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Hypohydration Effects on Physical & Cognitive Performance in Cold Environments

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ABSTRACT

Persons exercising in cold weather can incur substantial fluid losses and are advised to maintain hydration to sustain performance. Body water deficits or hypohydration (HYP) in excess of 2% body mass impairs endurance exercise performance in hot and temperate environments and HYP may also degrade cognitive performance in hot/temperate conditions. However the extent to which these performance decrements occur in cold environments with HYP is unknown. This study investigated whether HYP degrades physical and cognitive performance during cold exposure and if physical exercise could mitigate any cold-induced cognitive performance decline. On four occasions, eight volunteers (6 men, 2 women) were exposed to 3 h of passive heat stress, with (euhydration, EUH) or without (HYP, 3% body mass) fluid replacement. Later in the day, volunteers sat in a cold (2°C) or temperate (20°C) environment for 1 hour before performing 30 min of cycle ergometry at 50% $\dot{V}O_{2peak}$ followed immediately by a 30-min performance time trial. Performance was assessed by the total amount of work completed during the 30-min time trial. Volunteers also 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. Cognitive testing was conducted before and after exercise. Total work performed during the 30-min time trial was not influenced by environment but was less ($P < 0.05$) for HYP than EUH in the temperate trials. The corresponding change in time-trial performance (EUH minus HYP) was greater for temperate (-8%) than for cold (-3%) ($P < 0.05$). 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 during the 20°C trial in friend-foe discrimination and total response latency in the sentry duty task, but not on any other performance measures. In conclusion, these data demonstrate that 1) HYP impairs endurance exercise performance in temperate but not cold air; 2) cold stress per se does not impair time-trial performance; 3) moderate HYP had no effect on cognitive and psychomotor performance in a cold or temperate environment; and 4) aerobic exercise improved some aspects of military task performance during temperate air exposure.

1.0 INTRODUCTION

Persons exercising in cold weather can incur substantial fluid losses (14) and are commonly advised to maintain hydration to avoid cold injury and sustain performance. Despite these assertions, recent research shows that hypohydration (reduced body water) does not increase the risk of hypothermia or peripheral cold

injury (37; 38). Similarly, hypohydration in excess of 2% body mass impairs endurance exercise performance in hot and temperate environments with the magnitude of effect largest in the heat (6; 47). The extent to which this is true in cooler environments is unknown, but there is evidence that the mechanisms for hypohydration-mediated fatigue in warmer environments are blunted in the cold and may therefore have less impact.

Hyperthermia and cardiovascular strain are two major factors implicated in the genesis of hypohydration-mediated endurance exercise fatigue in hot and temperate environments (6). Both the independent and combined effects of hyperthermia and hypovolemia on cardiovascular strain dynamics in the heat have been elegantly described (17-19; 45). Recent examination of the same parameters during exercise in cooler environments (3 – 8°C) indicates that core temperature elevations associated with hypohydration are significantly reduced (19; 26). Tachycardia is also attenuated and stroke volume and cardiac output better preserved during progressive dehydration up to – 4% of body mass during both moderate (50%VO₂max) (26) and more intense (72%VO₂max) (19) exercise-cold stress. Taken together, cardiovascular strain attributed to hyperthermia and hypovolemia in warm and hot climates is blunted in cooler conditions, which may preserve endurance exercise performance.

Although multiple meteorological variables can influence endurance exercise success (57; 60), performances typically improve as air temperatures decline (57; 60). Laboratory (15) and field data (57) support an “optimal” air temperature threshold near 12°C; above or below this temperature, performance is relatively impaired (15). Endurance performance limitations in hot environments are well documented (34), but evidence during exercise-cold stress is complicated by the comparison reference temperature (15)(7), wearing heavily insulated clothing (40), and possibly the choice of an open-ended endurance exercise task (2; 15; 40). The best explanation for fatigue offered by cold performance studies also implicates factors other than cardiovascular strain or oxygen uptake as performance limiting. Competitive endurance athletes appear to perform at a high level coincident with significant body water losses in cool environments (6), but few studies have manipulated hydration state to experimentally compare the impact of hypohydration on performance in cold versus more temperate conditions. Those that have are difficult to interpret due to the absence of true control conditions (27) or wearing heavily insulated clothing (44).

