Commercial Heat Packs do not Influence Cognitive Performance Following Cold Water Immersion

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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.

EXECUTIVE SUMMARY

Exposure to cold water immersion (CWI) deteriorates cognitive performance, which negatively impacts warfighter readiness. Recovery of performance following CWI may be mediated by improving thermal perception, and the application of commercially-available heat packs may facilitate such a response. This work evaluated the effects of exogenous heat application on temperature sensation and cognition following 10 minutes of CWI. Thirty-six participants (age: 28 ± 6 yrs, 177 ± 7 cm, 79.8 ± 10.4 kg) had their heart rate, mean skin temperature ($\overline{T}_{sk}$), hand temperature (T_{hand}), core temperature (T_c), thermal sensation (TS), shivering sensation (SS), and cognitive performance (match-to-sample (MTS) and simple reaction time (SRT)) measured during a CWI and rewarming exercise. During rewarming, heat packs were applied to eight body sites for a treatment group. Compared with pre-immersion, CWI elicited significant reductions in T_c (37.3 ± 0.4 vs. 36.3 ± 1.0°C), T_{hand} (20.2 ± 3.2 vs. 9.2 ± 2.0°C), and $\overline{T}_{sk}$ (28.9 ± 2.5 vs. 14.1 ± 1.4°C) and impaired cognitive performance (RT_{SRT}: 278 ± 29 vs. 321 ± 58 ms). After 60-min rewarming, cognitive performance improved significantly compared to the start of rewarming (RT_{SRT}: 287 ± 28 vs. 333 ± 71 ms; TC_{MTS}: 22 ± 2 vs. 20 ± 3 trials correct). However, no group differences were observed for any cognitive measure between treatment and control. Findings from the current study suggest that external heat application does not influence any physiological, perceptual, or cognitive responses during rewarming.

Abbreviations:

ANOVA – analysis of variance

CWI – cold water immersion

MCMWTC – Marine Corps Mountain Warfare Training Center

MTS – match-to-sample

RT – reaction time

SRT – simple reaction time

SS – shivering sensation

T_c – core temperature

TC – trials correct

T_{hand} – hand temperature

TS – thermal sensation

$\bar{T}_{sk}$ – mean skin temperature

Introduction

Warfighters are often exposed to severe environmental stressors that degrade operational performance and impact mission readiness. Recovery from such environmental insults is critical to quickly reestablish warfighter effectiveness and meet mission objectives. It is well-documented that both physiological and cognitive impairments occur during severe cold stress such as cold water immersion (Tipton 1989; Pilcher et al. 2002; Seo et al. 2013). Efforts evaluating recovery from cold water immersion have largely focused on physiological recovery (i.e., core temperature (T_c) monitoring), with less attention given to cognitive recovery, which plays a significant role in warfighter readiness (Collis et al. 1977; Bristow et al. 1994; Giesbrecht et al. 1997; Miller et al. 2017). Current evidence suggests that it may take up to one hour, or longer, for T_c to return to normal (i.e., 37.0°C) following accidental hypothermia in field settings using recommended rewarming strategies (Giesbrecht et al. 1987). Cognition, however, is shown to be manipulated by temperature perception and may improve, or deteriorate, faster than changes in body temperature. To illustrate this, Gaoua et al. (2012) passively exposed participants to extreme heat stress for a brief period. While T_c did not change during this short exposure, the cognitive performance degradation observed suggests a strong association with temperature perception alterations. This response has also been documented upon exposure to cold air (Muller et al. 2012). It is possible, therefore, that cognitive performance may be quickly recovered in the cold by changing temperature perception.

Temperature perception is a powerful driver of human behavior (Gagge et al. 1967; Schlader et al. 2011). This is best exemplified by the behavior of donning or doffing clothing during exposure to hot or cold environments. For the warfighter attempting to recover from accidental hypothermia, a quick change in temperature perception may facilitate an improvement, allowing the warfighter to maintain optimal cognitive performance despite a reduction in body temperature. Commercially-available heat packs may be one technique to accomplish this, as they are quickly activated, easy to carry and transport, and can be externally-applied to almost any part of the body. By applying several heat packs to a mildly-hypothermic individual, an exogenous heat stimulus can be created to impact a large number of thermal receptors and, in theory, alter whole-body temperature perception.

The purpose of this work was to examine the influence of exogenous skin temperature warming and alterations in temperature sensation on cognitive responses following a whole-body cold water immersion during a military field training exercise. It was hypothesized that by applying an exogenous heat stimulus and thus likely improving temperature sensation, warfighters would improve their performance on cognitive tasks. These findings may reveal strategies that could be employed by warfighters and other populations that frequent cold environments to enhance performance following accidental immersion in cold water.

Methods

Study Design

This study was a parallel, non-randomized trial designed to assess the effects of exogenous heat application compared to a no-treatment control on skin rewarming, temperature perception, and measures of cognitive performance during a cold water immersion military training exercise.

Research Participants

Thirty-six active duty military personnel enrolled at the Marine Corps Mountain Warfare Training Center's (MCMWTC) Cold Weather Medicine course participated in this study. As a course requirement, participants are required to complete 10 minutes of immersion in a frozen pond followed by 60 minutes of field rewarming in a controlled setting under medical supervision (Figure 1). Participant age, height, weight, body mass index (BMI), and percent body fat are listed in Table 1. 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).

Fig. 1 Image showing the frozen pond with participants submerged for 10 minutes before the 60-minute rewarming exercise

Military Field Training Exercise

All testing was completed at the MCMWTC in Bridgeport, CA, at an elevation, air temperature, and water temperature of 2100 meters, -5°C and 1°C, respectively. MCMWTC staff instructed participants to avoid any alcohol, tobacco, or caffeine consumption 24 hours prior to the start of the cold water immersion and rewarming exercise. On the day of the exercise, participants convened in a classroom with course instructors for a final brief on immersion and rewarming procedures. All participants in the class convened at this time to account for cycling in core temperature throughout the day due to circadian rhythms. The class then relocated outside to a nearby area with a pond and deck that would serve as the sites for immersion and rewarming, respectively.

Per the MCMWTC's course procedures, participants completed immersion for 10 minutes. Following pond egress, participants remained in their wet clothing for an additional 10 minutes post-immersion before changing into dry clothing. During the final stage of the exercise, participants were instructed to passively rewarm in their sleeping bags for 60 minutes.

