

Hydration effects on cognitive performance during military tasks in temperate and cold environments

Gina E. Adam ^{a,*}, Robert Carter III ^b, Samuel N. Cheuvront ^a, Donna J. Merullo ^a,
John W. Castellani ^a, Harris R. Lieberman ^a, Michael N. Sawka ^a

^a U.S. Army Research Institute of Environmental Medicine, Natick, MA 01760, USA

^b Centre de Recherches du Service de Santé des Armées, La Tronche, France 38702

Received 21 June 2007; received in revised form 1 November 2007; accepted 20 November 2007

Abstract

Body water deficits or hypohydration (HYP) may degrade cognitive performance during heat exposure and perhaps temperate conditions. Cold exposure often induces HYP, but the combined effects of cold and HYP on cognitive performance are unknown. This study investigated whether HYP degrades cognitive performance during cold exposure and if physical exercise could mitigate any cold-induced performance decline. On four occasions, eight volunteers completed one hour of militarily-relevant cognitive testing: 30 min of simulated sentry duty/marksmanship, 20 min of a visual vigilance task, a self-report workload assessment, and a mood questionnaire. Testing was conducted in a cold (2 °C) or temperate (20 °C) environment before and after cycle ergometer (60 min at 60% of $\dot{V}O_{2peak}$) exercise. Each trial was preceded by 3 h of passive heat stress (45 °C) in the early morning with (euhydration, EUH) or without (hypohydration, HYP; 3% body mass) fluid replacement followed by prolonged recovery. HYP did not alter any cognitive, psychomotor, or self-report parameter in either environment before or after exercise. Cold exposure increased ($p < 0.05$) target detection latency in the sentry duty task, adversely affected mood and workload ratings, but had no impact on any other cognitive or psychomotor measure. After completing the exercise bout, there were modest improvements in friend–foe discrimination and total response latency in the sentry duty task, but not on any other performance measures. Moderate HYP had no effect on cognitive and psychomotor performance in either environment, cold exposure produced equivocal effects, and aerobic exercise improved some aspects of military task performance.

Published by Elsevier Inc.

Keywords: Hypohydration; Cold air exposure; Cognitive performance; Marksmanship; Mood

1. Introduction

Individuals exposed to cold environments may incur body water deficits (hypohydration, HYP) due to a variety of factors such as increased fluid loss as a result of diuresis, respiration, or sweating due to insulating clothing [1]. Recent work has also shown that individuals experience reduced thirst sensations in the cold [2], most likely leading to reduced fluid intake. These body water deficits were believed to adversely affect thermoregulation and military performance, although one field study demonstrated no significant dehydration in extended cold weather operations

[3]. These authors hypothesized that fluid intake was maintained due to the volunteers' awareness and recording of water intake [3], thereby suggesting that command attention placed on fluid replacement would sustain hydration during cold weather military operations [4]. Recent laboratory studies report that moderate HYP (~3% body weight loss) during cold exposure does not degrade either thermoregulation [5] or aerobic exercise performance [6].

Moderate HYP has been associated with cognitive performance declines during heat exposure [7], with effects on multiple domains of cognitive and task performance when HYP was induced by heat exposure or exercise [8] and when fluid loss is 2% or more of body weight [9,10]. Studies examining cognitive performance decrements from HYP in temperate conditions are often confounded by residual effects from prior heat exposure or concurrent heat exposure [7]. In contrast, two studies of HYP after

* Corresponding author. Kansas St., Bldg 42, Natick, MA 01760 USA. Tel.: +1 508 233 4840; fax: +1 508 233 4195.

E-mail address: gina.e.adam@us.army.mil (G.E. Adam).

12–24 h water deprivation in temperate conditions reported no declines in task performance due to HYP but did report changes in perceived tiredness [11] and self-rated alertness [12]. Although these studies have characterized changes in cognitive performance and subjective assessments of mental state, no mechanism has been clearly identified to explain the relationship between moderate HYP and cognitive performance. Furthermore, the effects of moderate HYP during cold exposure on cognitive and psychomotor performance are not known.

Cold exposure has equivocal effects on cognitive performance. Decrements in cognitive and psychomotor performance during cold exposure have been observed in accuracy in serial choice reaction time [13,14]; associative learning, working memory, and reasoning [15–17]; manual dexterity [18]; and applied military tasks such as command and control [19] and marksmanship [17]. Other studies have reported no effects of cold on cognitive performance after prolonged exposure [20,21]; whereas others have shown an improvement in cognitive performance with acute cold exposure, most notably in reaction time and auditory and visual recognition [14,16–18,22–24]. Explanations for these mixed effects include that simple tasks are less likely to be influenced by the cold as compared to more complex tasks and abilities [16,23,25–27], that performance declines at an ambient temperature threshold of 15 °C and below [15], and that cold stress accompanied by hypothermia more often degrades cognitive and psychomotor performance [17,25].

Individuals may incur significant heat loss with prolonged cold exposure in military and other occupational activities, but shivering and insulation result in core temperature remaining relatively stable [3]. Furthermore, exercise-induced heat production, clothing, or their combination can significantly raise body temperature even in air temperatures below 0 °C [28]. Individuals exposed to the cold may periodically perform physical work during exposure, and anecdotal reports suggest that such activity might restore attention and thereby cognitive performance; however, this has not been studied. We postulate that the mechanism whereby physical activity may improve cognitive performance in the cold is through warming the body and thus reducing or eliminating cold strain. To our knowledge, previous research has not determined the efficacy of performing physical exercise during cold exposure as a means to sustain cognitive performance.

This study was designed to determine if moderate HYP degrades cognitive and psychomotor performance during cold exposure. Cold exposure conditions were intended to elicit substantial heat removal (wind chill = −1 °C), but not induce hypothermia. In addition, the efficacy of employing physical exercise to warm the body and thus sustain cognitive performance during cold exposure was evaluated. It was hypothesized that hypohydration would degrade cognitive performance during cold exposure and that physical exercise would mitigate such deficits.