Moderate HYP has been associated with cognitive performance declines during heat exposure (25), with effects on multiple domains of cognitive and task performance when HYP was induced by heat exposure or exercise (7) and when fluid loss is 2% or more of body weight (20; 49). Studies examining cognitive performance decrements from HYP in temperate conditions are often confounded by residual effects from prior heat exposure or concurrent heat exposure (25). In contrast, two studies of HYP after 12-24h water deprivation in temperate conditions reported no declines in task performance due to HYP but did report changes in perceived tiredness (51) and self-rated alertness (33). 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 (10; 11); associative learning, working memory, and reasoning (16; 36; 48); manual dexterity (12); and applied military tasks such as command and control (59) and marksmanship (36). Other studies have reported no effects of cold on cognitive performance after prolonged exposure (30; 50); whereas others have shown an improvement in cognitive performance with acute cold exposure, most notably in reaction time and auditory and visual recognition (11; 12; 16; 29; 36; 53; 58). 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 (13; 16; 39; 41; 53), that performance declines at an ambient temperature threshold of 15°C and below (48), and that cold stress accompanied by hypothermia more often degrades cognitive and psychomotor performance (13; 36).

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 (8). Furthermore, exercise-induced heat production, clothing, or their combination can significantly raise body temperature even in air temperatures below 0°C (40). 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.

The purpose of this study was to compare the effects of hypohydration on endurance exercise and cognitive/psychomotor performance in temperate and cold air. Our hypothesis was that cold air would mitigate the decrement in exercise performance attributable to hypohydration in a temperate environment. A combination of air motion and low air temperatures was used to induce cold stress beyond previous studies, but without exceeding cold injury thresholds. It was hypothesized that hypohydration would degrade cognitive performance during cold exposure and that physical exercise would mitigate such deficits.

2.0 METHODS

2.1 Subjects

Eight healthy volunteers (age = 24 ± 6 yr, ht = 170 ± 6 cm, wt = 72.9 ± 11.1 kg, body fat 22 ± 6 %) participated in this study and completed all phases of experimentation. Subjects (6 men, 2 women) were physically active and moderately fit ($\text{VO}_{2\text{peak}} = 48 \pm 9$ ml/kg/min). Subjects were provided informational briefings and gave voluntary and informed written consent to participate. Investigators adhered to AR 70-25 and USAMRMC Regulation 70-25 on the use of volunteers in research and the appropriate Institutional Review Boards approved this study.

2.2 Preliminary Procedures

Each subject's $\text{VO}_{2\text{peak}}$ was measured using an incremental cycle ergometer protocol with continuous gas exchange measurements (TrueMax, ParvoMedics, Sandy, Utah). The calculated workload at 50% $\text{VO}_{2\text{peak}}$ was validated during 30-min of steady-state cycling one day later. The ergometer used (Lode Excalibur Sport, Lode, Groningen, The Netherlands) allows pedal-rate independent (hyperbolic) and dependent (linear) modes of cycling. Individual linear factors (LF) were calculated [$W = \text{LF} \times (\text{rpm})^2$] for each subject to reflect a 50% $\text{VO}_{2\text{peak}}$ exercise intensity at a pedal cadence of 60 rpm. The linear factor setting provided room to increase work output during the time trial before reaching maximal sustainable workloads, which were estimated from $\text{VO}_{2\text{peak}}$ testing at ~100 rpm. Practice trials included 30-min of steady-state cycling (50% $\text{VO}_{2\text{peak}}$), followed immediately by a 30-min performance time trial. Three practice sessions were used to reduce training and learning effects. Elapsed time was displayed and the total work (kJ) completed in 30-min was given as feedback for motivation to improve with each subsequent practice ride. Experimental test scenarios were the same as those used in practice except that subjects were blinded to all test parameters but elapsed time. Semi-nude body mass (shorts only) was measured after voiding and before breakfast each morning for 10-days to establish a normal individual baseline body mass for euhydration assessment on test days. All experimentation began within 3-days of completing preliminary procedures.

