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Influence of Core Temperature on Psychomotor Performance during Cold Weather Military Training

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Abstract

Purpose: Cold environments may deteriorate psychomotor performance due to slowing of neuronal signals, distractions caused by pain and discomfort, and loss of manual dexterity. The extent to which core temperature (T_c) influences psychomotor performance in the cold has not been established. Therefore, psychomotor performance and T_c were assessed during a cold weather military training exercise to evaluate this relationship.

Methods: Thirty-six military personnel (age: 26 ± 4 yr; ht: 175 ± 8 cm; wt: 79.1 ± 11.1 kg) participating in cold weather training volunteered for this study. Participants completed a 10-min immersion in cold (1℃) water, followed by 60 min of rewarming. Physiological, perceptual, and psychomotor assessments were made throughout the training. For analysis, participants were divided into groups based on their lowest achieved core temperature (<35.0℃ = HYP; 35.0–36.0℃ = CS-M; >36.0℃ = CS-S). Psychomotor performance was then compared among the groups to determine the influence of T_c on performance.

Results: Although cold water immersion deteriorated performance, no differences were observed among the three groups at any time point during the training for simple reaction time (HYP: 298 ± 49 ms; CS-M: 313 ± 55 ms; CS-S: 326 ± 53 ms; $p = 0.677$).

Conclusion: Findings suggest that cold water immersion deteriorates psychomotor performance which, even in the presence of mild hypothermia, is not directly influenced by T_c. Additional observations reveal large variations in T_c among a homogenous group in response to cold water immersion.

Keywords: cold water immersion, heat loss, hypothermia, cognition

Abbreviations

ANOVA	analysis of variance
CRT	choice reaction time
CS-M	moderate cold stress (core temperature > 35.0℃ but less than 36.0℃)
CS-S	slight cold stress (core temperature > 36.0℃)
HYP	hypothermic (core temperature < 35.0℃)
ms	millisecond
RW0	start of rewarming
RW15	15 min into rewarming
RW60	end of rewarming
SRT	simple reaction time
SS	shivering sensation
T_c	core temperature
T_{hand}	hand temperature
TS	thermal sensation
$\bar{T}_{sk}$	mean skin temperature

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Introduction

Many warfighters, occupational workers, and athletes are required to perform at high levels in austere environments to meet the demands of missions, work objectives, and athletic events. In cold environments, physiological responses to low ambient temperatures disrupt normal function and degrade performance (Fox, 1967; Mahoney et al., 2007; Pilcher et al., 2002; Stang & Weiner, 1970). A crucial aspect of performance includes psychomotor skills, which encompass the use of cognition and movement to execute specific tasks. These skills may be used to identify and respond to threats in hostile environments (warfighter), perform in high-stress and dynamic situations (occupational worker), or adjust swimming techniques to move efficiently through ever-changing sea states in open water (athlete) (Liebermann et al., 2005; Norrish & Cryer, 1990; Nuckton et al., 2000). Performing such tasks can be challenging in even the most ideal conditions, but when the presence of cold disrupts normal physiological and cognitive function, performance deteriorates quickly.

Psychomotor skills become compromised in cold environments due to slowing of signals that travel through neurons (de Jong et al., 1966; Oksa, 2002), distraction caused by intense feelings of cold and shivering (Cheung et al., 2007), dexterity loss due to cold muscles and diminished force production (Havenith et al., 1995; Heus et al., 1995), and a reduction in cerebral oxygenation caused by hyperventilation at the onset of cold water immersion (Mantoni et al., 2008). Measuring and monitoring these responses in field settings, where most cold exposure occurs for the aforementioned populations, pose a significant challenge. Given that many of the mechanisms that degrade psychomotor performance in the cold are related to body heat loss, it is likely that more simple measurements related to body temperature change, such as core temperature (T_c), could be used to quantify and predict psychomotor performance. However, the use of T_c as an indicator of psychomotor performance in cold environments has not been established.

The purpose of this study was to evaluate the specific relationship between critical T_c thresholds and psychomotor performance so that one might be able to anticipate performance decrements when measuring T_c in cold environments. This is an important aspect for those that operate or work in cold environments, wherein the use of physiologic monitoring devices may provide additional insights into safety and performance limitations. We hypothesized that lower T_c (greater heat loss) would result in worse performance compared with those who were able to maintain T_c (less heat loss) during exposure to cold stress. Identifying simple field measurements to explain performance outcomes, so that decrements can be anticipated and strategies to mitigate performance deterioration can be implemented, may provide useful information for those that venture into cold environments.