2. Materials and methods

2.1. Participants

Eight healthy Soldier volunteers (age = 24 ± 6 yr, ht = 170 ± 6 cm, wt = 72.9 ± 11.1 kg, body fat = 22 ± 6 %) completed all

phases of experimentation. The Soldiers (6 men, 2 women) were physically active and moderately fit ($\text{VO}_{2\text{peak}} = 48 \pm 9 \text{ ml/kg/min}$). Volunteers were not taking any medication, were non-smokers, and were otherwise healthy as determined by physical exam. The study protocol was approved in advance by the Human Use Review Committee at the US Army Research Institute of Environmental Medicine and the Human Subjects Research Review Board at the US Army Medical Research and Materiel Command (USAMRMC). Each volunteer provided written informed consent before participating. The investigators have adhered to the policies for protection of human subjects as prescribed in Army Regulation 70-25, and the research was conducted in adherence with the provisions of 32 CFR Part 219.

2.2. Experimental procedures

Two weeks prior to testing, volunteers were trained on a military marksmanship simulator and sentry duty paradigm. Sentry duty is a vital military task comprised of psychomotor skills and several cognitive components such as vigilance, target identification, and decision-making. The simulation used here has been shown in previous studies to be sensitive to a wide range of environmental and task demands [29]. Volunteers were also trained on a computer-based vigilance test shown to be sensitive to environmental conditions and nutritional interventions [30]. Training was conducted on these tasks until a baseline level of proficiency was established in order to reduce variability and protect against learning effects. In addition, participants were familiarized with the NASA-Task Load Index [NASA-TLX, [31]] and the Profile of Mood States [POMS, [32]], two self-report questionnaires that assess perceived workload and mood, respectively. Anthropometry measurements were made during this time-frame and peak oxygen uptake ($\text{VO}_{2\text{peak}}$) was measured using an incremental cycle ergometer (Lode Excalibur Sport, Lode, Groningen, The Netherlands) protocol with continuous gas exchange measurements (TrueMax, ParvoMedics, Sandy, Utah).

The design for this study is illustrated in Fig. 1. A repeated measures (2 hydration × 2 environment) experimental approach was employed. Each of four trials was separated by at least 48-h and all experiments were conducted at the same time of day. Women were tested in the follicular phase of their menstrual cycle to control for ovulatory fluctuations in body temperature. On the morning of each trial, body mass was measured with an electronic precision balance scale (Toledo 1D1, Worthington, OH). A standardized breakfast (~500 kcal and water *ad libitum*) was provided, after which volunteers rested in a seated position for approximately 1-h before moving to a hot room (45 °C, 50%rh, 1 m/s air speed) for 3-h of passive heat exposure with (euhydration, EUH) or without (hypohydration, HYP) fluid replacement. EUH and HYP trial assignment was counterbalanced. A 2-h recovery period followed in which a shower was permitted and a small snack was provided (250 kcal and 200 ml water). The precise fluid deficit incurred due to sweat and urine losses was calculated from the acute change in body mass from pre to post heat exposure, corrected for snack, and expressed as a percentage of pre-exposure body mass.

Following the 2-h recovery period, volunteers were instrumented with skin temperature thermistors (Concept Engineering,

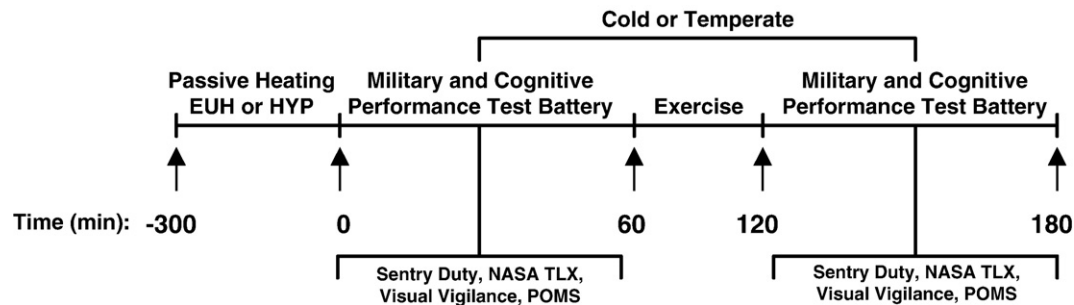


Fig. 1. Study design schematic. Each trial (EUH and HYP) was performed once each in cold (2 °C) and temperate (20 °C) conditions (2 × 2). Time intervals are not to scale.

Old Saybrook, CT) located at four sites (forearm, chest, thigh and calf). Mean skin temperature (T_{sk}) was calculated using the equation: $0.3 (T_{chest} + T_{forearm}) + 0.2 (T_{thigh} + T_{calf})$ [33]. Rectal body temperature (T_{re}) was measured continuously by a thermistor (Yellow Springs Instruments, Yellow Springs, OH) inserted 10 cm beyond the anal sphincter. Volunteers then entered an environmental chamber set to either cold (2 °C, 50%rh, 2.2 m/s air speed; wind chill of -1 °C) or temperate (20 °C, 50%rh, 1 m/s air speed) ambient temperatures which due to logistical reasons was counterbalanced for two of the subjects, but six of the subjects experienced the cold conditions prior to the temperate conditions. Minimal clothing was worn (t-shirt, shorts, socks, shoes), but cotton gloves and an ear band were provided to protect the hands and ears from the cold. These conditions were selected to induce significant heat loss, shivering and thermal discomfort, but not induce hypothermia. The cold strain index (CSI) was calculated according to Moran [34]. Experiments were conducted during the fall season to avoid winter cold habituation which might reduce the effects of cold stress.