Experimental Protocol

Prior to the start of immersion and rewarming, participants were randomly divided into either a treatment group that used commercial heat packs (HEAT; *n*=18) during passive rewarming or a control group that did not (CON; *n*=18) using a 1:1 allocation ratio, as determined by the principal investigator. Allocation was not concealed. Eight 9.5 x 12.7 cm HotHands[R] adhesive heating packs (Kobayashi, Dalton, GA) were applied to eight body sites to increase skin temperature and alter temperature perception during passive rewarming in the cold. As dry clothing was donned following immersion, research staff placed the pre-activated commercial heating packs on participants who were assigned to the HEAT group. To avoid potential harm by placing directly on the skin (contraindicated by the heat pack manufacturer), heat packs were first applied to a strip of moleskin (Medline Industries, Inc., Northfield, IL), which was then applied to participants' skin on the waistline area of the lower back (1 heat pack), lateral sides of the abdomen (2 heat packs), the dorsal side of the dominant hand (1 heat pack), ventral sides of feet (2 heat packs), on the back between each scapula (1 heat pack), and the sternum (1 heat pack); (Figure 2) . Previous work determined that the selected heat packs achieve maximal and average heating temperatures of 70°C and 57°C, respectively, within 30 minutes following activation (Sands et al. 2009). Research staff ensured heat packs were activated for 30 minutes prior to application on participants' skin.

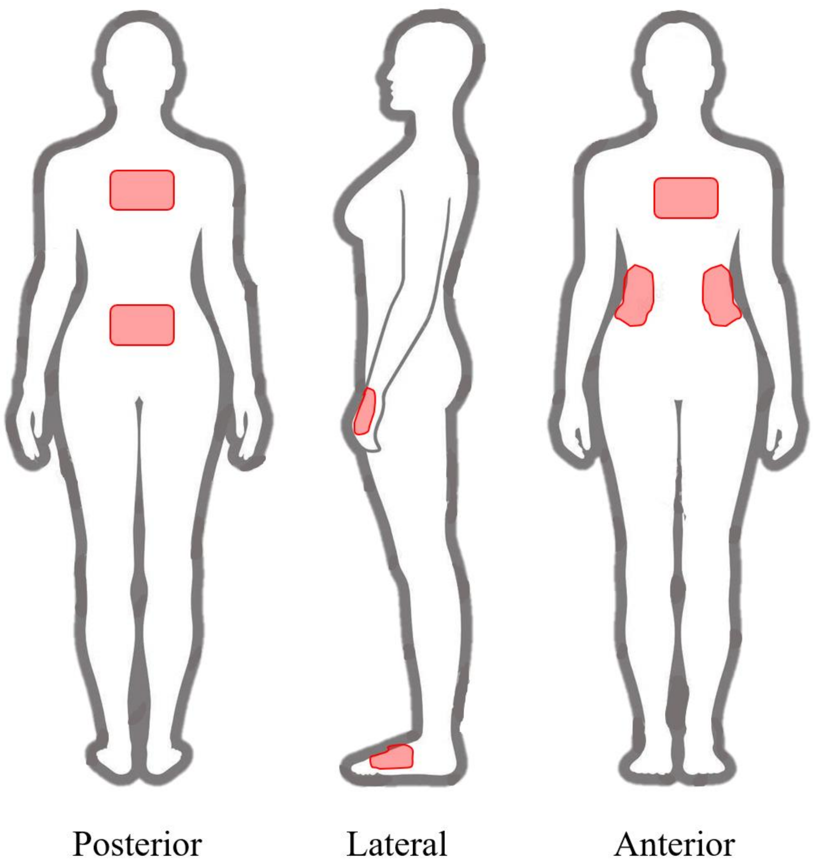

Fig. 2 Anatomical placement of eight commercial heating packs on subjects allocated to treatment group. One of the heat packs placed on the ventral side of the foot is omitted in this figure

In accordance with the timing and events of the military training exercise, cognitive, perceptual, and physiological measurements were recorded at seven stations: 1) indoors in ambient conditions (baseline), 2) prior to immersion (pre-immersion), 3) during 10 minutes of immersion (cold water immersion), 4) a 10-minute period of remaining in wet clothing after exiting the pond (post-immersion), 5) at the start of rewarming (rewarm 0), 6) after 15 minutes of rewarming (rewarm 15), and 7) at the conclusion of the 60-minute rewarming exercise (rewarm 60); (Figure 3).

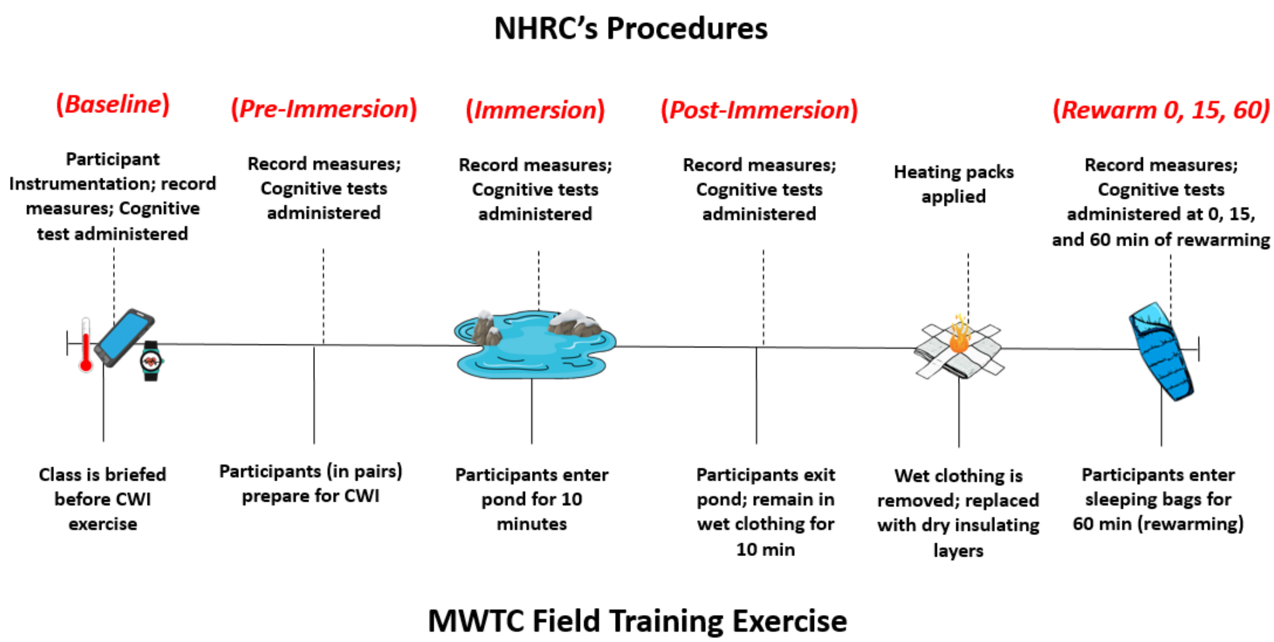

Fig. 3 Timeline of events during the cold water immersion and rewarming exercise. Items listed on the bottom of the timeline represent tasks and events implemented by MWTC. Items listed above the timeline represent experimental procedures implemented by NHRC

Physiological Measurements

Physiological measurements were recorded and stored each minute during the exercise. Heart rate (HR) was monitored with telemetry chest straps (Polar Electro, Lake Success, NY). Skin temperature measurements were collected using wireless transmitting dermal adhesive patches (Vital Sense, Respironics, Bend, OR) that were placed on the right side of the participants' body over the pectoralis muscle, medial deltoid, and the midpoint of the anterior thigh. These measurement sites were used to calculate mean skin temperature ($\overline{T}_{sk}$) in accordance with methods previously established (Ramanathan 1964). Additionally, hand skin temperature (T_{hand}) was measured on the dorsal side of the participants' non-dominant hand. T_c was measured wirelessly with an ingestible pill (Vital Sense, Respironics, Bend, OR) that was consumed the night before testing (ingestion time ~ 7 hours before testing). All temperature measurements were wirelessly transmitted and stored to portable Vital Sense monitors (Vital Sense, Respironics, Bend, OR) that were worn with each subject.

