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Torso Heating of Divers in Cold Water

ABSTRACT

Cold water immersion could compromise both the effectiveness and safety of a diver. This paper reports an evaluation of the utility of providing external heating to divers in cold water. Methods: Seven U.S. Navy divers wearing semidry suits were submerged in 7.2°C water for 2 h. In the heated condition, a total of 35 W was delivered to each of four heating pads (total area 2477 cm^2) placed on the torso of the divers. In the unheated condition, the participants received no external heating. Results: The participants believed they were more comfortable in the heated, than the unheated condition. However, objective data did not support this perception. In fact, heating the torso had a significantly detrimental effect on the body's thermoregulatory ability, and lacked a positive effect on manual dexterity. Cognitive test performance was not affected by the exposure. Discussion: Heating the torso did not have a positive effect on diver performance. Moreover, heating the torso of a diver may actually increase susceptibility to hypothermia.

INTRODUCTION

Much of the work carried out by military and commercial divers requires being submerged for long periods of time in a hostile environment in which seemingly minor errors can have terminal consequences (19). Compounding the difficulties of operating under water are the additional detrimental effects of cold on human performance.

The ability to use tools and manipulate objects effectively is necessary for both commercial and military diving operations. However, a number of cold exposure studies have demonstrated the negative impact of cold on manual dexterity (5,10). Physical performance is closely related to changes in local tissue temperature (22). It has been found that local cooling of the hands and forearms (while the body remains warm) will produce significant impairments of manual dexterity (10) and grip strength (5).

Cognitive performance is also impaired by cold water immersion. Small reductions of as little as 0.5°C in core temperature (36°C to 36.5°C) have been shown to increase response time and decreases accuracy in pattern recognition and attention tasks (7,8,12). To illustrate, Davis and colleagues (7) found a significant impairment on arithmetic, logical reasoning, and word recall and recognition as a result of diving in 5°C as compared to performance on land in 20°C air. Giesbrecht et al. (12) also reported that short-term memory was significantly affected by cold water exposure. Therefore, to preserve cognitive and manual performance in cold water there is a need for effective thermal protection for divers.

There are three types of dress for providing thermal protection for divers: wet suits, dry suits, and hot water suits. In moderately cold water (17–18°C) a wet suit has been found to provide insufficient thermal protection for immersions lasting longer than 4 h (2). Although a dry suit provides better insulation than a wet suit, it is bulky, and can cause buoyancy control problems, making it impractical for many of the missions carried out by special operations divers. A hot water suit keeps a diver warm by providing surface heated seawater (37– 40°C) via an umbilical to divers through a number of perforated hoses sewn into the suit (18). The disadvantages of hot water

suits are that they require a large amount of top side equipment, there are limitations on the distances a diver can travel underwater, and they can cause isotonic dehydration in long-duration dives (18). Thus, there is a need for adequate thermal protection for long-duration, cold water missions that do not have the limitations of wet, dry, or hot water suits. To address the limitations of these three types of dress, it is suggested that an external heating system may provide an effective alternative.

The few studies that have examined external heating in air have produced mixed results (3,4,13,27). Brajkovic et al. (3) provided torso heating during a $-25°C$ exposure and found that when the torso was heated under arctic cold weather gear, extremity comfort could be maintained. However, Goldman (13) was unable to maintain extremity comfort despite providing torso heating. Diving in cold water may exacerbate this issue because the thermal conductance of water is 25 times greater than that of air (27).

External heating systems are typically complex and require a large power supply (21). However, work at the U.S. Navy Experimental Diving Unit (NEDU) identified the Hydrotech Aqua Heat System (HAHS) as a system that could be worn under a wet suit, did not restrict freedom of movement, and had a power supply that was not prohibitively large. Preliminary testing of the HAHS at NEDU determined that 0.06 W z cm22 was the maximum amount of heating that could be provided to a diver. In that study, four participants were submerged up to the neck at a water temperature of 7.2°C for a maximum of an hour using the same semidry suit and heating pad con-figuration used in the experiment described in this paper (see later for a description). It was found that if $0.06 W/cm^2$ was exceeded, the temperature of the torso could become greater than the safety limit of 40.8°C set by the NEDU Institutional Review Board (IRB). The preliminary testing also demonstrated the importance of ensuring that the semidry suit was completely flooded prior to energizing the HAHS. A skin temperature of .40.8°C could be achieved in as little as 10 min if the semidry suit was not completely flooded. The study described in this paper follows on from the preliminary testing and assesses the effectiveness of the HAHS for use by a submerged diver.

