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Acute Cold Exposure and Cognitive Function: Evidence for Sustained Impairment

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Abstract

Several industries experience periods of cold exposure and rewarming throughout the workday but mental performance under these conditions is unknown. A better understanding of cognition during the rewarming phase after cold exposure may help reduce accidents and improve performance. Ten young men (wearing~0.1 clo) underwent 3 consecutive mornings trials where they were exposed to cold air (10°C) and then subsequently re-warmed (25°C air). A computerized test battery was administered during each stage of the protocol to determine working memory, choice reaction time, executive function, and maze navigation. Rectal and skin temperature, oxygen consumption, and thermal sensation were also measured throughout and showed a typical response. Relative to baseline performance, working memory, choice reaction time, and executive function declined during exposure to 10°C, and these impairments persisted 60 minutes into the recovery period (i.e. once physiological parameters had returned to baseline). Further work is needed to develop countermeasures to this predicament.

Keywords

cognition; thermoregulation; shivering; thermal sensation

1. Introduction

When exposed to a cold environment, the human body initiates a series of responses aimed at preventing a decline in core temperature (i.e. rectal temperature > 35°C). From a

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Conflicts of Interest None

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physiological standpoint, peripheral vasoconstriction and shivering serve to reduce heat loss and increase heat gain, respectively. From a psychological standpoint, healthy adults who perceive the environment as “cold” will usually add a layer of clothing or avoid the cold environment altogether. While this is an efficient response for the average person, military operations and wilderness survival often require prolonged exposure to the cold (Lieberman et al., 2009). It is under these extended cold exposures that memory, vigilance, reaction time, and decision making can become impaired.

With regard to cognitive function in the cold, experimental studies have shown both improvements and impairments (Makinen et al., 2006). Two primary theories have been offered to explain this pattern of findings. The early distraction hypothesis (Teichner, 1958) suggests that cold stress produces a shift in attention from the primary task and causes reduced vigilance and slower reaction time. The arousal hypothesis posits that a slight decline in core temperature is initially experienced as a challenge and greater attention is then devoted to completing cognitive tasks thus improving mental performance (Enander, 1987). These mixed findings are likely attributed to differences in the mode and duration of cooling as well as the cognitive task itself. Specifically, timed tasks such as the Digit Span (i.e. a task measuring working memory) may be affected more in the cold than non-timed tasks such as maze navigation.

Cognitive function during the rewarming phase after acute cold exposure is also practically relevant. For instance, search and rescue workers might rewarm in a shelter or helicopter and then return to the cold outdoors. Similarly, cold storage facilities encourage workers to take periodic rewarming breaks throughout the day (Ceron et al., 1995, Ozaki et al., 1998). Depending on the occupation, workers rewarming and recovering from cold exposure may need to make decisions or remember information. However, experimental evidence regarding cognition during the recovery phase is lacking. Thus, we designed a study where young healthy subjects were exposed to two hours of 10°C followed by two hours of rewarming/recovery in 25°C on three consecutive mornings. We hypothesized that performance on tests involving attention and reaction time would be impaired (relative to baseline), whereas no such effect would emerge on non-timed tests of executive function.

2. Methods

2.1. Subjects

Ten Caucasian men (23 ± 1 years old; 16 ± 1 years of education) of average height (183 ± 6 cm) and weight (85 ± 5 kg) volunteered to participate in this investigation. The study protocol was approved in advance by the Kent State Institutional Review Board and each subject completed a general medical history questionnaire and provided written informed consent before participating. All subjects were apparently healthy, with no known metabolic, cognitive, or cardiopulmonary disease. None were taking medication and all were enrolled as college students. Subjects had above average body composition (11 ± 4 % fat) and average aerobic fitness (45 ± 5 mL/kg/min). No participants had recent or sustained exposure to cold temperatures (i.e. acclimatization) that might impact their response to cold exposure. The studies were conducted during the months of April to June and all data were collected in a temperature controlled environmental chamber (Western Environmental, Napa, CA) at either 25°C or 10°C.

2.2. Procedures

This study utilized a thermal physiological approach to determine how cognitive function is affected by acute cold exposure and rewarming. Participants underwent acute cold exposure (ACE, two hours resting in 10°C air) and passive rewarming/recovery (REC, two hours resting in 25°C air) on three consecutive mornings from 0600–1000 hours. Due to the number of measurements per subject and relatively stable physiological responses in each stage, cognitive testing was conducted at four distinct time points: baseline in 25°C air (BASE), 60 minutes into acute cold exposure (ACE), 60 minutes after the removal from cold (REC-60), and 300 minutes after removal from cold (REC-300). Some tests were staggered by a few minutes due to technical constraints (e.g. the measurement of oxygen consumption requires headgear which would obstruct the subject's view). Each testing session was ~ 20 minutes in duration. As such, the primary cognitive measurements were obtained at approximately 0700 hours (ACE), 0900 hours (REC-60), and 1300 hours (REC-300).

