Published in final edited form as:

J Occup Environ Hyg. 2020 May ; 17(5): 243–252. doi:10.1080/15459624.2020.1726933.

Effect of continuous cooling on inhibition and attention while wearing firefighter's PPE in a hot environment

Ali M. Aljaroudi[a,b], **Darren S. Kadis**[c,d,*,#], **Amit Bhattacharya**[d], **Amanda Straucha**[a,‡], **Tyler D. Quinn**[a], **W. Jon Williams**[a]

[a]National Personal Protective Technology Laboratory (NPPTL), National Institute for Occupational Safety and Health (NIOSH), Centers for Disease Control and Prevention (CDC), Pittsburgh, Pennsylvania

[b]Department of Engineering Technology, Sam Houston State University, Huntsville, Texas

[c]Division of Neurology, Cincinnati Children's Hospital Medical Center, Cincinnati, Ohio

[d]Department of Environmental Health, University of Cincinnati, Cincinnati, Ohio

Abstract

Firefighting is physically and mentally strenuous, requiring rapid, appropriate decision-making in hot environments. Intact cognitive function is imperative to firefighters' effectiveness and safety. The study purpose was to investigate the effect of hyperthermia and the effect of body cooling on sustained attention and response inhibition while wearing firefighters' personal protective ensembles after exercise in a hot environment. Twelve healthy males were recruited to participate in two randomly assigned exercise sessions (walking on a treadmill for 40 min at 40% $\dot{V}O_{2max}$ while wearing firefighter's protective ensemble) in a hot environment: control (no cooling) and intervention (cooling). For intervention sessions, a cooling garment was worn underneath firefighter's protective ensemble and infused with 18 °C water supplied by an external water circulator. Participants performed a computerized Go/No-Go (a measure of cognitive function) test three times at baseline and post-exercise for each experimental session. Participants completed baseline testing while wearing cotton athletic clothing. The exercise continued until the core temperature reached ~39 °C (for all subjects regardless of cooling or non-cooling experimental sessions). Following hyperthermia, participants' physiological responses were significantly increased after exercise. Subjects' reaction time was significantly reduced (improved) after experiencing thermal strain and reaching hyperthermia. The cooling method had a significant impact on suppressing the physiological load, i.e., body cooling delayed the time to reach a T_c of 39 °C ($p \leq 0.05$), but not cognitive inhibition and attention (reaction time and accuracy). Unexpectedly, hyperthermia resulted in shorter reaction time following exercise (16.64

CONTACT W. Jon Williams, aun7@cdc.gov, NPPTL NIOSH CDC, 626 Cochrans Mill Road, Pittsburgh, PA, 15236.
*Neurosciences and Mental Health, Hospital for Sick Children, Toronto, Canada.
#Department of Physiology, University of Toronto, Toronto, Canada.
‡Environmental Science Center, Environmental Protection Agency (EPA), Fort Meade, Maryland.

Disclosure statement

The authors report no conflict of interest. The findings and conclusions in this report are those of the author(s) and do not necessarily represent the official position of the National Institute for Occupational Safety and Health, Centers for Disease Control and Prevention. Mention of a product or use of a photo does not constitute NIOSH endorsement.

± 5.62; $p < 0.03$), likely influenced by increased attention/vigilance. Hyperthermia may trigger an acute increase in alertness, causing decreased reaction time.

Keywords

Cognitive ergonomics; heat stress; hyperthermia

Introduction

Firefighting is a physically and mentally strenuous job requiring rapid, appropriate decision-making in extremely hot environmental conditions. Exposure to a hot environment while wearing encapsulated firefighters' personal protective ensemble (FFPPE) imposes stress on the normal homeostasis of body temperature, potentially resulting in heat stress and hyperthermia. The Threshold Limit Values (TLVs®) guidelines provided by the American Conference of Governmental and Industrial Hygienists (ACGIH®), the most used recommended heat exposure guidelines, are designed to ensure that heat balance and a stable body core temperature (T_c) does not exceed a lower average threshold safe limit of 38 °C (although some workers may achieve a T_c of 38.5 °C) for extended periods of work (ACGIH 1992). According to the guidelines provided by the National Fire Protection Association (NFPA) Standard 1584, firefighters' T_c is recommended to be maintained within the range 36 and 38 °C (NFPA 2008). These guidelines are particularly important considering that a clear correlation has been found between heat stress and unsafe work behaviors (Ramsey et al. 1983; Chang et al. 2017). These unsafe behaviors are likely a result of cognitive impairment (including attention and contextual awareness, information encoding and retrieval, and executive functioning) resulting from environmental heat stress or hyperthermia (Ramsey et al. 1983; Chang et al. 2017).

Today's firefighting systems and activities are complex and require mental focus. Thus, intact cognitive function is imperative to firefighters' effectiveness and safety. As the complexity of firefighting systems is increased, a greater cognitive load is imposed on the firefighter which, in turn, increases the likelihood for human error (inhibition). Prevention of human error (i.e., prevention of inhibition) has been a primary focus in modern human-technology interaction research and lends to the importance of the analysis of cognitive function under environmental and/or occupational stress. The physiological strain that is associated with working in hot environments has been shown to negatively affect firefighters' cognitive function (Hemmatjo et al. 2017; Cian et al. 2001). Additionally, some studies (Gaoua et al. 2011) reported negative effects of hyperthermia ($T_c \geq 39.0$ °C) on complex cognitive function. However, other studies that involve a simulated firefighting scenario provide inconclusive evidence that the exposure to heat stress leads to impaired cognitive function. For example, Lee et al. (2014) demonstrated that individuals exposed to induced hyperthermia experience an altered state of both working memory and alertness levels while other investigators have reported that exposure of individuals to induced hyperthermia does not affect cognitive function (Morley et al. 2012).

