PHYSIOLOGICAL CHALLENGES IN HARSH ENVIRONMENTS: NUTRITIONAL STRATEGIES FOR MILITARY AND OCCUPATIONAL OPERATIONS

by

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ABSTRACT

When humans are exposed to harsh environments, physical and mental performance is often substantially degraded. Few practical strategies are available to sustain performance under such conditions. The first of three studies evaluated the possible diuretic effect of caffeine following exercising in the heat. This is important for many U.S. military personnel who are engaged in combat situations in the Middle East, as dehydration may pose serious health issues. Eight participants completed four trials either with or without caffeine prior to the exercise and undertook a 3-h recovery period with or without fluid replenishment. Results revealed that ingestion of caffeine did not increase urine volume and did not increase fluid requirement during rest. In the second study, we examined the effects of menthol and caffeine on ventilatory and perceptual responses during simulated firefighting in the heat. Ten participants completed three trials, either with caffeine, menthol lozenges, or placebo. Contrary to the literature, menthol actually increased ventilatory loads (i.e., $\dot{V}_E$, $\dot{V}O_2$) and did not improve thermal or breathing comfort. The third study examined the effects of repeated dynamic exercise in the heat on mood and cognitive performance. Exercise in the heat substantially deteriorated mood states, but cognition was well maintained despite being at or near maximal heart rate, hypohydration, and hyperthermic state, suggesting possible coping mechanisms while working in multi-stressors situations. Neither caffeine nor menthol reduced the adverse impact of exercise-heat stress on mood. Current results provided information for military and occupational personnel performing

duties in hot environments: (1) there was no evidence that caffeine ingestion in moderation would impair fluid balance during prolonged exercise in the heat and recovery; (2) perceptual and mood state degraded to a similar extent as physical performance; (3) caffeine and menthol exerted no ergogenic effect for firefighting in the heat. More efforts are needed to help those at-risk workers to cope with multi-stressors environments in order to maintain operational efficiency.

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Never give in, never give up. Thank you all in my life.

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CHAPTER I

INTRODUCTION

Modern warfare now often requires soldiers to perform sustained operations to achieve mission success. Accordingly, military personnel are often exposed to multiple physical and mental stressors including sleep loss, inadequate nutrition, and inadequate recovery. Not surprisingly, drinking coffee is popular in the military community and is considered to improve physical and cognitive performances.

Caution remains due to caffeine's proposed diuretic effect. It is often suggested to avoid caffeine drinks while exercising in the heat. For military personnel, potential fluid deficit following caffeine ingestion is an important consideration because fluid replenishment is often limited and dehydration would not only impair performance but also could put soldiers into a life-threatening situation. Considering that there is no clear guidance regarding coffee consumption for military personnel, it is necessary to investigate caffeine's diuretic effect and to further establish fluid requirements. Exercise and hydration in the heat are of particular interest due to U.S. and coalition forces' engagement in Middle East areas wherein hot environments might further exaggerate physiological stress during warfare.

Similarly, firefighters are often exposed to multi-stressors situations, including environmental extremes, and intense and continuous physical activity. It is known that the self-contained breathing aspirator impairs the ability to perform high levels of physical activity.

Meanwhile, performing fire suppression and rescue missions in a harsh and demanding environment requires an optimal level of mental performance. Inability to maintain a quick and accurate decision making could well compromise mission success and put firefighters into potential life-threatening consequences. However, little research seeks practical nutritional supplements for firefighters during strenuous exercise in the extreme environmental heat. Menthol is appealing for its cooling effect and stimulation of breathing. Caffeine is known to improve cognitive performance; therefore, it may provide a practical aid for firefighters coping with multi-stressors in harsh environments.

The first aim of these studies was to examine effects of exercise and heat on caffeine's diuretic effect. Urine volume was measured. Moreover, fluid requirements during rest were examined. It was hypothesized that caffeine would only exert a mild diuretic effect following prolonged exercise in the heat.

The second aim of these studies was to examine effects of caffeine and menthol on ventilatory, perceptual, mood, and cognition during repeated exercise in the heat. Ventilatory response was continuously collected and mental performances were repeatedly evaluated. It was hypothesized that menthol would increase ventilation and reduced breathing discomfort; furthermore, use of caffeine and menthol would at least partially restore cognition and mood during simulated firefighting in the heat.

CHAPTER II

EFFECTS OF EXERCISE AND HEAT ON CAFFEINE'S DIURESIS: IMPLICATIONS FOR MILITARY OPERATIONS IN THE HEAT

Abstract

The purpose of this study was to determine the effect of exercise and an additional thermal stress on caffeine's diuresis during exercise and 3-h recovery. Caffeine naïve participants (n = 8) pedaled on a bike to achieve 2.5% body mass loss in a hot environment (35^{o}C WBGT, 40% RH) in four separate conditions: (1) with caffeine ingestion (6 mg per kg body mass) during exercise and 100% fluid replenishment (water) of body mass loss during recovery (CAF + HY); (2) without caffeine ingestion during exercise and 100% fluid replenishment during recovery (Non-CAF + HY); (3) with caffeine ingestion (6 mg per kg body mass) during exercise and no fluid replenishment during recovery (CAF + Non-HY); (4) without caffeine ingestion during exercise and no fluid replenishment during recovery (Non-CAF + Non-HY). Urine volume was not different ($p > 0.05$) regardless of rehydration status: 230 ± 162 ml (CAF + Non-HY) vs. 168 ± 77ml (Non-CAF + Non-HY); and 713 ± 201ml (CAF + HY) vs. 634 ± 185ml (Non-CAF + HY). For the 3-h rehydration condition, water retention ratio was higher ($p < 0.05$) in Non-CAF + HY (38 ± 12%) compared to CAF + HY (27 ± 16%), and consequently, caffeine ingestion caused higher hypohydration during rehydration conditions ($p < 0.05$). It is concluded that in practical terms there was no evidence that caffeine ingestion in moderation would impair fluid balance during prolonged exercise in the heat and recovery period.

Keywords: heat strain, dehydration, rehydration

Introduction

Current military doctrine places soldiers in unique situations in which operational forces are often engaged in sustained activities in order to achieve mission objectives. Since modern military operations are both physically and cognitively demanding, and recovery can often be inadequate, there has been an increased interest in caffeine as an effective dietary supplement to counter performance deficits in military settings (Lieberman and Tharion 2002; McLellan et al. 2005). The use of caffeine to extend operational effectiveness in military settings is likely to be encouraged.

Athletes have been advised to abstain from caffeine due to its diuretic effect (Sinclair and Geiger 2000). A review by Maughan and Griffin (2003) suggests that acute ingestion of a large dose of caffeine (> 250 mg) results in a short-term stimulation of urine excretion. Meanwhile caffeinated beverages have been reported to increase urine volume during the recovery period (González-Alonso et al. 1992). Opposing this viewpoint, a systemic review (Armstrong 2002) concluded that caffeine's diuretic effect is overstated and further may be minimized for habitual caffeine users. In support of this view, Armstrong and colleagues (2005) reported that chronic daily intakes of caffeine (> 250 mg), or a sudden increase in caffeine intake, do not impair fluid balance. Controversy still exists regarding the influence of caffeine on fluid balance.

For athletic and recreational populations, possibilities of detrimental fluid-electrolyte imbalances are less likely since caffeine consumption is generally moderate and accompanied with adequate access to fluid, making rehydration non-problematic. For the military population, the risk of dehydration is higher due to prolonged operations and limited fluid availability, particularly with current U.S. and coalition forces' engaged in the Middle East. Continual exposure to exercise-heat stress may eventually lead to serious health related consequences (Sawka et al. 2000).

To date only few studies have examined the combined effects of caffeine and exercise-heat stress on fluid balance for military population. Until this key question is addressed, caution should remain when prescribing the use of caffeine for operational forces in hot environments. Therefore, this study was designed to evaluate:

Aim 1: To examine the ability of exercise to attenuate caffeine's diuretic effect during exercise and recovery. We hypothesized that total urine volume would be similar with and without caffeine ingestion. Repeated times and days of prolonged operations in a hot environment represent a real-life military scenario. In examining this situation, there was no fluid intake during recovery, since rehydration in a real-life situation is often restricted. This approach enhances ecological validity.

Aim 2: To evaluate fluid requirements during recovery following consumption of caffeine. Fluid intake during recovery might mitigate the secretion of fluid regulating hormones and consequently caffeine might override antidiuretic hormones. It would seem more logical however that the stimulus of exercise would negate the already questionable diuretic influence of caffeine. We hypothesized that caffeine would exert mild (at most) diuretic effect after exercise, and there would be a slight increase in the fluid requirement during the recovery phase. Any impact on rehydration must be a concern for subsequent operations which is typical in military engagement.

These findings have applications for military personnel during sustained and/or subsequent missions in the heat.

Methods

Participants

Eight healthy male university students volunteered for this study. Physical characteristics including age, height, weight, and estimated body fat percentage (Durnin and Womersley 1974) were (mean ± standard deviation): 23 ± 4 yr, 178 ± 4 cm, 77.0 ± 15.0 kg, and 9.8 ± 3.9%, respectively. The physical characteristics are similar to the 50th percentile means in the U.S. Army's anthropometric database (Gordon et al. 1989).

Prior to beginning the study, participants were briefed on potential risks and benefits, signed a written informed consent, and completed a medical history questionnaire. Additionally, a questionnaire was administered to determine average daily caffeine consumption. This questionnaire asked for information about the type and volume of caffeinated beverages consumed daily, such as coffee, tea, soft drinks and energy drinks, daily consumption of chocolate bars and candies. Only those who regularly consumed less than 50 mg of caffeine per day were recruited in order to create an extreme-end pattern since a caffeine-naive population is believed to be more responsive to caffeine ingestion on fluid balance (Armstrong 2002). This study was approved by the local Institutional Review Board for protection of human subjects.