2.3 Experimental Procedures

A counterbalanced 2 x 2 (hydration x environment) experimental design was employed (1; 5). Each was separated by at least 48-hrs. Experiments were conducted at the same time of day and women were tested in the follicular phase of their menstrual cycle to control for circadian and ovulatory fluctuations in body temperature. On the morning of each trial, body mass was measured with an electronic precision balance scale (Toledo 1D1 accuracy ± 20 g, Worthington, OH) for comparison against within subject 10-day averages, and a 10-ml venous blood sample was collected for serum osmolality determination. A standardized breakfast was provided, after which subjects rested in a seated position for ~ 1 -hr before moving to a hot room (45°C, 50%rh, 1 m/s air speed) for 3-hrs of passive heat exposure with (euhydration, EUH) or without (hypohydration, HYP) fluid replacement. A 2-hr recovery period followed in which a shower was permitted and a small snack was provided (200 ml water and 250 kcal). The precise fluid deficit incurred 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-exercise body mass.

In the afternoon, subjects sat in a cold (2°C, 50%rh, 2.2 m/s air speed) or temperate (20°C, 50%rh, 1 m/s air speed) environment with minimal clothing (t-shirt, shorts, socks, shoes, cotton gloves and head band) for 1-hr (performing cognitive testing) before performing 30-min of cycle ergometry at 50%VO_{2peak} followed immediately by a 30-min performance time trial. No motivation was provided during the time trial and subjects performed without distraction from any data collection measurements. Time trial performance was assessed by the total amount of work (kJ) completed in 30-min. Rectal (T_{re}) and mean skin temperatures (T_{sk}) (42) and heart rate (HR) were collected remotely at regular intervals throughout testing. RPE was assessed at 30-min and again immediately following the completion of exercise. Gas exchange measurements were made once in the initial 10-min of exercise using an automated system and workloads adjusted to reflect a 50%VO_{2peak} intensity. After exercise, another hour of cognitive performance testing which was identical to the initial cognitive testing was completed.

2.4 Cognitive Tests

2.4.1 Sentry Duty Simulation

Sentry duty performance was measured using a marksmanship simulator (Weaponeer, Spartanics, Rolling Meadows, IL, USA) which presented pop-up targets at a simulated range of 300 meters. 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 minutes, during which time 120 targets were presented with inter-stimulus intervals ranging from 8 to 120 seconds. Of these targets, 50% were foes and 50% were friends, identified by an adjacent small red light illuminated during the first 0.5 sec 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 second 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 fireholds on friends), and number of targets detected (number of targets presented that were detected).

2.4.2 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 (28). 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 seconds. 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.

2.4.3 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 two minutes.

2.4 Statistical Analysis

Following tests for normality of distribution and equality of variances, treatment effects were analyzed using a paired t-test, one-way or two-way ANOVA for repeated measurements. A one-sample t-test was also used to compare performance effects against a hypothetical value of importance (32). When appropriate, Tukey's HSD procedure was used to identify pairwise differences among means following significant main and/or interaction effects. Where necessary, data were examined for violations of sphericity and F-values adjusted using Greenhouse-Geisser or Huynh-Feldt corrections. Significance was set at $p < 0.05$. All data are presented as means $\pm$ SD except where indicated.