It has been suggested that hyperthermia affects cognition by interfering with cerebral circulation and functional connectivity in the brain (Qian et al. 2014; Sun et al. 2013). Impaired cognitive function could endanger firefighters' safety and may result in lower response accuracy (inhibition). Another possible effect of impaired cognitive function among the firefighters is slow reaction time, which may lead to fatal accidents during firefighting. Given the risk associated with poor cognitive function, there is a need to assess strategies that could be used to address heat stress among firefighters. This focus is particularly important for determining workplace design parameters in occupational environments where impaired cognition could compromise safety.

There are two main types of cooling approaches: continuous cooling and non-continuous (pre/post activity) cooling methods, which utilize cooling garments and immersion strategies, respectively. However, it has been noted that the use of non-continuous cooling approaches such as hand and forearm immersions and head washing is not practical during actual firefighting scenarios since it requires the firefighters to remove their PPE. The use of continuous cooling options, such as liquid cooling garments, has been proposed to be more practicable (Hemmatjo et al. 2017).

Several studies have been conducted to determine the effectiveness of the management of the adverse effects of heat stress on firefighters' physiological and cognitive function (Hemmatjo et al. 2017; Cian et al. 2001; Barr et al. 2011). One recent study suggests that the use of continuous cooling approaches is effective in managing heart rate (HR) elevation and temporal temperature, indicating the effectiveness of the approach in controlling physiological effects associated with heat stress (Hemmatjo et al. 2017). This study also observed improved cognitive function when using continuous cooling approaches, marked by an improved response accuracy (inhibition). However, the level of effectiveness varies between different continuous cooling approaches. Barr et al. (2011) also suggested that the use of liquid cooling garments improved the physiological strain index (PSIIt is evident that continuous cooling provides a viable option through which the physiological and cognitive functions of firefighters can be improved. Moreover, the National Institute for Occupational Safety and Health (NIOSH) has investigated several continuous cooling methods determined that a continuous cooling method via a wearable liquid cooling garment (LCG) underneath the FFPPE is the most effective method to reduce thermal strain, enhance recovery, and extend exercise performance time in subsequent sessions of exercise. Although the "optimal" temperature (18 °C) of the circulating water was determined to be the most effective in reducing hyperthermia, the impact of the cooling method on sustained inhibition and response attention was not investigated (Kim et al. 2011).

Response inhibition can be defined as the ability to suppress pre-potent behavior that is inappropriate or no longer required, is critical for goal-directed behavior in everyday life (Williams et al. 2011). Response inhibition as a construct falls under the broader domain of executive functioning, which is considered central in decision-making. The opposite of inhibition is impulsivity, which may negatively impact decision-making. Impulsivity is the tendency to respond prematurely or in an unduly risky fashion. The emphasis in this working definition of impulsivity is on its potentially maladaptive nature; clearly, there are occasions when it is advantageous to respond quickly and in a risky manner. Response inhibition is commonly measured with some form of a continuous performance task that requires withholding a motor response. The Go/No-Go task is a classic test of "response inhibition", i.e., withholding the prepotent response (button pressing) during infrequent 'no-go' conditions. The construct of response inhibition is reflected in response accuracy (RA) (i.e., errors of commission—pressing when they should not—result in poorer scores).

To address the effect of hyperthermia on cognitive function, we hypothesized that (1) exposure to hot and humid environments would result in a decrease in attention and inhibition, and (2) continuous cooling would prevent or mitigate the effects of exposure to heat on attention and inhibition. Hence, the purposes of this study were to investigate the physiological effect of industrial hyperthermia (i.e., ≥ 38 °C Tc) and the efficacy of the continuous cooling method on inhibition and attention while wearing FFPPE during exercise in a hot environment.

Materials and methods

Study design

This cross-sectional study consisted of two experimental sessions: control (no cooling) and intervention (cooling) in order to investigate the effect of hyperthermia and the efficacy of continuous cooling on inhibition (i.e., improved response accuracy) and attention while wearing FFPPE during exercise in a warm (30 °C) and humid (70% RH) environment. Each subject served as his own control in this study. Therefore, the data reported are differences in an individual subject's response to one condition (no cooling or control) to that subject's response to cooling (experimental). Data from all subjects was collected in this manner and then treated as statistical means as described in the Statistical Analysis section below. The study was approved by the NIOSH Institutional Review Board (IRB) # 15-NPPTL-01.

Study population

A sample of 12 healthy, nonsmoking, physically fit men whose anthropometric characteristics ($\overline{X} \pm SD$) are as follows: age 24 ± 3.2 years; height 178 ± 8.7 cm; weight 78.1 ± 8.2 kg; BMI 24.8 ± 3.0 kg·m^2; $\dot{V}O_{2max}$ 56.3 ± 7.4 mL· kg^{-1}·min^{-1} were recruited to participate in this study. Only physically fit subjects (i.e., $\dot{V}O_2 \geq 45\,mL \cdot kg^{-1} \cdot min^{-1}$) between the ages of 21 and 40 years (a NIOSH IRB requirement), not taking any medications that might interfere with the safe conduct of the study or with the quality of the data collection (including alcohol/drug abuse), and be physically and mentally capable of performing the tasks required by the study, were recruited in order to comply with NIOSH IRB policy.