After sitting in the environment (cold or temperate) for 5 min, cognitive testing was initiated. Cognitive performance testing consisted of 30 min of Sentry Duty simulation, the NASA-TLX, 20 min of Scanning Visual Vigilance, and the POMS, in that order. At the completion of the hour of testing, volunteers performed 1-h of cycle ergometer exercise (total energy expenditure ~550 kcal) as described previously [6]. At the conclusion of exercise, another hour of cognitive performance testing which was identical to the initial cognitive testing was completed.

2.3. Cognitive performance measures

2.3.1. Sentry duty simulation

Sentry duty performance was measured using a marksmanship simulator (Weaponer, Spartans, Rolling Meadows, IL, USA) which presented pop-up targets at a simulated range of 300 m. The volunteers stood in a supported position holding a modified M-16 weapon and scanned the downrange scene for the appearance of individual targets. Each sentry duty session lasted 30 min, during which time 120 targets were presented with inter-stimulus intervals ranging from 8 to 120 s. Of these targets, 50% were foes and 50% were friends, identified by an adjacent small red light illuminated during the first 0.5 s that the target was presented. Participants were trained over a multi-day period to identify the targets, press a response key to indicate they had seen the target, and then fire at the foe targets, all within the 6 s period that the target remained visible.

This training was conducted such that participants achieved and maintained a stable level of marksmanship performance prior to entry into the experimental conditions. Performance measures on this task are target detection latency (time from target presentation to tapping of response lever), accuracy of shots (percentage of shots fired that were scored as hits), total response latency (total time from target presentation to firing of rifle), friend-foe discrimination (percentage of responses that were correct: fired at foes plus

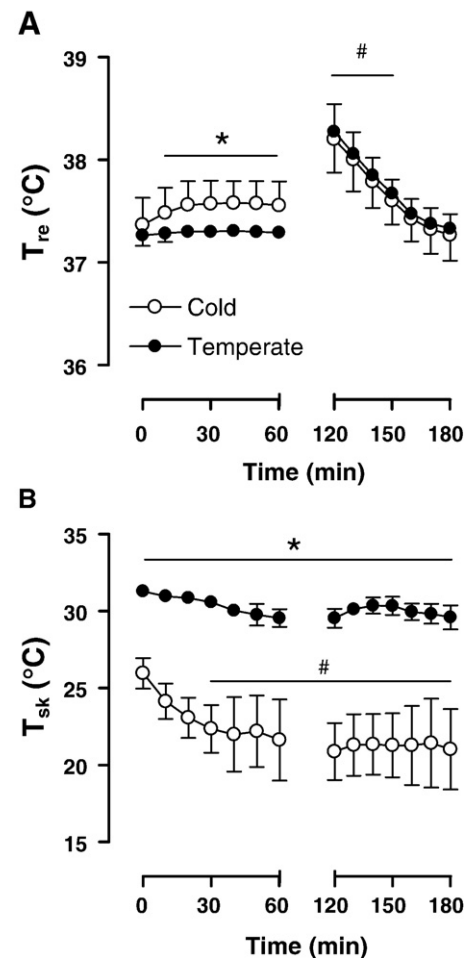


Fig. 2. Effect of environment and exercise on rectal (A) and mean skin (B) temperatures. Values are means ± SD. *Significant difference between cold and temperate; #Significant effect of time (A) 120–150 > 0–60 and 160–180 and (B) 30–180 < 0–20.

fireholds on friends), and number of targets detected (number of targets presented that were detected).

2.3.2. Scanning visual vigilance

Visual vigilance was measured using a computerized vigilance test which is sensitive to a wide variety of environmental conditions, nutritional factors, and sleep loss [30]. The test required participants to monitor a dark computer screen for the random appearance of an infrequent white dot which remained on the screen for 2 s. Upon detecting the stimulus, participants responded with a key press. The stimulus occurred on average once a minute. Performance measures on this task include hits, false alarms, and reaction time. This test was also administered multiple times in the training phases in order to eliminate the possibility of continued learning in the experimental trials.

2.3.3. Subjective assessments

Self-report assessments were made using the NASA-TLX and the POMS. The NASA-TLX is a 6-scale assessment of subject workload. Individuals rated their perceived mental demand, physical demand, temporal demand, effort, frustration, and performance during the marksmanship simulation on 100 point scales. The POMS assessed transient mood states by asking,

“How are you feeling right now?” Participants rated 65 adjectives on a 5-point scale; their responses were tabulated into six factor-analytically derived mood dimensions: tension–anxiety, depression–dejection, anger–hostility, vigor–activity, fatigue–inertia, and confusion–bewilderment. Each assessment was completed in less than 2 min.

2.4. Statistics

Treatment effects were analyzed using repeated measures analysis of variance. Where necessary, data were examined for violations of sphericity and *F*-values adjusted using Greenhouse-Geisser or Huynh-Feldt corrections. Tukey's HSD procedure was used to identify differences among means following significant main and/or interaction effects. An *a priori* power analysis selecting conventional α (0.05) and β (0.20) values showed that 8 subjects would be sufficient to detect a minimum difference in rectal temperature equal to twice the anticipated standard deviation (0.20 °C) [35]. This two-fold effect magnitude was selected based on the likelihood that the experimental perturbations would produce some unique and additive response variability. This sample size of 8 was also estimated to be sufficient to detect meaningful changes in