METHODS

Participants

There were seven U.S. Navy special operations personnel who volunteered to participate in the study. They were healthy, non-smoking men with the following characteristics: age, 37.4 yr (SD= 5.2); height, 178 cm (SD= 4.9); and weight, 89.9 kg (SD= 7.9). Although the divers were very experienced in diving in cold water, none of them had dived in water colder than 24°C in the month prior to the experiment, nor at all in the week prior to the experiment. Therefore, none of the participants were acclimatized to cold water. The study protocol was approved in advance by the IRB of NEDU. Each subject provided written informed consent prior to participation.

Instrumentation and Equipment

The study was conducted in the test pool at NEDU at a depth of 4.6 m with water temperature of 7.2°C. This temperature was chosen because this was the water temperature at which it was anticipated that the system would be used operationally. Participants wore a surface supplied MK 20 full face mask, a Mares semidry suit (a wet suit with dry suit fittings designed to reduce the circulation of water throughout the suit), along with a hood, booties, and gloves. The prototype HAHS consisted of four heating pads with a switch and power supply external to the garments. The pads were placed on the upper chest, abdomen, upper back, and lower back (2477 cm^2 of heating). Power was surface supplied using a 12V DC marine battery and voltage regulator which reduced the operating voltage at the heating pad to 6V DC. The heating pads were connected to the power supply using jacketed submersible cable and submersible plugs. A 3-mm neoprene insulating pad was worn between the heating pad and the skin of the diver.

Procedure

There were three phases to the experiment: pre-exposure, exposure, and post-exposure. These phases are outlined below in chronological order.

Pre-exposure: In the week prior to the first exposure, participants completed two practice trials of each of the manual dexterity and cognitive tests on dry land. On the day of the exposure, pre-dive weights were recorded and urine samples were collected to assess hydration status by measuring urine specific gravity. A pre-dive

hydration schedule consisted of at least 2 litres of fluid in the 4 hours prior to diving. A rectal temperature sensor was inserted before the participant donned the dive gear. Each diver was instrumented with skin temperature sensors at six different sites: center of right pectoralis; center of right rectus abdominis; trapezium, medial to scapula; center of thoracolumbar fascia; lateral tip of right little finger; and lateral tip of right little toe. These temperatures were monitored and recorded at 30 second intervals.

Following instrumentation checks, participants donned immersion gear. In the heated conditions, the participants also donned four heating pads. The order of conditions was randomly assigned to achieve a balanced design. To avoid possible cold acclimatization, none of the participants dived on consecutive days. It would have been desirable to blind the participants as to whether they were to be in the heated, or unheated, condition. However, due to the lack of a spare set of pads, this was not possible.

Exposure and tests: After the subject descended to the bottom of the NEDU test pool, they picked up an 8-lb (3.6-kg) SmartBell[w] from the pool bottom and slowly rotated their arms in a clockwise direction making 10 circle motions from their ankles to above their head. In addition, the same motion was completed 10 times in the opposite, counter-clockwise direction. This procedure was carried out to ensure the wet suit was flooded. The heating pads were energized after the participant had been submerged for 10 min and after the diver 's dress was flooded. Following this warm-up exercise, the participants then completed a series of hand-dexterity and cognitive tests. These tests included the Turning Test, Grip Strength Test (both hands), Trail Making, and Digit Span Test (forward and reverse). Each test is explained in detail below.

The Turning Test was one test from a larger battery of manual dexterity tests called the Minnesota Manual Dexterity Test (1,25). The purpose of this test was to measure simple, but rapid eye-hand-finger movements (1). For underwater testing purposes, a submersible version of the hardware was constructed. The only change from the dimensions of the standard Minnesota Dexterity Test was the height of the counters,

which were increased from 1.3 cm to 2.6 cm so that they could be picked up while wearing gloves. The measure of performance was the time, in seconds, that it took to complete two trials.