Methods

Study Design

Military training conducted at the Marine Corps Mountain Warfare Training Center in Bridgeport, CA provided an opportunity to measure physiological, perceptual, and psychomotor responses to cold water immersion and rewarming. During the training, participants volunteered to wear physiological monitoring equipment, provide perceptual ratings of temperature sensations, and participate in several psychomotor assessments. Participants' data were then analyzed to evaluate the influence of T_c on psychomotor performance.

Research Participants

Thirty-six active-duty military personnel (31 males, 5 females) volunteered as research participants for this study. Participant age, height, weight, and body fat percentage (estimated using circumference measurements and U.S. Navy body fat percentage equation; Hodgdon & Beckett, 1984) were collected at the time of study enrollment and prior to any cold exposure (demographic data presented in Table 1). Participants were recruited from a cold weather medicine course, wherein students were required to complete cold water immersion and rewarming activities to successfully complete the course. All participants provided informed consent in accordance with the Declaration of Helsinki and the study was approved by the Institutional Review Board at the Naval Health Research Center, San Diego, CA (Protocol # NHRC.2019.0007).

Experimental Protocol

Participants followed the Marine Corps Mountain Warfare Training Center's cold water immersion and rewarming procedures to fulfill requirements for the training, which was conducted onsite at the Marine Corps Mountain Warfare Training Center (elevation 2,100 m) at 0600 in ambient conditions (−5℃ air temperature, 0 m/s windspeed, and 1℃ water temperature).

Training requirements consisted of waiting to enter a pond (10 min), entering the pond (10 min; immersion to neck), exiting the pond (10 min), changing into dry clothing, and completing 60 min of rewarming. We defined these different phases of the training, which correspond to the timing of psychomotor assessments, as: pre-immersion, immersion, post immersion, start of rewarm (RW0), 15-min into rewarm (RW15), and end of rewarm (RW60). Participants wore standard-issued, non-cold-weather battle dress uniforms consisting of a cotton shirt, overcoat, and pants. Participants were allowed to wear athletic shoes for immersion. Once participants exited the pond and completed the post-immersion phase, they changed into dry, cold-weather

Table 1
Mean ± SD demographic information of participants divided by core temperature (T_c).

Group	N	Age (yr)	Height (cm)	Weight (kg)	BMI (kg/m^2)	Body fat (%)
CS-S	17	26 ± 5	175 ± 9	81.5 ± 11.7	26.7 ± 2.5[a]	22.0 ± 7.2
CS-M	12	24 ± 3	176 ± 8	79.5 ± 11.7	25.5 ± 2.6	16.5 ± 5.0
HYP	7	27 ± 4	175 ± 6	72.7 ± 6.1	23.6 ± 1.4[c]	16.9 ± 5.7
All	36	26 ± 4	175 ± 8	79.1 ± 11.1	25.7 ± 2.6	19.2 ± 6.7
p		0.290	0.851	0.212	0.027	0.054

Note. CS-S (cold stress, slight; T_c > 36℃), CS-M (cold stress, moderate; T_c 35–36℃), and HYP (hypothermic; T_c < 35℃). All 36 participants' information is also provided. A value $p < 0.05$ indicates difference between CS-S, CS-M, and HYP.
[a]Significantly different from HYP. [b]Significantly different from CS-M. [c]Significantly different from CS-S.

Figure 1. Psychomotor assessments conducted in water (1℃) during cold weather military training at the Marine Corps Mountain Warfare Training Center. Electroencephalography measurements (64-channel cap shown in photo; data not included in current paper) were also collected during this evaluation. Photo courtesy Naval Health Research Center.

clothing (shirt, down jacket, down pants, down mittens, and down slippers) and entered a down sleeping bag for 60 min.

Physiological and Perceptual Measurements

Participants wore heart rate monitors (chest strap; Polar Electro, Lake Success, NY), skin temperature sensors (Vital Sense, Respironics, Bend, OR), and ingested a temperature capsule (Vital Sense, Respironics, Bend, OR) for T_c measurement. Measurements were recorded each minute throughout the training. Skin temperature sensors were placed on the chest, shoulder, thigh, and hand (posterior). These sites, excluding the hand, were used to calculate mean skin temperature ($\bar{T}_{sk}$) using the Burton equation (Ramanathan, 1964). Hand skin temperature (T_{hand}) is reported separately from $\bar{T}_{sk}$. Participants ingested the T_c temperature capsule approximately 6 hr prior to the start of the training.

During each phase of the training, participants provided ratings of thermal sensation (TS; −4 very cold, −3 cold, −2 cool, −1 slightly cool, 0 neutral, +1 slightly warm, +2 warm, +3 hot, +4 very hot) and shivering sensation (SS; 0 no shivering, 1 slight shivering, 2 moderate shivering, 3 vigorous shivering) by visually observing a chart and verbally responding with their rating, which was recorded by research staff.