3.0 RESULTS

3.1 Hydration

Euhydration was estimated on the morning of each trial by a body mass within 1% of the average 10-day baseline. Two subjects $> 1\%$ lower than 10-day baseline were given additional water with breakfast. Serum osmolality (289 ± 1 mOsmol/kg) confirmed euhydration (25). The fluid deficit achieved before the start of each HYP trial was $-2.9 \pm 0.7\%$ and $-3.0 \pm 0.8\%$ of body mass for Cold and Temp, respectively. Values for EUH trials were -0.3 ± 0.6 (Cold) and $-0.4 \pm 0.7\%$ (Temp) of starting baseline. Differences were significant ($P < 0.05$) between hydration levels (HYP vs. EUH), but not between environments (Cold vs. Temp). Thus, subjects were adequately matched for pre-exercise hydration status in EUH and HYP trials.

3.2 Exercise Performance

Table 1 presents individual and mean time trial performance data. Total work in Temp HYP was lower than Temp EUH ($P = 0.012$). There was no effect of hydration in the Cold (Cold EUH vs. Cold HYP) and no independent effect of environment on performance (Cold EUH vs. Temp EUH). Associated mean power outputs from Table 1 were 140 ± 30 (Temp HYP), 152 ± 30 (Temp EUH), 154 ± 36 (Cold EUH), and 150 ± 35 (Cold HYP) W. Viewed individually, all 8 subjects performed worse when hypohydrated in temperate air, while only 5 of 8 experienced the same from hypohydration in the cold. Figure 1 presents the

% change in performance from EUH to HYP in Temp and Cold environments. The change was significantly larger for Temp ($-7.6 \pm 5.9\%$) than Cold ($-2.7 \pm 4.9\%$) ($P = 0.021$). The means and 95% confidence limits for performance (-12.6 to -2.7% Temp; -6.8 to 1.4% Cold) provide the likely range of the true change effects and illustrate why there is a difference between HYP and EUH within Temp, but not within Cold (i.e., confidence interval crosses zero for Cold). In addition, only the range of the confidence interval for Temp falls entirely outside the *a priori* zone of indifference ($P = 0.04$, one-sample t-test), which provides evidence that the negative effect of hypohydration on performance in temperate air is also of practical importance.

Subject #	Cold		Temperate	
	<u>EUH</u>	<u>HYP</u>	<u>EUH</u>	<u>HYP</u>
1	156.3	157.3	165.1	161.0
2	207.3	191.0	214.0	184.9
3	289.5	291.7	300.6	289.4
4	298.4	274.0	300.5	243.1
5	308.0	324.9	308.8	296.5
6	361.8	342.3	311.5	297.4
7	296.0	293.2	276.8	251.0
8	300.8	282.0	304.3	291.4
Mean	277.3	269.6	272.7	251.8*
SD	64.5	63.6	53.9	53.3

*Significantly lower ($P < 0.05$) than Cold EUH and Temp EUH

Table 1: Time trial work performance (kJ)

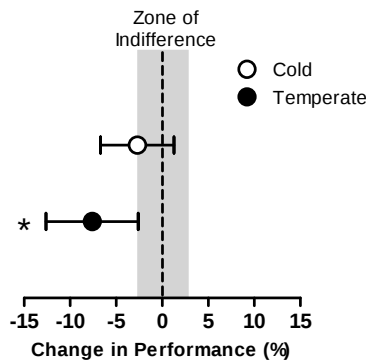


Figure 1: Percent change in performance from EUH to HYP in temperate and cold trials. Data are means; bars are 95% confidence intervals. Shaded area represents zone of indifference ($\pm 2.5\%$) based on the typical performance variability measured during practice sessions (see text for detailed explanation). * indicates significant difference between trials (paired t-test, $P = 0.021$) and significant difference from zone of indifference (one-sample t-test, $P = 0.044$).