Medical evaluation

Upon the first visit to the laboratory, oral and written informed consent were obtained from each subject after an orientation about both experimental procedures (control and intervention) and the nature of the study. Each subject completed a medical history questionnaire before participation and before beginning each test session. Subject eligibility was also determined after a physician conducted a medical history review, physical examination, and drug screen (an additional urine spot pregnancy screen was performed for female subjects as pregnancy was an exclusion criterion for this study).

Author Manuscript

Author Manuscript

Author Manuscript

Physical fitness evaluation

After receiving medical clearance to participate in the testing, eligible subjects performed a symptom-limited maximal graded exercise test to volitional fatigue (GXT) with electrocardiographic (ECG) and pulmonary metabolic measurements to assess total aerobic capacity (fitness level or $\dot{V}O_{2max}$) and maximal heart rate (HR_{max}). The accompanying ECG rhythm was evaluated to potentially reveal undiagnosed cardiovascular disease during physical stress. The subjects' $\dot{V}O_{2max}$ and HR_{max} were determined during the GXT using a modified Bruce protocol (Bruce 1971) consisting of ramping stages starting at 0% rather than 10% grade. The grade was started at 0% to assure that the calculated sub-maximal grade was low enough for comfortable walking while wearing FFPPE. Stage treadmill speeds remained unchanged from the standard Bruce protocol. A "maximal test" ($\dot{V}O_{2max}$) was achieved when the following criterion were met: (1) volitional fatigue, (2) a sustained R value of 1.15; and (3) no increase in O_2 consumption or HR with increasing load/time on the treadmill. The results from the GXT were used to determine the workload (~40% of the $\dot{V}O_{2max}$) for the experimental exercise sessions and the HR termination criteria (>90% HR_{max}). After successful completion of the GXT, a demonstration of test procedures was provided to each subject. A subjects' inability to achieve a $\dot{V}O_{2max} \geq 45\,mL \cdot kg^{-1} \cdot min^{-1}$ and/or any ECG abnormalities (e.g., dysrhythmias, conduction delays, S-T segments) would exclude a subject from participation in the study.

Experimental sessions

The overall sequence of the experimental procedure is illustrated in Figure 1. Prior to participation in the experimental phase of the study, subjects were randomly assigned to participate either in the Control (no cooling) or Intervention (cooling) phase. Because each subject served as their own control, each subject, regardless of their initial random assignment to either control or cooling, participated in both control and cooling experimental sessions while wearing FFPPE during treadmill exercise in the environmental chamber. Also, regardless of their random assignment, each subject completed a computerized Go/No-Go test conducted under ambient conditions (air temperature (TA): 20 °C, relative humidity (RH): 50%) while wearing athletic clothing (cotton t-shirt, cotton shorts, cotton socks, and athletic shoes). This served as a baseline of inhibition and attention outcome measures. The experimental Go/No-Go test sessions were conducted inside an environmental chamber T_A: 30 °C, RH: 70%) with the participant wearing FFPPE which included a self-contained breathing apparatus (SCBA). The experimental sessions while in the environmental chamber consisted of four stages: (1) 15-min stabilization during which the subjects were seated on a chair inside the chamber with the environmental conditions set at 30 ° C, 70% RH during which pre-exercise physiological measures were obtained; (2) 5-min "transition" (during which the study staff adjusted the treadmill incline and determined the belt speed that would be necessary to impose a relative workload equivalent to 40% $\dot{V}O_{2max}$ for that specific subject as determined by their maximal aerobic response during the maximal GXT); (3) 40-min treadmill exercise at 40% $\dot{V}O_{2max}$ immediately at the end of which the subjects were seated at a table and were instructed to perform a computer-based (Go/No-Go) test, adapted from previously published study protocol (Mueller and Piper 2014); and (4) the subjects were then moved out of the chamber and seated at room temperature for a 10-min recovery stage. The subjects were instructed to remove the FFPPE and change into clean clothes. Subjects were monitored and remained in the recovery stage (4) until T_c decreased to below 38 °C and HR decreased to < 100 b·min^{-1}; a cold liquid (water or sports drink) was provided *ad libitum* during the recovery stage.

Participants performed the computerized Go/No-Go test upon the first visit to the laboratory (baseline) under room temperature conditions (20 ° C, 50% RH) and immediately after exercise (immediately before the recovery stage—stage (3)) for each of the two experimental sessions. Thus, this test consisted of a 2 × 2 array with four stars, one in each square of the array. A single letter stimulus (P or R) is presented in one of the squares for a duration of 500 milliseconds (ms) with an inter-stimulus interval of 1,500 ms. In the first test type/condition (P-Go), participants were asked to press (hit) a button in response to the target letter, P, and withhold their response to the non-target letter, R. The ratio of targets (P) to non-targets (R) was 80:20. A second condition, a, reverse of the first (P-No-Go), was also administered in which participants were asked to respond to the target letter R and withhold their response to the non-target letter P. The ratio of targets to non-targets remained the same during the reversal (P-No-Go) condition (ratio of targets to non-targets—80:20). Together, the two conditions consisted of 320 total trials, each condition consisting of 160 trials. The outcome variables of the Go/No-Go test, derived directly from the software Psychology Experiment Building Language (PEBL) test battery, (Mueller and Piper 2014) are the percentage of response accuracy error (RA, %) and reaction time (RT, ms). RA was assessed by calculating the final percentage of the mean of the errors in both test conditions/types (all 320 trials). The "errors" consist of the number of omissions (misses) of the GO letter, and the number of commissions (or NO-GO errors). RT was assessed by calculating the mean time needed to apply the correct response to the target letter (hits) per each test condition/type.