Experimental design

A counter-balanced design was used and each participant completed four trials. For aim 1, trials consisted of exercise with caffeine (CAF) or no caffeine (Non-CAF), and no rehydration (Non-HY) during recovery: CAF + Non-HY and Non-CAF + Non-HY. For aim 2, trials consisted of exercise with CAF or Non-CAF, and during recovery phase, rehydration (HY) with tap water that equaled to 100% of body mass loss during the exercise phase: CAF + HY and

Non-CAF + HY. Each trial consisted of two phases: 1) exercise-heat exposure to lose 2.5% of initial body mass, immediately followed by 2) a three-hour recovery. For a given participant, each trial was performed at the same time of day and the same day of week so that fatigue and the circadian influences on hormonal secretion were minimized. Participants were instructed to refrain from any caffeine product for a minimum 24-h period prior to testing. They were also asked to avoid strenuous exercise and alcohol consumption the day before the experimental day.

Experimental protocol

Participants were instructed to drink at least 500 ml of water before sleep prior to the testing day and at least 500 ml of water 2 hours before reporting to the lab to maintain a euhydration status. On arrival to the laboratory, participants emptied their bladder and provided a urine sample, and body mass was measured (shorts only) (Detecto Scales Inc., Brooklyn, NY). To assess hydration status, urine specific gravity (USG) was determined via refractometer (SUR-NE, Atago Inc., Hingham, MA). A urine specific gravity < 1.020 indicated euhydration status (Armstrong et al. 1998), otherwise participants were asked to come back a week later.

For the caffeine trial, ten minutes prior to the exercise phase participants consumed caffeine capsules equal to 6 mg per kg of body mass. Then the participants entered an environmental chamber where the wet bulb global temperature (WBGT) was 35°C (Dry: 42°C, Wet: 31°C, Globe: 40°C, and relative humidity ~40%).

Participants dehydrated 2.5% of their body mass through cycling (Model 818E, Monark, Stockhom, Sweden). They were asked to cycle at a pace maintaining a perceived exertion of 12-13, which is classified as moderate intensity (Borg 1998). Tap water was provided equivalent to

400 ml per hour and total fluid intake during this phase was recorded. Body mass was checked routinely (every 30 min) throughout the dehydration protocol. Once the desired loss in body mass was attained, the participant was removed from the chamber.

Three hours of recovery followed on immediately after the exercise phase. Participants were instructed not to eat and maintain a light metabolic status (e.g., reading books, browsing the internet) throughout this period. For Aim 1, during the three-hour recovery period, no fluid was replaced. For Aim 2, during the three-hour recovery period, tap water volume equal to 25% of the body mass loss was replaced every 30 min during the initial two-hour recovery phase. Another study from our lab (Jones et al. 2010) suggested a higher fluid retention ratio for metered vs. bolus fluid intake. Also, this enhances ecological validity where soldiers are instructed to replace water conservatively in case of limited fluid availability (Nolte et al. 2010). Following the three-hour recovery, participants were weighed again (shorts only).

Statistical analyses

Since it is known that water exerts mild diuretic effect (Melin et al. 2001; Nose et al. 1988), data between the two rehydration trials (CAF + HY and Non-CAF + HY) and the two non-rehydration trials (CAF + Non-HY and Non-CAF + Non-HY) were not compared across. All data analyses were performed for the main effect of caffeine ingestion within the rehydration or non-rehydration trials. A repeated measures Analysis of Variance (ANOVA) was used to compare urine excretion at recovery intervals of 1 h, 2 h, and 3 h. Where appropriate, pair-wised student *t*-tests were used. Insensible water loss during the three-hour recovery period was calculated as: body mass (immediately after exercise phase) + 100% fluid replenishment (for the HY trials) - body mass (end of experimental trial) - total urine volume. For the HY trials, water retention ratio was calculated as: [body mass (end of experimental trial) - body mass (immediately after exercise phase)] ÷ 100% fluid replenishment × 100%. All data were reported as mean values and standard deviations. Differences were considered to be significant at an alpha < 0.05 level.

Results

Mean total caffeine ingestion was 463 ± 89 mg and 459 ± 84 mg (range from 350 mg to 600 mg), for CAF + Non-HY and CAF + HY, respectively. Comparing the two rehydration trials or two non-rehydration trials, there was no difference in body mass or USG at the beginning of exercise and at the end of the experimental trial (Table 1). For the rehydration trials, caffeine ingestion caused significant statistical difference ($p < 0.05$) in hypohydration (Table 1). For the non-rehydration trials, fluid intake during the exercise phases were significantly different ($p = 0.02$). Also as shown in Table 1, the duration of dehydration protocol was not different ($p > 0.05$) with or without caffeine ingestion.

Table 1 Body mass (BM), fluid intake during dehydration protocol (Dh FI), hypohydration, urine specific gravity (USG), and total exercise duration (EX duration)

Variable	CAF + Non-HY	Non-CAF + Non-HY	CAF + HY	Non-CAF + HY
Initial BM (kg)	77.5 ± 15.0	77.0 ± 14.3	77.1 ± 15.2	76.8 ± 15.1
Final BM (kg)	75.4 ± 14.6	75.2 ± 14.1	76.3 ± 15.2	76.2 ± 15.1
ΔBM (kg)	2.0 ± 0.5	1.8 ± 0.3	0.8 ± 0.3	0.6 ± 0.3
Hypohydration (%)	2.6 ± 0.4	2.4 ± 0.4	1.1 ± 0.4[a]	0.8 ± 0.4
Dh FI (ml)	575 ± 128	700 ± 239[b]	550 ± 141	600 ± 151
Initial USG	1.012 ± 0.007	1.012 ± 0.006	1.012 ± 0.006	1.010 ± 0.006
Final USG	1.021 ± 0.004	1.023 ± 0.006	1.004 ± 0.001	1.004 ± 0.002
EX duration (min)	95 ± 25	102 ± 32	95 ± 33	92 ± 19

[a] Significantly different from Non-CAF + HY ($p < 0.05$)
[b] Significantly different from CAF + Non-HY ($p < 0.05$)

Urine volume is given in Table 2. No detectable difference was observed following caffeine ingestion ($p > 0.05$). Fig. 1 shows the relative fluid distribution following the 3-h rehydration period. Insensible water loss was no different for CAF + HY (0.7 ± 0.4 kg) vs. Non-CAF + HY (0.5 ± 0.3 kg). However, water retained in the body was significantly lower in CAF + HY (0.5 ± 0.4 kg) compared to Non-CAF + HY (0.7 ± 0.3 kg) ($p = 0.01$). Accordingly, the water retention ratio was greater in Non-CAF + HY (38 ± 12%) compared to CAF + HY (27 ± 16%) ($p = 0.01$).

Table 2 Urine volume during the 3-h recovery

Experimental Condition	Urine Volume (ml)			
	1st Hour	2nd Hour	3rd Hour	Entire 3-h
CAF + Non-HY	123 ± 105	61 ± 93	46± 38	230 ± 162
Non-CAF + Non-HY	77 ± 63	27 ± 23	64 ± 62	168 ± 77
CAF + HY	151 ± 89	168 ± 101	394 ± 169	713 ± 201
Non-CAF + HY	109 ± 65	136 ± 61	390 ± 162	634 ± 185

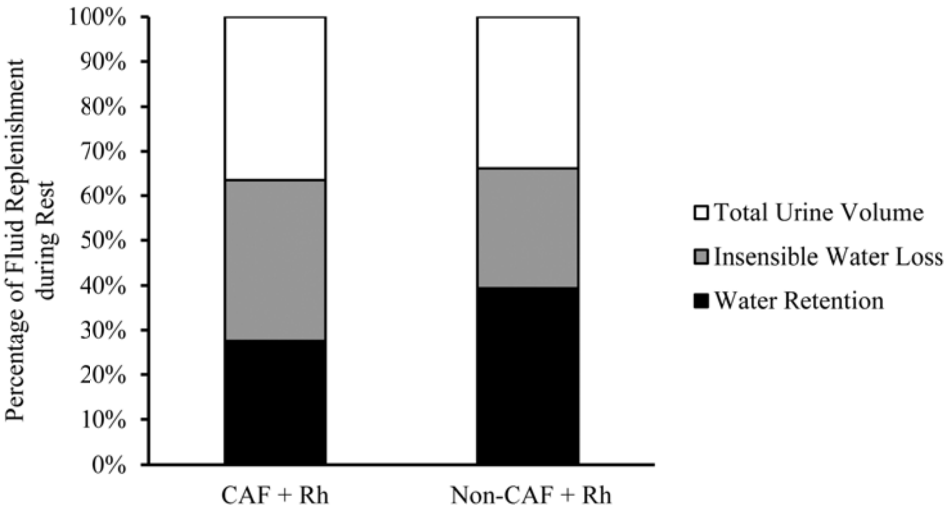

Fig. 1 Route of fluid replenishment during 3-h recovery period.

Discussion

The purpose of the present study was to determine the impact of exercise and an additional thermal stress on caffeine's diuretic effect. Urine volume was not different when no fluid replacement was present; moreover, even with 100% fluid replenishment of water, which is considered to be diuretic and would suppress fluid regulating hormones (Melin et al. 2001; Wade and Claybaugh 1980), there were no treatment differences for a 3-h recovery. Current results provide evidence against claims that caffeine would compromise fluid balance during and after exercise, although caffeine would be expected to have a different impact in a totally sedentary situation.