Psychomotor Assessments

Psychomotor assessments were chosen based on military relevance (i.e., vigilance, reaction time, memory) and ease of comparison to other studies using similar assessments in cold environments. These assessments, which evaluated simple reaction time (SRT) and choice reaction time (CRT) with a working memory component, were conducted at the beginning of pre-immersion, immersion (in the water), post-immersion, RW0, RW15, and RW60 (Hasselmo & Stern, 2006; Niemi & Näätänen, 1981). For assessments obtained during immersion, participants entered the water to the level of the neck and completed the psychomotor assessment, which was placed on a wooden platform on the edge of the ice (Figure 1). Psychomotor assessments, developed and administered using E-Prime 3.0 software (Psychology Software Tools, Pittsburg, PA), were presented on a 10-inch tablet (Acer America, San Jose, CA)

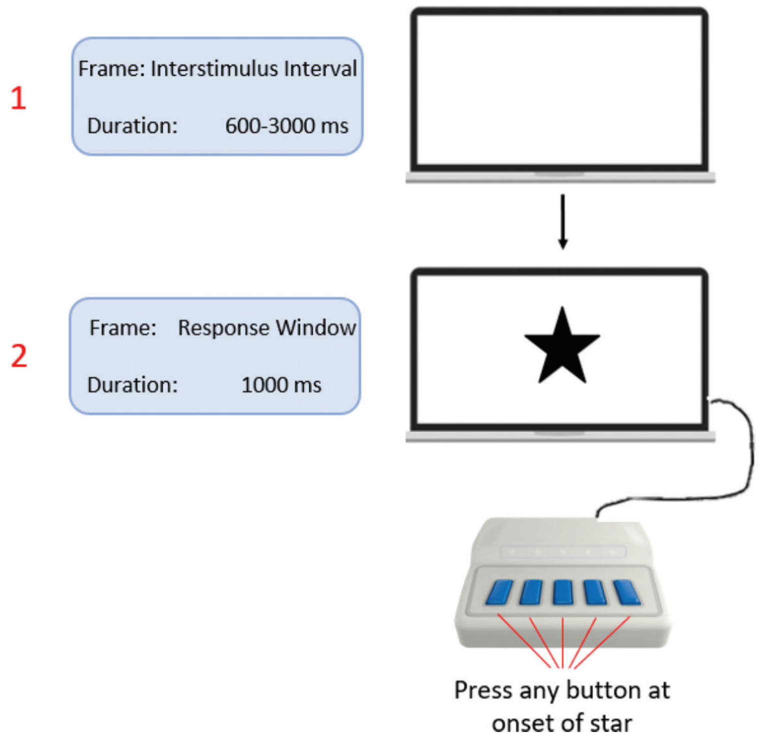

Figure 2. Administration of the SRT task with stimulus, monitor, and response box.

with an attached response pad (Psychology Software Tools, Pittsburg, PA) that recorded responses in milliseconds (ms). SRT and CRT were assessed immediately at the start of each phase of the training and the order of SRT and CRT assessments was randomized. The duration of each psychomotor assessment, which included SRT and CRT tasks, averaged seven minutes. To minimize the effect of learning and demonstrate familiarization with the assessments, participants were given practice attempts and were required to complete the SRT assessment once and achieve a minimum score of 75% on three CRT assessments. This familiarization occurred on the day prior to the training exercise.

For SRT, participants were asked to respond as quickly as possible as soon as a black star (stimulus) appeared on the tablet screen (Figure 2). Participants responded, using their dominant hand, by pressing any of the 5 buttons on the response pad. The response window (allowable response time) was 0 to 1,000 ms. Responses outside this window were not used in the mean SRT calculation. The randomized interstimulus interval (the timing between each stimulus) ranged between 300 and 600 ms and there were 40 trials (black star presentations) per assessment. The mean SRT was calculated for each assessment.

For CRT, participants were shown an initial image (4 × 4 multicolor square) on the tablet screen for 2,000 ms that they were asked to memorize (Figure 3). After 2,000 ms of viewing this image, the tablet screen went blank for a randomized time between 600 and 3,000 ms. Following this blank screen, two secondary images, both of which were 4 × 4 multicolored squares, then appeared on the screen. Participants were asked to determine, as quickly as possible, which of the secondary images (left image or right image) matched the initial image. Alternatively, participants could choose that neither of the secondary images matched the initial image. Participants were given 3,000 ms to make this decision. Responses (left match, no match, or right match) corresponded to buttons on the response pad and were recorded in ms. Twenty-five CRT trials were provided per assessment and mean CRT was calculated for each assessment (only correct responses included).