The physiological outcome measures of HR, T_c, and T_{sk} were obtained twice: pre- and post-exercise for each experimental session. Although each physiological variable was monitored continuously throughout the testing for safety purposes, each physiological variable shown in Table 1 represents a 1-min average of that variable obtained during the last minute of both the pre-exercise stabilization phase (Stage 1) and the post-exercise phase (Stage 4).

Materials and instrumentation

Experimental personal protective ensemble—A standard FFPPE (Morning Pride Mfg. LLC, Dayton, OH) with an SCBA (Scott NXG2 AIRPAK with 45-min rated carbon cylinder; Scott Health & Safety, Monroe, NC) was used as the experimental personal protective ensemble. The purpose of wearing the SCBA was to ensure that subjects were exposed to the same weight as experienced by firefighters in the field (total weight of FFPPE including SCBA is 20.50 kg). The SCBA cylinder was not used as a respirator in this study, and the airline was not connected to the face mask.

Environmental (climate) chamber—A walk-in test chamber (WM-Series, Russell Technical Products, Inc., Holland, MI) was used to create the environmental exercise conditions specified by the study protocol (30 ± 2 °C; 70 ± 5% RH).

Liquid cooling garment (LCG)

An LCG (Kim et al. 2011) was used in this study as the continuous cooling application. The garment is designed such that it selectively cools specific regions of the body with greater heat exchange capabilities as described elsewhere (Koscheyev et al. 2002). This garment employs Tygon plastic tubing stitched into the inner surface of the fabric in order to ensure contact with the skin for heat exchange (Koscheyev et al. 2002). The tubing was continuously infused with cooled water (18 °C) supplied by an external water circulator. Body surface areas covered by the garment tubing were head, torso, forearm, and thigh.

HR was measured using an FDA-approved wireless monitor (BioHarness III, Zephyr Technology Corporation, Annapolis, MD) strapped to the chest of each participant prior to starting the experimental session and was worn until the end of recovery. Core temperature (T_c) was measured by a rectal probe (4600 precision rectal thermistor; YSI Temperature, Dayton, OH) inserted 13 cm beyond the anal sphincter (accuracy ± 0.05 °C, between 25–50 °C) connected by wire to a computer software (Laboratory Virtual Instrument Engineering Workbench [LabVIEW], National Instruments Corporation, Austin, TX) which synchronizes the data, allowing for real time measurement of T_c.

Skin temperature (T_{sk}) was measured by thermistors (SQ2020–1F8 skin temperature logger; Grant Instruments Ltd., Cambridgeshire, UK) attached to four skin sites (chest, shoulder, thigh, and calf). Temperature measurements from these skin sites were used to calculate mean T_{sk} using a weighting coefficient (Ramanathan 1964). Both T_c and T_{sk} were continuously measured for the duration of each experimental session (Stages 1–4) and stored every second throughout each session and then represented as one-min average values by a data acquisition system. Weight loss from sweating (W, kg) was obtained by calculating differences between pre- and post-exercise seminude body weights (± 2 g) by a precision platform weighing scale (Electronic Scale series 4450; GSE, Farmington Hills, MI).

Statistical analysis

Descriptive summary statistics ($\bar{x} \pm$ s.d.) were calculated for all outcome measures. A Shapiro Wilks test was conducted to determine the normality of the data. Then, we conducted an ANOVA with non-parametric data to evaluate the cognitive data from our study. The literature supports the claim that ANOVA is a robust statistical method when data deviates from normality and when coupled with the Shapiro Wilks statistical test for normality (Schmider et al. 2010). An ANOVA, with repeated measures (time inside the chamber [baseline/pre- vs. post-] × cooling mode [i.e., no cooling vs. cooling]), was used to examine the effects of hyperthermia and the interaction of continuous cooling on all measurements except for RT. A three-way ANOVA within subjects effects (time inside the chamber [baseline vs. post-] × cooling mode[no cooling vs. cooling] × test type [Go vs. No-Go]), was conducted to analyze the RT in order to find the effect of reaction type in addition to the effects of hyperthermia and the interaction of continuous cooling. In order to find the effect of hyperthermia, simple effect of the time report from the ANOVA analysis was used. The interaction effects between time and cooling (in addition to test type) were used to find the impact of cooling.

R software (version 3.3.2, The R Foundation for Statistical Computing, Vienna, Austria) was used for all statistical analyses. An alpha value of $p \leq 0.05$ was considered statistically significant for all comparisons.

Results

Descriptive summary statistics

Study dependent variables are summarized in Table 1 as descriptive statistics [$\bar{x} \pm$ s.d.] used in both sessions: control (no cooling) and intervention (cooling). The data are based on the fact that all subjects completed the entire 40-min exercise as outlined in the study protocol.

Physiological measures

The participants' physiological responses (T_c, T_{sk}, HR) increased while W decreased by the end of exercise (Stage 3) during exposure to hot conditions. However, continuous cooling had a significant impact on suppressing the elevation of all physiological responses. The p-values, mean differences (M_{diff}), and standard error (SE) of final physiological values in each session derived from the two-way ANOVA performed on the physiological responses as a function of elevation/range and time spent exercising in the chamber in two sessions (control (no cooling), intervention (cooling)) is summarized in Table 2.

