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THERMAL COMFORT AND THERMAL SENSATION DURING EXPOSURE TO HOT, HOT-HUMID AND THERMONEUTRAL ENVIRONMENTS

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13. ABSTRACT *(Maximum 200 words)*

It was hypothesized that high skin wettedness and elevated skin temperature would negatively affect psychophysical performance. Twelve volunteers participated in a four-hour experiment in each environmental condition [Condition 1 (COND 1): Ta = 28°C, 50% rh; Condition 2 (COND 2): Ta = 36°C, 50% rh; and Condition 3 (COND 3): Ta = 36°C, 75% rh]. Tc was significantly higher in COND 2 (37.2 + 0.3°C) and COND 3 (37.3 + 0.3°C) compared to COND 1 (36.8 + 0.2°C) during the four-hour experiments ($p < 0.05$). Mean skin temperature was lower in COND 1 (32.4 + 0.12°C), than COND 2 (35.3 + 0.10°C) and COND 3 (35.6 + 0.13°C, $p < 0.05$). Mean heat flow was higher in COND 1 (57 + 2 W), than COND 2 (6 + 2 W) and COND 3 (11 + 5 W, $p < 0.05$). The thermal comfort and thermal sensation assessments reflected the physiological responses. The subjective index of thermal discomfort effectively discriminated among the environments. The ESQ subjective heat index scores were higher for COND 2 and COND 3 compared to COND 1 ($p < 0.05$). These subjective responses tracked skin wettedness. Skin wettedness averaged over the entire body surface was related to thermal comfort ($R^2 = 0.94$. This research provided evidence that skin wettedness predicted thermal comfort effectively in all environments tested. The subjective assessment of thermal comfort discriminated between all environments and the heat index derived from the USARIEM Environmental Symptoms Questionnaire discriminated between the neutral and the two hot environments. Unfortunately, several indices derived from the Environmental Symptoms Questionnaire had limited utility to discriminate among significantly different environments.

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EXECUTIVE SUMMARY

It was hypothesized that high skin wettedness and elevated skin temperature would negatively affect psychophysical performance. Three environments were chosen so that the ambient dry bulb temperature (T_a) and the relative humidity (rh or dew point temperature) could be manipulated independently so that the impact of each factor on psychophysical measurements could be determined. Twelve volunteers participated in a four-hour experiment in each environmental condition [Condition 1 (COND 1): $T_a = 28°C$, 50% rh; Condition 2 (COND 2): $T_a = 36°C$, 50% rh; and Condition 3 (COND 3): $T_a = 36°C$, 75% rh]. T_c was significantly higher in COND 2 (37.2 $\pm$ 0.3°C) and COND 3 (37.3 $\pm$ 0.3°C) compared to COND 1 (36.8 $\pm$ 0.2°C) during the four-hour experiments ($p<0.05$). Mean skin temperature was lower in COND 1 (32.4 $\pm$ 0.12°C), than COND 2 (35.3 $\pm$ 0.10°C) and COND 3 (35.6 $\pm$ 0.13°C, $p<0.05$). Mean heat flow was higher in COND 1 (57 $\pm$ 2 W), than COND 2 (6 $\pm$ 2 W) and COND 3 (11 $\pm$ 5 W, $p<0.05$). Water loss from sweating was significantly greater in COND 2 (0.6$\pm$0.2 kg) and COND 3 (0.6$\pm$0.2 kg) than COND 1 (0.1$\pm$0.1 kg) ($p<0.05$). Heart rate was significantly higher in both COND 2 (74 $\pm$ 12) and COND 3 (78 $\pm$ 9) than in COND 1 (60 $\pm$ 6) in the last hour of the four-hour experiments ($p<0.05$). Mean arterial pressure was unchanged during the four-hour experiments and was not different between conditions due to heart rate compensation. The USARIEM Environmental Symptoms Questionnaire (ESQ) cardiopulmonary discomfort index scores indicated an elevated cardiopulmonary discomfort for COND 3 compared to COND 1 and COND 2 ($p<0.05$) and probably reflected the higher heart rate in COND 3 compared to the other two environments.

