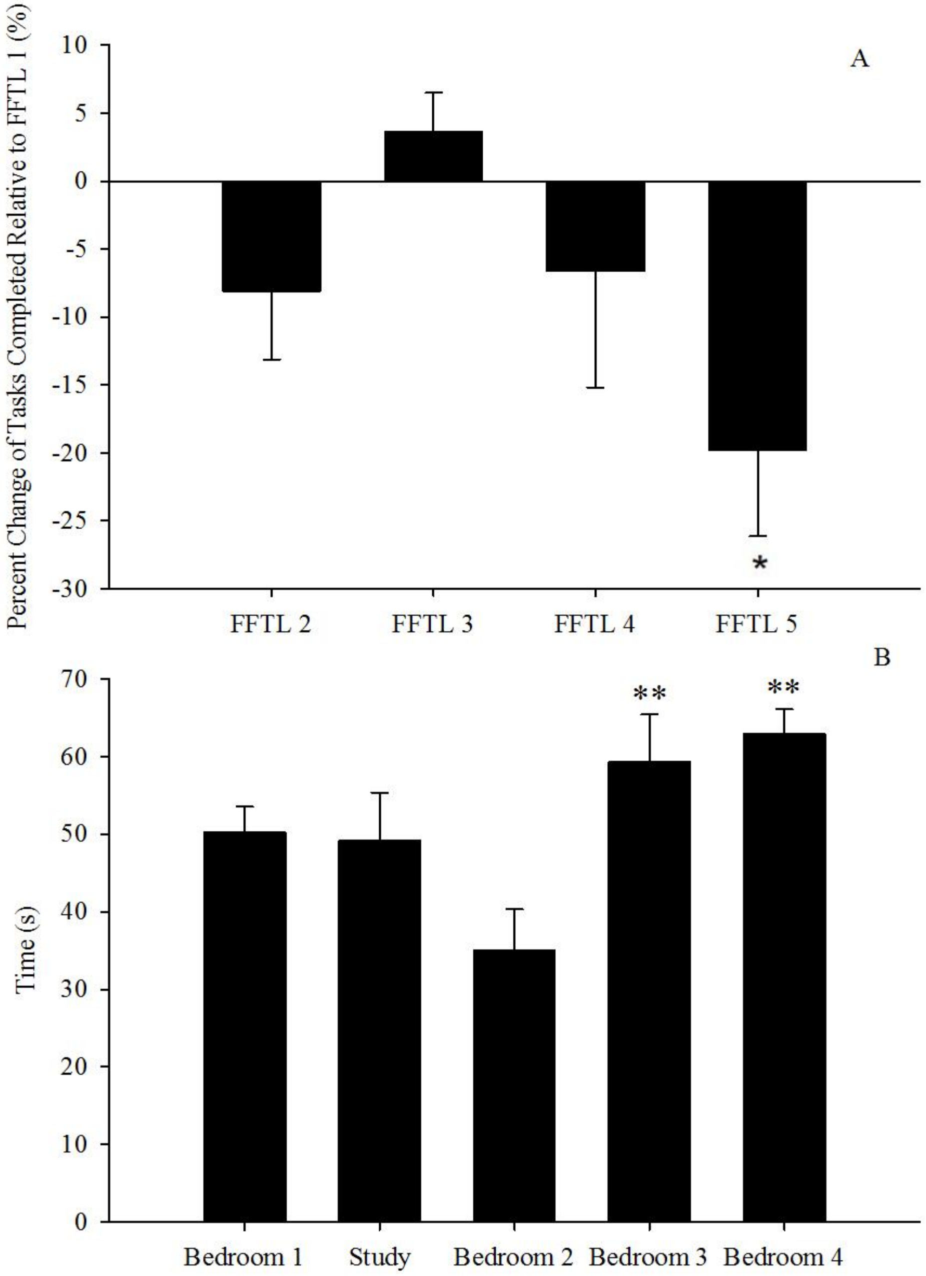


Figure 7.2: Data from the FFTL revealing the percent change of tasks completed (A), and room search time (B).

*indicates different from FFTL 1 ($p \leq 0.05$)
**indicates different from Bedroom 2 ($p \leq 0.05$)