Inhibition and attention measures

Response accuracy (RA)—There was no significant effect of hyperthermia (no cooling) or the cooling intervention on RA induced by exercising in the environmental chamber (0.001 ± 0.005, $p = 0.41$). A significant reduction in RT was observed after heat exposure (no cooling; $p \leq 0.05$). There were no significant differences with the cooling application (Table 3).

Discussion

This study investigated the physiological and inhibition/attention responses to hyperthermia, and the interaction of continuous cooling on the hyperthermia responses, induced by exercising in hot conditions while wearing FFPPE. The primary findings of this study were that hyperthermia, induced by exercise in the heat while wearing encapsulated FFPPE, increased the physiological responses (T_c, T_{sk}, HR, and sweat rate [as represented by decreased body weight]) above the pre-exposure values. Although the increase in the physiological response to heat was blunted when subjects were exposed to continuous cooling, the exposure to heat did not affect attention and inhibition in the present study. The effect of demographic factors could not be evaluated since the study utilized a young, healthy, male population each demonstrating a high level of physical fitness as indicated by having a $\dot{V}O_{2max}$ of $\geq 45\ \mathrm{mL \cdot kg^{-1} \cdot min^{-1}}$.

Physiological responses

The continuous cooling interaction effects on the individual's physiological responses are in agreement with the current study hypothesis, as well as with previous studies (Barr et al. 2011; Kim et al. 2011; Mokhtari and Sheikhzadeh 2014; Jang et al. 2015). The current and previous studies have shown that, when using the continuous cooling method, significant improvements in physiological responses after a stressful exercise (40% $\dot{V}O_{2max}$) in a warm humid environment (30 °C, 70% RH) while wearing FFPPE were observed. In the absence of the cooling method (no cooling), the physiological responses (HR, T_c, T_{sk}, sweat rate) were significantly elevated ($p < 0.05$) and negatively affected during the exercise in the warm humid conditions (control session). During the study, the participants' T_c exceeded the limit of industrial hyperthermia (ACGIH 1992) (38.25 ± 0.36 °C). The cardiovascular response (HR) also exceeded the ACGIH recommended elevation level (171 ± 15 b·min^{-1}).

A significant T_{sk} elevation (36.9 ± 0.6 °C) occurred due to an increased microclimate temperature. The microclimate temperature is the temperature of the thin layer of air that exists between the surface of the skin and the inner surface of the clothing PPE and exerts the greatest thermal stress on an individual wearing PPE. The encapsulating nature of the FFPPE likely prevented body heat transfer to the surrounding environment (Barr et al. 2010). Thus, the subjects experienced increased "futile" sweating that resulted in a significant level of dehydration, leading to weight loss (1.23 ± 0.11 kg) due to the encapsulating microclimate of the FFPPE.

The interaction effect of continuous cooling on the physiological responses indicate that the body cooling strategy using LCG underneath the FFPPE is an effective method for reducing thermal stress under warm, humid conditions. The cooling interaction significantly suppressed the increase seen in participants' T_c when compared to exercising without the cooling application (average temperature change: 0.42 ± 0.9 °C decrease with cooling). Additionally, the cooling application maintained mean T_c below 38 °C (average T_c: 37.8 ± 0.5 °C) for most of the study participants which was evidence for adequate control of heat stress within this subject group. Also, a significant decrease in HR elevation was found with the cooling application with a mean difference of 29 ± 4 b·min^{-1} decrease ($p < 0.01$) compared to no cooling. This indicated that cooling had a positive impact on reducing cardiovascular strain associated with thermal stress. Moreover, significant reductions in T_{sk} elevation (1.6 ± 0.2 °C decrease) and dehydration level via weight loss (0.54 ± 0.18 kg) were found with the cooling interaction.

Sustained inhibition and response attention

The study results show that hyperthermia produced no significant effect on RA. A possible explanation for this would be if the T_c had not increased enough to impair the participants' RA. A study conducted by Bandelow et al. (2010) shows that the RA, derived from a block tapping computerized test, improved when T_c increased, and the beneficial effect was not observed beyond 38.2 °C. Moreover, Simmons et al. (2008) suggested that a rise in T_c induces a systematic improvement in the capacity to focus and RA in response to such a stimulus. Because of this, we speculate that the inhibition task given to participants was not challenging enough to detect the effect of heat or that the modest increase in T_c was not sufficient enough to alter RA. This is supported by studies that have shown that the degree of cognitive impairment resulting from heat stress is related to the intensity of the heat stress and the complexity of the task leading to the creation of thermal tolerance limits for workers (Hancock and Vasmatzidis 2003; Wing 1965).

The present findings of RT are in contrast with the study hypothesis, but in agreement with some of the published literature. Some studies suggest that RT improves with mild heat strain, but impairment will happen at high levels of hyperthermia (Racinais et al. 2008; Lee et al. 2014). The present study shows that hyperthermia resulted in a significantly shorter (improved) reaction time (RT; $p \leq 0.01$) following exercise while wearing FFPPE in a warm, humid environment. This change seen in reaction time may likely be caused by an increase in attention/vigilance activities in the area of the brain (dorsolateral prefrontal cortex) responsible for executive functioning, memory, cognition, and reasoning. Increased activities in this area of the brain have been reported following exposure to hyperthermia (Morley et al. 2012). Hyperthermia could have triggered an acute increase in alertness, causing a decrease in RT. Future research would explore possible effects of higher T_c elevation while wearing FFPPE in order to investigate the relationship between these negative physiological and inhibition/attention reactions.