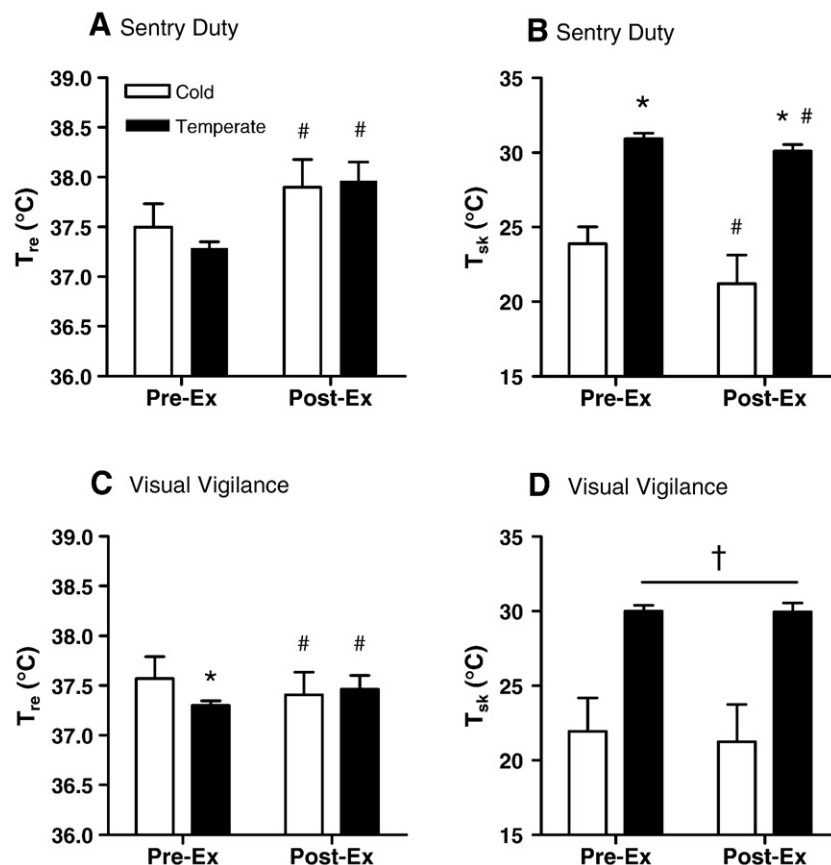


Fig. 3. Effect of environment and exercise on (A) rectal and (B) mean skin temperatures when collapsed across time for the duration of the sentry duty task and NASA-TLX and (C) rectal and (D) mean skin temperatures when collapsed across time for the duration of the visual vigilance task and POMS. *Significant difference (cold vs. temperate within time); #Significant difference (pre vs. post within temperature). †Significant difference (cold vs. temperate; main effect of temperature only).

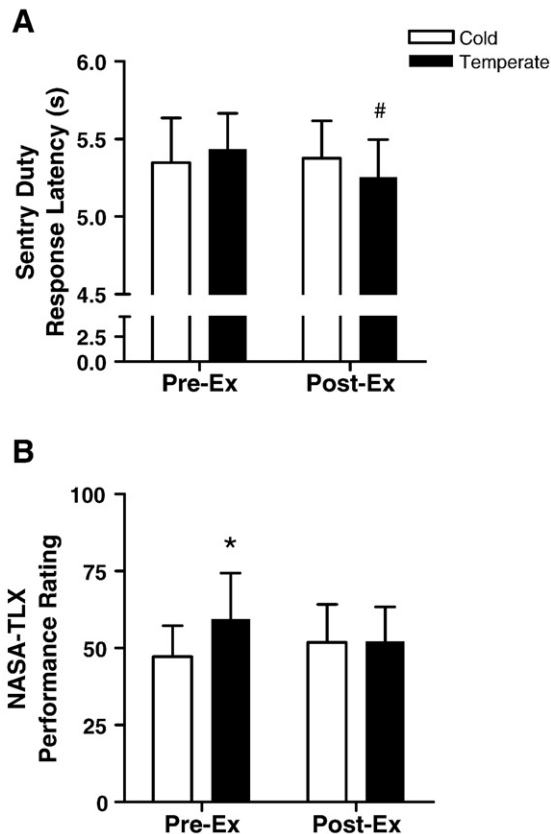


Fig. 4. Effect of environment and exercise on sentry duty response latency (A) and NASA-TLX Performance Scale rating (B). *Significant difference (cold vs. temperate within time); #Significant difference (pre vs. post within temperature).

cognitive performance tests for which practice sessions were employed to reduce variability (learning effects). Significance was set at $p < 0.05$. All data are presented as mean $\pm$ SD.

3. Results

Each volunteer completed all four trials. The average fluid deficit for HYP ($-3.0 \pm 0.8\%$, range from -2.7% to -3.5%) was greater than EUH ($-0.3 \pm 0.7\%$, range from 0.0 to -0.5%) ($p < 0.05$). During the 2-h rest and recovery period that followed the morning heat exposure, skin temperature and heart rate returned to baseline levels. However, core temperature remained slightly higher in HYP compared with EUH, which reflects expected dehydration effects on core temperature [36].

3.1. Hydration

Initial analyses for this study assessed the effects of hypohydration and cold exposure on cognitive and sentry duty task performance. As such, two-way repeated measures ANOVAs with hydration and temperature as independent variables were conducted separately for performance data collected pre-and post-exercise. There were no effects of hydration on any performance variables associated with either sentry duty or visual vigilance. Hydration was therefore eliminated as a factor for subsequent

analyses. To simplify presentation, each volunteer's performance data for EUH and HYP in each environment was averaged to one score ($n = 8$) for comparison between Cold and Temperate conditions.

3.2. Body temperature

Fig. 2(A/B) provides the rectal and mean skin temperature responses to environment and exercise over time. Rectal temperatures were higher in the cold than in temperate conditions during 50 of the initial 60 min of task performance but did not differ from each other after exercise (Fig. 2A). Rectal temperatures for the 30 min following exercise were higher than temperatures before exercise and the final 20 min of the trial (Fig. 2A). Mean skin temperatures were significantly lower in the cold than in temperate conditions throughout testing. Over time, mean skin temperatures remained constant in temperate conditions but dropped significantly over the first 30 min in the cold before reaching a plateau at $\sim 22^\circ\text{C}$ (Fig. 2B).