Statistical Analysis

For analysis, all 36 participants were divided into groups based on their lowest achieved T_c that occurred during the cold water immersion and rewarming exercise. These groups were classified as those with only slight T_c decreases (i.e., T_c was maintained above 36.0℃) in response to cold stress (CS-S; $n = 17$), those with moderate T_c decreases (i.e., T_c fell below 36.0℃ but was maintained above 35.0℃) in response to cold stress (CS-M; $n = 12$), and those whose T_c fell below 35.0℃ and met the clinical definition of hypothermia (HYP; $n = 7$). Groups were divided for analysis in an effort to provide greater definition pertaining to the degree of cold stress (i.e., heat loss) experienced by participants, which include slight and moderate cold stress, and hypothermia.

Demographic data (age, height, weight, BMI, body fat percent) were analyzed using a one-way analysis of variance (ANOVA) to examine differences among CS-S, CS-M, and

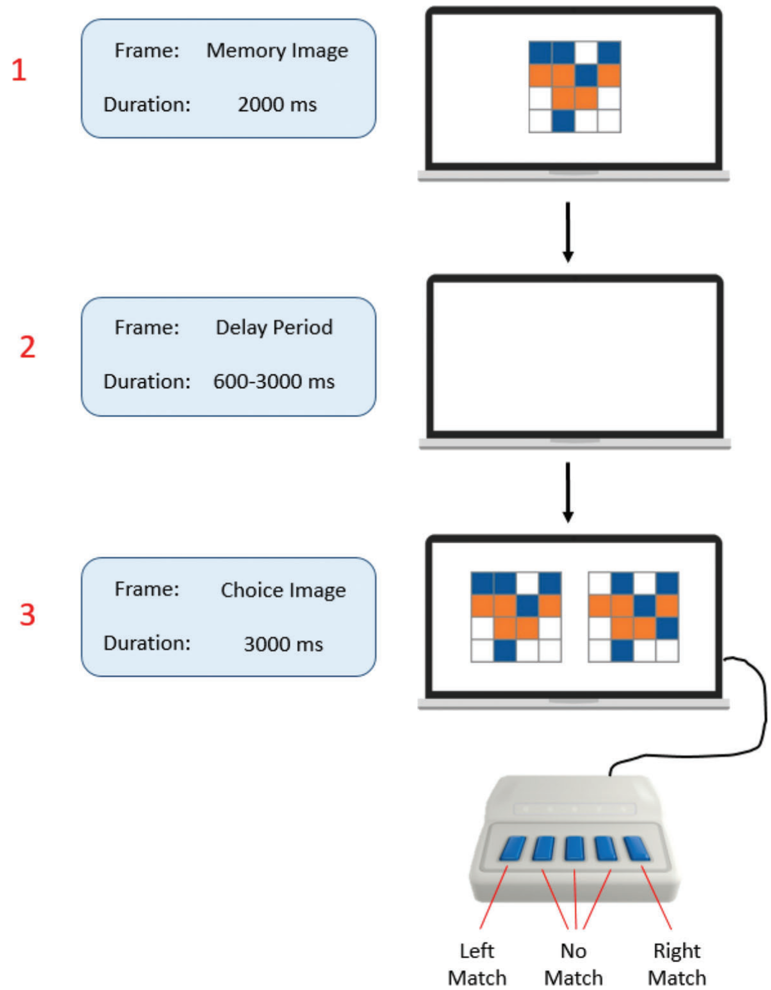

Figure 3. Administration of the CRT task with stimulus, monitor, and response box.

HYP. Significant group differences were followed up with *post hoc* tests using a Bonferroni correction for multiple comparisons. Cohen's *d* effect sizes were also calculated for demographic data that did not reach statistical significance, as large effects sizes in the presence of nonsignificant comparisons could provide supportive evidence for varying responses to cold water immersion. Physiological (T_c, $\bar{T}_{sk}$, T_{hand}), perceptual (TS, SS), and psychomotor (SRT, CRT) data were analyzed using a 3 group (CS-S, CS-M, HYP) × 6 time (pre-immersion, immersion, post-immersion, RW0, RW15, RW60) repeated measures ANOVA. Significant interactions, as well as main effects for time and group, were followed up with *post hoc* tests using a Bonferroni correction for multiple comparisons. The alpha level in each analysis was set at $p < 0.05$.