3.3 Physiological Responses

3.3.1 Metabolic Rate

Metabolic rates during the initial 30-min of cycling were calculated from a 2-min gas sample made 5-min into exercise and adjusted to reflect $\sim 50\%$ of $\text{VO}_{2\text{peak}}$. All measurements were similar ($P > 0.05$) at 49 ± 6 (Cold EUH), 51 ± 5 (Cold HYP), 47 ± 2 (Temp EUH) and $48 \pm 3\%$ (Temp HYP) $\text{VO}_{2\text{peak}}$. Subjects were therefore matched among trials for exercise intensity preceding the cycling time trial.

3.3.2 Cardiovascular Strain and Thermoregulatory Strain

Figure 2 A and B represent HR and perceived exertion responses to exercise at 30 and 60-min of exercise. Data collected at rest were unreliable due to extreme shivering in the cold trials and were therefore excluded from the analysis. All 60-min HR exceeded 30-min values ($P < 0.05$). HR for Temp HYP at 30-min was higher than for Temp EUH and Cold HYP. Both Temp HYP and Cold HYP were higher than Temp EUH (~ 5 b/min, $P > 0.05$) and Cold EUH (~ 11 b/min, $P < 0.05$) at 60-min. RPE increased over time with no differences among trials (60-min $>$ 30-min, $P < 0.05$). T_{re} increased significantly over time in all trials (Figure 3A). At rest, T_{re} was higher in both Cold compared to Temp trials due to rigorous shivering. No differences among trials were seen at 30-min, but Temp HYP was higher than Cold EUH (0.4°C , $P < 0.05$) and Temp EUH (0.3°C , $P < 0.05$) at exercise cessation. T_{sk} was significantly lower in the Cold (Fig 3B) and was independent of hydration status.

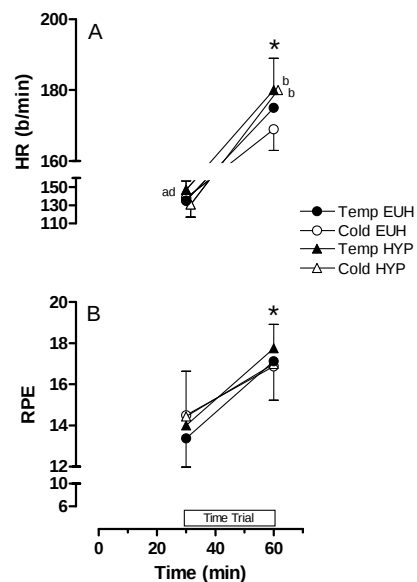


Figure 2: Effect of hydration and environment on heart rate (HR; A) and ratings of perceived exertion (RPE; B). Values are mean $\pm$ SD. ^{a,b,c,d} Significant differences ($P < 0.05$) from corresponding values for temperate EUH, cold EUH, temperate HYP, and cold HYP, respectively. *Significant effect of time (60 > 30-min; $P < 0.05$).

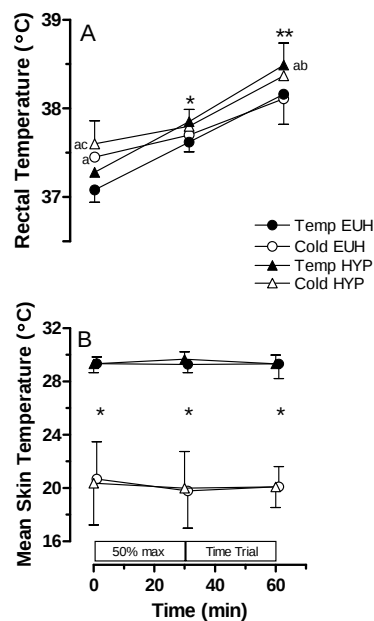


Figure 3. Effect of hydration and environment on rectal (A) and mean skin temperatures (B). Values are mean $\pm$ SD. Significance by letter designation is indicated in Figure 2. Significant effects of time ($P < 0.05$): * 30 > 0 min; ** 60 > 30 and 0 min for rectal temperature (A). *Significant effect of temperature (temperate > cold) ($P < 0.05$) for mean skin temperature (B).