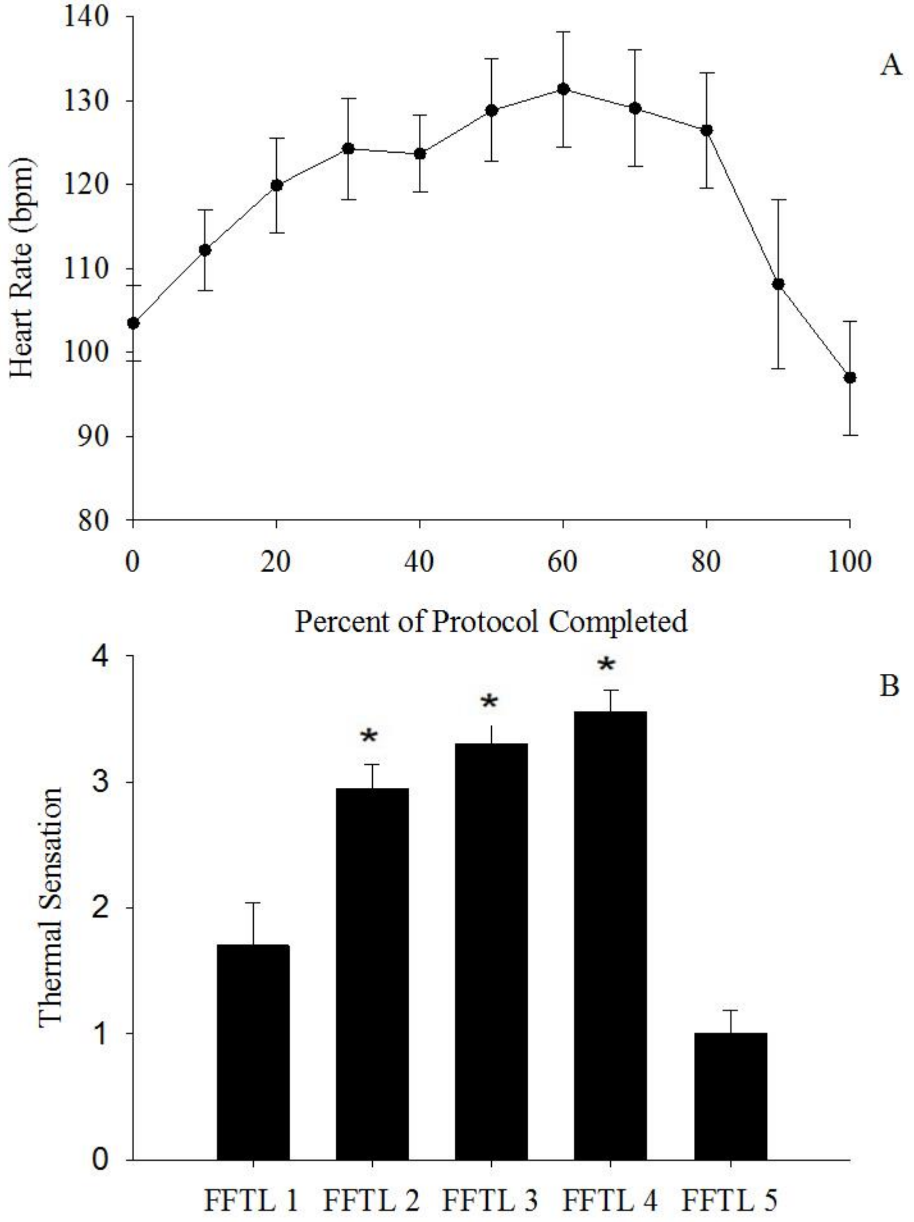


Figure 7.3: Mean HR (A) depicted over the percent of protocol completed during the EIHS protocol and thermal sensation (B) following each FFTL game play trial. *indicates different from FFTL 1 and 5 ($p \leq 0.05$)

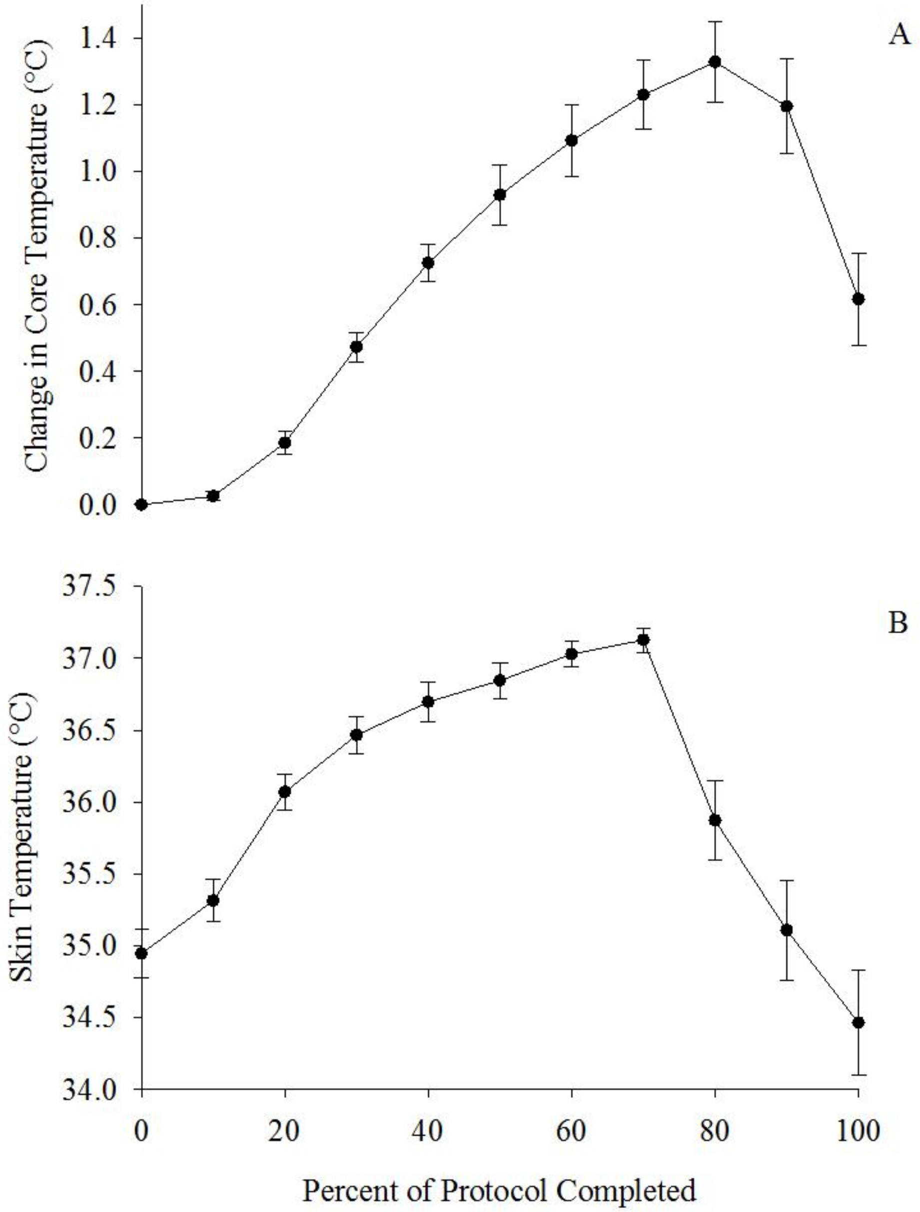


Figure 7.4: The mean ΔT_{core} (A), and Tsk (B), depicted over the percent of protocol completed during the EIHS protocol.

7.5 Discussion

The main findings from this study are the decline in memory recall following an active cooling recovery protocol and the increase in room search duration at a T_{core} of 38.3°C despite no observed impairments in percent of correct responses during the exercise portion of the protocol.

Morley et al. (2012) reported that recall on a memory test (evaluating short-term memory) was reduced at 60 and 120-min after treadmill exercise in 33-35°C, at a similar workload, while wearing PPE and following a recovery and rehydration protocol. In the current study, the time lapse from completing FFTL 1 and FFTL 3 (the first and last assessment trial involving information that was represented for recall following active cooling at FFTL 5 was 89.3 ± 4.8-min and 38.7 ± 2.5-min, respectively). Given this impairment even with active cooling raises the possibility that memory recall could be even more impaired in situations where active cooling protocols are not used due to the associated delay in T_{core} returning to baseline and interference with long-term memory encoding.