Results

Demographics

Demographic data were compared among the three groups (CS-S, CS-M, HYP) to confirm homogeneity of the sample population. Age [$F(2,33) = 1.29$, $p = 0.290$], height [$F(2,33) = 0.16$, $p = 0.851$], weight [$F(2,33) = 1.63$, $p = 0.212$], and percent body fat [$F(2,33) = 3.19$, $p = 0.054$] were not different among groups (Table 1). BMI, however, was lower in HYP compared with CS-S [$F(2,33) = 4.06$, $p = 0.027$]. Cohen's *d* effect size calculations indicate the following effect sizes between groups for age (Large: CS-M vs HYP, $d = 0.85$; Medium: CS-S vs CS-M, $d = 0.48$; Small: CS-S vs HYP, $d = 0.22$), height (Small: CS-S vs CS-M, $d = 0.12$; CS-S vs HYP, $d = 0.0$; CS-M vs HYP, $d = 0.14$), weight (Large: CS-S vs HYP, $d = 0.94$; CS-M vs HYP, $d = 0.73$; Small: CS-S vs CS-M, $d = 0.17$), and percent body fat (Large: CS-S vs CS-M, $d = 0.89$; CS-S vs HYP, $d = 0.78$; Small: CS-M vs HYP, $d = 0.07$).

Physiological and Perceptual

Physiological and perceptual findings are reported with comparisons between timepoints and among groups. Significant time effects (Table 2) were present for all physiological and perceptual measurements, including

T_c [$F(5,165) = 69.30$, $p < 0.001$], $\bar{T}_{sk}$ [$F(5,165) = 56.46$, $p < 0.001$], T_{hand} [$F(5,165) = 32.92$, $p < 0.001$], TS [$F(5,165) = 41.34$, $p < 0.001$], and SS [$F(5,165) = 33.36$, $p < 0.001$]. In particular, T_c decreased during cold water immersion but did not fully return to pre-immersion temperatures following rewarming, $\bar{T}_{sk}$ decreased during cold water immersion and recovered to higher temperatures after rewarming (compared with pre-immersion), and T_{hand} became colder during immersion and fully recovered following rewarming. Perceptual measurements of TS indicate that participants felt cool at pre-immersion, became colder during immersion, and returned to near-neutral TS following rewarming. Similar findings for SS were observed, in that minimal shivering occurred during pre-immersion, followed by moderate shivering during immersion, and cessation of shivering after rewarming.

Group comparisons indicate that, other than T_c [$F(2,33) = 52.47$, $p < 0.001$], which was purposefully separated into distinct groups for analysis, there were no significant group differences for $\bar{T}_{sk}$ [$F(2,33) = 0.92$, $p = 0.409$], T_{hand} [$F(2,33) = 0.17$, $p = 0.843$], TS [$F(2,33) = 3.30$, $p = 0.050$], and SS [$F(2,33) = 0.42$, $p = 0.663$] (Table 3).

Psychomotor

Psychomotor results are reported with comparisons between timepoints (Table 2) and among groups (Table 3) for both SRT and CRT. A significant time effect was observed for SRT [$F(5,110) = 11.49$, $p < 0.001$], but not CRT [$F(5,110) = 1.87$, $p = 0.105$]. Specifically, compared with pre-immersion, SRT became longer during immersion, post-immersion, and RW0 and showed partial recovery at RW60. No group differences were observed for either

Table 2
Mean ± SD physiological, perceptual, and psychomotor results for each time point of the cold water immersion and rewarming exercises (for all participants).

	T_c (℃)	$\bar{T}_{sk}$ (℃)	T_{hand} (℃)	TS	SS	SRT (ms)	CRT (ms)
Pre-immersion	37.4 ± 0.4[b]	24.5 ± 5.7[b]	17.2 ± 4.6	−1.4 ± 1.3[b]	0.9 ± 0.7	253 ± 57[b]	1310 ± 233
Immersion	36.9 ± 0.7[a]	22.9 ± 5.4[b]	15.2 ± 5.5[a,b]	−3.3 ± 0.8[a,b]	1.7 ± 1.1[a,b]	322 ± 58[a]	1322 ± 234
Post-immersion	36.2 ± 0.9[a,b]	17.2 ± 4.2[a,b]	10.5 ± 2.6[a,b]	−2.9 ± 1.7[a,b]	2.0 ± 1.0[a,b]	376 ± 119[a]	1470 ± 265
RW0	35.9 ± 0.9[a,b]	24.6 ± 3.2[b]	15.3 ± 2.4[b]	−2.9 ± 1.1[a,b]	2.4 ± 0.9[a,b]	349 ± 88[a]	1417 ± 340
RW15	36.7 ± 0.7[a,b]	30.0 ± 2.9[a,b]	18.8 ± 2.9	−1.7 ± 1.6[b]	2.0 ± 0.8[a,b]	324 ± 54[a,b]	1458 ± 247
RW60	36.9 ± 0.4[a]	32.5 ± 1.5[a]	19.3 ± 3.2	0.1 ± 1.6[a]	0.5 ± 0.7	283 ± 37[a]	1393 ± 203
p	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	0.105

[a]Significantly different from pre-immersion. [b]Significantly different from RW60. Significance at $p < 0.05$.