Perceptual and Cognitive Measurements

Perceptual measurements for thermal sensation (TS) and shivering sensation (SS) were recorded at each of the seven stations using scales commonly used in thermal physiology research (Zhang et al. 2004; Badjatia et al. 2008). Participants were shown each scale and were asked to verbally indicate how they felt. TS was rated as -4 = very cold, -3 = cold, -2 = cool, -1 = slightly cool, 0 = neutral, +1 = slightly warm, +2 = warm, +3 = Hot, +4 = very hot and SS as 0 = no shivering, 1 = slight shivering, 2 = moderate shivering, 3 = vigorous shivering. After the collection of measurements at each station, participants immediately began a battery of cognitive tests.

Cognitive function was measured using two validated tests that were administered immediately after perceptual measurements throughout the stations of the exercise. Reaction time and working memory were assessed using Simple Reaction Time (SRT) and Match-to-Sample (MTS) tests, respectively (Niemi and Naatanen 1981; Hasselmo and Stern 2006). In addition to memory, the MTS task also incorporated elements of learned association, attention, and visual-spatial discrimination. The battery of cognitive tests was administered using E-Prime 3.0 software (Psychology Software Tools, Pittsburgh, PA) and displayed on a 25.7 cm Acer One 10 portable electronic tablet (Acer America, San Jose, CA). Responses were recorded using a millisecond accurate timing response box (Psychology Software Tools, Pittsburgh, PA). The order of administration between the SRT and MTS tasks was randomized during each administration of the cognitive battery.

The SRT task presented a 3.4 x 3.4 cm black star (stimulus) that appeared at the center of the screen's display. Participants were instructed to respond as quickly as possible at the onset of the stimulus by pressing any of 5 buttons on the timing response box (Figure 4). There were 40 trials (i.e., the onset of star images) during the task, with each star stimulus having a maximum allowable response time of 1000 milliseconds (ms), which was defined as the response window. Responses outside of this window were classified as anticipatory and late responses, which were not included in mean reaction time calculations for each testing session. The inter-stimulus interval was random and ranged between 600-3000 ms between each stimulus presentation. Participant feedback (i.e., reaction time, late response, anticipatory response) was not given to participants during or after the completion of the task as to not influence their performance. The completion of the SRT task was analyzed for mean reaction time (RT_{SRT}). In each trial of the MTS task, participants were presented with two stimuli separated by time. The first stimulus was a response-independent "memory image" – a 4-square by 4-square tri-colored grid which could have any combination of the 16 squares in the grid colored orange, blue, or white. This 4.0 x 4.0 cm image was presented for 2000 ms to participants so that the image could be memorized. The image then disappeared, and the screen's display remained blank for a time period that was randomized over an interval of 600-3000 ms. Responses were not collected during this period. The presentation of the second stimulus, the “choice images,” two 4-square by 4-square tricolored grids (left grid vs. right grid), followed. Participants were instructed to determine which of the two “choice images” were identical to the original “memory image” previously presented, or if neither of the two images were identical to the original (non-match). Participants were given a maximum of 3000 ms to make this determination, which was defined as the response window. Responses were recorded using a 5-button response box which had buttons that were presented horizontally next to one another. Buttons 1 (left-most) and 5 (right-most) were used to indicate a left match and right match, respectively, of the two possible “choice images” to the original “memory image”, while pressing any of buttons 2, 3, and 4 (middle buttons) represented a non-match (Figure 5). Twenty-five trials were presented in this task, which was fixed to comprise 20 matching and 5 non-matching trials that were presented in random order. The MTS task was analyzed for mean reaction time (RT_{MTS}) and for the number of trials correct (TC_{MTS}).