Previous work in our laboratory (Williams-Bell, 2015, submitted for publication) utilizing a standardized cognitive assessment battery (Cambridge Neuropsychological Test Automated Battery; CANTAB) at similar levels of T_{core} revealed that visual episodic memory and visuospatial working memory are impaired when firefighters' T_{core} reached 38.5°C, with further impairments in visuospatial working memory at 39.0°C. In addition, following the same active cooling recovery and rehydration protocol as the current study, all measured aspects of cognitive function were restored to initial levels. However, the

CANTAB assessment battery utilized in the previous study did not evaluate long-term memory.

Despite the lack of impairment in percent change of tasks completed at increasing levels of T_{core}, the time required to search bedrooms 3 and 4 was significantly longer than searching bedroom 2. Cian et al. (2000) found that although error scores were unchanged decision-making time was impaired, albeit following a dehydration protocol. In addition, Radakovic et al. (2007) reported decreased errors and longer movement times following treadmill exercise in the heat. Although these studies do not align completely with the current data, Bandelow et al. (2010) determined that elevated T_{core} during exercise may result in a slowing of psycho-motor response speed on working memory, fine motor speed, and visual sensitivity reaction time. In general, an increased decision making time to establish a correct response could lead to detrimental and even fatal consequences on the fire ground.

There are several possible explanations for the differences between the results of our previous work and the current study. Firstly, the cognitive tasks encountered using the FFTL were similar to those experienced during live-simulations and actual emergencies, which the participants are extensively trained for. This would classify the participants in the current study as highly skilled on the tasks assessed within the FFTL. Previous work by Hancock (1986a) has suggested that individuals with a high skill level on a given task are more capable to withstand the effects of heat stress compared to unskilled counterparts. This is likely attributable to the development required before the processes in successful task performance become automatic (Hancock, 1986a). Secondly, the cognitive assessments implemented following active cooling recovery in our previous study utilized reaction time, sustained attention, and working memory tasks. The current study implemented a representative simulation where the Fire Marshall requires a firefighter to recall particular details from when they were inside the burning structure. Memory recall was assessed by employing questions demanding recollection of events that occurred approximately 40-min or longer since the last scenes (FFTL 1, 2, and 3) were played with respect to the particular questions being evaluated. This suggests that the focus for this portion of the assessment was on long-term memory as it required recall of information that appeared more than 20s in the past (Atkinson et al., 1968).

In particular, episodic long-term memory refers to the ability to retrieve memories of events and the supporting processes required to form these memories, whereas working memory holds and manipulates information over brief durations (Ranganath et al., 2005). Information is processed and stored in working memory (or short-term memory) and if organized and rehearsed properly it will become stored more permanently in long-term memory until it needs to be retrieved (Norman, 2013). The hippocampus appears to be a major factor for long-term memory encoding, but is also relevant for working memory (Axmacher et al., 2010). Axmacher et al. (2010) and Ranganath et al. (2005) have observed that maintaining multiple items in working memory (which would be the case during each FFTL scene) will interfere with long-term memory encoding within the hippocampus. Furthermore, Axmacher et al. (2007) found that although medial temporal lobe (MTL) activity is historically considered to be a primary factor in long-term memory, increasing working memory load with multiple items results in activation of neural processes in the MTL. The studies by Axmacher et al. (2007, 2010) and Ranganath et al. (2005) may help explain the current data in that information assessed through memory recall following active cooling recovery was impaired through encoding interference compared to no change in working memory responses earlier in the EIHS protocol. It is possible that the increase in heat stress throughout the EIHS protocol along with the multiple items in working memory would both increase hippocampal activation and ultimately impair long-term memory encoding. However, the duration of time from when the specific tasks were displayed (FFTL 1, 2, and 3) until when they were requested to be recalled (FFTL 5) may also be a factor in the disruption for long-term memory encoding.

Although greater work remains before firm conclusions can be drawn, the results from the study presented here have confirmed the potential application of serious gaming technology to assess cognitive function in firefighters and the possibility of employing serious games for decision making skills training under conditions of heat stress. Although no impairment in cognitive function was observed during the exercise portion of the EIHS protocol, a ceiling effect in the FFTL serious game may be the cause. This would have resulted in the task level activities being too simple and less vulnerable to the effects of heat stress, similar to simple cognitive tasks reported in previous studies (Hancock et al., 2003). In addition, the observed increase in the search of bedroom 3 and 4 (Figure 2B) at FFTL 3 (T_{core} of 38.3°C) may be due to a slightly different layout in room floor plan compared to the rooms searched in FFTL 2. Future research should examine the difficulty level of each task to remove the potential for ceiling effects and determine the specific effect of heat stress on cognitive function using the firefighter serious game. In addition, the means of scoring in the game dealt with whether the individual completed or did not complete the particular task. Future versions of the serious game could incorporate tasks that, if not completed or not properly completed, will result in adjustments to the game play scenario. Furthermore, the addition of a control group that plays the serious game without exercise and heat stress will provide information on the specific effects of heat stress in comparison to possible time effects.

The next logical step in this research is to determine the capacity for using serious games to supplement training applications in the fire service. The majority of serious games and virtual simulations employed in the fire service revolve around tactical decisions from a macro-perspective (Williams-Bell et al., 2015a). However, recent hardware and computational advancements are providing designers and developers of serious games the opportunity to create applications that employ a high level of fidelity and novel interaction techniques using off-the-shelf consumer-level hardware and devices. Such interactive devices allow participants to interact with their application using a natural user-interface that employs gestures, thus removing the game controller and its inherent limitations. With the availability of such novel interactive devices, serious games have the potential to implement individual and task level activities that are typically trained at the fire academy (Williams-Bell et al., 2015a). Previous research has found that games can promote the development of a variety of skills including analytical, spatial, strategic and psychomotor skills, learning and recollection capabilities, and visual selective attention (Mitchell et al., 2004). Furthermore, a systematic review conducted by Connolly et al. (2012) suggested that the most frequently occurring outcomes of playing serious games are knowledge acquisition, content understanding, and affective and motivational outcomes. Serious games can improve performance on working memory, auditory perception, selective attention tasks (Barlett et al., 2009), and higher-order scientific reasoning skills (Mayer et al., 2004), and exhibit real-world decision making, ultimately eliciting higher-level cognitive function (Steinkuehler et al., 2008). The continued improvements in serious game technology and wearable garments implementing haptic feedback could provide firefighters with simulations that are highly interactive and resemble realistic emergency scenarios.