Average temperature across time in each performance testing block is displayed in Fig. 3. During the time periods related to the sentry duty task and NASA-TLX assessments, there were no significant differences in rectal temperatures between temperate and cold air conditions but temperatures were higher after exercise than before (Fig. 3A). For this same time period, mean skin temperatures were lower in cold than temperate conditions and lower after exercise than before (Fig. 3B). When collapsing temperature values for the time periods associated with visual vigilance and POMS, mean rectal temperatures showed a significant temperature and exercise interaction. Rectal temperatures were lower in temperate than cold conditions before exercise, but after exercise there were no rectal temperature differences between temperate and cold air conditions (Fig. 3C). Skin temperatures for this testing period were greater in temperate than cold conditions and exercise had no effect on skin

Table 1
Performance measures

Measure	Temperature		Exercise	
	Temperate	Cold	Before	After
<i>Sentry duty simulation</i>				
Target detection latency (s)	0.94(0.21)	1.06(0.23)*	0.99(0.21)	1.01(0.24)
Accuracy of shots (%)	40.18(16.75)	48.12(19.15)	45.42(18.07)	42.89(18.74)
Total response latency (s)	5.36(0.26)	5.35(0.24)	5.39(0.25)	5.32(0.24)
Friend-foe discrimination (%)	98.03(1.89)	97.67(2.24)	97.52(2.27)	98.19(1.81) *
Number of targets detected	238.75(1.39)	239.19(1.17)	239.13(1.26)	238.81(1.33)
<i>Scanning visual vigilance</i>				
Hits	11.31(4.37)	7.78(6.12)	9.22(5.77)	9.88(5.45)
False alarms	5.20(3.03)	6.27(2.76)	5.63(2.26)	5.83(3.50)
Reaction time	1.47(0.19)	1.35(0.49)	1.37(0.44)	1.45(0.31)

* Indicates significant main effect at $p < 0.05$.

Performance data were collapsed over the hydration variable, $n = 8$.

Table 2
Subjective measures

Measure	Temperature		Exercise	
	Temperature	Cold	Before	After
<i>NASA-TLX</i>				
Mental demand	56.88(21.82)	65.00(24.39)*	59.53(23.01)	62.34(23.94)*
Physical demand	53.91(21.05)	69.69(17.08)*	59.53(20.98)	64.06(20.41)
Temporal demand	53.75(20.41)	60.00(21.89)	55.47(21.37)	58.28(21.34)
Performance	55.78(13.31)	49.53(11.19)	53.28(13.87)	52.03(11.41)
Effort	61.25(15.25)	69.84(19.05)*	64.84(16.19)	66.25(19.28)
Frustration	48.44(26.99)	63.59(16.58)	52.97(23.70)	59.06(23.33)
<i>Profile of mood states</i>				
Tension–anxiety	9.38(5.81)	16.19(5.90)*	12.56(6.63)	13.00(7.02)
Depression–dejection	7.50(9.79)	13.38(9.42)	9.56(8.56)	11.31(11.32)
Anger–hostility	8.16(9.51)	13.62(12.71)	9.72(10.17)	12.06(12.72)
Vigor–activity	10.06(5.02)	5.97(3.86)*	8.50(4.68)	7.53(5.17)
Fatigue–inertia	8.59(5.08)	10.13(5.07)	8.31(4.94)	10.41(5.10)*
Confusion–bewilderment	7.41(4.51)	9.16(4.01)	7.72(4.01)	8.84(4.61)
Total mood disturbance	30.97(33.75)	56.50(35.13)*	39.38(33.34)	48.09(39.61)*

*Indicates significant main effect at $p < 0.05$.

Performance data were collapsed over the hydration variable, $n = 8$.

temperature (Fig. 3D). The CSI before exercise was 3.6 ± 0.6 , indicating a moderate level of cold strain for the volunteers.

3.3. Performance and subjective measures

Hypohydration did not have a significant effect on any measure of cognitive performance. Since no significant effects of hydration effects were found, this factor was eliminated from the following data presentation. Cognitive performance scores and subjective ratings were calculated by collapsing the values from EUH and HYP trials. Each volunteer's performance scores were reduced to a single mean score before comparing cold with temperate trials. This permitted evaluation of the effects of environment on cognitive performance both before and after exercise.

3.3.1. Sentry duty

Of the five dependent measures assessing speed and accuracy on the sentry duty task, only detection latency showed a significant main effect for temperature: time to detect targets was longer in the cold compared to temperate. For exercise, accuracy of friend–foe discrimination was greater after exercise than before. A significant interaction between temperature and exercise was seen for total response latency, $F[1,7] = 8.648$, $p < 0.05$. Total response latency was significantly longer in the temperate condition before exercise ($5.437 \text{ s} \pm 0.23$) than after exercise ($5.256 \text{ s} \pm 0.24$), but did not differ in the cold condition either before ($5.347 \text{ s} \pm 0.29$) or after ($5.377 \text{ s} \pm 0.24$) exercise (Fig. 4A). Table 1 displays the results for the dependent measures from the sentry duty task for the temperature and exercise conditions.

3.3.2. Visual vigilance

Performance on the Scanning Visual Vigilance task was not significantly affected by either temperature or exercise, with no differences in stimuli detections, false alarms or mean reaction time. Table 1 shows the results for the dependent measures from the visual vigilance task in the temperature and exercise conditions.

3.3.3. NASA-TLX

For the six scales of the NASA-TLX ratings of perceived workload, there were significant main effects of temperature for Mental Demand, Physical Demand and Effort, with demand ratings higher in the cold than temperate conditions for each scale. Exercise also had a significant effect on mental demand ratings: mental workload was rated as higher after exercise compared to before exercise. Additionally, there was a significant interaction between temperature and exercise for the performance rating scale, $F[1,7] = 6.530$, $p < 0.05$. Participants perceived their performance as better in the temperate condition (59.38 ± 15.0) than in the cold condition (47.19 ± 10.1) before exercise (Fig. 4B) but these ratings did not differ after exercise. Results of all six scales are shown in Table 2 for the temperature and exercise conditions.