The available literature suggests that caffeine intake exceeding a threshold of 250-300 mg could result in an acute increase in urine excretion (Maughan and Griffin 2003). However, our results suggest that in our conditions, a mean dose of 460 mg (6 mg per kg of body mass) did not alter urine excretion. This supports previously reported data. In a study with a caffeine dose, similar to ours, of 5 mg per kg (mean of 553 mg), participants exercising at 70-75% maximal oxygen uptake to exhaustion, did not experience extra urine loss compared to no-caffeine (Falk et al. 1990). Similarly, following cycling exercise, a moderate dose of 320 mg of caffeinated drinks did not induce additional acute body water loss compared to no-caffeine (Kovacs et al. 1998). The role of exercise is further evidenced by a study showing that, a large dose of caffeine (8.7 mg per kg body weight, or mean of 586 mg) exerted diuretic effect at rest but not during exercise (Wemple 1997). This suggests that exercise alone, or in combination with heat, is a mediating factor on caffeine's diuresis.

Moreover, the mean duration for the dehydration exercise phase was 1.5 h, correspondently, the effective time window for caffeine's diuretic effect equals 4.5 h total and this is the foundation for our conclusions. A data collection period less than 6 h is often considered to be an acute response to caffeine, and previous research has questioned whether such an acute response could be generalized to real life applications, during which the global effect of caffeine is suggested to be monitored over 24 h periods (Armstrong et al. 2007).

It is our opinion that the current protocol's duration would representatively depict a full picture of caffeine's diuretic effect under our conditions. First, it is known that caffeine's half-life is 2.5 to 4.5 h in young subjects (Massey 1998), and neither exercise nor additional thermal stress should affect caffeine's pharmacokinetics (McLean and Graham 2002). Since it is believed that direct effect of caffeine is to inhibit reabsorption of sodium, thereby inducing an increased Na^+ excretion and secondly reducing water reabsorption (Brater et al. 1983); therefore, the current data collection of 4.5 h during exercise and recovery provided enough duration for caffeine to exert its diuretic action. Second, the literature generally suggests that the diuretic action of caffeine starts quickly and slows later (Neuhäuser-Berthold et al. 1997). Taken together, we believe that if there were a strong diuretic action from caffeine, such an effect should override the effect of exercise and fluid regulating hormones during this 4.5-h data collection period, which did not occur in our results. Furthermore, studies with either a 16-h (Dias et al. 2005) or 24-h (Armstrong et al. 2005) data collection period with a high dose of caffeine (6 mg per kg body mass), did not reveal any further diuretic effect during free living conditions. Apparently, exercise alone, or in combination with heat, could sufficiently defend total body fluid regulation even with a high dose of caffeine ingestion.

Three defensive mechanisms might explain less diuresis from caffeine. First, prolonged exercise-heat stress would redistribute blood flow to active muscles and the skin, with a concomitant relative decrease in blood flow to the liver and the kidneys (Rewell 1973; Smith et al. 1952). This is particularly true when exercise intensity is high and hypohydration becomes severe in the heat. Since the effect of caffeine on urine excretion is believed to be the result of a tubular effect in the kidney (Brater et al. 1983), less delivery of blood flow to the kidneys during exercise is associated with less active diuretic compounds stimulating the kidneys, which could result in less diuretic action from caffeine during the exercise phase.

Second, prolonged exercise with or without heat exposure has been shown to increase the circulating concentrations of the main fluid-regulating hormones (i.e., plasma arginine vasopressin, aldosterone and atrial natriuretic peptide), and the fluid-regulating hormone (plasma arginine vasopressin) would remain elevated after exercise (Melin et al. 2001). Under these conditions, the increased fluid-regulating hormones would produce more concentrated urine through an increase in the kidneys' reabsorption of Na^+ and free water (Poortmans 1984). Development of dehydration in exercise and/or heat exerts an anti-diuresis.

The last possible defensive mechanism would be elimination of caffeine. An early study reported reduced excretion of caffeine compounds in urine with the presence of exercise (Schlaeffer et al. 1984). Kovacs and colleagues (1998) examined caffeine excretion following exercise. It was reported that mean urine caffeine excretion was 243 µg, 504 µg, and 540 µg for caffeine doses of 150 mg, 225 mg, and 320 mg, respectively. Additionally, sweat caffeine excretion significantly exceeded early-void urinary caffeine excretion, being 2087 ug, 3223 ug, 4446 ug for caffeine doses of 150 mg, 225 mg, and 320 mg, respectively. A more recent study (Chambaz et al. 2001) suggested a similar, almost 4 fold increase in caffeine excretion in sweat

(15.2 mg), compared to urine excretion (4.3 mg). Though limited data are available for the disposal route of caffeine following exercise and/or heat exposure, current knowledge leads us to note that sweat caffeine excretion could compete with urinary excretion.

In reference to our study, heat exposure and prolonged exercise induced a marked loss of body fluid, mainly through sweating; therefore, similar to the effect of reduced kidney blood flow during exercise, reduced delivery of caffeine to and elimination from kidneys was possibly offset by large sweat caffeine excretion reducing any diuretic action of caffeine. In summary, the above three mechanisms, alone or in combination, could explain the similar urine excretion with or without a high dose of caffeine. Though intense exercise and environmental heat are stressors for military personnel, these stressors mitigate caffeine-induced diuresis.

Another major purpose of this study was to examine fluid requirements during recovery. Overall water retention ratio was under 40% (Fig. 1). Final urine specific gravity indicated diluted urine following rehydration equal to 100% of body fluid loss during exercise. This is in agreement with previous research due to known diuretic effect of water (Nose et al. 1988). In addition, rehydration after exercise is associated with reduced concentration of fluid-regulating hormones, which would compromise the kidneys' concentrating ability (Melin et al. 2001). For modern military operations, repeated missions occur often and chances of partial or adequate recovery are compromised. From the aspect of rehydration following exercise with or without heat exposure, military personnel who need a rapid recovery of water and electrolytes should be cautious about consuming water as a rehydration drink. Alternatively, drinks rich in electrolytes are considered to be optimal for recovery from body fluid deficit, as is suggested by a recent study (Nolte et al. 2010) evaluating the effect of *ad libitum* water for maintaining total body water during a military march.

Data also suggest that hypohydration was significantly higher with caffeine ingestion during rehydration trials. Statistically, 1.1 ± 0.4% of hypohydration for CAF + HY was higher ($p < 0.05$) compared to 0.8 ± 0.4% for Non-CAF + HY; however, practically, the mean difference in the loss of body weight was only 0.2 kg. We consider this statistical difference was biased from the insensible water loss.

We rigorously controlled the recovery phases; however, the insensible water loss for CAF + HY was 0.7 ± 0.4 kg, tended to be higher ($p = 0.08$) than that found in Non-CAF + HY (0.5 ± 0.3 kg), which is inconsistent with calculated insensible water loss of 0.4 ± 0.3 kg for CAF + Non-HY and 0.4 ± 0.2 kg for Non-CAF + Non-HY. Considering that urine excretion was similar between the two rehydration trials, the difference in insensible water loss explained the higher water retention ratio found in Non-CAF + HY. It is unclear whether this is an error effect (e.g., less experimental control) or results from other factors. Scientifically we draw conclusion that caffeine ingestion would increase hypohydration and fluid requirement during the rehydration conditions; however, such difference was minimal (~200 ml) and likely would not impact health and performance.

Conclusions

The current study somewhat simulates a condition that military personnel may often encounter in many Middle East countries and enhances its ecological validity for generalizing to the military community. We found caffeine ingestion (mean 460 mg) did not alter urine volume during and after exercise. In practical, caffeine ingestion also did not impact the hydration status after exercise-heat exposure. These findings would imply that the use of caffeine in moderation (3-4 cups of regular brewed coffee, 150 mg caffeine per 150 ml) would not place healthy young individuals at higher risks of dehydration. In light of the positive effects of caffeine on physical and cognitive performance, there is no reason for restricting regular coffee consumptions for modern military operations in the heat.

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CHAPTER III

EFFECT OF MENTHOL ON VENTILATORY AND PERCEPTUAL RESPONSES DURING SIMULATED FIREFIGHTING IN THE HEAT

Abstract

The effects of menthol lozenges on ventilatory and perceptual responses were evaluated during simulated firefighting in a hot environment (35°C WBGT, 40% relative humidity). Ten participants performed a repeated intermittent exercise and rest regime on two separate days. Participants either took menthol (MTL) or placebo (PLA) lozenges prior to the beginning of each exercise period. Results revealed that menthol lozenges significantly increased $\dot{V}_E$ (MTL: 45.0 ± 6.6 L·min^{-1} vs. PLA: 41.4 ± 5.8 L·min^{-1} and MTL: 52.7 ± 9.7 L·min^{-1} vs. PLA: 46.5 ± 7.0 L·min^{-1}, for 1st and 2nd treadmill exercise, respectively) and $\dot{V}O_2$ (MTL: 26.7 ± 2.0 ml·kg^{-1}·min^{-1} vs. PLA: 25.2 ± 2.3 ml·kg^{-1}·min^{-1} and MTL: 28.8 ± 2.3 ml·kg^{-1}·min^{-1} vs. PLA: 26.9 ± 1.9 ml·kg^{-1}·min^{-1}, for 1st and 2nd treadmill exercise, respectively) ($p < 0.02$). Such effects on ventilation disappeared during later stepping exercise ($p > 0.05$). Ratings of thermal sensation and breathing comfort were no different ($p > 0.05$). It was concluded that menthol could alter breathing pattern and increase ventilatory loads in the heat. There was no ergogenic effect of menthol on ventilatory and perceptual responses that previous research has shown.

Keywords: SCBA, protective clothing

Introduction

The high metabolic demand of firefighting is not only a result of strenuous muscular work, but also due to the heavy equipment (Gledhill and Jamnik 1992), the impermeable nature of firefighter protective clothing ensemble (Romet and Frim 1987), and the external environmental stresses (Smith et al. 1997). In addition, the hazardous work environments require firefighters to wear a self-contained breathing apparatus (SCBA) for respiratory protection, but at the expense of a substantial reduction in maximal external work capacity (Eves et al. 2005). This is based upon observations that the SCBA resulted in a sharp decrease in $\dot{V}_E$ and consequently an impaired $\dot{V}O_2$ max (Eves et al. 2005; Louhevaara et al. 1985). Firefighting is acknowledged to be one of the most physically demanding occupations (Gledhill and Jamnik 1992).