One interpretation of hyperthermia effects on attention/inhibition has been proposed in a study (Schmit et al. 2017) suggesting that an inverted U-shaped relationship appears between the level of hyperthermia and cognitive function and may reflect the neural challenge imposed by multiple accumulating stressors (i.e., cognitive demand and increasing heat strain). This study suggested that heat stress consistently improves both simple and complex cognitive processes when $T_c \leq 38.5$ °C (Schmit et al. 2017). However, beyond this threshold, cognitive performance plateaus before declining at a T_c greater than ~39 °C, with the more complex cognitive functioning impaired first. While the upwards part of the U-curve may be explained through heat related cognitive arousal, the downward component has been suggested to reflect the inability of the "cognitive reserve" to process such accumulation of constraints (Gaoua et al. 2011).

The inhibition/attention data results in this study do not support the hypothesis in that the cooling application provided no significant impact on attention and inhibition when exercising (40% $\dot{V}O_{2max}$) while wearing FFPPE in a warm humid environment (30 °C, 70% RH). This may be due to the cooling method parameters (water temperature, vest materials, circulation tubes, etc.), in combination, being insufficient to elicit the change in cognition proposed in the hypothesis. The attention and inhibition effect may only be observed at lower cooling temperatures than those used in the present study. Further investigation into the attention and inhibition of a lower temperature when applying the cooling methods would address this issue.

Study limitations

There were three main limitations of this study: testing conditions, study population, and cooling parameters. The study was completed using controlled conditions in an environmental chamber. The warm and humid environmental conditions were set to simulate the average heat conditions faced by firefighters under non-live burn conditions in sub-tropical regions (e.g., southern United States adjacent to the Gulf of Mexico). However, firefighters face far more extreme conditions than what were used in this study (e.g., structural fires). Therefore, the study findings should be used with caution considering the limitations mentioned above. The study also created a hot/humid environment during exercise for 40 min, which may not comprehensively represent actual bouts of firefighting. Some of the routine exposure to heat on the fire ground may be limited by the air supply provided by and SCBA (~15–20 min) (Williams et al. 2011). The study participants were recruited from the general population with strict health and physical fitness criteria due to the difficulty in recruiting professional firefighters. The study population only represents a relatively young and healthy population which excluded those with specific health issues. This limitation is unavoidable due to the strict exclusion criteria essential in conducting laboratory-based studies as subject safety is paramount. Finally, the parameters of the cooling method (i.e., water temperature and vest and tubes materials) might have been limited in its ability to provide complete beneficial effects to attention and inhibition.

Conclusions

The study results suggest that exercising in a warm and humid environment, combined with the additional burden from wearing encapsulating FFPPE, is physically demanding can impose a significant physiological and thermal burden. This increase physiological burden can lead to industrial hyperthermia and high heat-related fatigue levels. Although the present study was physiologically stressful (increased T_c, T_{sk}, and HR), the neurological elements of attention and inhibition were not altered by hyperthermia. The observed decrease in reaction time may also have been caused by an increased activity in the area of the brain (dorsolateral prefrontal cortex) responsible for executive functioning, memory, cognition, and reasoning. Increased activity in this area of the brain has been reported following exposure to hyperthermic conditions (Morley et al. 2012; Johnson and Kobrick 2001; McMorris et al. 2006). Hyperthermia could also have triggered an acute increase in alertness, causing a decrease in reaction time. The improved reaction time may be associated with a subtle, non-significant change in firefighters' response accuracy. Although the increase of firefighters' response accuracy error was not significant, is seems that even subtle improvements may be critical to increase firefighters' response accuracy in order to prevent unsafe practices. The utilization of body cooling via a wearable liquid cooling garment underneath the FFPPE significantly decreased both the physiological and thermal strain. However, attention and inhibition may not receive any obvious benefit from the liquid cooling according to the limitations of the cooling method utilized in this study. Nevertheless, the addition of cooling to the firefighters' repertoire of equipment can work to reduce the severity of and negative consequences associated with industrial hyperthermia. Reducing industrial hyperthermia may maintain a firefighters' reaction times and avoid unsafe decision-making during firefighters' practices, improving their performance and productivity.

Acknowledgments

This study was a part of Dr. Aljaroudi's dissertation work at the University of Cincinnati Education Research Center (UC ERC) doctoral program, conducted during his fellowship at the NPPTL. The authors thank all subjects for their time and participation. The authors also thank the NPPTL Evaluation and Testing Branch for kindly permitting us to use their Environmental Chamber for this study. We thank Aitor Coca, Ph.D., Jung-Hyun Kim, Ph.D., and Tianzhou Wu, MS for their support during data collection. We also thank Lorenna Altman and Cyndy Cox from the University of Cincinnati for their technical support. We thank Raymond Roberge, MD for medical monitoring and screening during data collection.

Funding

The study was funded in part from the NIOSH ERC Grant #T42OH008432 and with NIOSH/NPPTL internal discretionary funding.

References

ACGIH 1992. 1992-1993 Threshold Limit Values for Chemical Substances and Physical Agents and Biological Exposure Indices. Cincinnati (OH): ACGIH Signature Publications.