Prior to each experiment, subjects slept in the laboratory (2200–0500). Instrumentation and baseline measurements were obtained from 0500–0600 and the subjects underwent 10° acute cold exposure from 0600–0800 followed by passive rewarming/recovery in 25°C air from 0800–1000. The subjects remained seated for the four-hour study. Researchers administered the Integneuro™ and recorded rectal temperature, skin temperature, oxygen consumption (an index of shivering), and thermal sensation at predetermined time points. During the experiments, subjects wore only athletic shorts, socks, and gloves (~0.1 clo, same clothing worn for all three days). The gloves were removed during cognitive testing. This low level of insulation was chosen to elicit peripheral vasoconstriction and mild to moderate shivering during cold exposure; these two factors have been suggested as contributing factors to cold-induced cognitive deficits. It should be acknowledged that subjects showered and ate lunch after being removed from the environmental chamber at 1000 hours.

2.3. Instrumentation and Measures

Rectal temperature (°C) was measured via thermistor inserted 13 cm (ER400-12, Respiratory Diagnostic Products, Irvine, CA). Skin temperature (°C) was measured by thermistors (Model 409B, Yellow Springs Instruments, Yellow Springs, Ohio) attached to the chest, triceps, forearm, thigh, and calf on the right side of body. All skin thermistors were held in place by waterproof tape (Hytape, Brooklyn, New York) and mean skin temperature was calculated as previously described (Toner et al., 1986). Temperature data were logged into a PC at one minute intervals (iNet-100HC, Omega Engineering, Stamford, Connecticut). A True Max 2400 metabolic cart (ParvoMedics, Sandy, UT) was used to determine oxygen consumption at predetermined time points (each 5 minutes in duration). Thermal sensation was quantified via verbal report (0=unbearably cold to 8=unbearably hot) (DuBois et al., 1990). Body temperatures and oxygen consumption were not measured at the REC-300 time point because subjects were no longer required to be in the chamber at this time (Figure 1).

Cognitive function was assessed using the Integneuro™ computerized test battery. This program provides visual and auditory instruction and the participant responds using a touch screen. The Integneuro™ program is a valid and reliable measure of cognitive function in young healthy people (Paul et al., 2005, DuBois et al., 1990). Furthermore, the tests in this battery are sensitive to cognitive deficits that occur with age and disease (Clark et al., 2006). Pilot testing revealed that 10°C air and subsequent 25° rewarming did not cause the screen to malfunction or become blurred. Specific tests of the Integneuro™ include: attention and working memory (Digit Span), reaction time (Choice Reaction Time), and executive function (Verbal Interference, Executive Maze Task). Each testing session took 20 min to complete, which is consistent with similar experiments in this discipline (Makinen et al., 2006). All tests were scored at a central facility.

The Digit Span task assesses attention and working memory. This task is intrinsically similar to the Match-to-Sample which has been used in several thermal physiology studies

(Paakkonen et al., 2008, Makinen et al., 2006, O'Brien et al., 2007, Thomas et al., 1989). For the Digit Span, subjects are presented with a series of digits on the touch-screen, separated by a one-second interval. The subject is then immediately asked to enter the digits on a numeric keypad on the touch-screen. Subjects are required to recall the digits in forward order for the first part and reverse order in the second part. In each part, the number of digits in each sequence is gradually increased from 3 to 9 digits, with two sequences at each level. The dependent measure is the total number of correct trials forward and backward.

The next component of the Integneuro™ is the Choice Reaction Time task; versions of this test have been used in previous cold studies (Ellis, 1982, O'Brien et al., 2007). In this task, one of four circles on the screen becomes illuminated and the subject is required to touch the illuminated circle as quickly as possible. Twenty trials are administered with a random delay between trials of 2–4 s. Mean reaction time is the dependent variable used in analysis.

The Verbal Interference task assesses the ability to inhibit automatic and irrelevant responses. This is similar to the Stroop test (Golden, 1978), with responses made by tapping the touch screen. Verbal Stroop test have been used in previous cold physiology studies (Muller et al., 2011, Ellis, 1982). In Verbal Interference Part I, all words are printed in black ink and subjects are asked choose the corresponding color as quickly as possible (e.g. "blue" printed in black ink and the subject should tap blue). In Verbal Interference Part II, words are printed in incongruent colors (e.g. "red" printed in blue ink and the subject should tap blue). Total number of words correctly tapped is the dependent variable analyzed.