Recently, Mündel and Jones (2009) investigated swilling a menthol solution on exercise capacity in the heat, and found that fatigue was delayed and participants showed a hyperventilation during the menthol treatment. Given the firefighters' need to undertake physically demanding work in thermally stressful environments while wearing a SCBA, this may provide a situation where menthol has practical application.

Menthol is of great interest in this study for two particular reasons. First, the oral cavity is a major airway entrance during strenuous exercise and when menthol is administrated orally, menthol increases the sensation of both nasal and oral airflow (Eccles 2003). Previous research has shown that nasal inhalation of menthol reduced respiratory discomfort associated with loaded breathing (Nishino et al. 1997). Second, one of its major effects when applied to the mucosal surfaces is to trigger a cool sensation (Eccles 2003) and the cool sensation is often perceived as refreshing and pleasant. The use of menthol might provide relief effect from thermal discomfort during dynamic exercise in the heat. Therefore, menthol application during firefighting is clearly appealing from a physiological point of view.

The present study attempted to evaluate the findings of Mündel and Jones (2009), regarding menthol's effects on ventilatory and perceptual responses (i.e., thermal comfort, breathing comfort) during simulated firefighting in a thermally stressful environment. Reducing stressors for these at-risk occupational workers could be of great importance for their health, safety, and performance, as well as those they serve.

Methods

Participants

Ten university students volunteered for this study. All participants were physically active, non-smoking males, and unacclimatized to heat during the study period. Unacclimatized participants were used because heat acclimation is suggested to cause adaptation of exercise ventilation during hyperthermia and therefore may mask potential effect of menthol on ventilatory responses (Beaudin et al. 2009). In order to participate in this study, a minimum aerobic fitness of 40 $ml \cdot kg^{-1} \cdot min^{-1}$ for $\dot{V}O_2$ max was required according to the suggested recruiting standards of firefighters (Bilzon et al. 2001). Participants' age, height, weight, body fat percentage, and $\dot{V}O_2$ max were 24 ± 4 yr, 179 ± 6 cm, 76.3 ± 15.3 kg, 8.4 ± 4.8% body fat, and 52.8 ± 5.3 $ml \cdot kg^{-1} \cdot min^{-1}$, respectively. This study was approved by the local institutional review board for the protection of human subjects.

Experimental design

Each participant visited the laboratory on four separate occasions. The first visit entailed the assessment of the participant's $\dot{V}O_2$ max and maximal heart rate (HR max), as well as establishing the individualized workload. The $\dot{V}O_2$ max was assessed on a motorized treadmill using a graded exercise test (running constant speed at 3.1 $m \cdot min^{-1}$ and grade increased by 2% every 2 min) till volitional exhaustion. The highest number recorded during the test was considered to be their $\dot{V}O_2$ max and HR max.

The workload for each participant was determined prior to the heat exposure by spirometry (Parvo 2400, ParvoMedics, Snady, UT**)**. Full firefighting protective gear was worn during this period. The workload during treadmill exercise consisted of 4 min of walking on a motor-driven treadmill (Model 18-60 Treadmill; Quinton Instrument Co., Seattle, WA) at 1.6 $m \cdot s^{-1}$ and at a grade to elicit a metabolic rate of 60% $\dot{V}O_2$ max followed by 1 min of 10 arm curls. Arm curls were done with a bar weighing 4.5 kg. For the stepping exercise, participants performed 4 bouts of constant-cadence stepping exercise. Participants were guided to follow the beeps of a metronome at a rate of 25 $steps \cdot min^{-1}$ on a 40-cm high platform. Each stepping exercise lasted for 4 min with 10 arm curls between two bouts over 1-min. The stepping exercise was intended to simulate stair climbing, a common strenuous activity for firefighters. In this visit, participants were familiarized with all testing protocols, the sensations of wearing a gas measuring air-cushioned face mask, and the various measurement scales.

Trials were conducted in a counter-balanced order. All experimental trials were conducted on a weekly basis and each participant performed all of their trials at the same time of day of week to avoid any circadian variations on dependent variables.

For the experimental trials, participants took one menthol (MTL) or placebo (PLA) lozenge prior to each treadmill/stepping exercise. Each menthol lozenge (Chloraseptic® Sore

Throat Lozenges, Prestige Brands, Inc., Irvington, NY) contained 10 mg of menthol and 6 mg of benzocaine. The placebo lozenge (Cepacol Fizzlers, Combe Inc., White Plains, NY) contained 6 mg of benzocaine. Participants were told to keep menthol or placebo lozenge naturally dissolved in the mouth as such a fashion would allow menthol lozenge to last for 20 min in our pilot study.

Experimental protocol

All data were collected in a heat chamber and a laboratory area. During the experimental trials, participants exercised in the heat chamber at a wet bulb global temperature (WBGT) of 35°C (wet: 31°C, dry: 45°C, globe: 43°C; ~40% relative humidity). Participants rested in the laboratory where the ambient temperature was 21 ± 1°C and 45 ± 3% relative humidity.

During the experimental trials, participants don a heart rate monitor (Polar Electro Inc., Lake Success, NY). Participants wore the firefighter protective clothing and a SCBA tank. The firefighter protective clothing included coat, pants, and gloves. A cotton t-shirt and shorts were worn under the clothing ensemble. Also, running shoes were worn instead of firefighting boots to avoid unnecessary discomfort. The total weight of the firefighting gear was ~ 24 kg.

After dressing, participants took one lozenge and entered the heat chamber and performed the 1st 20-min treadmill exercise. The treadmill exercise protocol consisted of 4 repeated bouts of 4-min of walking followed by 1-min of arm-curls. After the 1st treadmill exercise, participants exited the heat chamber and undertook a 15-min rest period in a seated position to simulate firefighter recovery. A second lozenge was provided, and then participants repeated the 2nd treadmill exercise and 2nd rest period. Participants were provided a third lozenge on the same protocol schedule and re-entered the heat chamber and performed 4 bouts of constant cadence stepping exercise. An air cushioned gas measuring face mask was worn throughout the exercise periods. Fluid replenishment (tap water) (MTL: 1535 ± 909 ml, PLA: 1394 ± 546 ml) was only provided during rest periods.

Measurements

$\dot{V}_E$, $\dot{V}O_2$, f_c, heart rate

Respiratory gas exchange was continuously collected and analyzed (Parvo 2400, ParvoMedics, Sandy, UT) throughout the exercise periods for determination of the ventilatory variables. Electronic gas analyzers were calibrated with a certified reference gas tank (15.7% O_2 and 4.2% CO_2) and atmospheric air (20.9% O_2 and 0.03% CO_2) prior to each experimental trial. A 7-liter syringe (Hans Rudolph, Kansas City, MO) was used to calibrate the measurement of ventilation. Mean values for minute ventilation ($\dot{V}_E$), oxygen consumption ($\dot{V}O_2$), and breathing frequency (f_c) were calculated for a representative 20-min sample. Heart rate (HR) was monitored and recorded every 5 min throughout the exercise periods.

Thermal sensation, breathing comfort

Thermal sensation (TS) (Young et al. 1987) was based on a scale that varies from 0 (“Unbearably Cold”) to 8 (“Unbearably Hot”) and were recorded every 10 min throughout exercise periods. Breathing comfort (BC) (Abadie and Carroll 1993) was recorded every 10 min throughout exercise periods. These scales were each presented on large charts, and participants pointed to indicate their current rating.

Statistical analysis

A two-way repeated measures Analysis of Variance (ANOVA) was used to compare MTL and PLA for HR, TS, and BC. When a significant main effect was found, a Tukey’s least significant difference (LSD) post-hoc test was performed to reveal the difference. For ventilation variables ($\dot{V}_E$, $\dot{V}O_2$, f_c), Student's paired *t* tests were performed with Bonferroni correction. To determine the responders and nonresponders to the menthol treatment, individual data ($\dot{V}_E$) were also compared by computing the least mean difference yielding a $p < 0.05$ at a power of 80% using the mean observed standard deviation. All values were reported as mean values and standard deviations. Alpha was set at 0.05 level.

Results

There was one menthol trial and one placebo trial stopped 5 min early due to participant's volition. Heart rate responses throughout the experimental period are presented in Fig. 1. HR naturally increased. At the end of the 20-min stepping exercise, mean heart rates corresponded to 94 ± 6% and 95 ± 5% of HR max, for MTL and PLA, respectively. There were no significant differences between the two conditions ($p > 0.05$).