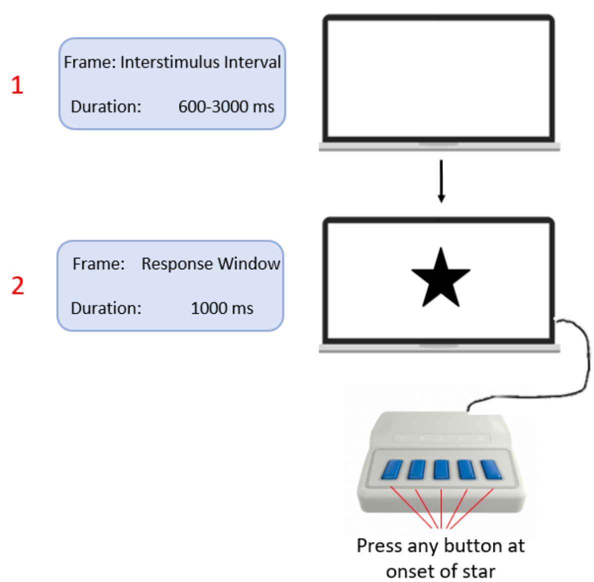

Fig. 4 Administration of the SRT task with stimulus, monitor, and response box

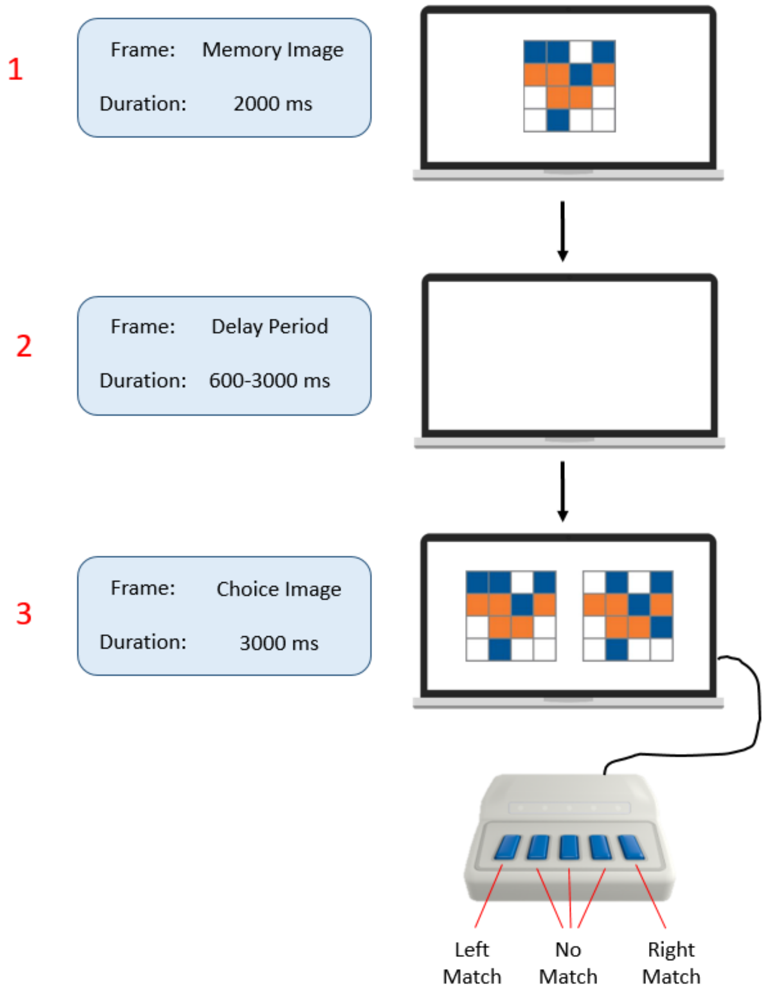

Fig. 5 Administration of the MTS task with stimulus, monitor, and response box

On the day before the exercise, participants were required to demonstrate familiarization with the cognitive tasks so that a learning effect could be eliminated before baseline testing. To show competency with the instructions of the tests, the devices used, length of test, and the stimuli presented, participants completed the SRT task once and the MTS as many times as needed to achieve three scores of at least 75%. These scores need not be consecutive.

Statistical Analyses

Physiological, perceptual and cognitive data were analyzed prior to analyzing data from the rewarming exercise to document responses to cold water immersion. Comparisons for T_c, $\overline{T}_{sk}$, T_{hand}, HR, RT_{SRT}, RT_{MTS}, and TC_{MTS} were analyzed with repeated measure analysis of variance (ANOVA). Multiple comparision *post hoc* using a Bonferroni correction were used to determine differences, if any, between pre-immersion, immersion, and post-immersion values and a partial eta squared (η_p^2) was used to represent effect sizes for the independent variables. Non-parametric analyses (Freidman tests with post hoc Wilcoxin signed-ranked tests) were conducted to compare differences in SS and TS among pre-immersion, immersion, and post-immersion time points. A Kendall Coefficient of Concordance (Kendall's W) was used as a measure of the Friedman tests effect size.

Rewarming data were evaluated to determine the effect of heat pack use (i.e., enhanced rewarming) on physiological, perceptual, and cognitive measures. For perceptual data, Freidman tests, with post hoc Wilcoxin signed-rank tests, were used to compare the changes in SS and TS among post-immersion, rewarm 0, rewarm 15, and rewarm 60. A Mann-Whiney U test was also used to compare SS and TS measurements at post-immersion, rewarm 0, rewarm 15, and rewarm 60 between CON and HEAT.

Physiological and cognitive data (T_c, $\overline{T}_{sk}$, T_{hand}, HR, RT_{SRT}, RT_{MTS}, and TC_{MTS}) were analyzed with a 3 (station: rewarm 0, 15, and 60) by 2 (treatment: CON, HEAT) two-way repeated measures ANOVA so that comparisons could be made between the use and absence of commercial heat packs. Bonferroni post hoc tests were used to follow up any significant main effects or interactions. To ensure no existing differences were present between the CON and HEAT groups before evaluating the efficacy of heat packs, independent samples t-tests were used to compare physiological, perceptual, and cognitive differences between groups prior to heat pack application (post-immersion). Data are presented as mean ± SD, and statistical significance is considered when $p < 0.05$.

Results

Physiological, Perceptual, and Cognitive Responses to Cold Water Immersion

Results from repeated measurement analysis for T_c revealed a significant main effect for time ($p < 0.001$; $\eta_p^2 = 0.755$), with follow-up analyses indicating a reduction in T_c during post-immersion (35.5 ± 1.1°C) compared with both pre-immersion (37.3 ± 0.4°C; $p < 0.001$) and immersion (36.3 ± 1.0°C; p < 0.001). Additionally, immersion T_c was lower when compared with pre-immersion ($p < 0.001$). A similar main effect for time ($p < 0.001$) was observed for measurements of $\overline{T}_{sk}$ ($p < 0.001$; $\eta_p^2 = 0.953$) and T_{hand} ($p < 0.001$; $\eta_p^2 = 0.866$). $\overline{T}_{sk}$ recorded during post-immersion (18.8 ± 1.4°C) was lower than pre-immersion (28.9 ± 2.5^{o}C; $p < 0.001$), yet higher than immersion (14.1 ± 1.4^{o}C; $p < 0.001$). Immersion $\overline{T}_{sk}$ was lower than pre-immersion ($p < 0.001$). Post-immersion T_{hand} (12.6 ± 2.6^{o}C) was also lower than pre-immersion (20.2 ± 3.2^{o}C; $p < 0.001$) and higher than immersion (9.2 ± 2.0^{o}C; $p < 0.001$). Immersion T_{hand} was lower than pre-immersion ($p < 0.001$). Analysis of HR revealed a main effect for time ($p = 0.002$; $\eta_p^2 = 0.542$) with follow-up tests indicating higher HR at immersion (100 ± 11 bpm) compared with pre-immersion (86 ± 11 bpm; p = 0.006) and post-immersion (86 ± 12 bpm; $p = 0.010$).

Non-parametric analyses for TS and SS examined changes in perception between pre-immersion, immersion, and post-immersion and indicated significant effects of time for both TS ($p < 0.001$; Kendall's W = 0.710) and SS ($p < 0.001$; Kendall's W = 0.575). Follow-up Wilcoxon Signed Rank Tests revealed TS to be lower (i.e., participants felt colder) for both immersion (-3.2 ± 0.8; $p < 0.001$) and post-immersion (-3.1 ± 1.2; $p < 0.001$) compared with pre-immersion (-1.1 ± 1.1). Additionally, pre-immersion SS values (0.5 ± 0.5) were lower (i.e., less perceived shivering) compared with immersion (1.0 ± 1.0; $p = 0.003$) and post-immersion (1.8 ± 0.8, $p < 0.001$). Participants reported significantly more shivering during post-immersion compared with pre-immersion and immersion ($p < 0.05$).

		Sample Size (n)	Mean ± STD	p value
Age (yrs)	*HEAT*	18	27 ± 5	
	CON	18	28 ± 6	0.572
	All Participants	36	28 ± 6	
Height (cm)	*HEAT*	18	176.8 ± 7.3	
	CON	18	176.1 ± 7.4	0.759
	All Participants	36	177.0 ± 7.0	
Weight (kg)	*HEAT*	18	78.8 ± 10.3	
	CON	18	80.7 ± 10.8	0.578
	All Participants	36	79.8 ± 10.4	
BMI (kg/m^2)	*HEAT*	18	25.1 ± 2.1	
	CON	18	26.0 ± 3.0	0.310
	All Participants	36	25.6 ± 2.6	
% Body Fat	*HEAT*	18	17.7 ± 5.2	
	CON	18	18.1 ± 5.4	0.835
	All Participants	36	17.9 ± 5.3	

Table 1. Table presenting participant characteristics and the statistical differences between HEAT and CON for the characteristics presented. * Significantly different ($p < 0.05$) between HEAT and CON.