3.4 Cognitive Responses

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.

3.4.1 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 ($p < 0.05$). Total response latency was significantly longer in the temperate condition before ($5.437 \text{ sec} \pm 0.23$) than after exercise ($5.256 \text{ sec} \pm 0.24$), but did not differ in the cold condition either before ($5.347 \text{ sec} \pm 0.29$) or after ($5.377 \text{ sec} \pm 0.24$) exercise (Figure 4A). Table 2 displays the results for the dependent measures from the sentry duty task for the temperature and exercise conditions.

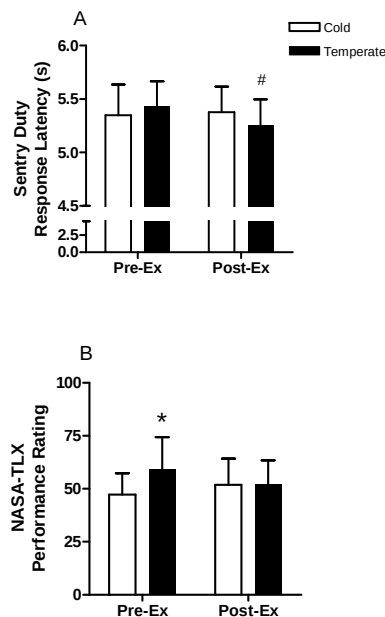


Figure 4. Effect of environment and exercise on sentry duty response latency (A) and NASA-TLX Performance Scale rating (B). *Significant difference (cold vs. temperate within time); #Significant difference (pre vs. post within temperature).

Measure	Temperature		Exercise	
	Temperate	Cold	Before	After
<u>Sentry Duty Simulation</u>				
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)
<u>Scanning Visual Vigilance</u>				
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 $p < .05$

Table 2. Cognitive Performance Measures

3.4.2 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 2 shows the results for the dependent measures from the visual vigilance task in the temperature and exercise conditions.

3.4.3 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 ($p < 0.05$). 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 (Figure 4B) but these ratings did not differ after exercise. Results of all six scales are shown in Table 3 for the temperature and exercise conditions.

Measure	Temperature		Exercise	
	Temperate	Cold	Before	After
<u>NASA-TLX</u>				
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)
<u>Profile of Mood States</u>				
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 $p < .05$

Table 3. Subjective Measures and Mood States

3.4.4 Profile of Mood States (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 3.

4.0 DISCUSSION

This study determined the effects of hypohydration on endurance exercise performance in temperate and cold air. In accordance with our hypothesis, the principal finding of this study is that hypohydration by – 3% body mass impaired cycling time trial performance in a temperate, but not a cold, environment. In addition, we found that cold stress per se did not reduce physical performance. Furthermore for the cognitive measures, a) moderate dehydration 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.

The % change in performance (EUH – HYP) within cold ($-2.7 \pm 4.9\%$) and temperate ($-7.6 \pm 5.9\%$) environments was statistically different (Figure 1). The 95% confidence limits were plotted about the mean to provide insight into the likely range of the true change value (Figure 1). These limits were also applied in the traditional sense to examine the importance of the change relative to an evidentiary standard other than zero (9; 24; 32). This standard is the zone of indifference selected a priori as any value within the typical noise of the performance measurement (i.e., 2.5% coefficient of variation). While the choice of 95% confidence limits for this integrated analytic approach is admittedly conservative (23; 24), the fact that the entire Temp confidence interval lies outside this zone (Figure 1) strongly supports the conclusion that the performance impairment due to hypohydration in temperate environments is both statistically significant and of practical importance. No statistical difference in performance was observed between EUH and HYP in cold air, but since half of the Cold interval lies outside the zone of indifference, the meaning of this effect is ambiguous at best (9; 24; 32).