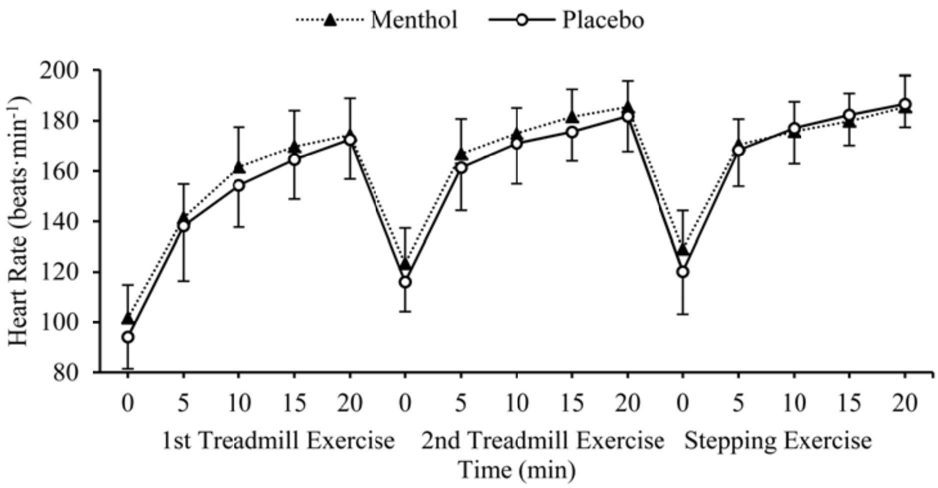

Fig. 1 Mean (±SD) heart rate responses throughout the exercise periods

Ventilatory responses

Ventilatory responses throughout the exercise periods are presented in Table 1. Mean 20-min minute ventilations were significantly higher for MTL compared to PLA condition (MTL: 45.0 ± 6.6 $L\cdot min^{-1}$ vs. PLA: 41.4 ± 5.8 $L\cdot min^{-1}$, $p = 0.003$ for 1st treadmill exercise; MTL: 52.7 ± 9.7 $L\cdot min^{-1}$ vs. PLA: 46.5 ± 7.0 $L\cdot min^{-1}$, $p = 0.004$ for 2nd treadmill exercise). The oxygen uptakes were significantly higher for MTL compared to PLA condition (MTL: 26.7 ± 2.0 $ml\cdot kg^{-1}\cdot min^{-1}$ vs. PLA: 25.2 ± 2.3 $ml\cdot kg^{-1}\cdot min^{-1}$, $p = 0.01$ for 1st treadmill exercise; MTL: 28.8 ± 2.3 $ml\cdot kg^{-1}\cdot min^{-1}$ vs. PLA: 26.9 ± 1.9 $ml\cdot kg^{-1}\cdot min^{-1}$, $p < 0.001$ for 2nd treadmill exercise). For breathing frequency, MTL increased by a mean of 5 $breaths\cdot min^{-1}$ compared to PLA during 2nd treadmill exercise ($p = 0.023$). $\dot{V}_E/\dot{V}O_2$ was not statistically different ($p > 0.05$) between the two conditions.

Table 1 Minute ventilation ($\dot{V}_E$), oxygen uptake ($\dot{V}O_2$), breathing frequency (f_c), and $\dot{V}_E/\dot{V}O2$ during menthol and placebo trial

Ventilation Variables	1st Treadmill Exercise		2nd Treadmill Exercise		Stepping Exercise	
	Menthol	Placebo	Menthol	Placebo	Menthol	Placebo
$\dot{V}_E$ ($L\cdot min^{-1}$)	45.0 ± 6.6*	41.4 ± 5.8	52.7 ± 9.7*	46.5 ± 7.0	46.8 ± 6.9	43.6 ± 4.4
$\dot{V}O_2$ ($ml\cdot kg^{-1}\cdot min^{-1}$)	26.7 ± 2.0*	25.2 ± 2.3	28.8 ± 2.3*	26.9 ± 1.9	25.0 ± 3.6	24.2 ± 3.4
f_b ($breath\cdot min^{-1}$)	29 ± 7	27 ± 4	34 ± 9	29 ± 4	32 ± 6	30 ± 6
$\dot{V}_E/\dot{V}O_2$	27.3 ± 4.2	26.4 ± 2.5	29.4 ± 4.2	27.8 ± 2.8	30.5 ± 4.5	29.4 ± 3.7

* Significantly different from placebo, $p < 0.017$.

Analysis of individual data (Fig. 2) revealed that seven of ten participants increased their minute ventilation in response to the menthol treatment during 1st treadmill exercise, while half of the participants responded to the menthol treatment during 2nd treadmill exercise, and three participants responded to the menthol treatment during the last stepping exercise.

Perceptual responses

Participants' perceptual responses are presented in Fig. 3. Whereas there was no main treatment effects, TS increased in an almost linear fashion, and TS at the end of the stepping exercise were above "7" ("Very Hot") for both conditions (MTL: 7.1 ± 0.8, PLA: 7.2 ± 0.9, $p > 0.05$). A similar trend was found in breathing comfort, though no main treatment effects between the two conditions, BC dropped steadily to a perceived level of "Very Uncomfortable".

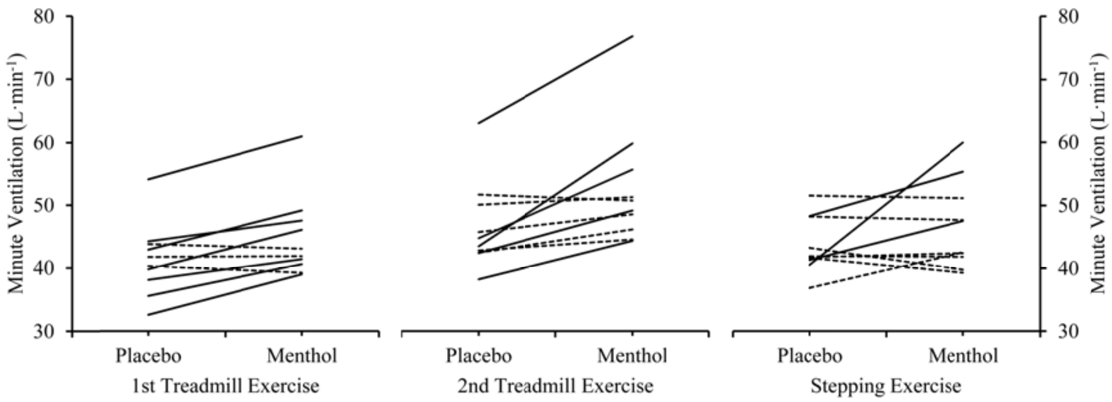

Fig. 2 Individual responses to menthol on minute ventilation during simulated firefighting. The solid line represents responder, and the dotted line represents non-responder.

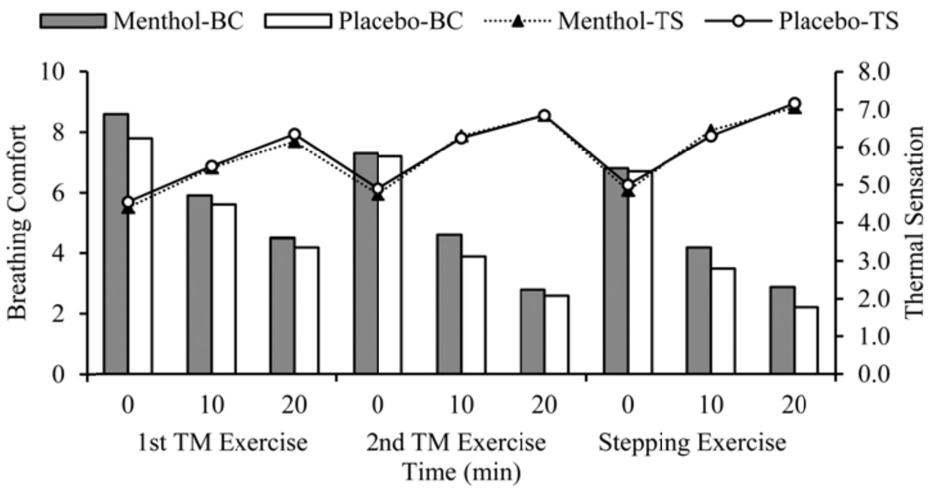

Fig. 3 Ratings of breathing comfort (BC) and thermal sensation (TS) throughout the exercise periods. For the breathing comfort scale, each number represents the following: 10 = "Very, very comfortable", 8 = "Very comfortable", 6 = "Fairly comfortable", 4 = "Fairly uncomfortable", 2 = "Very uncomfortable", 0 = "Very, very uncomfortable". The values are means; standard deviation was removed for clarity purpose.

Discussion

We evaluated the effects of menthol on ventilatory and perceptual responses during dynamic exercise in the heat. In our study, simulated firefighting was performed repeatedly while participants wore firefighting clothing and a SCBA tank. For our treatment, we used commercially available menthol lozenges. Minute ventilation increased in a similar manner as previously reported (Mündel and Jones 2009) following menthol treatment. However, increased oxygen uptake suggests that there is no advantage in performance under the exercise-heat stress situation in our study.

Mündel and Jones (2009) reported a mean increase of 8 L·min^{-1} in $\dot{V}_E$ during a menthol swilling condition where no changes in $\dot{V}O_2$ were detected. Though we found mean ventilation increased by ~ 3.6 L·min^{-1} (~ 8%) during the 1st treadmill exercise and ~ 6.2 L·min^{-1} (~ 13%) during the 2nd treadmill exercise, oxygen uptakes were also correspondently increased by ~ 1.5 ml·kg^{-1}·min^{-1} (~ 5.6%) during the 1st treadmill exercise and ~ 1.9 ml·kg^{-1}·min^{-1} (~ 7.1%) during the 2nd treadmill exercise. Whereas $\dot{V}_E/\dot{V}O_2$ was not different between the two conditions, these findings suggest that metabolic cost increased following menthol treatment. Such responses are unexpected. A previous study using a similar dose of menthol in oral administration (11-mg menthol lozenge) reported that menthol caused a subjective sensation of improved airflow (Eccles et al. 1990). Also, Mündel and Jones (2009) found swilling menthol solution reduced the effort of breathing whereas our participants did not indicate better breathing comfort (Fig. 3).

The mechanism(s) accounting for increased $\dot{V}_E$ and $\dot{V}O_2$ were not investigated in this study. A potential modulator for this response could be explained by an altered drive of breathing. A literature review has indicated that menthol could inhibit the drive of breathing

(Eccles 2003). We speculated that oral administration of menthol might alter the breathing pattern, which seems to be a negative factor for coping with heavy breathing during dynamic exercise in the heat. Physiological adaptations during prolonged submaximal exercise in the heat include decreased tide volume and increased breathing frequency following the elevation of body core temperature (Hayashi et al. 2006). And it has been reported that professional firefighters actually develop a specific breathing pattern, by increasing f_b in order to reduce the breathlessness during exercise with SCBA use (Donnovan and McConnell 1999). It is possible that potential inhibition of the drive of breathing with menthol administration could stress the overall ventilatory system and therefore unexpectedly increased the energy cost of breathing in our experimental condition as evidenced from increased oxygen uptake.