Results from the SRT task showed a significant main effect of time for RT_{SRT} ($p < 0.001$; $\eta_p^2 = 0.484$). Follow-up tests revealed longer RT_{SRT} at post-immersion (355 ± 76 ms; $p = 0.002$) and immersion (321 ± 58 ms; $p = 0.010$) compared with pre-immersion (278 ± 29 ms). Results from MTS tasks indicate a significant effect of time for both RT_{MTS} ($p = 0.019$; $\eta_p^2 = 0.267$) and

TC_{MTS} ($p = 0.025$; $\eta_p^2 = 0.246$). RT_{MTS} and TC_{MTS} were both only different between pre-immersion and post-immersion ($p = 0.045$ and $p = 0.013$, respectively), with no differences observed between immersion and pre-immersion or post-immersion (Table 2).

	Pre-Immersion	**Immersion**	**Post-Immersion**
T_c (°C)	37.3 ± 0.4	36.3 ± 1.0§	35.5 ± 1.1†
T_{hand} (°C)	20.2 ± 3.2	9.2 ± 2.0§	12.6 ± 2.6†
$\bar{T}_{sk}$ (°C)	28.9 ± 2.5	14.1 ± 1.4§	18.8 ± 1.4†
HR (bpm)	86 ± 11	100 ± 11*	86 ± 12†
TS	-1.1 ± 1.1	-3.2 ± 0.8*	-3.1 ± 1.2*
SS	0.5 ± 0.5	1.0 ± 1.0*	1.8 ± 0.8†
RT_{SRT} (ms)	278 ± 29	321 ± 58*	355 ± 76*
RT_{MTS} (ms)	1298 ± 226	1528 ± 210	1534 ± 227*
TC_{MTS} (#)	20 ± 3	17 ± 4	20 ± 3†

Table 2. *Table presenting the physiological, perceptual, and cognitive measurements obtained prior to onset of the rewarming exercise. * Significantly different (p < 0.05) from Pre-Immersion, † Significantly different (p < 0.05) from Pre-Immersion and Immersion, ‡ Significantly different (p < 0.05) from Immersion, § Significantly different (p < 0.05) from Pre- and Post-Immersion.*

Physiological, Perceptual, and Cognitive Responses during Rewarming

Heating packs were applied to the HEAT group immediately prior to the start of rewarming. To ensure that no differences between participants assigned to CON and HEAT were present prior to heat pack application, independent t tests were used to compare CON vs. HEAT for all measures. Results confirmed that no differences were present between participants assigned to CON and HEAT at the time heat packs were applied.

Mixed ANOVAs, comparing CON and HEAT during rewarming (Table 3), revealed a significant main effect of time for T_c ($p < 0.001$; $\eta_p^2 = 0.611$), but no significant group ($p = 0.686$; $\eta_p^2 = 0.011$) or group x time interaction ($p = 0.542$; $\eta_p^2 = 0.014$). At *rewarm 0* (36.0 ± 0.8°C), T_c was lower compared with *rewarm 15* (36.8 ± 0.4°C; $p < 0.001$) and *rewarm 60* (36.8 ± 0.4°C; $p < 0.001$). $\overline{T}_{sk}$ demonstrated a similar rewarming response, in that a main effect for time was observed ($p < 0.001$; $\eta_p^2 = 0.918$), but no group ($p = 0.720$; $\eta_p^2 = 0.005$) or group x time interaction ($p = 0.310$; $\eta_p^2 = 0.045$). $\overline{T}_{sk}$ at *rewarm 0* (28.1 ± 2.1°C) was lower than *rewarm 15* (32.5 ± 1.4°C; $p < 0.001$) and *rewarm 60* (32.7 ± 1.6°C; $p < 0.001$). A main effect for time was observed for T_{hand} ($p < 0.001$; $\eta_p^2 = 0.811$), but no group ($p = 0.991$; $\eta_p^2 = 0.057$) or group x time interaction ($p = 0.076$; $\eta_p^2 = 0.040$) was present. T_{hand} at *rewarm 0* (18.7 ± 4.2°C) was lower than *rewarm 15* (20.4 ± 3.9°C; $p = 0.003$) and *rewarm 60* (20.5 ± 4.1°C; $p = 0.002$). Analysis of HR during rewarming revealed a main effect for time ($p = 0.002$; $\eta_p^2 = 0.625$) with no group ($p = 0.363$; $\eta_p^2 = 0.076$) or group x time interaction ($p = 0.945$; $\eta_p^2 = 0.005$). Specifically, HR increased from *rewarm 0* (96 ± 2 bpm) to *rewarm 15* (109 ± 4 bpm; p = 0.026). The remaining 45 minutes of rewarming were characterized by a significant depression in HR, with *rewarm 60* (82 ± 14 bpm) significantly lower than both *rewarm 0* ($p = 0.007$) and *rewarm 15* ($p < 0.001$).

		Rewarm 0	Rewarm 15	Rewarm 60
T_c (°C)	*HEAT*	35.9 ± 0.9	36.7 ± 0.4	36.8 ± 0.4
	CON	36.1 ± 0.8	36.8 ± 0.5	36.8 ± 0.4
	All Participants	36.0 ± 0.8	36.8 ± 0.4*	36.8 ± 0.4*
T_{hand} (°C)	*HEAT*	18.2 ± 4.2	20.5 ± 4.4	20.9 ± 4.6
	CON	19.2 ± 4.3	20.4 ± 3.6	20.1 ± 3.7
	All Participants	18.7 ± 4.2	20.4 ± 3.9*	20.5 ± 4.1*
$\overline{T}_{sk}$ (°C)	*HEAT*	27.8 ± 2.1	32.4 ± 1.6	32.7 ± 1.9
	CON	28.4 ± 2.1	32.6 ± 1.1	32.6 ± 1.2
	All Participants	28.1 ± 2.1	32.5 ± 1.4*	32.7 ± 1.6*
HR (bpm)	*HEAT*	99 ± 10	111 ± 15	83 ± 17
	CON	93 ± 3	107 ± 15	80 ± 8
	All Participants	97 ± 8	109 ± 15*	82 ± 14†
TS	*HEAT*	-2.6 ± 0.9	-1.2 ± 1.3	0.3 ± 1.3
	CON	-2.4 ± 1.3	-1.1 ± 1.7	0.3 ± 1.8
	All Participants	-2.6 ± 1.1	-1.1 ± 1.5*	0.3 ± 1.6†
SS	*HEAT*	2.3 ± 0.7	1.6 ± 0.9	0.1 ± 0.3
	CON	2.2 ± 0.9	1.5 ± 0.8	0.3 ± 0.6
	All Participants	2.2 ± 0.8	1.5 ± 0.8*	0.1 ± 0.5†
RT_{SRT} (ms)	*HEAT*	333 ± 67	311 ± 52	286 ± 31
	CON	332 ± 75	316 ± 50	288 ± 26
	All Participants	333 ± 71	314 ± 50	287 ± 28†
RT_{MTS} (ms)	*HEAT*	1444 ± 259	1496 ± 195	1466 ± 211
	CON	1539 ± 243	1537 ± 265	1391 ± 204
	All Participants	1496 ± 251	1518 ± 233	1426 ± 208‡
TC_{MTS} (#)	*HEAT*	19 ± 3	21 ± 3	21 ± 3
	CON	20 ± 2	20 ± 3	22 ± 2
	All Participants	20 ± 3	20 ± 3	22 ± 2†

Table 3. Table presenting the group differences in the physiological, perceptual, and cognitive measurements recorded during the rewarming exercise. * Significantly different ($p < 0.05$) from Rewarm 0, † Significantly different ($p < 0.05$) from Rewarm 0 and Rewarm 15, ‡ Significantly different ($p < 0.05$) from Rewarm 15. No differences between heat pack and no heat pack were observed at any time point.