Bandelow S, Maughan R, Shirreffs S, Ozgünen K, Kurdak S, Ersöz G, Binnet M, Dvorak J. 2010. The effect of exercise, heat, cooling and rehydration strategies on cognitive function in football players. Scand. J. Med. Sci. Sports 20(3):148–160. doi:10.1111/j.1600-0838.2010.01220.x [PubMed: 21029202]

Barr D, Gregson W, Reilly T. 2010. The thermal ergonomics of firefighting reviewed. Appl Ergon. 41(1):161–172. doi:10.1016/j.apergo.2009.07.001 [PubMed: 19664755]

Barr D, Reilly T, Gregson W. 2011. The impact of different cooling modalities on the physiological responses in firefighters during strenuous work performed in high environmental temperatures. Eur J Appl Physiol. 111(6):959–967. doi:10.1007/s00421-010-1714-1 [PubMed: 21079990]

Bruce RA. 1971. Exercise testing of patients with coronary heart disease. Principles and normal standards for evaluation. Ann Clin Res. 3(6):323–332. [PubMed: 5156892]

Chang CH, Bernard TE, Logan J. 2017. Effects of heat stress on risk perceptions and risk taking. Appl. Ergon 62:150–157. doi:10.1016/j.apergo.2017.02.018 [PubMed: 28411725]

Cian C, Barraud PA, Melin B, Raphel C. 2001. Effects of fluid ingestion on cognitive function after heat stress or exercise-induced dehydration. Internat. J. Psychophysiol 42(3):243–251. doi:10.1016/S0167-8760(01)00142-8

Gaoua N, Racinais S, Grantham J, El Massioui F. 2011. Alterations in cognitive performance during passive hyperthermia are task-dependent. Int. J. Hypertherm 27(1):1–9. doi:10.3109/02656736.2010.516305

Hancock PA, Vasmatzidis I. 2003. Effects of heat stress on cognitive performance: The current state of knowledge. Int. J. Hyperth 19(3):355–372. doi:10.1080/0265673021000054630

Hemmatjo R, Motamedzade M, Aliabadi M, Kalatpour O, Farhadian M. 2017. The effect of practical cooling strategies on physiological response and cognitive function during simulated firefighting tasks. Health Promot Perspect. 7(2):66–73. doi:10.15171/hpp.2017.13 [PubMed: 28326286]

Jang Y-J, Kim J-H, Lee J-Y. 2015. Effects of menthol on thermoregulatory responses after exercise-induced hyperthermia. Extr. Physiol. Med 4(S1):A6.

Johnson RF, Kobrick JL. 2001. Psychological aspects of military performance in hot environments. In: Pandolf KB, Burr RE, Wenger CB, Pozos RS, editors. Medical aspects of harsh environments, vol. 1. Fort Detrick: U.S. Army Medical Research and Materiel Command; 2001.

Kim J-H, Coca A, Williams WJ, Roberge RJ. 2011. Effects of liquid cooling garments on recovery and performance time in individuals performing strenuous work wearing a firefighter ensemble. J. Occup. Environ. Hyg 8(7):409–416. doi: 10.1080/15459624.2011.584840 [PubMed: 21660834]

Koscheyev VS, Coca A, Leon GR, Dancisak MJ. 2002. Individual thermal profiles as a basis for comfort improvement in space and other environments. Aviat Space Environ Med. 73(12):1195–1202. [PubMed: 12498548]

Lee JKW, Koh ACH, Koh SXT, Liu G, Nio AQX, Fan P. 2014. Neck cooling and cognitive performance following exercise-induced hyperthermia. Eur J Appl Physiol. 114(2):375–384. doi:10.1007/s00421-013-2774-9 [PubMed: 24318656]

McMorris T, Swain J, Smith M, Corbett J, Delves S, Sale C, Harris RC, Potter J. 2006. Heat stress, plasma concentrations of adrenaline, noradrenaline, 5-hydroxytryptamine and cortisol, mood state and cognitive performance. Int. J. Psychophysiol 61(2):204–215. doi:10.1016/j.ijpsycho.2005.10.002 [PubMed: 16309771]

Mokhtari Yazdi M, Sheikhzadeh M. 2014. Personal cooling garments: A review. J. Text Inst 105(12):1231–1250. doi: 10.1080/00405000.2014.895088

Morley J, Beauchamp G, Suyama J, Guyette FX, Reis SE, Callaway CW, Hostler D. 2012. Cognitive function following treadmill exercise in thermal protective clothing. Eur J Appl Physiol. 112(5):1733–1740. doi:10.1007/s00421-011-2144-4 [PubMed: 21892644]

Mueller ST, Piper BJ. 2014. The Psychology Experiment Building Language (PEBL) and PEBL Test Battery. J. Neurosci. Methods 222:250–259. doi:10.1016/j.jneumeth.2013.10.024 [PubMed: 24269254]

NFPA 2008. Standard on the rehabilitation process for members during emergency operations and training exercises. Quincy (MA) National Fire Protection Association. 2008. (NFPA Codes and Standards: NFPA 1584).

Qian S, Jiang Q, Liu K, Li B, Li M, Li L, Yang X, Yang Z, Sun G. 2014. Effects of short-term environmental hyperthermia on patterns of cerebral blood flow. Physiol Behav. 128:99–107. doi:10.1016/j.physbeh.2014.01.028 [PubMed: 24530482]

Racinais S, Gaoua N, Grantham J. 2008. Hyperthermia impairs short term memory and peripheral motor drive transmission. J. Physiol 586(19):4751–4762. doi:10.1113/jphysiol.2008.157420 [PubMed: 18703579]

Ramanathan NL. 1964. A new weighting system for mean surface temperature of the human body. J. Appl. Physiol 19(3):531–533. doi:10.1152/jappl.1964.19.3.531 [PubMed: 14173555]

Ramsey JD, Burford C, Beshir MY, Jensen RC. 1983. Effects of workplace thermal conditions on safe work behavior. J. Safety Res 14(3):105–114. doi:10.1016/0022-4375(83)90021-X