7.6 Conclusion

This study revealed that the implementation of a serious game, depicting a two-storey residential fire, did not correspond with cognitive impairment during an EIHS protocol. However, following an active cooling recovery regimen, memory recall was reduced compared to initial performance. Secondly, the results establish the capabilities of a serious game to record and evaluate the progress and decision making skills of participants during a firefighter simulation. Future research will focus on improving the sensitivity of the individual task level activities implemented into the serious game to determine the precise effect of EIHS on real-life decision making on the fire ground.

7.7 Practical Implications

- Impairments in memory recall were observed following an active cooling recovery protocol, which may provide inaccurate information after an emergency incident.
- The lack of impairments at different levels of T_{core} throughout the EIHS protocol may be due to the experience level of the participants to complete the necessary tasks within the FFTL serious game.

- Serious games have the potential capacity to be implemented in the fire service as an assessment and training tool.

CHAPTER 8 – General Discussion

8.1 Summary and Interpretation of Main Findings

The primary objective of this thesis was to evaluate the effects of EIHS on cognitive function in firefighters. The main results indicate that certain aspects of cognitive function, in particular visuospatial memory and visual episodic memory, are impaired at a T_{core} of 38.5°C with additional impairments in visuospatial memory at a T_{core} of 39.0°C. In addition, when implementing a more ecologically valid assessment tool in the form of a serious game simulation representing the decision making required during task level firefighting duties, there were no decrements in the percent change of tasks completed during the EIHS protocol; however, following active cooling recovery memory recall was impaired. Overall, these findings provide further insight into the physiological and psychological demands required of firefighters and the potential performance limitations when firefighters are challenged with hot and humid environmental conditions.

In Chapter 4, the results partially confirmed our hypothesis that cognitive function would be impaired with increasing T_{core}. Although visuospatial memory declined at T_{core} values of 38.5 and 39.0°C, there were no decrements in visual episodic or visuospatial memory at 37.8°C nor were there any decrements in sustained attention, simple reaction time, and spatial working memory following EIHS. The latter findings are consistent with previous results following exercise in the heat (Rayson et al., 2005, Morley et al., 2012). Despite the increase in T_{core} at the end of the EIHS protocol, the lack of impairment may be due to the achievement of static hyperthermia for a period of time after firefighters removed their PPE (Hancock, 1986b) to perform the post-test or the observation of a falling T_{core} throughout the post-test assessment (Allan et al., 1979b). The application of these findings can be combined with previous work examining the tolerance time of firefighters working in the heat (Selkirk et al., 2004b, McLellan et al., 2006). This previous work identified the time to reach a T_{core} of 38.5°C while performing similar intensity exercise to be 53-min, which based on the current findings, suggests that certain aspects of cognitive function may decline at this point. This additional information can provide Incident Commanders with the ability to relocate firefighters who have been working continuously in 35°C and 50% relative humidity off the front lines and into less physically demanding and less hazardous job tasks. Furthermore, the current results further emphasize the importance of an active cooling recovery protocol to not only reduce cardiovascular and heat strain in the firefighter but also restore cognitive function to initial levels. This countermeasure has previously been proven to be the most practical and effective method of combating heat stress in the fire service (Selkirk et al., 2004a) while failure to promote adequate heat loss following an emergency scenario could lead to additional physiological and cognitive impairments during any subsequent emergency while on-duty.

The study described in Chapter 5 aimed to complement the findings from Chapter 4 by detailing the practice effects that may be associated with short duration, repeated measurements using the CANTAB assessment battery. In particular, the addition of a dual task in the form of treadmill walking did not impair performance and proved to be a feasible modality to administer the CANTAB during exercise. Previously, the only known study to examine reliability of CANTAB utilized a two test model with the second test being conducted approximately 4 weeks apart. For the 2 tests that revealed impairments during EIHS in Chapter 4 (PAL and SSP), our repeatability results suggest that some ICC values were larger than previous work (Lowe et al., 1998) and that two-way ANOVA analyses revealed no improvements within or between sessions for either test. In addition, of the remaining 3 tests (SWM, RTI, RVP), RTI and RVP revealed the largest and most consistent ICC values. Reaction time (or response latency on SWM and RVP) was recorded for each of these tests, which has previously been revealed to have an ICC greater than 0.55 (Lowe et al., 1998, Falleti et al., 2006). However, total errors on SWM and total correct rejections on RVP revealed improvements from test 1 to test 2 indicating that these tests should employ familiarization sessions, with a minimum of a double baseline, until no further practice effects are observed.

In general, based on the combined results of Chapters 4 and 5, the decrements observed in SSP and PAL at T_{core} of 38.5°C appear to be affected by the dynamic increase in T_{core} and not due to any reliability issues with repeated cognitive testing or with the inclusion of treadmill exercise. It was essential to include treadmill exercise during aspects of the cognitive assessment battery as many of the critical decisions required of firefighters will occur during periods of dynamic exercise when working on the front line of an emergency. The improvements observed for SRT in Chapter 4 can be assumed to be resulting from the EIHS protocol as neither the non-exercise nor exercise group in Chapter 5 revealed any change on the RTI test. The results indicate that the CANTAB is suitable for repeated measures cognitive testing provided that appropriate familiarization strategies are put into place, specifically for SWM and RVP.