Non-parametric repeated measures analyses indicated a reduction in SS (*rewarm 0*: 2.2 ± 0.8, *rewarm 15*: 1.5 ± 0.8, *rewarm 60*: 0.1 ± 0.5; $p < 0.001$; Kendall's W = 0.793) and increased TS (*rewarm 0*: -2.6 ± 1.1, *rewarm 15*: -1.1 ± 1.5, *rewarm 60*: 0.3 ± 1.6; p < 0.001; Kendall's W = 0.750) throughout the rewarming exercise. Individual Mann-Whitney U tests identified no difference between CON and HEAT for SS at *rewarm 0* ($p = 0.838$), *rewarm 15* ($p = 0.919$), and *rewarm 60* ($p = 0.240$), and TS at *rewarm 0* ($p = 0.999$), *rewarm 15* ($p = 0.861$), and *rewarm 60* ($p = 0.969$).

A main effect of time for RT_{SRT} ($p < 0.001$; $\eta_p^2 = 0.291$) was observed during the 60-minute rewarming, with RT_{SRT} values decreasing from *rewarm 0* (333 ± 71 ms) to *rewarm 15* (314 ± 50 ms) and *rewarm 60* (287 ± 28 ms); (Figure 6). No group ($p = 0.903$; $\eta_p^2 = 0.001$) or group x time interaction ($p = 0.993$; $\eta_p^2 = 0.001$) was present. Follow up tests indicate that *rewarm 60* was lower than both *rewarm 0* ($p < 0.001$) and *rewarm 15* ($p < 0.001$).

During the MTS task, a main effect of time for RT_{MTS} ($p < 0.05$; $\eta_p^2 = 0.092$) was observed during the 60-minute rewarming (Figure 7). No group ($p = 0.776$; $\eta_p^2 = 0.003$) or group x time interaction ($p = 0.062$; $\eta_p^2 = 0.086$) was observed for RT_{MTS}. Follow up tests indicate that *rewarm 60* (1426 ± 208 ms) was lower than *rewarm 15* (1518 ± 233 ms; p = 0.04), but that no differences were present when *rewarm 0* (1496 ± 251 ms) was compared with *rewarm 15* ($p = 0.999$) and *rewarm 60* ($p = 0.375$).

The number of correct trials increased during rewarming, as indicated by a main effect for time for TC_{MTS} ($p < 0.001$; $\eta_p^2 = 0.220$); (Figure 8). However, no group ($p = 0.606$; $\eta_p^2 = 0.009$) or group x time interaction ($p = 0.071$; $\eta_p^2 = 0.087$) was present. Follow up tests revealed a greater number of correct trials for *rewarm 60* (22 ± 2) compared with both *rewarm 0* (20 ± 3; p < 0.001) and *rewarm 15* (20 ± 3; p = 0.014).

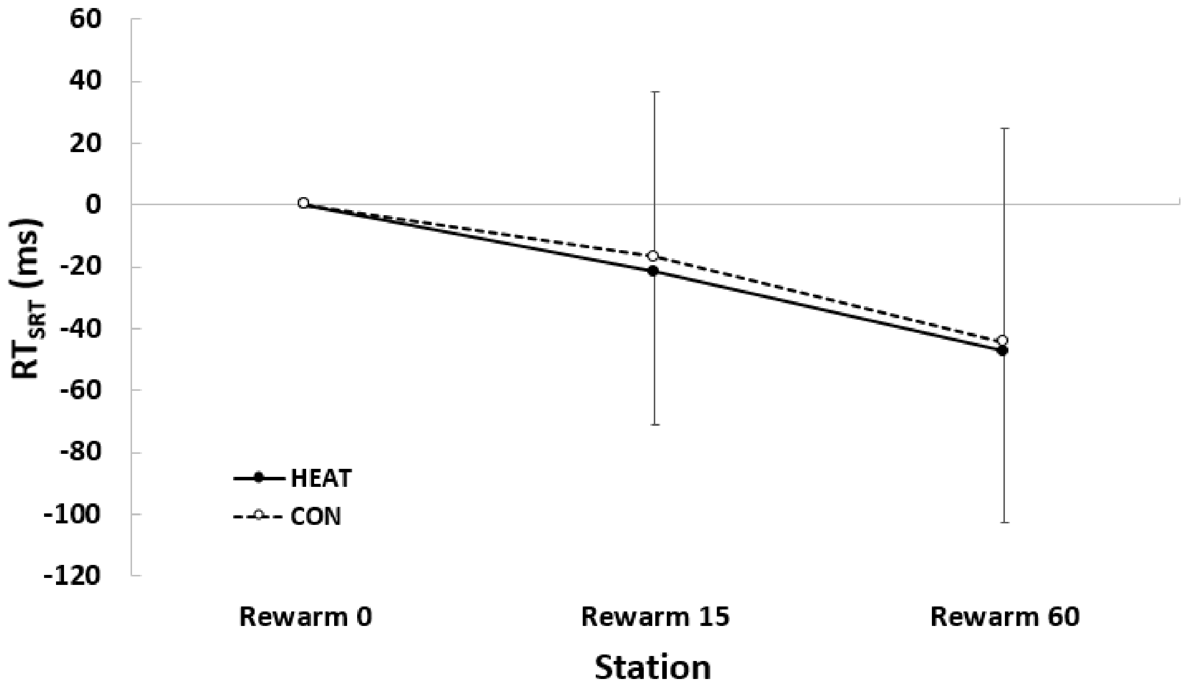

Fig. 6 Change in Simple Reaction Time task reaction time values (ms) from the onset of rewarming (Rewarm 0). There were no differences between the groups at any time point. Error bars represent one SD