The Executive Maze Task is a computerized adaptation of the Austin Maze, which measures spatial memory. This task requires participants to learn a sequence of directional steps in a non-timed fashion. Learning sequences and mazes have been used in previous cold temperature experiments (O'Brien et al., 2007, Paakkonen et al., 2008, Payne and Cheung, 2007). In the Executive Maze Task, subjects are presented with a grid (8 × 8 matrix) of circles and asked to identify the hidden path through the grid by tapping arrows on the touch screen. Distinct auditory and visual cues are presented for correct and incorrect responses. The trial ends when the subject completed the maze twice without error or after 10 min has elapsed. The dependent variables include the number of maze errors and maze overruns.

2.4. Data Analysis

Rectal temperature, mean skin temperature, and oxygen consumption were analyzed with a 3 (day) by 9 (BASE, ACE 30, ACE 60, ACE 90, ACE 120, REC 30, REC 60, REC 90, REC 120) repeated measures analysis of variance. Thermal sensation (change from baseline) was analyzed with the Wilcoxon sign nonparametric test.

Analyses from a previous report (Spitznagel et al., 2009) indicated no cumulative effect of sequential cold exposure trials on these cognitive tests and thus data across all trials were pooled in an effort to optimize statistical power. Generalized estimating equations (GEE) for panel data in Stata v10 (StataCorp LP, College Station, Texas) were used to examine cognitive function. GEE allows simultaneous testing of multiple time points and provides a more conservative significance test when the variables of interest are known to be correlated to each other. It is frequently used for data in which serial assessment is utilized. All positively skewed outcomes were log-transformed prior to analysis, but raw scores are shown in Table 1. Any outcome observations that were extreme outliers as determined by Mahalanobis Distances were excluded on analysis-by-analysis basis (total = 3 / 540 total test administrations, < 1% excluded). Alpha values were set at $p < .05$ and all data are presented as mean ± standard deviation.

3. Results

A typical physiological response to cold occurred on Day 1, Day 2, and Day 3. There was no main effect for day and no day by time interaction, but there was a significant main effect for time for each variable (all $p < 0.001$). As shown in Figure 1, mean skin temperature (Δ ~ −9°C), oxygen consumption (Δ ~ 3 mL/kg/min), and thermal sensation (from "neutral" to "cold" or "cool") all showed a dramatic change during exposure to 10°C air which was coincident with a moderate increase in rectal temperature (Δ ~ 0.2°C). During recovery in 25°C air, rectal temperature declined slightly (Δ ~ −0.2°C) while the other parameters returned to baseline levels. Importantly, physiological responses to this experimental paradigm were not different across days but each individual day was a significant stressor.

Analyses from a previous report (Spitznagel et al., 2009) indicated that cognitive function was not different across three consecutive days of cold exposure and rewarming. As such, general estimation equation analyses showed that exposure to cold temperatures adversely impacted performance on Digit Span ($z = -1.95$, $p = .05$), Choice Reaction Time ($z = 3.34$, $p = .001$), Verbal Interference Part 1 ($z = -4.42$, $p < .001$), and Verbal Interference Part 2 ($z = -2.73$, $p < .01$). As shown in Table 1, performance on Digit Span (an index of working memory) declined during ACE and remained impaired at REC-60. Relative to baseline, Choice Reaction Time declined during ACE and remained impaired at REC-60. Verbal Interference 1 similarly was lower during ACE and REC-60. Contrary to expectations, Verbal Interference 2 improved during ACE and REC-60, relative to baseline. However, comparing BASE and REC-300 for this task suggests that BASE scores fell below the normal range for healthy adults, a pattern commonly found in studies of serial cognitive assessment. No effect was found for Executive Maze test performance ($z = 1.15$, *ns*), which is likely due to large inter-individual variability.

4. Discussion

Consistent with previous work, our results indicate that some aspects of cognitive function are reduced during acute cold exposure. The current study extends these findings and demonstrates that cognitive dysfunction persists into the recovery period after removal from the cold. This pattern emerged despite multiple measures of cold stress (e.g. core/skin temperatures, thermal sensation) being at baseline levels. This is the first report of this phenomenon in healthy human subjects and we speculate that the causes are due to both physiological and psychological factors. These findings could be practically relevant in the workplace where individuals experience cold and rewarming throughout the day or on different days. For instance, wilderness paramedics who are attending to a skiing injury victim in a warm shelter may have lingering cognitive impairments.