Chapter 6 presented a review of serious game technology and virtual simulations that are currently utilized for training in the fire service. In the past 20 years, a variety of different simulation based tools have been developed to aid the fire service in personnel coordination (Dugdale et al., 2004, Li et al., 2004, Toups et al., 2007b, Toups et al., 2011, Cha et al., 2012, Environmental Tectonics Corportation, 2012), incident response (Tate, 1997, St.Julien et al., 2003), and incident command level decision making (Dugdale et al., 2004, Li et al., 2004, Querrec et al., 2004, Cha et al., 2012, Environmental Tectonics Corportation, 2012). The tasks required of the individual firefighter who are working at emergency scenes on the front line have not entirely been simulated within serious games. Although there is a need to incorporate the decision making skills of incident commanders into more realistic training scenarios, it also becomes essential to recreate the tasks and cognitive demands encountered by the individual firefighter. Training scenarios that incorporate ‘live-burns’ require a substantial amount of safety personnel to be present, including additional safety guidelines, and require large financial costs. These factors render live training to be done infrequently providing the majority of training to be conducted while ‘on-the-job’. The ability to incorporate these individual task level duties into a serious game provides a more economical tool that can be implemented in addition to live-fire training. Serious game technology also provides the potential to imbed assessment strategies that provide the participant with feedback to continually improve their performance and ultimately provide an effective training tool.

This review of the serious game literature involving the fire service lead to the development of the FFTL serious game. Chapter 7 detailed the FFTL serious game and the effects of an EIHS protocol on task performance during the game simulation. The results indicated that firefighter performance on the individual tasks were not affected by increasing levels of T_{core} throughout treadmill exercise. This is consistent with the notion that individuals who are highly skilled on a particular task will not be affected by heat stress to the same extent as those who are novice (Hancock, 1986a). In contrast, memory recall was impaired following an active cooling recovery protocol when compared to the percentage of tasks completed at initial levels. This finding is similar to a previous study that found decrements in memory recall at 60 and 120-min following exercise in the heat albeit the specific cognitive test implemented was utilized to assess short-term memory recall (Morley et al., 2012). Furthermore, due to the length of time that the specific tasks had to be recalled from the serious game scenario (approximately 40-min and longer), the encoding for long-term memory may have been impaired due to the dynamic increase in T_{core} and the number of items being stored in working memory (Axmacher et al., 2007, Axmacher et al., 2010) during each stage of the FFTL. This impairment can be critical at an emergency scene where recall of specific details involved in the operations may be overlooked or improperly described at the post-incident debrief. The failure to show differences at the individual levels of T_{core} may also have been due to the way that performance was scored. The level of difficulty in each room search may not have been equivalent suggesting that the score for each search may not be comparable to the previous room. Additionally, a firefighter control group who play the game with a constant T_{core} should be included in future studies.

8.2 Limitations

8.2.1 CANTAB Assessment Battery

Computerized cognitive testing batteries have become increasingly popular for clinical and research administration over the past thirty years (Schatz et al., 2002). They have a major advantage over paper-and-pencils tests in that they that provide straightforward administration, consistent feedback, and precise measurements that are not possible with traditional methods (Schatz et al., 2002). However, one major assumption that is inferred for most automated testing batteries is that the test-retest reliability is high when performing repeated measurements (Lowe et al., 1998). To try to address this limitation, a reliability study was conducted in Chapter 5 of this thesis. Although not all reliability measures were consistently high, the tests that revealed impairments in cognition in the firefighters (SSP and PAL) were not shown to have practice effects within or between 2 sessions conducted in a 7 day period suggesting that changes seen in Chapter 4 were not due to practice effects. It is difficult to determine if the lack of practice effects in Chapter 5 are entirely due to the different presentations of the particular task or potentially from mental fatigue (Falleti et al., 2006). Despite these possibilities, the main results indicate impairments in certain aspects of cognitive function which implies that if any practice effects were evident then the decrements observed in Chapter 4 might actually be larger.

8.2.2 Firefighter Task Level Serious Game

The development of the FFTL serious game may have limitations during the EIHS protocol. The tasks implemented during each stage of the FFTL may be limited by ceiling effects which were unable to elicit any changes occurring in cognitive function. This limitation might be two-fold: the difficulty of the tasks employed may not have been at the level necessary to be sensitive to changes in cognition or the serious game may not be sophisticated enough to replicate real-life scenarios in a virtual simulation. The changing environment within a fire scene requires more advanced computational tools and sophisticated models (Korhonen et al., 2007) which may currently be out of the scope for modern serious games. Despite these limitations, previous research has suggested that high fidelity simulations are not required to achieve learning following training (Norman et al., 2012), therefore it may not be necessary to utilize high fidelity in serious games for evaluation purposes.

8.2.3 Exercise-Induced Heat Stress Protocol

The implementation of an EIHS protocol utilizing treadmill exercise has been used in a variety of research designs exposed to heat stress (Selkirk et al., 2001, Selkirk et al., 2004a, Selkirk et al., 2004b, Morley et al., 2012, Parker et al., 2013). It has been shown that laboratory treadmill exercise in the heat produces lower heart rate and T_{core} results compared to simulated firefighting activities in an environmental chamber or live-fire scenario (Horn et al., 2015). Despite the differences that have been reported between simulated activities and laboratory treadmill exercise, the studies in this thesis elicited treadmill exercise in order to produce a dynamic increase in T_{core} and induce a UHS condition. The dynamic increase in T_{core} has been previously reported as being the primary factor in decrements associated with cognitive function (Gibson et al., 1979, Hancock et al., 2003). The ability to induce UHS using previously implemented exercise intensities (Selkirk et al., 2004b) provided sufficient cardiovascular and heat strain to evaluate the associated impairments in cognitive function.

8.3 Conclusions

EIHS revealed impairments in visuospatial memory and visual episodic memory using a computerized neuropsychological assessment battery whereas memory recall on a firefighting serious game showed decrements following an active cooling recovery protocol. The decline in performance on the computerized neuropsychological assessment battery could possibly be attributed to the reduction in cognitive resources as described by the Global Workspace Theory (Baars, 1993), due to dynamic increases in T_{core} from heat stress, required to adequately perform on the administered tests. These results are supported by the lack of practice effects observed in repeated measures testing of cognitive domains when examined in both a non-exercising and a light intensity exercise group.

The use of serious game technology to improve the ecological validity of the cognitive tasks being assessed did not reveal any changes in task performance as T_{core} increased. This is most likely due to the high skill level of the participants. However, memory recall following an active cooling recovery protocol involving hand and forearm submersion in 15-20°C water was impaired potentially due to the dynamic increase in T_{core} from the EIHS protocol and the number of items in working memory during the FFTL decreasing the ability to encode information into long-term memory. Taken together, these results contribute further understanding into the cognitive impairments experienced at an emergency and provide additional knowledge for Incident Commanders to improve the safety of all personnel.