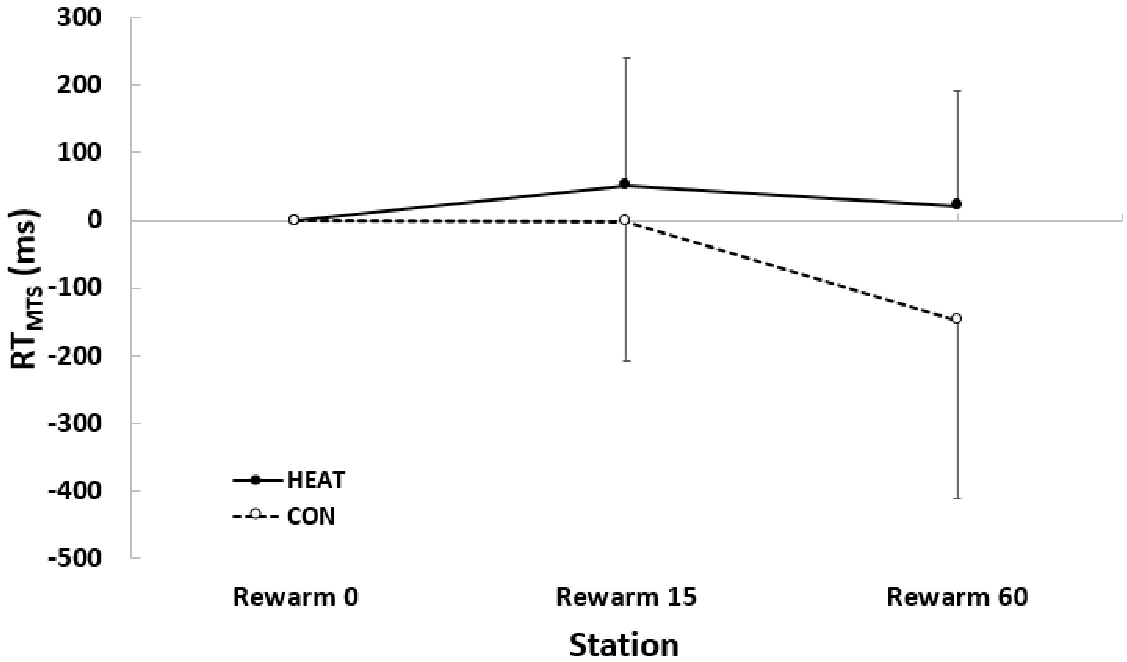

Fig. 7 Change in Match-to-Sample reaction time values (ms) from the onset of rewarming (Rewarm 0). There were no differences between the groups at any time point. Error bars represent one SD

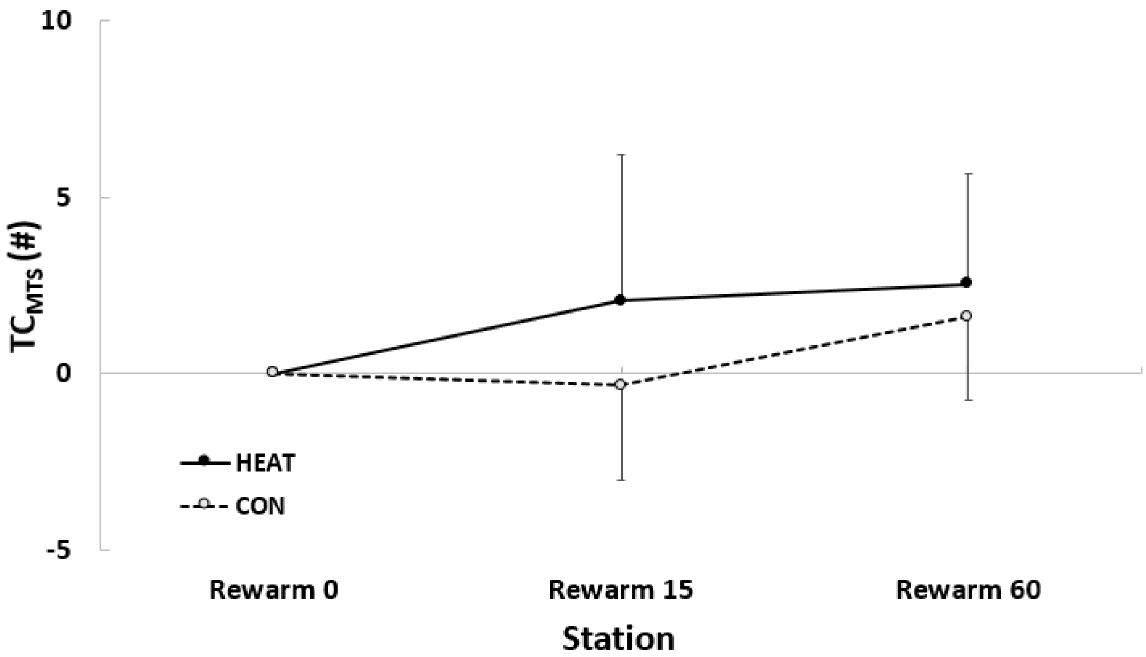

Fig. 8 Change in Match-to-Sample task accuracy (number of trials correct) from the onset of rewarming (Rewarm 0). There were no differences between the groups at any time point. Error bars represent one SD

Discussion

The present study attempted to determine if the use of commercially-available heat packs would, when applied to the skin at multiple body sites, provide a stimulus to alter thermal perception and subsequently improve cognitive performance following cold water immersion. Analyses and interpretations have led to two main findings. First, impairments in cognitive performance were observed as a result of cold water immersion, evidenced by decreased MTS accuracy and increased RT during and following immersion. Second, rewarming responses were similar between CON and HEAT for all measurements, suggesting that the use of heat packs did not influence physiological, perceptual, or cognitive performance. Contrary to our hypothesis, our findings suggest that exogenous heat application on the skin did not improve cognitive performance.

Physiological, Perceptual, and Cognitive Responses to CWI

Immersion in cold water is a continuous threat for warfighters that operate in cold environments and around open bodies of water (ocean, lakes, rivers, swamps, etc.). Immersion can occur from breaking through ice, ditching aircraft, falling overboard, forced water crossings dictated by mission requirements, or when entering swamps and marshes to remain undetected (Molnar 1946; Wittmers and Savage 2001; Brooks 2008). Numerous variables, such as water temperature and velocity, depth and duration of immersion, thermal protection, and individual differences all influence human responses to immersion in cold water and, thus, the degree of performance impairment. In the present study, we observed significant reductions in body temperature (T_c, $\overline{T}_{sk}$, T_{hand}), which are in alignment with responses reported by others (Tipton 1989; Castellani and Young 2016). T_c decreased by nearly 2°C within 20 min (start of immersion to end of post-immersion), indicating rapid heat loss and an opportunity to adequately assess recovery. Participants also reported feeling greater sensations of cold and shivering as a result of cold water immersion. Cognitive performance deteriorated during and following immersion, as evidenced by longer reaction times and reduced accuracy. Longer reaction times in cold water environments are also supported by others (Stang and Wiener 1970). It is unknown whether reductions in cognitive performance are due to changes in body temperature or other factors, such as distracting effects caused by cold and shivering sensation. These findings suggest a significant cold water immersion stimulus that was powerful enough to disrupt physiological homeostasis and negatively influence performance.