An alternative explanation for this result would be resulted from pattern of administrating menthol-containing products. Mündel and Jones (2009) had their participants swilling menthol solution for a short time and fluid was available throughout, and this was repeated every 10 min during the entire protocol period. Whereas in our study, we used lozenges via oral administration and no fluid was available during exercise since in our study the participants continued to wear the gas measuring mask for the entire exercise periods (this also meets ecological validity where current SCBA setting does not allow fluid replenishment at the same time). Each menthol lozenge could last (naturally dissolves in the mouth) for the entire 20-min exercise period and our participants often mentioned that the menthol lozenge (while not the placebo lozenge, which dissolves within 1 min of ingestion) became unpleasant due to its sweetness. This was especially true after the second bout of exercise, during which participants were already dehydrated and reported being thirsty. It might happen that repeated stimulation with menthol orally accompanied with fluid consumption favors ventilatory responses during exercise-heat stress. In short, current results could not clearly explain whether such responses were due to the pharmacological effect of menthol or the specific pattern of administration.

Considering this was a very inexpensive and practical treatment, we also analyzed the individual data (Fig. 2). Menthol seemed to exert its effect initially and tended to be less effective after a short period of time. We repeated the simulated workouts, since in field situations this is a common scenario for firefighters to change the SCBA gas tank after 20 to 40 minutes (depending on bottle size and activity). From our results, participants responded by increasing $\dot{V}_{\mathrm{E}}$ with menthol lozenge during the 1st treadmill exercise (total of 7 responders); 35 min after, still half of the participants responded during the 2nd treadmill exercise, and there were 3 responders after a total of 60 min exercise plus 30 min of rest.

Lack of significant perceptual responses was surprising. One of the major effects of menthol is to induce a sensation of coolness (Eccles 2003). Also, administrating menthol orally reduced the breathing discomfort during loaded breathing (Nishino et al. 1997). However, neither ratings of thermal sensation nor breathing comfort (Fig. 3) supported those notions. It is possible that the high heat content of air in our enclosed chamber area (35^{o}C WBGT) coupled with the long duration of exercise may have overwhelmed any cool and refreshing effect of menthol. During the experimental time, the air cushioned mask was described as wet and uncomfortable, not to mention that heated air was breathed throughout the 60-min exercise period. The combination of heat and humidity was previously determined as primary factors for mask and breathing's acceptability during exercise situation (Nielsen et al. 1987).

Conclusions

The current results did not support using menthol for firefighters during rescue and disaster relief missions in the heat. The increase in $\dot{V}_E$ and $\dot{V}O_2$ together with the lack of a positive perceptual response would not be useful for firefighters. Future studies are needed that focus on the mechanisms underlying these altered ventilatory responses. Impaired ventilatory responses while wearing SCBA are still considered to be a detrimental factor for firefighters' health and performance. It is necessary for exercise physiologists to further explore possible solutions to reduce this occupational stressor.

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CHAPTER IV

EFFECTS OF CAFFEINE AND MENTHOL ON COGNITION AND MOOD DURING SIMULATED FIREFIGHTING IN THE HEAT

Abstract

This study examined the separate effects of caffeine and menthol on cognition and mood during simulated firefighting in the heat. Participants (N = 10) performed three trials in a counterbalanced order, either with 400 mg caffeine (CAF), menthol lozenges (MTL), or placebo (PLA). Exercise induced significant dehydration (> 3%) and elevated rectal temperature (> 38.9°C), for all three conditions. Neither CAF nor MTL reduced perceived exertion compared to PLA ($p > 0.05$). Mood ratings were significantly deteriorated over time ($p < 0.05$), but there was no difference among the three conditions. Simple reaction time, short-term memory, and retrieval memory did not alter with treatments or repeated evaluations. Reaction accuracy for a math test remained the same throughout the experimental period; reaction time for the math test was significantly faster after exposure to the heat ($p < 0.05$). There was no ergogenic effect observed in math test for the treatments compared to PLA. It is concluded that, exhaustive exercise in the heat severely impacted mood, but minimally impacted cognition. These treatments failed to show ergogenic benefits in a simulated firefighting paradigm in a hot environment.

Keywords: perceived exertion, dehydration, protective clothing

Introduction

While the physiological consequences for firefighting have been extensively studied, less is understood about cognition and mood during rescue missions in harsh and demanding environments. Firefighters are often exposed to multi-stressors, including intense and sustained physical activity, environmental extremes, anxiety, uncertainty, and obligations of victim rescue. There is considerable anecdotal documentation of these multi-stressors negatively impacting on the ability to process cognitive information and act quickly, effectively, and decisively (Grandjean and Grandjean 2007; Hancock and Vasmatzidis 2003). Furthermore, a firefighting job is characterized by shift work which can contribute to episodic sleepiness, and cause deterioration of alertness and operational efficiency. Impaired cognition and mood would eventually increase risks of injuries and accidents.

Caffeine and menthol might provide a practical intervention during firefighting missions. Caffeine's well-documented stimulating effect on human mood and cognition include increased alertness, attention, and vigilance (Lieberman 2001). Meanwhile, menthol also has an arousal effect (Eccles 2003). Menthol-containing products, such as mints and lozenges, are commonly used in situations where drowsiness occurs or when one needs to maintain alertness such as during long duration driving. Therefore caffeine and menthol might offer simple solutions for combating fatigue and increasing arousal during sustained firefighting.

When engaged in disaster relief, victim rescue, and fire suppression duties, failure to detect any dangerous situations can be critical and life-threatening. Administrators need to be aware of the potential for cognitive deficits in highly stressful situations and seek potential interventions to mitigate adverse effects. Therefore, this study examined the separate effects of caffeine and menthol on cognition and mood during a simulated firefighting exposure. We hypothesized that in a heat stress prolonged exercise condition, caffeine and menthol would increase cognitive performance and improve mood across time relative to placebo. When cognitive performance is essential and must be maintained during exposure to hazard stressors, administration of caffeine and menthol may provide positive benefits.

Methods

Participants

Ten males, unacclimatized to heat, volunteered to participate in this study. They were confirmed to be regular coffee drinkers, consuming at least one cup of regular coffee per day. Their physical characteristics were age: 24 ± 4 yr, height: 179 ± 6 cm, weight: 76.3 ± 15.3 kg, percentage of body fat: 8.4 ± 4.8%, and $\dot{V}O_2$ max: 52.8 ± 5.3 ml·kg^{-1}·min^{-1}. To minimize possible placebo effects of caffeine, the full nature of the study was not revealed to the participants. This study was approved by the local Institutional Review Board for protection of human subjects and all subjects provided written informed consent prior to data collection.

Experimental design

The study was a subset of a larger study designed to evaluate the effect of menthol on ventilatory responses during simulated firefighting in the heat. The alternate study purposes had no effect on the current investigation. In general, this study used a placebo-controlled, counter-balanced cross-over repeated measures design. This study required participants to complete four laboratory visits. The first visit consisted of preliminary testing, workload determination, and familiarization. The remaining three visits were experimental trials: placebo (PLA), caffeine (CAF), and menthol (MTL).

Experimental trials were conducted once per week. For CAF, caffeine was administered in capsule form (400 mg of caffeine) ten minutes prior to the 1st treadmill exercise. For the MTL trial, participants took menthol lozenges (10-mg menthol, 6-mg benzocaine) (Chloraseptic, Prestige Brands, Irvington, NY), or placebo lozenges (6-mg benzocaine) (Cepacol Fizzlers, Combe Inc., White Plains, NY) for CAF and PLA trials.

Each of the three treatment trials consisted of a baseline assessment of cognition and mood (described below) followed by repeated post-treatment assessments of cognition and mood. Before each experimental day, participants were asked to refrain from consuming any caffeine-containing drinks or food from 8 P.M. the previous evening until completion of the trial during the experimental day. Also, participants were informed to keep euhydrated before the experimental trials.

Experimental Protocol

The first visit was to determine individual's $\dot{V}O_2$ max, maximal heart rate (HR max), and individual workloads (for detail see Zhang et al. In preparation). In general, the workload consisted of 4 min of walking on a motor-driven treadmill (Model 18-60 Treadmill; Quinton Instrument Co., Seattle, WA) to elicit a metabolic rate of 60% $\dot{V}O_2$ max followed by 1 min of 15 arm curls. Participants were required to complete a familiarization trial to ensure that they were acquainted with the exercise regime, equipment (e.g., clothing, gas measuring face mask), and measurement scales. Three sets of cognition and mood tests were also introduced and practiced during the familiarization period to reduce potential learning effects. Participants verbally confirmed their confidence with all experimental protocols after the initial visit.

The environmental setting for three 20-min exercise periods was 35°C wet bulb global temperature (WBGT) (wet: 31°C, dry: 45°C, globe: 43°C; 40% relative humidity). During two 15-min recovery periods, participants were seated in the main laboratory room where the ambient temperature was 21 ± 1°C (45% relative humidity).

Immediately upon arriving at the laboratory, participants were asked to provide a urine sample to verify the hydration status. Participants were not tested if they were dehydrated (urine specific gravity > 1.020). Participants' nude body weight (shorts only) was measured on a calibrated scale (Detecto Scales Inc., Brooklyn, NY). Participants then self-inserted a rectal thermocouple (Physitemp, Clifton, NJ) 8 cm beyond the anal sphincter. The rectal temperature (T_{re}) was monitored with a portable system (Physitemp Thermalert model TH-8, Clifton, NJ). Participants donned a Polar heart rate monitor (Polar, Stamford, CT). During the experimental trial, participants wore firefighter protective clothing and a self-contained breathing apparatus (SCBA) tank (but the SCBA was not operable during testing). The firefighter protective clothing included coat, pants, and gloves. A cotton t-shirt and shorts were worn inside the clothing ensemble. Also, running shoes were worn instead of firefighting boots to prevent injuries. The total weight of the firefighting gear was ~24 kg.