Maximal handgrip strength was measured using a hand dynometer (Grip Strength Test). Subjects performed three maximal voluntary contractions (MVC) with their dominant hands, and the average of these three was recorded. Because the participants were wearing gloves, the added bulk of the neoprene did not allow all fingers to fit into the head of the dynometer grip. Therefore, the participant's little finger rested outside the grip head. The measure of performance was the mean grip strength (of all three MVCs) for each hand in Newtons.

The Trail Making Test was taken from the Halstead-Reitan Neuropsychological Test Battery (23). The test consisted of two parts (A and B). Each part required the participant to connect 25 encircled dots by making pencil lines in the appropriate order. Part A required that the lines be drawn through the numerical circles in order (i.e., 1 to 2, 2 to 3…through 25). Part B required that the line be drawn through numerical and alphabetical circles in alternating order (i.e., 1 to A, A to 2, 2 to B…through L to 13). Any error in sequencing had to be corrected by the participant immediately. The measure of performance to complete each of the two trials was time in seconds.

The Digit Span Test was presented to assess attention, concentration, vigilance for auditory stimuli, and short-term memory. The test consisted of two parts. In the first part, a series of numbers from three to eight digits in length were read to the participants. After the number series had been read, the participant was then instructed to repeat the numbers (out loud) in the same order that was presented to them. In the second part, a separate series of numbers ranging in length from two to eight digits were read to the participants. After the number series had been read, the participant was then instructed to repeat the numbers (out loud) in the reverse order that was presented to them. In addition to attention, concentration, vigilance for auditory stimuli, and short-term memory, this task required a degree of mental manipulation and mental flexibility. One point was awarded each time a series of digits was repeated correctly. The point system applied for both conditions of the test. Once a participant was incorrect on two consecutive trials of a given digit series, the test was then

terminated. The maximum possible score was 12 under each of the two conditions.

Following the completion of the hand dexterity and cognitive tests, participants then sat idle at the bottom of the test pool with their back against the wall and watched a movie. During this time, the participants were asked a series of questions at 15-min intervals related to their thermal status. Answers to these questions provided information to help monitor personnel and to allow assessment of risk for participants. At 10 min prior to the end of the 2-h exposure the subjects then undertook the same series of hand-dexterity and cognitive tests which had been completed at the beginning of the exposure. Each exposure lasted a maximum of 2 h.

Post-exposure: Once the exposure phase of the study was complete, the subjects exited the water, were stripped of all dive gear, skin sensors and thermistor, were escorted directly to a heated bath, and were asked to complete a heating pad comfort questionnaire and to provide information on their level of cold intensity during the dive. The following questions were asked, with responses provided on a five-point Likert scale

- Your perceived comfort during the exposure? (1 very poor to 5 very good);
- If heated, the effectiveness of the system? (1 no effect to 5 very big effect);
- The effect of the exposure on your physical performance? (1 no effect to 5 very big effect); and
- The effect of the exposure on your mental performance? (1 no effect to 5 very big effect).

Statistical Analysis. The time courses of the change in temperature from the starting temperature for the finger, toe, and core were described by nonlinear curve fitting to competing models using the method of least squares employing a modified Gauss-Newton algorithm (Systat 11, Systat Software Inc., Richmond, CA). TableCurve 2D (Systat Software Inc.) was used to identify the best fit descriptive model. For each model, further variants were tested, with a hypothesized positive effect of external heating being tested against the null hypothesis of no effect of heating. The goodness of fit of these models was evaluated by the F-test (20).

The Wilcoxon signed rank test (the nonparametric equivalent of the repeated measures t-test) was used to quantify the effects of the exposure on the performance of the cognitive and hand dexterity tests, and assess whether performance was better on the tests at the end of the exposure in the heated as compared with the unheated condition. The Wilcoxon signed rank test was also used to compare the responses to the subjective discomfort questions between the heated and unheated conditions.

It is important to indicate that the power to detect a difference is low due to the small sample size (an estimate of the power of the Wilcoxon signed rank test with seven subjects is 0.2). However, as is the case with the majority of studies of cold immersion, it is difficult to obtain sample sizes sufficiently large to obtain statistical power. This type of research is very resource intensive in terms of specialized facilities, equipment, and people (in the current study, it required eight people to support two divers). Therefore, although obviously undesirable, low subject numbers are often beyond the control of the experimenter.