Table 3
Mean ± SD physiological, perceptual, and psychomotor results for each core temperature (T_c) group.

	Group	T_c (℃)	$\bar{T}_{sk}$ (℃)	T_{hand} (℃)	TS	SS	SRT (ms)	CRT (ms)
Pre-immersion	CS-S	37.6 ± 0.3[a,b]	26.2 ± 5.4	17.7 ± 4.5	−1.9 ± 1.3	1.0 ± 0.8	262 ± 33	1319 ± 246
	CS-M	37.2 ± 0.3[c]	22.3 ± 5.7	16.1 ± 4.0	−0.8 ± 1.1	0.7 ± 0.5	265 ± 34	1268 ± 232
	HYP	37.1 ± 0.5[c]	24.1 ± 5.7	18.1 ± 6.0	−1.3 ± 1.4	0.9 ± 0.7	179 ± 134	1396 ± 228
Immersion	CS-S	37.4 ± 0.5[a,b]	22.7 ± 6.1	15.5 ± 5.7	−3.4 ± 0.8	2.0 ± 1.0	326 ± 67	1308 ± 222
	CS-M	36.6 ± 0.5[c]	22.6 ± 4.8	14.3 ± 4.1	−3.1 ± 0.8	1.6 ± 1.2	325 ± 52	1342 ± 279
	HYP	36.3 ± 0.9[c]	23.7 ± 5.3	16.2 ± 7.3	−3.3 ± 0.8	1.3 ± 1.1	292 ± 40	1321 ± 217
Post-immersion	CS-S	36.8 ± 0.5[a,b]	16.6 ± 3.8	10.4 ± 2.5	−3.4 ± 1.2	2.1 ± 1.1	387 ± 96	1558 ± 281
	CS-M	35.9 ± 0.5[a,c]	17.5 ± 4.7	11.1 ± 2.9	−2.8 ± 1.6	1.8 ± 1.0	372 ± 164	1374 ± 242
	HYP	35.1 ± 0.5[b,c]	18.1 ± 4.6	9.7 ± 2.2	−2.1 ± 2.7	2.1 ± 0.7	340 ± 67	1382 ± 168
RW0	CS-S	36.6 ± 0.5[a,b]	24.2 ± 3.3	15.1 ± 2.3	−3.0 ± 1.1	2.4 ± 1.0	362 ± 109	1406 ± 430
	CS-M	35.7 ± 0.2[a,c]	24.5 ± 3.1	16.2 ± 1.7	−2.6 ± 1.0	2.2 ± 0.8	333 ± 58	1347 ± 156
	HYP	34.6 ± 0.9[b,c]	25.9 ± 2.9	14.4 ± 3.4	−3.1 ± 1.1	2.7 ± 0.5	344 ± 77	1676 ± 246
RW15	CS-S	37.1 ± 0.4[a]	29.7 ± 2.8	19.2 ± 3.3	−2.1 ± 1.3	1.8 ± 1.0	334 ± 48	1493 ± 290
	CS-M	36.7 ± 0.4[a]	29.8 ± 3.4	19.2 ± 2.3	−0.9 ± 1.4	2.0 ± 0.6	299 ± 54	1388 ± 181
	HYP	35.7 ± 0.8[b,c]	31.1 ± 2.3	17.4 ± 2.6	−2.1 ± 2.0	2.3 ± 0.8	354 ± 70	1517 ± 249
RW60	CS-S	37.2 ± 0.3[a,b]	32.4 ± 1.6	19.4 ± 3.4	−0.5 ± 1.5	0.4 ± 0.7	285 ± 36	1425 ± 176
	CS-M	36.8 ± 0.3[a,c]	32.3 ± 1.5	20.0 ± 1.9	0.9 ± 1.2	0.5 ± 0.7	282 ± 42	1330 ± 158
	HYP	36.4 ± 0.3[b,c]	33.0 ± 1.1	17.6 ± 4.0	0.0 ± 2.2	0.7 ± 1.0	279 ± 35	1439 ± 424

Note. CS-S (cold stress, slight; $T_c > 36$℃), CS-M (cold stress, moderate; T_c 35–36℃), and HYP (hypothermic; $T_c < 35$℃). Comparisons between groups are within each time point.
[a]Significantly different from HYP. [b]Significantly different from CS-M. [c]Significantly different from CS-S. Significance at $p < 0.05$.