Participants took either one menthol lozenge (MTL trial) or placebo lozenge (CAF and PLA trials) and entered the heat chamber. They first completed a simple reaction test, followed by a short-term memory test, math test, and a mood assessment. Then participants completed the 1st 20-min treadmill exercise, then exited the heat chamber, and completed the 1st 15-min recovery period. No fluid consumption was allowed during exercise periods as participants continued to wear the gas measuring mask. Water was freely available during all recovery periods and volume (ad lib) consumed was recorded. The 2nd lozenge was taken prior to the 2nd treadmill exercise. Then participants repeated the 20-min treadmill exercise. Immediately after the 2nd treadmill exercise, participants completed a simple reaction test, short-term memory test, math test, and mood assessment in the heat chamber. Then participants exited the heat chamber and completed the 2nd 15-min recovery period. The 3rd lozenge was provided prior to the stepping exercise. Participants then re-entered the heat chamber and performed 4 bouts of constant cadence stepping exercise at a cadence of 25 $steps \cdot min^{-1}$ (using a metronome) on a 40-cm high platform. Each stepping exercise lasted for 4 min with a brief 1-min 15 arm curls interval between two bouts. Immediately after the stepping exercise, participants completed the last simple reaction test, a retrial memory test, a math test, and a mood assessment in the heat chamber. Upon doffing all gear except shorts, participants were weighed again at the end.

Measurements

T_{re}, HR, body weight loss, RPE

T_{re} and HR were monitored and recorded every 10 min throughout all trials. Body weight loss was calculated as change in pre-test and post-test nude body weight adjusted by total fluid intake. RPE (Borg 1998) were recorded every 10 min throughout the trial. The RPE scale was presented on a large chart, and participants were asked to indicate their current rating, using the index finger.

Simple reaction test

The simple reaction test (http://faculty.washington.edu/chudler/java/dottime.html) was performed on a laptop computer. In a task box orbiting on the computer screen, participants had 30 sec to mouse-click a black dot that randomly appeared in a 6 × 10 grid of white circles.

Participants were required to click on the target dot as soon as they detected the dot. For every correct click, one point was added and every incorrectly clicked circle (e.g., miss clicked the closing dot) resulted in one point taken away. The total reaction score was recorded at the end.

Short-term memory test

In short-memory test, a list of 15 words was presented via automated PowerPoint slides on a laptop screen at a rate of one word every 4 seconds. All of the words were nouns between four and seven letters long. No plurals or names were used. Participants were told to remember as many words as possible. Immediately after 1 min of memory, participants were given 2 min to use a pencil to write down (no order required) all the words that they could remember on a piece of blank paper. The dependent variable was the number of words correctly recalled (the higher, the better; no penalty for words not on the list).

Math test

The serial addition/subtraction test was a mental mathematical test requiring sustained attention. This test has been shown to be a reliable and valid measurement of sustained attention (Thorne et al. 1983). For this test, two randomly selected digits and either a plus or minus sign were presented on a paper. The participant performed test and entered the least significant digit of the result (e.g., “7,5,+” equals 12, so write down 2). There were total of 20 addition/subtraction tasks performed during each math test. The dependent variables were response accuracy (number of correct responses; the higher, the better), response time (speed of response; the quicker, the better).

Retrieval memory test

At the end of the stepping exercise, participants were shown 30 words which consisted of the 15 words shown at the 2nd short-memory test plus 15 new distracter words. Participants had

2 min to decide which words were in the earlier list of 15. The dependent variables were the number of correct responses (correctly accepting target words and correctly rejecting distracter words) and the number of false responses (wrongly accepting a distracter as being in the original list). The finals score was calculated from correct responses minus false responses.

Mood

Mood was assessed using 100-mm visual analogue rating scales (Smith et al. 1999). These 18 scales (e.g., Tense/Calm, Muzzy/Clear-headed, Antagonistic/Friendly) can be categorized into three factors: alertness, hedonic tone, and tension. Each factor score was calculated by summarizing the scores of the individual mood adjectives (e.g., Anxiety Mood = Relaxed/Excited + Troubled/Tranquil + Tense/Calm), and was later used in the statistical analysis. These scales are reported to be sensitive to caffeine administration for fatigued personnel (Smith et al. 1999).

Statistics analyses

A repeated measures Analysis of Variance (ANOVA) was used, and when a significant main effect was found, Fisher's *LSD* was performed to identify specific differences. All values were reported as mean values and standard deviations. Statistical difference was considered to be significant at alpha ≤ 0.05.

Results

Physiological responses

Heart rate responses are shown in Fig. 1. Heart rate was significantly elevated relative to baseline throughout the exercise periods. There was no significant difference in heart rates among the three conditions ($p > 0.05$). At the end of the experimental protocol, rectal temperatures were 39.0 ± 0.2°C, 39.0 ± 0.2°C, 39.1 ± 0.1°C, for PLA, MTL, and CAF, respectively ($p > 0.05$). Exercise-heat stress resulted in mean dehydration of 3.1 (± 0.7)%, 3.1 (± 0.7)%, 3.0 (± 0.7)%, for PLA, MTL, and CAF, respectively ($p > 0.05$).

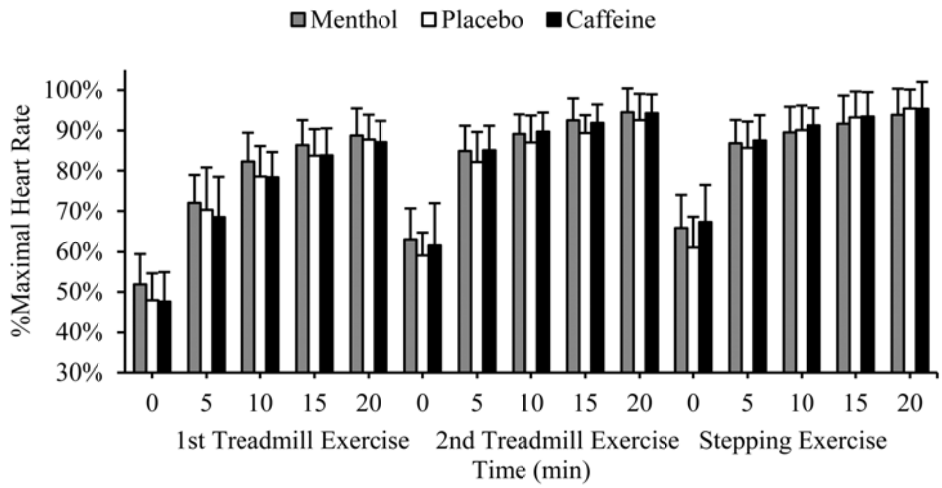

Fig. 1 Mean (±SD) heart rate responses throughout the exercise periods

Perceptual, mood, and cognition responses

Effects of caffeine and menthol on perceived exertion were shown in Fig. 2. RPE significantly increased during the exercise periods ($p < 0.05$). There was no difference in RPE among the three conditions ($p > 0.05$). Exercise and heat stress caused dramatic decreases in all three mood ratings (Fig. 3) ($p < 0.05$), but treatments did not significantly impact the mood ratings during the experimental period ($p > 0.05$).

Changes in cognition are summarized in Table 1. Generally, neither simple reaction test, short-term memory test, nor retrieval memory test were affected by experimental exposure to the heat and exercise or treatments ($p > 0.05$). For the math test, repeated exercise and recovery intervals did not alter the response accuracy ($p > 0.05$); however, participants showed faster response times ($p < 0.05$) during the two post-exposure tests. There was no difference in math test performance among the three treatments ($p > 0.05$).

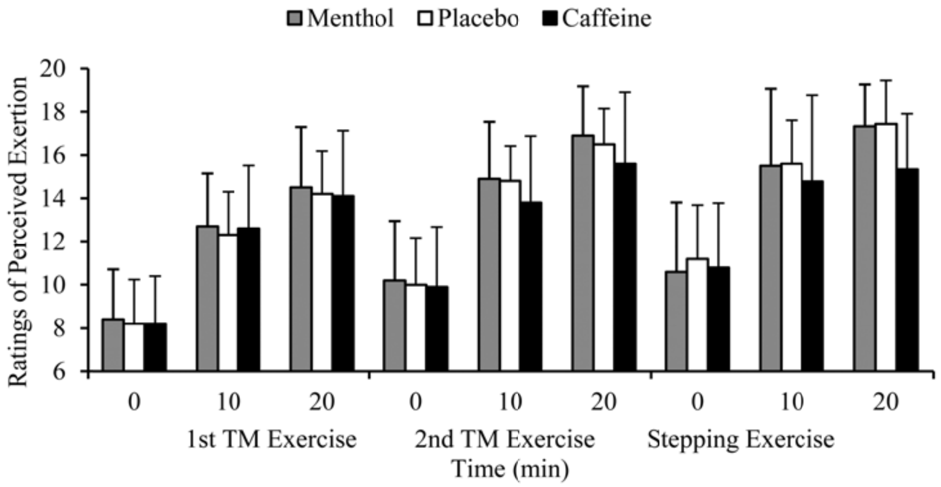

Fig. 2 Mean (±SD) ratings of perceived exertion throughout the treadmill (TM) and stepping exercise periods