Similar to previous studies using a working memory test (O'Brien et al., 2007, Thomas et al., 1989), performance on the Digit Span Task was reduced during ACE. We further the literature by showing that working memory is also impaired (relative to baseline) during the immediate rewarming phase (REC-60). Choice reaction time was slower during ACE and this effect was still evident 60 minutes after removal from the cold. This is in contrast to a study by O'Brien et al (2007) where complex reaction time was unaffected by exposure to 10°C air after an acute lowering of core temperature to ~35°C via cold water immersion. Performance on the Executive Maze was not affected by cold exposure or rewarming, which is consistent with a previous study using a virtual reality assessment of navigation during water immersion (Payne and Cheung, 2007). This data suggests that learning sequences of data in a non-timed fashion is not affected by cold exposure. Future studies are needed to clarify how the mode (i.e. conductive, convective heating) and duration of rewarming affect cognitive function.

Executive function, as judged by the Verbal Interference 1, was reduced during both ACE and REC-60, while findings from Verbal Interference 2 are more complicated. Overall, participants appeared to improve upon exposure to the cold environment, followed by a decline at REC-60. It is most likely that these findings are attributable to lower than average performance at baseline, although other possibilities may exist. Nevertheless, Verbal Interference 2 performance was lower during REC-60 than ACE, which is a novel and valid finding because physiological parameters were stable (i.e. not undergoing reflex thermal adjustments) at this time. Previous data using a time-based verbal response Stroop test showed no effect of cold exposure (5°C, 1 clo) on the interference score (an index of global performance, similar to Verbal Interference 2) but participants did read more words (similar to Verbal Interference 1) during exposure to cold air (Muller et al., 2011). The discrepancy between studies is not entirely clear but a learning effect cannot be completely excluded, as naming incongruent colors is a novel task for research volunteers.

In a cold workplace, safety and performance might be adversely affected if cognitive function was impaired. Within the context of this experimental study, reaction time, working memory, and executive function declined during cold exposure and recovery. These types of abilities are mediated by frontal brain regions (Tsuchida and Fellows, 2009) and are known to be adversely impacted by cold stress. A recent series of studies raise the possibility that brain temperatures are somewhat independent from both core and esophageal temperatures (Harris et al., 2008, Zhu et al., 2009). However, it is unknown whether temperatures may actually differ across brain regions and whether that pattern helps to account for the differential impact of cold exposure on different cognitive abilities. Future neuroimaging studies may help explain how rewarming from a cold stimulus impacts brain function in the workplace.

Neither the early distraction hypothesis nor arousal hypothesis would predict the current findings. This is especially true during the recovery period because it is unlikely that 25°C air and thermoneutral physiological parameters would either arouse or distract the subject. The precise mechanisms of impaired cognitive function were beyond the scope of this study but some speculation might encourage future research. It is possible that acute vascular changes within the brain may produce cognitive dysfunction. Vasoconstriction has been shown in a number of vascular beds (e.g. renal artery, brachial artery, cutaneous circulation) in response to skin cooling (Wilson et al., 2007, Wilson et al., 2002); the specific effects of skin cooling on the brain are not clear. Another possibility is that the catecholamine dysregulation associated with cold exposure reduces cognitive function. Catecholamines are particularly important for tests involving complex attentional functions and executive/frontal systems functions (Hyafil et al., 2009) which are consistent with the observed pattern of deficits in the current study.

It is unlikely the current results are due to shivering. Shivering (as assessed visually and by measuring oxygen consumption) was mild to moderate during the measured time points but was minimal during the Integneuro™ test sessions. Furthermore, the touch-screen based tests require very little motor ability and shivering did not occur during the recovery period. The observed results are also not consistent with the afterdrop phenomenon, the continued reduction in core temperature after removal from a cold environment (Hayward et al., 1984). Core temperature did decline during REC, but the subjects were not hypothermic to begin with (i.e. at ACE 120). It is likely that actual hypothermia would result in even further impairments in cognitive function and this requires further study. One could also argue that our subjects may have developed a mild cold acclimation by Day 3 of the experiment. Our physiological and psychological data do not support this concept, but rather suggest that this occupationally relevant paradigm of cold exposure on consecutive mornings impairs some aspects of cognitive function.