3.3.4. POMS

Of the six mood sub-scales of the POMS, temperature significantly affected Tension–Anxiety and Vigor–Activity. Tension–Anxiety was higher in the cold than in the temperate condition and Vigor–Activity was lower in cold vs. temperate. There was a main effect of exercise on ratings of Fatigue–Inertia which was increased after exercise. Furthermore, a seventh scale (total mood disturbance, TMD) derived from all the other scales showed main effects of both temperature and exercise with cold and exercise both producing adverse effects on mood. All of the mean mood ratings from the temperature and exercise conditions are shown in Table 2.

4. Discussion

This study examined the effects of moderate dehydration and exercise on cognitive and militarily-relevant task performance during cold exposure (-1°C wind chill). The cold exposure was sufficient to induce moderate cold strain but not hypothermia. The hypohydration level was sufficient to elicit physical performance decrements in temperate conditions but not cold conditions [6]. The exercise intensity and duration were selected so that a vigorous task could be completed by most fit individuals. The performance tasks were selected due to their relevance to cognitive and task performance in the military operational environment.

The primary findings from this study were that: a) moderate dehydration (-3% body mass) did not degrade cognitive or sentry duty performance during cold or temperate air exposure, b) cold exposure (without hypothermia) increased target detection time during sentry duty performance with participants perceiving the task to be more demanding and experiencing degraded mood, c) physical exercise had a positive effect on

sentry duty friend–foe discrimination and also improved total response latency in the temperate condition but increased volunteers' evaluation of mental demand and fatigue, and d) neither cold nor exercise affected visual vigilance performance.

This study demonstrates that the combination of moderate dehydration and cold stress conditions employed herein do not degrade cognitive or military task performance. Physiologically, cold differs from resting heat or temperate exposure by increasing sympathetic nervous system activity. There is some suggestion that mild cold stress may produce a beneficial arousal response [37] which could potentially ameliorate the impact of dehydration in this environment. In hot or temperate conditions, dehydration of 2% or more generally degrades cognitive performance [8–10], though not always [11,12]. Although our study used prior heat stress exposure to dehydrate subjects, similar to others [10], we allowed participants to return to near baseline body temperature levels and observed no cognitive performance decrement after HYP. The absence of a temperate condition—HYP effect on cognitive performance in this experiment may be due to the use of militarily-relevant tasks with a longer duration than some of the short-duration cognitive tasks employed elsewhere [8–10].

Cold stress, *per se*, degraded military task performance but not vigilance performance, and resulted in increases in perceived workload and altered mood. Volunteers had increased target detection times (12.5 %) during sentry duty performance in the cold, but generally were able to detect targets, make decisions regarding those targets, and fire accurately at simulated foes in both temperature conditions. These data are consistent with the findings of others [38,39] who also found no changes in shooting accuracy during 2-h of cold air exposure at an ambient temperature of 4–5 °C when using a marksmanship task which was not timed and did not require target identification decisions. The ability to rapidly detect a threat during sentry duty is significant in the military operational environment. In contrast to sentry duty, no performance deviations were observed in a computer-based visual vigilance task. Visual vigilance could be considered a simpler task than sentry duty, and therefore less susceptible to cold exposure [25–27]. Participants also reported experiencing more tension and a decrease in vigor when exposed to the cold and perceived the mental and physical demands of the sentry duty task to be greater in the cold.

Participant responses to the environmental stressors may explain the absence of a broad cold-induced decrement in cognitive and psychomotor performance. In addition to reporting increased mental and physical task demands in the cold, volunteers rated the effort required to perform the task as higher in the cold. This increase in participant-reported effort may reflect actual mental compensation for the task demands which thus negated the impact of cold exposure. A similar argument has been used to explain an absence of expected effects when dehydrated [11].

Another potential reason for a limited change in cognitive performance in cold includes the lack of a significant fall in core temperature, which has previously been related to changes in cognition and marksmanship performance [16,17,25,26]. Falls in core temperature are thought to produce arousal which

potentially results in increased central nervous system efficiency [24] leading to behavioral changes such as decreases in reaction time [14,16,17,24]. However, in this study, we produced moderate cold strain without hypothermia, as indicated by the absence of a decline in core temperature. In fact, the observed increase in core temperature in the cold condition is not unexpected due to shivering and peripheral vasoconstriction. This response is commonly observed early in cold air conditions [40,41].

Although there were limited cold-induced cognitive performance decrements, some aspects of performance did improve after exercise as hypothesized. In the sentry duty paradigm, friend–foe discrimination accuracy was enhanced after exercise and total response latency was faster after exercise in the temperate conditions. This performance improvement may be due to body temperature changes resulting from exercise: rectal temperatures rose in response to exercise. While the overall improvement in friend–foe discrimination accuracy and the faster response speed after exercise in the temperate conditions could be due to increased core temperatures, the fact that a reduction in latency is not seen in the cold environment may be explained by the further decline in skin temperatures after exercise, suggesting that this drop in skin temperature is more detrimental to performance than the benefit derived from the increased core temperature. Some researchers have suggested that skin temperature changes are the catalyst for cognitive performance decrements, positing that cold ambient temperatures cool the skin which distracts participants, thereby drawing attention away from task performance [15,42].

Aside from warming the body, exercise may improve performance through an arousal effect. The improvement noted in sentry duty performance but not visual vigilance is consistent with the findings of other research showing that an hour of exercise improved complex cognitive performance [43]. In a recent review, it was noted that the relationship between exercise-induced arousal and cognitive performance was complex, but posited that exercise not only modifies the speed of information processing but may also facilitate more complex cognitive performance such as decision-making and problem-solving [44]. The observed improvement in response speed and decision accuracy in the sentry duty paradigm lends empirical support to this view.