RESULTS

The results from the study have been separated into the physiological, cognitive, and manual dexterity effects.

Physiological
The graphs of the temperatures for rectal, finger, and toe temperatures are shown in Fig. 1, panels A, B, and C, respectively (all seven participants completed the two hour exposure in both conditions). It can be seen that the temperature drop seems to be greater in the heated condition than the unheated condition.

   Using the statistical technique described in the methods, it was found that the fits for the change in temperature from the initial temperature for the heated and unheated conditions were statistically different for finger ($F_{3,1196}$ = 4232, P<0.05), toe ($F_{2,1198}$ = 9903, P<0.05), and rectal temperatures ($F_{2,1410}$= 498.98, P<0.05). Therefore, a two-curve model had significantly better fit than attempting to fit the heated and unheated data to a single curve.
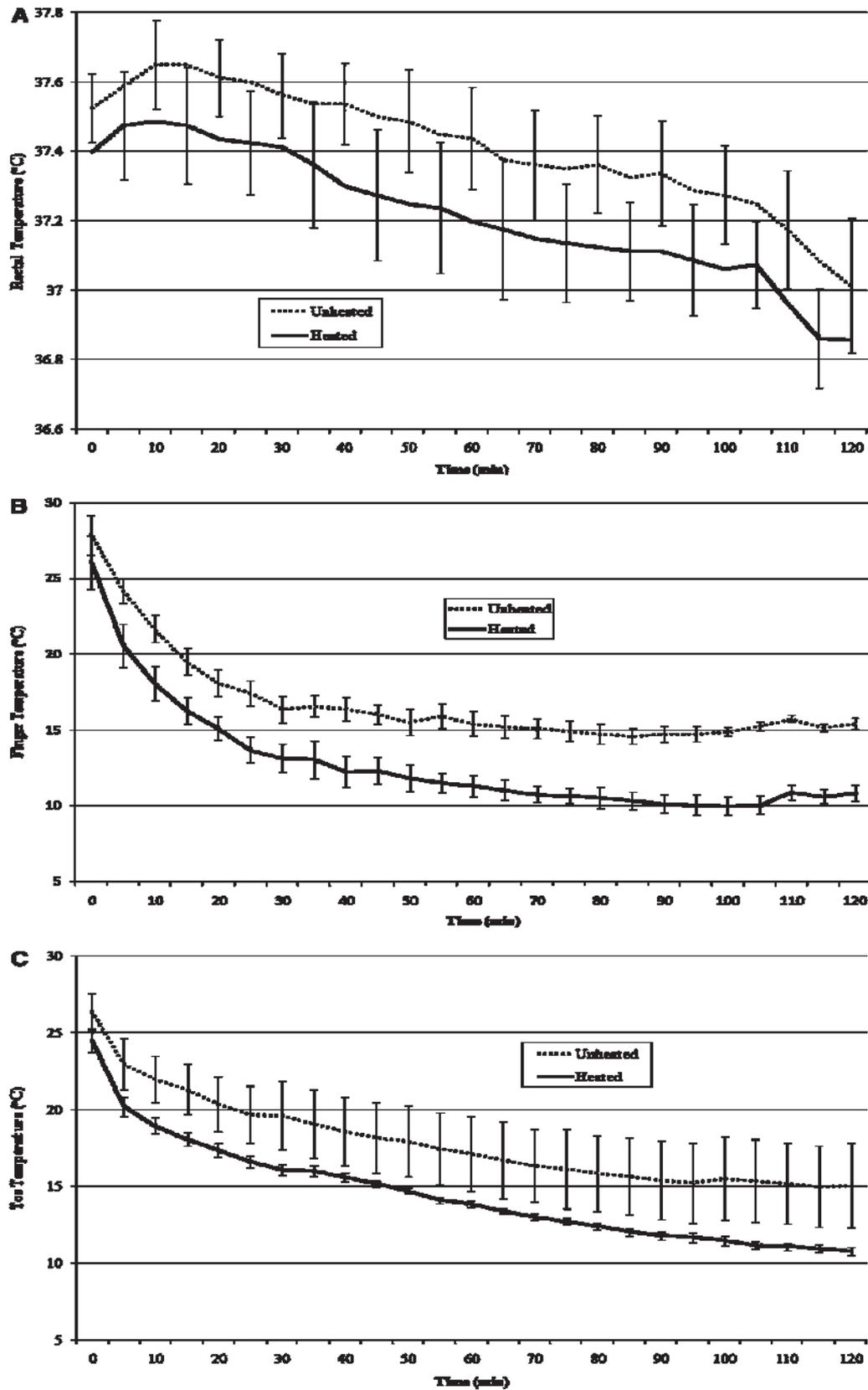
Figure 1. A. Rectal temperature vs. time; B. Finger temperature vs. time; C. Toe temperature vs. time (Mean and SD).