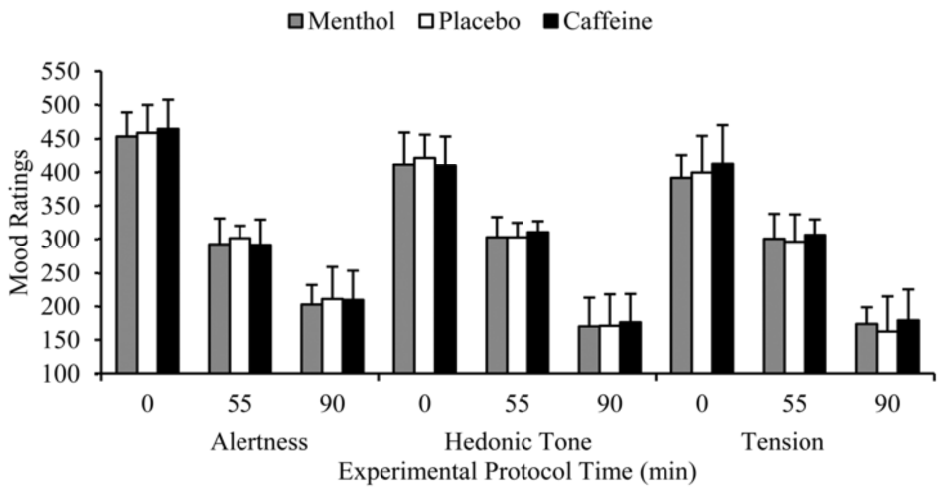

Fig. 3 Mean (±SD) mood ratings over the experimental period. For alertness ratings, higher scores = more alert; for hedonic tone ratings, higher scores = more sociable, happy etc.; for tension ratings, higher scores = more calm. The values are means (SD shown as bar). * Significantly different from pre-exposure (0 min), $p < 0.05$ † Significantly different from mid-exposure (55 min), $p < 0.05$

Table 1 Effects of caffeine and menthol on cognition during the experimental period

Test	Test Variable	Experimental Conditions								
		Placebo			Menthol			Caffeine		
		Pre-	Mid-	Post-	Pre-	Mid-	Post-	Pre-	Mid-	Post-
Simple reaction test	Reaction score	26 ± 2	26 ± 2	26 ± 3	26 ± 2	26 ± 2	26 ± 3	25 ± 2	26 ± 2	27 ± 3
Math test	Response accuracy	20 ± 0	19 ± 1	20 ± 0	19 ± 1	20 ± 0	20 ± 0	20 ± 1	19 ± 1	20 ± 1
	Response time (sec)	31.12 ± 13.20	27.80 ± 8.56*	28.92 ± 9.82*	33.50 ± 9.88	28.72 ± 8.39*	27.95 ± 7.15*	33.94 ± 13.21	26.51 ± 7.23*	28.53 ± 11.21*
Short-term memory test	Words recalled	8 ± 1	8 ± 2	-	8 ± 1	8 ± 2	-	7 ± 2	8 ± 2	-
Retrieval memory test	Words recalled	-	-	9 ± 3	-	-	9 ± 2	-	-	9 ± 3

* Significantly different from pre- (exposure) test, $p < 0.05$

Discussion

Possible changes in cognition during firefighting are little known due to limited data. In this study, repeated firefighting-simulating exercise was performed in a hot environment. After a 90 min experimental period (including 15 min for each of two recovery periods), exercise-heat stress caused over 2.5% dehydration and a hyperthermic state, which are considered to be detrimental for both physical and mental performances (Barr et al. 2010; Grandjean and Grandjean 2007). Consistent with previous research (Barr et al. 2010), heart rate remained above 80% of participants' maximal heart rate during most of the exercise periods as a consequence of strenuous exercise, heat strain, and progressive dehydration. All these physiological adaptations indicated that the current laboratory-based simulations effectively resembled physical challenges in field environments. Based on the experimental conditions and results of this study, cognition of firefighters should not be impaired for short missions under one hour, though mood could be negatively affected under multi-stressors. Furthermore, acute administration of caffeine or menthol presented no ergogenic effect on perceptual, mood, or cognitive responses, at least under current test conditions of a high heat strain and a dynamic exercise protocol. To our knowledge, this is the first study seeking practical interventions on mental performance during simulated firefighting.

Maintenance of a positive mood (i.e., alertness, calmness) is essential for numerous critical activities such as fire suppression, victim search and rescue, and evacuation. All mood states substantially deteriorated even with regular recovery periods. Though there is no direct comparison in the literature for firefighting studies, similar findings are well documented for soldiers conducting military operations in multi-stressors environment (Lieberman et al. 2002).

From these data, working in a multi-stressors environment brings about a rapid transition from positive mood to a state that might impact on the mission success.

It is logical to believe that caffeine administration, which may partially restore the mood states, could be beneficial under such circumstances. However, neither caffeine nor menthol provided any positive effect on mood during the experimental time. There was also no effect on perceived exertion. Though one previous study (Hogervorst et al. 2008), employing a similar exercise regime of cycling at 60% oxygen uptake for 150 min, reported no effect of caffeine on global RPE, the majority of the literature points to the direction that caffeine could reduce RPE (Doherty and Smith 2005). A recent study of swilling a menthol solution also suggested that menthol reduced global RPE and delayed time to fatigue (Mündel and Jones 2009). It is unlikely that the current protocol duration was too short to observe positive effects of caffeine on mood, since peak plasma time of orally administered caffeine usually presents within 45 min period (Mumford et al. 1994).

Two possibilities exist as to why our hypothesis was not supported. One is that the intense nature of exercise and extreme environment may suppress any possible effect of caffeine or menthol. None of previous studies had tested a condition that involved in combination of protective clothing, heat strain, and near maximal exercise capacity. It is possible that the challenging stress testing protocol overwhelmed any small positive effect of caffeine or menthol on mood and perceptual responses (i.e., 6% of advantage in RPE, Doherty and Smith 2005). An alternative possibility is that our participants were less accustomed to the firefighting scenario (e.g., clothing ensemble, SCBA tank, extreme radiate heat, profuse sweating), and therefore might have over-responded to the testing conditions, blunting any positive effect of treatments on cognition or mood ratings.

Literature suggested that caffeine has an analgesic effect (Sawynok 2011). Current results could not confirm caffeine treatment would allow better tolerance to intense exercise in the heat. However, at the last time point of experimental trial, the self-reported perceived exertion in the caffeine trial was two units lower, ~15 (correspondent to "Hard") compared to the menthol and control trials of ~17 (correspondent to "Very Hard"). Though statistically there was no difference among the three conditions, it is unclear whether this was a stable response or it could be a trend that caffeine actually turns out reducing perceived exertion beyond one hour of exercise.

The cognition tests were selected due to their relevance to specific operations firefighters often encounter in a fire scene. For examples, the ability to maintain sustained attention (math test) and rapidly detect threats is significant in a hazardous environment: reaction to intervene and take appropriate actions; and memory to recall of important details. During a dehydrated and fatigued state, it was anticipated that caffeine and menthol might exert a positive effect on information processing ability. However, our results found caffeine and menthol failed to alter the cognition processing during dynamic heat exposure. It should be noted that these measurements are sensitive to effects of caffeine when a person is fatigued (Smith et al. 1999); meanwhile, Lieberman et al. (2006) have suggested simple cognition tests are more sensitive and suitable for use in a multi-stressors environment than complex tests.

Our results suggested information processing capacity, speed, and accuracy were well maintained over the experimental period. This is similar to the findings involving a group of UK firefighters in which no change in rapid visual information processing, spatial memory span, and choice reaction time were detected following a firefighting simulation (Rayson et al. 2005). This is consistent with previous research, where simple reaction tests (Hancock 1982; Hancock et al. 2007; Cian et al. 2001) and long-term memory tests (Cian et al. 2000; Cian et al. 2001) were least affected by thermal strain or hydration status. Hence, prolonged exposure to heat may exert enhancement in cognition (Hancock 1982; Hancock et al. 2007), evidenced here, in that the completion time of the math test was actually improved (i.e., shortened) during later bouts of exercise without sacrificing accuracy.

Therefore, despite the rigorous nature of exercise and the extreme environment, cognition was well maintained in our testing conditions over three firefighting work/recovery transitions. It should also be pointed out that, our participants were well rested before each experimental trial. In real world situations, continuous shift work is typical for many occupations, and a state of sleep deprivation creates practical situations where both caffeine and menthol might be expected to exert their ergogenic effects. This paradigm warrants further testing.

It was surprising to find that participants were able to maintain cognition function despite less favorable mood ratings. From a positive standpoint, this possible defensive mechanism would allow firefighters to continue working at a high operational efficiency; on the other hand, firefighters may also expose themselves into greater risks of accidents. This observation should also be explored further.

Conclusions

This study examined potential simple and practical nutritional interventions for performance deficits in a multi-stressors work environment. Working in a thermal stressful environment dramatically deteriorated mood states and increased perceived exertion. Surprisingly, cognition was minimally altered during exercise-heat exposure. Furthermore, under this challenging multi-stressors environment, no potential ergogenic effects were found with caffeine or menthol. Both physiological and cognitive performances are critical for the health, safety, and operational effectiveness for firefighting. Impact of exercise in hazardous environments on cognition and mood warrants more attention for planning and preparing firefighters.

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CHAPTER V

CONCLUSIONS

Conclusions from these studies suggest that: (1) caffeine ingestion in moderation (< 460 mg) is not associated with fluid imbalance, and there is no reason for restricting regular coffee consumption for modern military operations in the heat; (2) for military operations in the heat, it is essential to replace the fluid loss routinely, and efficacy of rehydration with water was relative low (< 40% fluid retention ratio) and could only partially restore body mass loss; (3) current results did not find ergogenic effect of menthol and caffeine; and (4) deterioration in mood states (e.g., alertness) during exercise-heat stress is inevitable, however, this reduction may not reflect changes in cognition, such as sustained attention. Overall, the impact of harsh environments on physical and mental performance should be seriously considered for planning and preparation for military and occupational operations. More research is needed so that appropriate interventions could be recommended for these high-risk occupations.