To more fully evaluate the efficacy of exercise for mitigating cognitive performance declines in the cold, future studies could utilize a design with and without exercise. While learning effects due to repeated presentation of the tasks were not expected in this study due to the training periods provided, a non-exercising control group would solidify conclusions drawn about the effects of exercise. Future studies that compare exercise and non-exercise conditions are warranted as are additional studies that investigate the mechanisms whereby exercise acts to improve cognitive performance. Finally, this study evaluated cognitive performance and self-report assessments at single time points within the temperature conditions. Utilizing tests that allow for multiple performance assessments or measurements across time would provide a more thorough picture of cognitive performance changes across the duration of cold exposure.

Finally, the relationship between exercise, cold exposure, and cognitive performance may be mediated by neuroendocrine responses which were not evaluated here. A recent study measured adrenergic responses to cold air and cognitive stress, finding increased norepinephrine levels in cold exposure and elevated epinephrine levels when cold stress and cognitive stress were combined even though core temperatures did not change [45]. Using temperature conditions (22 °C and 4 °C) which are similar to those reported here and by others [45], another investigation measured an increase in epinephrine with cold air exposure [19]. Although they saw no correlations between physiological and behavioral measures, these data suggest that further examination of adrenergic response to cold exposure is warranted. More specifically, these responses, along with subjective measures of cold discomfort and cold strain, may be another tool for differentiating between thermal stress and thermal strain and their independent associations with cognitive performance.

Future work in this area should examine the relationships between cold exposure, physiological responses to cold, and cognitive, behavioral, and mood responses to cold stressors. Research should be conducted to elucidate not only the dose–response relationship of cold stress and cold strain indices with cognitive performance but also the time-dependent nature of this relationship, as well as the duration of the beneficial effects of exercise.

5. Summary

This study found no effects of hypohydration on cognitive and military task performance during temperate or cold exposure. The cold exposure paradigm did result in significant cold strain and large reductions in skin temperature, but did not produce hypothermia. There were modest effects of cold exposure on sentry duty performance, mood and perceived workload, but not on visual vigilance. Exercise produced some performance improvement, which was not limited to the cold condition. Further studies should utilize additional cognitive, psychomotor, and militarily-relevant tests to gain a clearer understanding of the relationship between cold stress and strain, exercise, and performance.

Acknowledgement

Disclaimer: Approved for public release; distribution is unlimited. The opinions or assertions contained herein are the private views of the author(s) and are not to be construed as official or reflecting the views of the Army or the Department of Defense. The investigators have adhered to the policies for protection of human subjects as prescribed in Army Regulation 70-25, and the research was conducted in adherence with the provisions of 32 CFR Part 219. Human subjects participated in these studies after giving their free and informed voluntary consent. Investigators adhered to AR 70-25 and USAMRMC Regulation 70-25 on the use of volunteers in research. Any citations of commercial organizations and trade names in this report do not constitute an official Department of the Army endorsement of approval of the products or services of these organizations.

References

- [1] Freund BJ, Sawka MN. Influence of cold stress on human fluid balance. In: Marriott BM, Carlson SJ, editors. *Nutritional Needs in Cold and High-Altitude Environments*. Washington, D.C.: National Academy Press; 1996. p. 161–79.
- [2] Kenefick RW, Hazzard MP, Mahood NV, Castellani JW. Thirst sensations and AVP responses at rest and during exercise-cold exposure. *Med Sci Sport Exerc* 2004;36(9):1528–34.
- [3] Headquarters, Department of the Army. TB MED; 2005. p. 508.
- [4] O'Brien C, Freund BJ, Sawka MN, McKay J, Hesslink RL, Jones TE. Hydration assessment during cold-weather military field training exercises. *Arctic Med Res* 1996;55(1):20–6.
- [5] O'Brien C, Young AJ, Sawka MN. Hypohydration and thermoregulation in cold air. *J Appl Physiol* 1998;84(1):185–9.
- [6] Cheuvront SN, Carter RI, Castellani JW, Sawka MN. Hypohydration impairs endurance exercise performance in temperate but not cold air. *J Appl Physiol* 2005;99(5):1972–6.
- [7] Institute of Medicine. Dietary reference intakes for water, potassium, sodium, chloride, and sulfate. Washington, D.C. The National Academies Press; 2005.
- [8] Cian C, Barraud PA, Melin B, Raphael C. Effects of fluid ingestion on cognitive function after heat stress or exercise-induced dehydration. *Int J Psychophysiol* 2001;42(3):243–51.
- [9] Sharma V, Sridharan K, Pichan G, Panwar M. Influence of heat-stress induced dehydration on mental functions. *Ergonomics* 1986;29(6):791–9.
- [10] Gopinathan PM, Pichan G, Sharma VM. Role of dehydration in heat stress-induced variations in mental performance. *Arch Environ Health* 1988;43(1):15–7.
- [11] Szinnai G, Schachinger H, Arnaud MJ, Linder L, Keller U. Effect of water deprivation on cognitive-motor performance in healthy men and women. *Am J Physiol Regul Integr Comp Physiol* 2005;289(1):R275–80.
- [12] Neave N, Scholey AB, Emmett JR, Moss M, Kennedy DO, Wesnes KA. Water ingestion improves subjective alertness, but has no effect on cognitive performance in dehydrated healthy young volunteers. *Appetite* 2001;37(3):255–6.
- [13] Ellis HD. The effects of cold on the performance of serial choice reaction time and various discrete tasks. *Hum Factors* 1982;24(5):589–98.
- [14] Ellis HD, Wilcock SE, Zaman SA. Cold and performance: the effects of information load, analgesics, and the rate of cooling. *Aviation Space & Environmental Medicine* 1985;56(3):233–7.
- [15] Sharma VM, Panwar MR. Variations in mental performance under moderate cold stress. *Int J Biometeorol* 1987;31(1):85–91.
- [16] Giesbrecht GG, Arnett JL, Vela E, Bristow GK. Effect of task complexity on mental performance during immersion hypothermia. *Aviat Space Environ Med* 1993;64(3 Pt 1):206–11.
- [17] O'Brien C, Mahoney C, Tharion WJ, Sils IV, Castellani JW. Dietary tyrosine benefits cognitive and psychomotor performance during body cooling. *Physiol Behav* 2007;90(2–3):301–7.
- [18] Enander A. Effects of moderate cold on performance of psychomotor and cognitive tasks. *Ergonomics* 1987;30(10):1431–45.
- [19] van Orden KF, Benoit SL, Osga GA. Effects of cold air stress on the performance of a command and control task. *Hum Factors* 1996;38(1):130–41.
- [20] Slaven GM, Windle CM. Cognitive performance over 7 days in a distressed submarine. *Aviat Space Environ Med* 1999;70(6):604–8.
- [21] Marrao C, Tikuisis P, Keefe AA, Gil V, Giesbrecht GG. Physical and cognitive performance during long-term cold weather operations. *Aviat Space Environ Med* 2005;76(8):744–52.
- [22] Mäkinen TM, Palinkas LA, Reeves DL, et al. Effect of repeated exposures to cold on cognitive performance in humans. *Physiol Behav* 2006;87(1):166–76.
- [23] Thomas JR, Ahlers ST, House JF, Schrot J. Repeated exposure to moderate cold impairs matching-to-sample performance. *Aviat Space Environ Med* 1989;60(11):1063–7.
- [24] Van Orden KF, Ahlers ST, Thomas JR, House JF, Schrot J. Moderate cold exposure shortens evoked potential latencies in humans. *Aviat Space Environ Med* 1990;61(7):636–9.
- [25] Enander AE, Hygge S. Thermal stress and human performance. *Scand J Work Environ & Health* 1990;16(Suppl 1):44–50.