8.4 Future Directions

The results from this thesis suggest that impairments in cognitive function begin to be observed at a T_{core} of 38.5°C, although decrements in other cognitive areas may also be present during dynamic increases in T_{core}. Using the experimental model implemented in this thesis, research examining the cognitive measures that were obtained before and after exercise could be incorporated during dynamic increases in T_{core} to provide a further understanding of how a multitude of cognitive domains are affected by UHS. In addition, as suggested in Chapter 7, comparing skill level of participants based on years of firefighting may provide further insight into the factors that cause impairments which become evident during heat stress in firefighters. Furthermore, combining additional experimental groups based on age, aerobic fitness level, and body fat percent will allow for a more precise determination of who is most affected by heat stress while wearing protective clothing.

Although this thesis dealt with the assessment of cognitive function during EIHS, utilizing serious game technology provides a novel application to train cognitive tasks at the individual level in firefighters. If training can be accomplished using this medium, a research design can be developed to determine the effectiveness of the individual task level training in combating the negative effects of heat stress. Games by definition require the player to make meaningful decisions in order to make progress in the game scenario. Serious games or simulations are no different in this regard and are designed from the ground up to ensure that players must make decisions that affect the outcomes of the simulation. There have been numerous researchers looking at evaluating the decision making ability of players in games (Linehan et al., 2009) as well as designing games specifically to train decision making in particular scenarios (Fumarola et al., 2008, Garcia et al., 2008). Cognitive, and motor skill training are separate and distinct entities but may be performed in tandem. Motor skill learning is also influenced by the baseline abilities of the performer and the inherent difficulty of the task. If the individual is not adequately challenged, learning will be less than optimal. Likewise, if task difficulty significantly exceeds the ability of the performer learning performance is also predicted to be poor (Guadagnoli et al., 2004). In terms of the fire service, this becomes an additional research question to determine how novice skill level (college pre-fire service students, firefighter recruits) and expert skill level (veteran firefighters) perform on a serious game training simulation as well as how training may be beneficial in decreasing the impact of heat stress.

Although the cognitive and motor learning processes are different, typically these two actions are executed in tandem. It has been suggested that the mental processing resources required for a given task may vary as a function of expertise (Hsu et al., 2008). Firefighter performance is a complex blend of technical, cognitive and decision making skills, each of which requires mental processing resources (Hsu et al., 2008). The simultaneous allocation of mental processing resources to the performance of 2 tasks is referred to as dual-tasking. Under dual-tasking conditions, the total mental processing load appears to be equal to the sum of the mental processing resources required for each individual task (Engle et al., 2003, Rikers et al., 2004). Unfortunately, humans have a limited amount of mental processing resources available (Broadbent, 1958, Wickens, 2002) and exceeding these limitations as a result of dual-tasking may have detrimental effects on performance of one or both of the tasks (van Merri nboer et al., 2002).

Take the example of a firefighter who needs to make a decision about safe positioning in order to avoid hazards (cognitive task) while lifting a hose (motor task). If both tasks are novel, share the same mental processing resources, and need to be executed at the same time, one or both may be executed sub-optimally. Training of the motor task until it is executed in an automatic way without the need for cognitive processing changes the need in sharing of these resources across the 2 tasks. Thus it could be hypothesized that training of the proper technique of lifting the hose until the firefighter does not need to think about the steps necessary to execute this task may alleviate the need for cognitive processing and therefore all the cognitive resources may be redirected towards decision making processes. Similar hypotheses have been tested within a surgical domain (Kurahashi et al., 2011).

The next logical step would be to develop additional scenarios, with varying levels of difficulty that could be utilized as a longer duration training program to improve decision making of firefighters under heat stress. A similar experimental protocol to the one utilized in Chapter 7 could be implemented before and after a 4-week training program using the serious game. One group of firefighters would be placed in the training group while another group of firefighters would not receive training with the serious game but be tested at the same points pre and post-training. The serious game training protocol would include different levels of the simulation (i.e. easy, medium, and hard difficulty) that the firefighter would progress through over the course of the training program. In addition, the training levels of the serious game would provide feedback for the firefighter regarding their results and performance in order to improve their decision making skills at each level of difficulty. This particular study would provide valuable information on the effectiveness of serious game training for the fire service and whether this type of training regimen would be a cost-effective tool to improve decision making skills on the fire ground.

Another interesting future direction could be to determine the specific brain regions, through neuroimaging techniques, that are associated with successful performance on a firefighting simulation. This information will help determine if the neural networks assessed using computerized neuropsychological assessment batteries can be translated into the ‘real life’ tasks encountered in a serious game. This will provide researchers with further knowledge into the specific effects that heat stress can have on particular brain regions associated with the firefighting tasks. Future research can provide Incident Commanders with greater understanding of the hazardous effects related to the occupation in an attempt to minimize injuries and casualties while on-duty and make the profession safer for firefighters and ultimately all members of the community.

APPENDICES

Appendix A – Additional data from Chapter 4

A.1 Physiological Profile

A physiological profile of each of the 19 participants was recorded from an incremental treadmill test to maximum (VO_{2peak}, HR_{max}), predicted one-repetition maximum (1-RM) tests and dynamic muscular endurance tests. Mean data for each measure is depicted in Table A.1.

Table A.1: Anthropometric, incremental treadmill test, and muscular strength and endurance data for 19 firefighters.

$\dot{V}O_{2\ max}$ ($mL \cdot kg^{-1} \cdot min^{-1}$)	HR_{peak} ($beats \cdot min^{-1}$)	Combined Handgrip (kg)	1-RM Bench Press (kg)	1-RM Leg Press (kg)
45.2 ± 5.5	184 ± 12	47.3 ± 1.4	86.5 ± 3.9	249.9 ± 11.0
1-RM Shoulder Press (kg)	**1-RM Biceps Curl (kg)**	**Bench Press Endurance (# of reps)**	**Leg Press Endurance (# of reps)**	
53.3 ± 2.1	40.2 ± 2.3	28.8 ± 1.7	24.1 ± 3.3	

A.2 Heart Rate

Heart rate responses for the 30°C and 35°C conditions are depicted in Figure A.1 as percent of maximum heart rate (as measured from the incremental treadmill test).