Physiological, Perceptual, and Cognitive Responses to Rewarming

Several techniques can be employed to facilitate recovery from accidental cold water immersion in field settings, such as spontaneous rewarming (i.e., shivering), physical activity, body-to-body warming, and ingestion of warm fluids (van der Ploeg et al. 2010; Dow et al. 2019). Efforts to identify rewarming techniques that are superior to others have resulted in similar outcomes. Giesbrecht et al. evaluated three rewarming techniques in hypothermic participants and noted that, although T_c after drop was greater when physical activity was used for rewarming, the end result was similar recovery times for external heat application, shivering, and treadmill exercise (Giesbrecth et al. 1987). With respect to external heat application, Giesbrecht et al. discuss the possibility that external heat application may influence temperature receptors and actually reduce the stimulus for shivering, therefore contributing to less heat production (Giesbrecht et al. 1997). This was considered when designing the current study, yet the aim was not to improve heat production in participants, but rather alter temperature sensation so that participants felt warmer and shivered less. Although each heat pack is reported to attain an average temperature of 57°C and eight heat packs were placed at different sites on the body (approximately equal to 15-20% of body surface area), we observed no differences in TS or SS between HEAT and CON during rewarming. This finding held true for all other physiological measurements, including T_c, T_{hand}, $\overline{T}_{sk}$, and HR.

Our primary objective was to identify improvements in cognitive performance resulting from external heat pack application during cold stress. This concept has been used successfully in the reverse situation, in which skin cooling during heat stress improved cognitive performance and, therefore, it stands to reason that the possibility exists for cold stress (Gaoua et al. 2011). Furthermore, a thorough review paper on thermal stress and cognitive performance by Taylor et al. concludes that "…it seems that increasing thermal comfort (rather than mitigating T_c increases) may be effective in maintaining complex cognitive function in passively experienced thermally stressful environments" (Taylor et al. 2016). Unfortunately, we failed to observe any differences in cognitive performance between CON and HEAT during rewarming, suggesting that either a) the stimulus of external heat application was not strong enough to influence TS, SS, or $\overline{T}_{sk}$, b) the cognitive tasks selected for evaluation were not affected by the rewarming stimulus, or c) the cold stress was so significant that any possible benefits in external heat application were masked. Pilcher et al., in a comprehensive review on thermal stress and cognitive performance, indicates that cognitive tasks are affected by cold differently and that varying severity of cold stress plays an important role in the degree to which cognitive tasks are impacted (Pilcher et al. 2002). However, the current findings suggest that reaction time and working memory are impaired by severe cold water immersion, but not influenced by external heat application during 60-minute rewarming.

Although commercial heat packs are widely used among the general population to reduce hand discomfort during mild cold stress, evidence from the current study suggests that their use is limited in scope for warfighters exposed to severe stress, at least with respect to improving cognitive performance. Prevention and preparation (i.e., appropriate thermal protection) for cold exposure remain superior recommendations to mitigate the detrimental effects of cold stress for warfighters. In the case of accidental hypothermia, donning dry, insulating clothing, along with metabolic heat production through shivering, remain as supported recommendations. Although continued research efforts are warranted on this topic, the use of commercial heat packs to improve aspects of cognitive performance are not supported at this time.

Limitations and Future Research

There are several limitations that require attention, including research design, heat pack efficacy, and cognitive test selection. Although external validity increases with field research that mimics actual conditions that warfighters may encounter during military operations, the degree of control of external factors, such as participants completing cognitive tasks in the presence of noise and other distractors, is lost. We attempted to control for as many factors as possible to obtain true measures of performance, yet it is likely that cognitive responses could have been different if conducted in a more controlled setting (i.e., quietly indoors). Another research design limitation pertains to the blinding of participants as to whether they were in the treatment or control group. Although there was no effect of heat pack application on any of the outcome measures in this study, the use of sham heat packs not emitting any heat could be important for future findings investigating the use of heat pack application. The efficacy of heat packs is unknown, as we failed to measure the temperature of heat packs at any time during the study. We only verified that each heat pack was warm at the time of application to the skin, but a significant amount of variability could have been present in heat pack temperatures. We also attempted to control for this by activating all heat packs 30 minutes prior to application for each participant.

The size of the external heat pack and the temperature monitoring patch precluded placing both on the same hand. However, a measurement of hand temperature was thought to still be of interest. Future work will need to incorporate temperature measurements of each heat pack to ensure all work effectively and uniformly. Cognitive task selection could have also influenced our findings. As previously mentioned, cognitive tasks are not impacted by cold equally and selection of different tasks could have resulted in different outcomes.

Despite the lack of differences between CON and HEAT, future work should continue to focus on enhancing skin temperature rewarming and evaluating changes in cognition that accompany alterations in thermal perception. Caution should be taken, however, when skin temperature rewarming is used, as heat production can possibly be reduced (i.e., shivering stimulus lessened) with external heat application (Giesbrecht et al. 1987). A balance must be met to achieve changes in temperature perception without abolishing shivering.

Conclusion

Warfighters, as well as others that frequent cold water environments, are at increased risk for physiological and cognitive impairments. Such impairments can drastically impact performance and reduce warfighter readiness and effectiveness, thus compromising missions. Findings from the current study suggest that external heat application does not influence any physiological, perceptual, or cognitive responses during rewarming. Future efforts should attempt to identify strategies that will allow for faster rewarming and quicker recovery of cognitive performance so that warfighters may quickly reengage and maintain operational readiness.

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14. ABSTRACT
Purpose: Exposure to cold water immersion (CWI) deteriorates cognitive performance, which negatively impacts warfighter readiness. Recovery of performance following CWI may be mediated by improving thermal perception, and application of commercially-available heat packs may facilitate such a response. This work evaluated the effects of exogenous heat application on temperature sensation and cognition following 10-min of CWI. Methods: Thirty-six participants (age: 28 ± 6 yrs, 177 ± 7 cm, 79.8 ± 10.4 kg) had their heart rate, mean skin temperature ($\bar{T}_{sk}$), hand temperature (Thand), core temperature (Tc), thermal sensation (TS), shivering sensation (SS), and cognitive performance (match-to-sample (MTS) and simple reaction time (SRT)) measured during a CWI and rewarming exercise: pre-immersion, immersion, post-immersion, and at 0-min, 15-min, and 60-min of a rewarming exercise. Following post-immersion, participants changed into dry clothing and heat packs were applied to eight body sites for a treatment group. Results: Compared with pre-immersion, CWI elicited significant reductions in Tc (37.3 ± 0.4 vs. 36.3 ± 1.0°C), Thand (20.2 ± 3.2 vs. 9.2 ± 2.0°C), and $\bar{T}_{sk}$ (28.9 ± 2.5 vs. 14.1 ± 1.4°C) and impaired cognitive performance (RTSRT: 278 ± 29 vs. 321 ± 58 ms). After 60-min rewarming, cognitive performance improved significantly compared to the start of rewarming (RTSRT: 287 ± 28 vs. 333 ± 71 ms; TCMTS: 22 ± 2 vs. 20 ± 3 trials correct). However, no group differences were observed for any cognitive measure between treatment and control, indicating that external heat application did not influence cognitive recovery.

15. SUBJECT TERMS
immersion; cognitive performance; thermal perception; hypothermia

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