Hand Dexterity and Cognitive Tests

The mean and standard deviations for the hand dexterity and cognitive tests are summarized in Table I. It took significantly longer to complete the Turning Test at the end of the exposure as compared to the beginning of the dive in both the unheated (W = 24, P<0.05) and heated conditions (W = 22, P<0.05). Grip strength for the dominant hand was significantly weaker at the end of the dive as compared to the beginning of the dive in the heated (W= 24, P<0.05) and unheated conditions (W = 24, P< 0.05). For the non-dominant hand, grip strength was significantly weaker at the end of the dive as compared to the beginning of the dive in the unheated (W = 28, P<0.05), but not the heated conditions (W = 14, P<0.05). A comparison of performance in the heated and unheated conditions at the end of the exposure did not show any significant differences. There were also no significant differences in the performance on the cognitive tests based upon exposure, or condition (pooled mean for Trails A = 25.8 s, SD = 6.6; pooled mean for Trails B = 50.2 s, SD = 21.5; pooled mean for forward digit span = 8.6 digits, SD = 2.1; and pooled mean for backward digit span = 6.4 digits, SD = 2.3).

TABLE I. Performance on manual dexterity and cognitive tests.

	Heated				Unheated			
	Start		Finish		Start		Finish	
Test	Mean	St dev	Mean	St dev	Mean	St dev	Mean	St dev
Turning (s)	158*	61.4	200	48.8	145*	38.2	211	82.0
Dominant grip strength (N)	324*	41.0	264	57.0	307*	46.0	265	48.0
Nondominant grip strength (N)	331	45.0	310	76.0	307*	46.0	265	57.0

* Significant difference at P< 0.05, between start and finish within each condition.

Subjective Discomfort

Table II summarizes the responses to the questions regarding the comfort of the exposure collected after each dive for which significant differences were found between the heated and unheated conditions.

TABLE II. Comfort level during each exposure.*

	Unheated		Heated	
Question	Mean	St Dev	Mean	St Dev
Your perceived comfort during the exposure?†	1.9	0.9	2.7	1.0
Effect of exposure on your mental performance?‡	2.7	1.1	2.0	1.0

* Differences between unheated and heated conditions were significant at P< 0.05.
† Scale: 1 5 very poor to 5 5 very good.
‡ Scale: 1 5 no effect to 5 5 very big effect.

The divers felt significantly more comfortable in the heated, as compared to the unheated condition (W = 15, P<0.05). The participants also felt that the exposure had a great effect on their mental performance in the unheated as compared to the heated condition (W = 15, P<0.05). There was no significant difference in the participants opinion on whether the exposure would effect physical performance between the heated and unheated conditions (pooled mean = 3.7, st dev = 0.7; W = 4, P< 0.05), and the respondents rated the effectiveness of the heating system as 'good' (mean = 4.0; SD = 0.8).

DISCUSSION

Physiological Data
The provision of external heating to the torso of a diver resulted in a significantly greater drop in rectal and extremity temperatures than compared to an unheated diver. The reason for analyzing the change in temperature, rather than the measured temperatures, was to control for the differences in start temperature between the divers. It is possible to offer three explanations for the higher start temperature in the heated condition: small sample size, calibration error, or psycho-physiological response.