Schmider E, Ziegler M, Danay E, Beyer L, BüHner M. 2010. Is it really robust? Reinvestigating the robustness of ANOVA against violations of the normal distribution assumption. Methodol. 6(4):147–151. doi:10.1027/1614-2241/a000016

Schmit C, Hausswirth C, Le Meur Y, Duffield R. 2017. Cognitive functioning and heat strain: Performance responses and protective strategies. Sports Med. 47(7):1289–1302. doi:10.1007/s40279-016-0657-z [PubMed: 27988874]

Simmons SE, Mündel T, Jones DA. 2008. The effects of passive heating and head cooling on perception of exercise in the heat. Eur J Appl Physiol. 104(2):281–288. doi:10.1007/s00421-007-0652-z [PubMed: 18172673]

Sun G, Qian S, Jiang Q, Liu K, Li B, Li M, Zhao L, Zhou Z, von Deneen KM, Liu Y. 2013. Hyperthermia-induced disruption of functional connectivity in the human brain network. PLoS One. 8(4):1–10. doi:10.1371/journal.pone.0061157

Williams WJ, Coca A, Roberge R, Shepherd A, Powell J, Shaffer RE. 2011. Physiological responses to wearing a prototype firefighter ensemble with enhanced chemical/biological hazard protection. J. Occup. Environ. Hyg 8(1):49–57. doi:10.1080/15459624.2011.538358 [PubMed: 21154108]

Wing JF. 1965. Upper thermal tolerance limits for unimpaired mental performance. Aerosp Med. 36(10):960–964. [PubMed: 5860097]

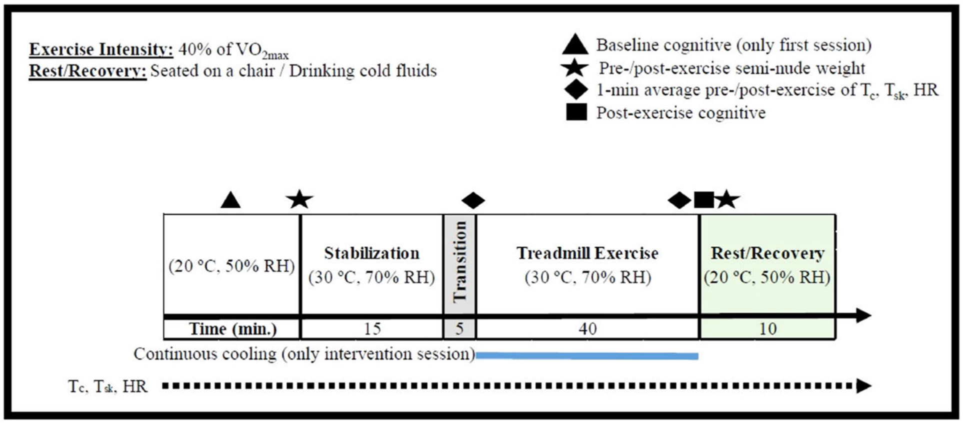

Figure 1.
Schematic of the sequence of the experimental procedures.

Table 1.

Mean ± standard deviation of dependent variables.

Physiological Variable(s)	Control (No Cooling)		Intervention (Cooling)	
	Pre	**Post**	**Pre**	**Post**
T_c, °C	36.9 ± 0.3	38.3 ± 0.4	36.9 ± 0.3	37.8 ± 0.5
T_{sk}, °C	34.8 ± 0.5	36.9 ± 0.6	34.2 ± 0.5	35.3 ± 0.5
HR, $b \cdot min^{-1}$	82 ± 13	171 ± 15	91 ± 19	142 ± 25
W, kg	77.3 ± 8.2	76.1 ± 8.0	77.4 ± 8.0	76.6 ± 8.0
Inhibition/ Attention Variable(s)		**Baseline**	**Post-Control**	**Post-Intervention**
Error of Response Accuracy (RA), %		3.1 ± 1.5	3.0 ± 2.4	3.3 ± 2.1
Reaction Time (RT); ms	Go	407.5 ± 25.4	390.8 ± 32.6	393.4 ± 27.2
	No-Go	497.5 ± 49.8	459.6 ± 56.3	471.4 ± 55.7

Table 2.

Results of the physiological response examination.

Variable	**Simple Effect**		**Interaction Effect**	
(n = 12)	**M_{diff} ± SE (Control [Post − Pre])**	**P**	**M_{diff} ± SE (ΔControl−ΔIntervention)**	**P**
T_c, °C	1.3 ± 0.1	< 0.01*	0.4 ± 0.1	0.01*
T_{sk}, °C	2.1 ± 0.2	< 0.01*	1.6 ± 0.2	< 0.01*
HR, b·min^{-1}	89 ± 3	< 0.01*	29 ± 4	0.01*
W, kg	1.2 ± 0.1	< 0.01*	0.54 ± 0.18	< 0.01*

Table 3.

Results of the sustained inhibition and response attention function examination.

Variable		Simple Effect		Interaction Effect	
		Mdiff (SE)		Mdiff (SE)	
(n = 12)		Post Control − Baseline	P	(ΔControl − ΔIntervention)	P
Error of Response Accuracy (RA), %		0.10 ± 1.8	0.41	0.37 ± 0.43	0.22
Reaction Time (RT); ms	Go	16.6 ± 5.6	0.03*	2.57 ± 7.0	0.72
	No-Go	37.9 ± 7.5	< 0.01*	11.8 ± 6.1	0.08