- [26] Palinkas LA. Mental and cognitive performance in the cold. *Int J Circumpolar Health* 2001;60(3):430–9.
- [27] Pilcher JJ, Nadler E, Busch C. Effects of hot and cold temperature exposure on performance: a meta-analytic review. *Ergonomics* 2002;45(10):682–98.
- [28] Patton JF, Vogel JA. Effects of acute cold exposure on submaximal endurance performance. *Med Sci Sports Exerc* 1984;16(5):494–7.
- [29] McBride SA, Merullo DJ, Johnson RF, Banderet LE, Robinson RT. Performance during a 3-hour simulated sentry duty task under varied work rates and secondary task demands. *Mil Psychol* 2007;19(2):103–17.
- [30] Lieberman HR, Coffey B, Kobrick J. A vigilance task sensitive to the effects of stimulants, hypnotics, and environmental stress: the Scanning Visual Vigilance Test. *Behav Res Meth Instrum Comput* 1998;30(3):416–22.
- [31] Hart SG, Staveland LE. Development of NASA-TLX (Task Load Index): results of empirical and theoretical research. In: Hancock PAE, Meshkati NE, editors. *Human mental workload*. Oxford, England: North-Holland; 1988. p. 139–83.
- [32] McNair DM, Lorr M, Droppleman LF. San Diego, CA: Educational and Industrial Testing Service; 1971.
- [33] Ramanathan NL. A new weighting system for mean surface temperature of the human body. *J Appl Physiol* 1964;19(3):531–3.
- [34] Moran DS, Castellani JW, O'Brien C, Young AJ, Pandolf KB. Evaluating physiological strain during cold exposure using a new cold strain index. *Am J Physiol Regul Integr Comp Physiol* 1999;277(2):R556–64.
- [35] Consolazio FC, Johnson RE, Pecora LJ. Physiological variability in young men. In: Consolazio FC, Johnson RE, Pecora LJ, editors. *Physiological Measurements of Metabolic Functions in Man*. New York, NY: McGraw-Hill; 1963. p. 453–80.
- [36] Sawka MN, Francesconi RP, Young AJ, Pandolf KB. Influence of hydration level and body fluids on exercise performance in the heat. *JAMA* 1984;252(9):1165–9.
- [37] Hoffman RG. Human psychological performance in cold environments. In: Pandolf KB, Burr RE, editors. *Medical Aspects of Harsh Environments*, Volume I. VA: Office of the Surgeon General U.S. Army; 2001. p. 383–410. Falls Church.
- [38] Reading JE, Kincaid PS, Roberts DE, Hesselink RL, Pozos RS. San Diego, CA: Naval Health Research Center; 1994.
- [39] Tikuisis P, Keefe AA, Keillor J, Grant S, Johnson RF. Investigation of rifle marksmanship on simulated targets during thermal discomfort. *Aviat Space Environ Med* 2002;73(12):1176–83.
- [40] Castellani JW, Stulz DA, Degroot DW, et al. Eighty-four hours of sustained operations alter thermoregulation during cold exposure. *Med Sci Sports Exerc* 2003;35(1):175–81.
- [41] Kenefick RW, Mahood NV, Hazzard MP, Quinn TJ, Castellani JW. Hypohydration effects on thermoregulation during moderate exercise in the cold. *Eur J Appl Physiol* 2004;92(4–5):565–70.
- [42] Teichner WH. Reaction time in the cold. *J Appl Psychol* 1958;42(1):54–9.
- [43] Grego F, Vallier JM, Collardeau M, Rousseau C, Cremieux J, Brisswalter J. Influence of exercise duration and hydration status on cognitive function during prolonged cycling exercise. *Int J Sports Med* 2005;26(1):27–33.
- [44] Tomporowski PD. Effects of acute bouts of exercise on cognition. *Acta Psychol (Amst)* 2003;112(3):297–324.
- [45] Thomas JR, Ahlers ST, House JF, et al. Adrenergic responses to cognitive activity in a cold environment. *J Appl Physiol* 1990;68(3):962–6.