As discussed earlier, the sample size is smaller than would have been desirable. However, no obvious outliers were identified. Secondly, despite calibrating the sensors each day, and examining temperature change rather than the temperature readings, it is not possible to completely rule out sensor error. However, this would require the same error to have occurred in the finger, toe, and rectal temperature sensors. Therefore, this is unlikely. Thirdly, it may be that there was some kind of psycho-physiological response in which the participants knew they were going to be

entering cold water without any heating and so their body reacted to this knowledge by increasing the temperature of the extremities. There is evidence that people can learn to control their body and extremity temperature (9). So perhaps after years of diving in cold water the divers have developed this skill. Nevertheless, the important physiological finding was that there was a larger change in rectal, finger, and toe temperatures in the heated as compared to the unheated condition.

Heating the torso of a submerged diver appears to interrupt the body's natural thermoregulatory system. When the body is cooled, vasoconstriction reduces peripheral blood flow, delaying the cooling of deeper peripheral tissue (24). This mechanism combined with increased thermogenesis explains why there is an initial increase in rectal temperature early in a cold exposure (14). There are variations in how vasoconstriction is controlled in different areas of the body (15). The feet and hands are under the complete control of the adrenergic sympathetic nervous system, whereas the trunk is under the dual control of the noradrenergic, active vaso-constrictor system, and an active vasodilator system (24). Thus, providing external heating to the skin of the torso appears to disrupt the balance between these two thermoregulatory systems and leads to significantly lower extremity and core temperatures than when a diver is unheated.

Recent evidence has shown that the thermal status of a diver has implications beyond hypothermia, but also has consequences for the probability of suffering from decompression sickness (DCS; a syndrome that consists of symptoms and signs ranging from joint pain to various neurological disturbances, paralysis, and death; 26). It has been shown that being warm during decompression has beneficial effects in terms of reducing DCS risk, particularly when decompressing from a long-duration dive (11). Therefore, the research presented in this article would suggest that using as much passive thermal protection (e.g., thick wet suits, hoody, gloves, booties, full face mask, etc.) as is practical is more effective, and safer, than providing external heating to a diver.

Hand Dexterity and Cognitive Tests
Hand dexterity and grip strength: Comparing task performance at the beginning and end of the exposures showed significant losses in hand strength and manual dexterity.

As discussed in the introduction, local hand temperature is the main factor influencing manual performance (7,12). Therefore, it is unsurprising that heating provided to the torso of the participants does not have a beneficial effect on grip strength or manual dexterity.

Trails A and B: No significant differences were found for the Trails A or B tasks. Other researchers have concluded that cold affects tasks that are complex, perceptually demanding, or require concentration (7,12). Coleshaw et al. (6) found that memory was not impaired until the body core temperature falls below about 36.7°C. Therefore, the lack of significant effects on the Trails tasks as a result of the exposure may have been due to the fact that the participants' core temperatures did not get sufficiently low (the mean coldest rectal temperature in the current study was 37°C, SD 5 0.3°C).

Digit span: As with the performance on the Trails tests, there was not a significant effect of time or condition on the forward or backward digit span tests. Similar findings have been reported in the research literature (7,12). Therefore, as with the Trails tests, participants were not sufficiently cold for performance on the digit span tests to have been affected.

Subjective Discomfort

Participants reported feeling significantly more comfortable in the heated condition than the unheated condition. Similarly, the divers thought that the exposure would be less detrimental to mental performance in the heated conditions than the unheated condition. These perceptions are in stark contrast to the evidence from the physiological and cognitive tests performance. Other researchers have also concluded that humans are unable to reliably assess how cold they are. Hoffman and Pozos (17) found that 0.51 was the highest correlation observed between perceived temperature and actual temperature. Arieli et al. (2) found that there was a positive correlation between a subjective assessment of cold and rectal temperature for the first hour of submersion in cold water, but not after that. Therefore, cold sensation would not appear to be a useful metric in determining how cold the body actually is, and other indices such as exposure time and water temperature are more reliable. Hoffman (16)

postulates that when rapidly cooled in cold water, individuals have difficulty separating feelings of pain and discomfort from feelings of cold.

CONCLUSION

This study demonstrated that applying external heating to the torso of a cold submerged diver lead to the subjective belief of the participants that they were more comfortable and that the heating had a positive effect on performance. However, the objective data collected did not support this perception. In fact, heating the torso had a significantly detrimental effect on the body's thermoregulatory ability and a lack of a positive effect on the manual dexterity of participants. Therefore, heating the torso of a diver may actually increase susceptibility to hypothermia.

ACKNOWLEDGMENTS

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