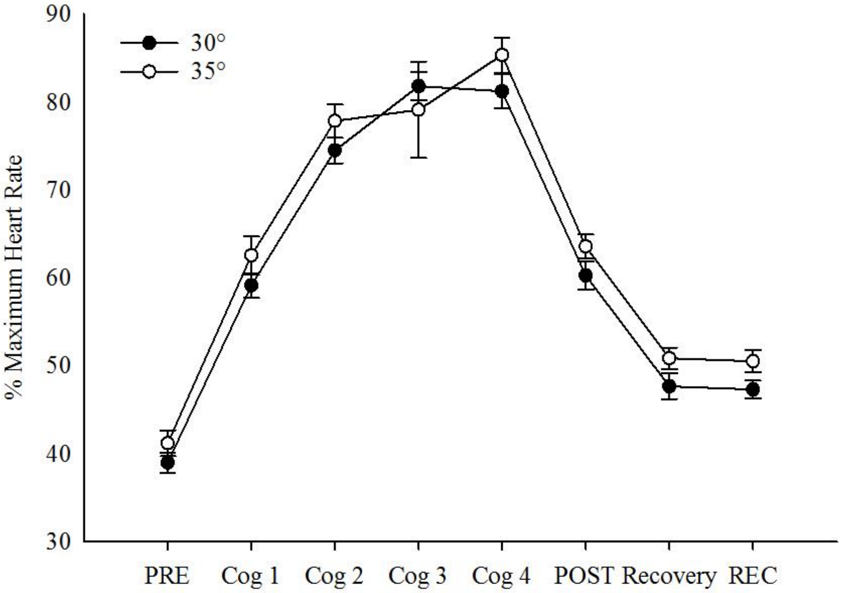


Figure A.1: Mean values for percent of maximum heart rate (measured from the incremental treadmill test) during each of the cognitive assessments (PRE, Cog 1, 2, 3, 4, POST, REC) and active cooling recovery (Recovery).

A.3 Gas Exchange

Mean data for gas exchange within each condition at the two time points assessed (upon remounting the treadmill after completing cog 2 and cog 3) for the 30°C (1.51 ± 0.07 and 1.61 ± 0.08 $L{\cdot}min^{-1}$) and 35°C condition (1.62 ± 0.06 and 1.63 ± 0.07 $L{\cdot}m^{-1}$), resulting in a percentage of maximum oxygen consumption of 40 ± 1, 42 ± 2, and 44 ± 1, 43 ± 2 % for the 30°C and 35°C conditions, respectively ($p > .05$).

A.4 Subjective Measures

Mean values for thermal sensation were recorded at Cog 2 (2.5 ± 0.2 vs 2.8 ± 0.2), Cog 3 (3.2 ± 0.2 vs 3.4 ± 0.1), and Cog 4 (3.4 ± 0.2 vs 3.6 ± 0.1) in the 30°C and 35°C conditions, respectively. Mean values for thermal comfort were recorded at Cog 2

(-1.3 ± 0.3 vs -1.4 ± 0.4), Cog 3 (-3.0 ± 0.2 vs -2.7 ± 0.3), and Cog 4 (-3.4 ± 0.2 vs -3.3 ± 0.2) in the 30°C and 35°C conditions, respectively. RPE for the 30°C condition was 12.2 ± 0.3, 15.4 ± 0.6, 16.4 ± 0.7 and in the 35°C condition was 13.6 ± 0.6, 15.5 ± 0.6, 16.4 ± 0.7 for Cog 2, Cog 3, and Cog 4, respectively.

A.5 Calculation of the Heat Stress Index

The rate of change in T_{core} experienced in this study (0.9 and $1.4°C \cdot h^{-1}$)are expected when examining the heat strain index (HSI) based on the work intensity and environmental conditions. The HSI value represents the heat loss required to maintain a thermal steady state (E_{req}) divided by the maximum potential for evaporation (E_{max}) from the body through the PPE environment (McLellan et al., 2013). An HSI value less than 1.0 represents a compensable heat stress environment, whereas an HSI value greater than 1.0 results in an uncompensable heat stress situation where the rate of heat storage will continue to increase and eventually result in physical and cognitive impairments (McLellan et al., 2013). The HSI can be determined by:

$E_{req} = (M - W_{ex}) + A_D \cdot (T_a - T_{sk}) \cdot I_T^{-1}$ (Armstrong et al., 2010)

where A_D is the Dubois surface area (m^2), I_T is the total thermal clothing insulation ($m^{2} \cdot °C \cdot W^{-1}$), T_{sk} is the mean skin temperature, and T_a is the ambient temperature.

$E_{max} = 16.5 \cdot i_m \cdot I_T \cdot A_D \cdot (P_{sk} - \varphi_a \cdot P_a)$ (Armstrong et al., 1988)

where 16.5 is the Lewis Relation ($°C \cdot kPa^{-1}$), i_m is the Woodcock vapor permeability coefficient, P_{sk} is the skin saturation vapor pressure, φ_a is the ambient relative humidity, and P_a is the ambient saturation vapor pressure.

The values inputted into the formulas for T_{sk}, T_a, P_{sk}, φ_a, and P_a were 37°C, 30°C, 6.26 kPa, 50%, 1.1 kPa for the 30°C condition and 37°C, 35°C, 6.26 kPa, 50%, 2.8 kPa for the 35°C condition. The metabolic heat produced was 410 W for both conditions based on the predicted VO_2 for moderate-intensity workload at 4·5 $km.h^{-1}$ and 2.5% grade. The insulation factor of the TFS structural firefighting PPE is 1.55 clo (0.240 $m^{2} \cdot {}^{\circ}C^{-1} \cdot W^{-1}$) with a Woodcock vapor permeability coefficient of 0.27 (Selkirk et al., 2004b). The calculated HSI value when exercising on the treadmill at the moderate-intensity workload was 1.64 and 2.21 in the 30°C and 35°C conditions, respectively, providing further evidence of the UHS nature of the experimental design. The HSI value, while wearing PPE in a seated, non-exercising condition (as would be the case during the cognitive assessment trials of PRE, POST, and REC) and assuming a resting VO_2 of 3.5 $mL \cdot kg^{-1} \cdot min^{-1}$ in the 30°C and 35°C conditions would be 0.21 and 0.47, respectively. These values can be considered conservative as the calculation assumes that the individual is fully encapsulated in PPE; however, the participants in the current study wore only bunker pants during the PRE, POST, and REC cognitive assessment trials, which would further reduce the actual HSI value.