SRT [$F(2,22) = 0.40$, $p = 0.677$] or CRT [$F(2,22) = 0.67$, $p = 0.522$].

Discussion

This study evaluated physiological, perceptual, and psychomotor responses in military personnel during a cold water immersion and rewarming military exercise to determine the influence of T_c on psychomotor performance. Findings from this study highlight two important considerations for those that operate, work, or compete in cold weather environments. First, although T_c was different among the three groups, which was anticipated by study design, psychomotor performance was not different among the groups, suggesting that T_c is likely not the primary physiological factor driving the deterioration of psychomotor performance upon exposure to cold stress. Second, despite the same environmental conditions and exposure protocol, clothing ensembles, and homogeneous characteristics of all participants, there was large T_c variability (ranging from 33.4 to 37.8℃) immediately following cold water immersion. This information is valuable for these populations, as anticipating large variances in T_c could lead to better preparedness (i.e., taking actions to prevent hypothermia and establishing rewarming/recovery protocols).

Influence of Core Temperature on Psychomotor Performance

Findings from the current study indicate that T_c declined to levels of hypothermia (i.e., <35℃) with an associated psychomotor performance deterioration similar to those with minimal or no decline in T_c (i.e., >36℃). The reasons for this lack of T_c influence on psychomotor performance could be many, and other factors like skin temperature, cognitive distraction, or loss of manual dexterity could have a greater influence on psychomotor performance than T_c. Specifically, a drop in skin temperature that reduces manual dexterity, along with activation of nociceptors and thermal receptors that cause uncomfortable cold sensations and distraction, could interact to limit psychomotor performance (Enander, 1987). Studies examining the influence of peripheral measurements on psychomotor performance have revealed other mechanisms that cause performance deterioration, as Muller et al. (2012) suggest that acute cold exposure with no change in T_c, but reduced skin temperature, can lead to poor psychomotor performance.

It is also plausible that T_c did not influence the specific tasks (SRT and CRT) used in the current study, as it has been established that not all cognitive and psychomotor performance tasks deteriorate to the same extent in cold environments. Pilcher et al. (2002) published a meta-analysis examining ten studies that report on cognitive performance in the cold and, indeed, many of these studies report conflicting findings across cognitive tasks. Pilcher et al. indicate that the most impacted aspects of cognitive performance by cold are reasoning, learning, and memory (grouped as one category). Minimal or no effects of cold were observed for reaction time, attention/perceptual, and mathematical processing tasks (Pilcher et al., 2002). To examine the role of T_c across varying cognitive tasks assessed in the cold, Coleshaw et al. (1983) isolated T_c following cold water immersion to determine its influence on memory, data recall, speed, and accuracy. Coleshaw et al. lowered T_c to 34–35℃ using cold water immersion and then transferred participants to a warm bath. When cognitive assessments were administered, subjects felt thermally comfortable and had warm skin, yet their T_c was still between 34 and 35℃. They reported that short-term memory was impaired, learned memory was unaffected, mathematical processing speed was impaired, and mathematical accuracy was unaffected (Coleshaw et al., 1983). Therefore, even though participants were hypothermic, it appears that the extent of performance deterioration may relate to temperature change sensitivity among different brain regions that are responsible for the execution of different tasks. This could explain why different cognitive tasks are influenced dissimilarly when lower T_c, and presumably lower brain temperatures, is experienced. However, to identify specific regions of brain activation during cold stress and cognitive testing, more robust research methods are required that incorporate whole-body cold stress, cognitive performance assessment, and electrophysiological and T_c measurements.

Electrophysiological activity of the brain's response to whole-body cold stress is not well defined, and even less is known about brain activity during cognitive testing in cold environments or when hypothermic (Jones et al., 2017). Several studies have examined brain activity during the cold pressor test, but this is not representative (i.e., no T_c change) of the severity of cold stress experienced during whole-body cold exposure. Both FitzGibbon et al. (1984) and Jones et al. (2019) measured brain activity during cold water immersion and hypothermia while participants underwent visual evoked potential testing, but given that these are the only available investigations on the topic, the issue is still not adequately addressed. Additionally, these studies were either underpowered (FitzGibbon et al., 1984; $n = 5$) or did not offer specific explanations as to how T_c could have influenced cognitive and psychomotor performance (Jones et al., 2019). Although minimal influence of T_c on cognitive performance in cold environments has also been reported by others (O'Brien et al., 2007), the precise interactions of T_c, brain temperature and activity, and cognitive performance are yet to be determined.