Several methodological considerations of the current study may limit generalizability to other samples. Sample-related factors include the modest sample size, narrow age range, and use of only male subjects. Further, as the cognitive impact of cold temperatures remains poorly understood, the most appropriate temperature and duration of cold exposure for examination has not been established. It is possible that exposure to lower temperatures or a longer exposure may produce different findings than those found in the current study. The Integneuro™ test does not measure vigilance or simulated sentry duty, which is relevant to military operations (Flouris et al., 2007, Tikuisis and Keefe, 2007, Marrao et al., 2005). Additionally, there is some reason to believe that thermoregulation differs by racial/ethnic groups and gender, and little is known about the impact of these demographic variables on cold-related cognitive dysfunction (Glickman et al., 2002, Farnell et al., 2008, Glickman-Weiss et al., 2000).

In summary, the current results indicate that cognitive function is reduced during acute cold exposure and acute recovery. Future studies could determine both the underlying mechanisms and countermeasures to this predicament.

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Practitioner Summary

This study showed that working memory, choice reaction time, and executive function declined during exposure to 10°C air, and these impairments persisted 60 minutes into the rewarming period (i.e. once measurable physiological parameters had returned to normal). Individuals may be at risk for injury after removal from a cold environment.

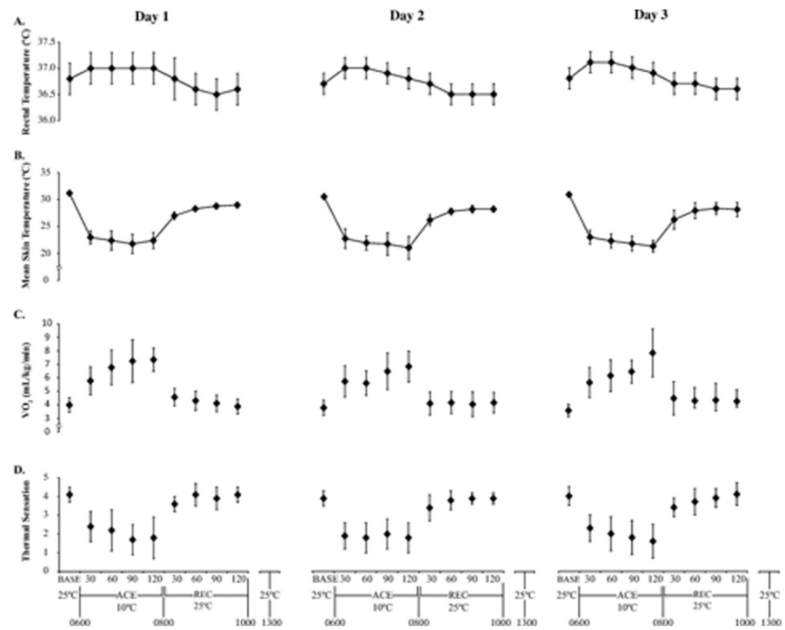

Figure 1.
Physiological and perceptual responses to acute cold air exposure (ACE) and recovery (REC) on three consecutive mornings. Rectal (panel A) and skin temperature (panel B) were monitored continuously while oxygen consumption (VO_2, panel C) and thermal sensation (panel D) were quantified at distinct time points. Cognitive measurements were obtained at baseline, and approximately 0700, 0900, and 1300 hours each day.

Table 1

Cognitive Function Across Trials: Before, During, and After Acute Cold Exposure (10°C).

Integneuro™ Test	Units	BASE	ACE	REC-60	REC-300
Digit Span *	correct trials	7.4 ± 1.4	7.1 ± 2.5	7.2 ± 2.3	7.9 ± 3.0
Choice Reaction Time *	msec	630 ± 98	690 ± 116	728 ± 124	649 ± 106
Verbal Interference-1 *	correct words	22.7 ± 4.0	21.4 ± 3.4	21.4 ± 3.7	24.4 ± 4.2
Verbal Interference-2	correct words	17.3 ± 4.2	19.5 ± 2.9	18.8 ± 3.0	21.4 ± 3.1
Maze Error Total	number	30.1 ± 14.6	28.6 ± 15.7	24.6 ± 10.4	29.0 ± 26.4
Maze Overrun	number	12.3 ± 9.0	14.6 ± 8.1	12.4 ± 6.1	17.2 ± 17.8

BASE denotes prior to environmental chamber entry; ACE denotes acute cold exposure, REC-60 denotes approximately 60 min after removal from cold environment and REC-300 denotes approximately 300 min after removal from cold environment. M ± SD.

* denotes significantly poorer performance at ACE and REC-60 than BASE and REC-300.