Appendix B – Additional data from Chapter 7

B.1 Physiological Profile

A physiological profile of each of the 10 participants was recorded from an incremental treadmill test to maximum (VO_{2peak}, HR_{max}), predicted one-repetition maximum (1-RM) tests and dynamic muscular endurance tests. Mean data for each measure is depicted in Table 12.

Table B.1: Data from the incremental treadmill, muscular strength, and endurance tests for 10 firefighters.

$\dot{V}O_{2\ max}$ ($mL \cdot kg^{-1} \cdot min^{-1}$)	HR_{peak} ($beats \cdot min^{-1}$)	Combined Handgrip (kg)	1-RM Bench Press (kg)	1-RM Leg Press (kg)
44.5 ± 2.0	181 ± 3	107.6 ± 5.5	88.3 ± 3.8	366.1 ± 23.2
1-RM Shoulder Press (kg)	1-RM Biceps Curl (kg)	Bench Press Endurance (# of reps)	Leg Press Endurance (# of reps)	
54.6 ± 2.9	45.1 ± 1.7	32.5 ± 2.5	25.1 ± 1.9	

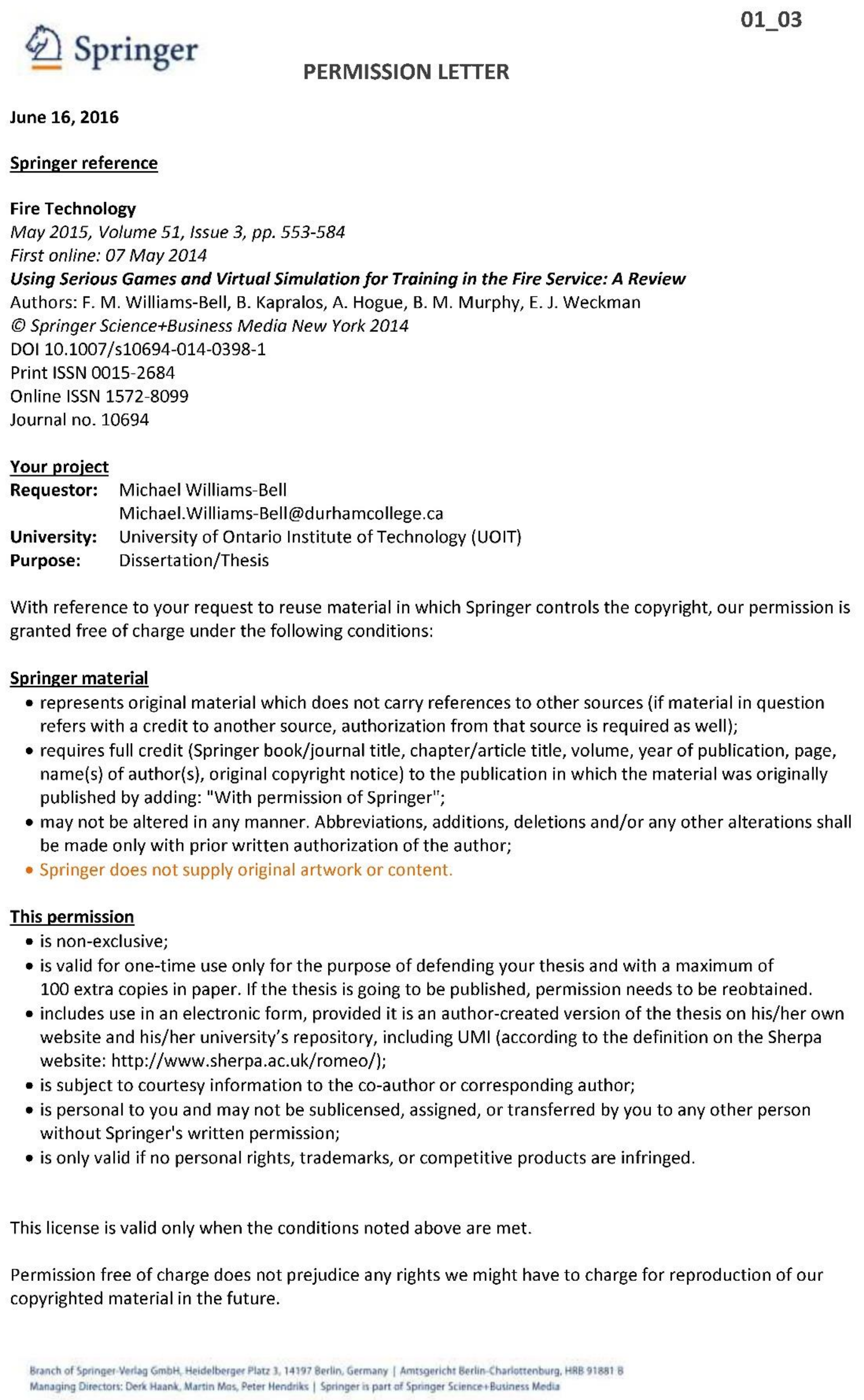
B.2 Subjective Measures

Mean values for thermal comfort record at baseline, and following FFTL 1, 2, 3, 4, and 5 were recorded 1.5 ± 1.5, 0.1 ± 0.4, -2.0 ± 0.4, -3.0 ± 0.3, -3.4 ± 0.2, and 0.8 ± 0.4, respectively. Mean values for RPE were 11.1 ± 0.7, 14.7 ± 0.8, 15.8 ± 0.9, and 16.8 ± 1.0, for FFTL 1, 2, 3, and 4. No RPE was recorded following FFTL 5 due to the short duration of the tasks required.

B.3 Heat Stress Index

The calculation for the HSI is detailed in Appendix A.5 and relates only to the 35°C condition implemented in this study. Therefore, the HSI was calculated at 2.21 for the firefighters exercise in this environmental condition.

APPENDIX C – Copyright Permission Letter



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