Variability of Core Temperature Responses to Cold Water Immersion

In recent investigations of warfighters performing cold water immersion training, large variations in heat loss were observed, resulting in T_c that ranged from 33 to 38℃ (Cooper et al., 2017), similar to the findings we report in the current study. T_c is a byproduct of the body's heat loss and gain, which is strongly influenced by environmental factors and individual variances such as vascular response, subcutaneous fat amount, body surface area, muscular composition, and metabolic rate (Hayward & Keatinge, 1981; Sessler et al., 1990; Stocks et al., 2004). When exposed to cold stress, changes in each of these elements can contribute to large variations in heat loss among individuals. We observed significant BMI differences, as well as large effect sizes for weight and percent body fat (primarily between CS-S and HYP), among the groups. Although these findings are not novel with respect to explanations that have been provided for heat loss in cold environments, they likely contribute, at least in some part, to the variances in heat loss observed in the current study.

Explanations for heat loss variability can also be presented on a neural level, as Mittleman and Mekjavic (1991) suggest that differences in central thermosensitivity could be responsible for variable T_c responses to cold water immersion, a theory that also has relevance to cognitive and psychomotor performance. Their findings are supported by others that have shown variability in temperature sensitivity of neurons in the hypothalamus that influence thermoregulation (Baldino & Geller, 1982; Nakayama, 1985). For example, one could have slightly more warm-sensitive neurons (i.e., better thermoregulatory capability in warm versus cold environments) or may have greater sensitivity in cold-sensitive neurons, leading to better thermoregulation in the cold. Our findings of variable heat loss rates in a homogeneous group immersed in cold water provide additional evidence to support the many others that report this finding (Brazaitis et al., 2014; Molnar, 1946; Nuckton et al., 2000; Wittmers & Savage, 2001). Such wide-ranging T_c responses to cold water immersion should be taken into consideration for those who anticipate cold water immersion exposure among many individuals, even if they have similar characteristics. Similar T_c outcomes following cold water immersion should not be assumed.

Limitations

Several limitations are present in the current study relating to study design, cognitive task choice, and study noise that should be considered when interpreting findings. First, the study was embedded in a field military training exercise and the design was, therefore, confined to the limitations of the training exercise. For example, water and air temperature, although measured, were not strictly controlled. Air and water temperatures did not change drastically during data collection, but they were not chosen by investigators or precisely controlled, as they would be in laboratory settings. It should be noted that our findings could vary if repeated under different water or air temperatures, as differences in ambient temperature can influence performance differently (Mäkinen et al., 2006; O'Brien et al., 2007). Second, cognitive tasks were designed to meet the timing requirements of the training exercise. Had more time been allotted, a more comprehensive test battery covering more aspects of cognitive performance could have been conducted. We chose SRT and CRT given the strong military relevance to vigilance (rapidly identifying stimuli; SRT) and quick decision making (CRT), which are essential components to military performance (Liebermann et al., 2005). It must be acknowledged that different cognitive tasks could result in different outcomes, as T_c may not have influenced performance on the tasks used in this study, but may influence other aspects of cognitive performance. Lastly, participants were instructed to focus on testing and limit noise and talking. Although we attempted to maintain a quiet environment free of outside distractions, we cannot confidently state that distractions to the participants were not present during testing. This limitation may detract from the internal validity of the study, but does improve the ecological validity, wherein the testing environment parallels a realistic operational setting where many distractions are likely present. Although we observed a deterioration in psychomotor performance that does not appear to be influenced directly by T_c, these limitations should be considered when interpreting study results.

Conclusion

Findings from the current study suggest that a 10-min cold (1℃) water immersion deteriorates psychomotor performance which, even in the presence of mild hypothermia, is not directly influenced by T_c. As such, additional measurements are needed to adequately quantify and predict psychomotor performance deterioration in cold environments. Additional observations reveal large variations in T_c among a homogeneous group in response to cold water immersion. These findings should be considered for populations that frequent cold water environments. Future work should seek to evaluate other psychomotor tasks and identify other contributing physiological factors that impact performance in cold environments.

Declarations

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Declarations of interest: none.

Ethics approval: The study protocol was approved by the Naval Health Research Center Institutional Review Board in compliance with all applicable federal regulations governing the protection of human subjects. Research data

were derived from an approved Naval Health Research Center, Institutional Review Board protocol number NHRC.2019.0007.

Consent to participate: Informed consent was obtained from all individual participants included in the study.

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