The preservation of endurance performance in cold air when hypohydrated may be explained by differences in cardiovascular and oxygen uptake dynamics. Although the present experiment was not designed to assess the mechanisms behind performance changes, reasonable explanations can be gleaned from our observations when combined with the work of others. For example, Gonzalez-Alonso et al. (17-19) demonstrated that tachycardia (via hyperthermia) and hypovolemia explain most of the reduction in cardiac output between EUH and HYP in hot environments, with similar effects of lesser magnitude in the cold (19). In addition, hypovolemia reduces VO_2max and endurance capacity even in the presence of normothermia and cool skin (35). It is conceivable that hypovolemia and a higher T_{re} ($\sim 0.30^\circ\text{C}$) and HR (~ 5 b/min) in Temp HYP (Figure 2A) reduced stroke volume, cardiac output, and oxygen uptake enough to reduce performance (253 kJ) relative to Temp EUH (273 kJ) despite similar efforts (Figure 2B). However, the preservation of performance in Cold HYP (270 kJ) vs. Cold EUH (277 kJ) occurred with similar T_{re} differences and a larger HR disparity (11 b/min) between HYP and EUH (Figure 2A). It therefore remains possible that cold skin in

Cold HYP (Fig 3B) maintained a larger central blood volume and better preserved stroke volume and cardiac output (19; 26; 31; 35; 46). Similar T_{re} and HR at exhaustion between Cold HYP and Temp HYP also seem to support this conclusion since performance in Temp HYP, but not Cold HYP, was less than Cold and Temp EUH (Table 1).

The finding that cold stress per se did not reduce performance (Temp EUH vs. Cold EUH) (Table 1) is in opposition to others (2; 15; 40), but comparisons are made difficult by several methodological factors. For example, Galloway and Maughan (15) found that time to fatigue at 4°C was reduced compared with 11°C, but no different from 20°C, or improved relative to 31°C. Patton and Vogel (40) compared -20°C and 20°C, but wearing heavily insulated clothing at -20°C limits the interpretation of reduced performance at the latter temperature. Both of these studies and that of Adolph and Molnar (2) also used open-ended endurance exercise tasks. Adolph and Molnar (2) suggested that the most important predictor of performance in the cold using this kind of task was exposure time and cold tolerance. Indeed, Cabanac and Leblanc (3) demonstrated that simultaneous exposure to cold and exercise fatigue produces a sensory conflict resolved by compromise toward the least displeasing input signal, but others (15; 40) implicate local muscle effects for accelerated fatigue under similar circumstances. Exposure time in this experiment was fixed, which may have alleviated motivation issues related to cold tolerance. Post-experiment interviews even suggest that total work in Cold EUH and Cold HYP may have actually been augmented by cold avoidance (3). It is inconclusive whether using time to exhaustion, rather than a time trial, would (2; 40), or would not (15) have altered the performance outcomes observed herein between 2°C and 20°C.

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 (22) 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 (7; 20; 49), though not always (33; 51). Although our study used prior heat stress exposure to dehydrate subjects, similar to others (20), 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 (7; 20; 49).

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 (43; 55) 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 (13; 39; 41). 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 (51).

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 (13; 16; 36; 39). Falls in core temperature are thought to produce arousal which potentially results in increased central nervous system efficiency (58) leading to behavioral changes such as decreases in reaction time (11; 16; 36; 58). 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 (4; 26).

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 (48; 52).

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 (21). 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 (56). 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 (54). Using temperature conditions (22°C and 4°C) which are similar to those reported here and by others (54), another investigation measured an increase in epinephrine with cold air exposure (59). 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.

SUMMARY

We conclude that moderate hypohydration impairs endurance performance in temperate, but not cold, air. Cold stress per se had no effect. Application of these findings to competitive endurance exercise contested in environments similar to those described herein is logical, but tentative given the subject population tested. These findings are nonetheless of phenomenological importance.

This study also 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.

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 or approval of the products or services of these organizations.

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