The thermal comfort and thermal sensation assessments reflected the physiological responses. Subjects were "comfortable" at 28°C and closer to "neutral" than "cool". Immediately upon exposure to 36°C (COND 2 and COND 3) subjects reported a warm sensation that was unchanged during the four-hour exposure (COND 2 = 74 $\pm$ 2 ND and COND 3= 81 $\pm$ 3 ND). These values were significantly higher than COND 1 (35 $\pm$ 3 ND, $p<0.05$). The subjective index of thermal discomfort effectively discriminated among the environments. Immediately upon exposure to COND 3, subjects perceived more discomfort than comfort and this was relatively constant for the four-hour exposure (61 $\pm$ 5 ND). COND 1 was considered "comfortable" for the entire four-hour exposure (16 $\pm$ 2 ND). However, exposure to COND 2 was not different from COND 1 immediately upon entering, but over the time course of the exposure subjects perceived increasing thermal discomfort (44 $\pm$ 7 ND). By the beginning of the third hour of exposure, thermal discomfort was not different between COND 2 and COND 3, but both COND 2 and COND 3 had higher discomfort than COND 1 ($p<0.05$). The ESQ subjective heat index scores were higher for COND 2 and COND 3 compared to COND 1 ($p<0.05$). These subjective responses tracked skin wettedness. The skin on the chest was fully wet after five minutes in COND 3 and averaged 1.47 $\pm$ 0.20 (ND) for the remainder of the four-hour exposure. The skin on the chest was fully wet by the start of the second hour of exposure in COND 2 (0.94 $\pm$ 0.29). Chest skin was minimally wet in COND 1 (0.14 $\pm$ 0.05) and was significantly drier than COND 2 and COND 3 ($p<0.05$). Forearm and calf wettedness were lower than the chest. Forearm wettedness was higher in COND 3 (0.55 $\pm$ 0.21) than COND 1 (0.05 $\pm$ 0.01) and COND 2 (0.25 $\pm$ 0.18) ($p<0.05$). Calf wettedness was higher in COND 3 (0.24 $\pm$ 0.19) and COND 2 (0.20 $\pm$

0.20) than COND 1 (0.02 $\pm$ 0.03) (p<0.05). Skin wettedness averaged over the entire body surface was related to thermal comfort (R^2 = 0.94). Simple reaction time averaged 1.3 $\pm$ 0.3 sec in COND 1, 1.3 $\pm$ 0.2 sec in COND 2 and 1.4 $\pm$ 0.2 sec in COND 3.

This research provided evidence that skin wettedness predicted thermal comfort effectively in all environments tested. The subjective assessment of thermal comfort discriminated between all environments and the heat index derived from the USARIEM Environmental Symptoms Questionnaire discriminated between the neutral and the two hot environments. Unfortunately, several indices derived from the Environmental Symptoms Questionnaire had limited utility to discriminate among significantly different environments.

INTRODUCTION

SCIENTIFIC BACKGROUND

Thermal comfort defined by Fanger (4) "as a state in which he (sic) expresses satisfaction with the thermal environment, i.e., he (sic) would prefer neither a warmer nor a colder environment". Fanger continues, "it seems reasonable to assume that human performance in general is optimal when man is in thermal comfort" (4). Thermal comfort varies between individuals and is affected by the environmental conditions, the clothing worn and the activity performed. A quick review of the environmental conditions encountered during recent deployments of U.S. Army warfighters suggests thermal comfort is hard to achieve. Therefore, the effect of "thermal discomfort" must be factored into military performance scenarios.

Core temperature in humans is regulated over a relatively narrow range from 36-40°C during exercise and exposure to environmental extremes. Skin temperature, on the other hand, follows the ambient temperature and has a much larger range (18; 24). Humans change their behavior to offset changes in body temperature, and have exquisite physiologic mechanisms to closely regulate body temperature. Elegant studies from the John B. Pierce Foundation Laboratory described the relative roles of thermal discomfort, core and surface temperatures and skin wettedness during environmental exposure (1-3; 6-8; 23). These investigations used rationale indices, physical characteristics of the environment or the relative roles of core and surface temperatures to characterize thermal comfort or discomfort. More recently, the contribution of core and surface temperatures to thermal comfort was re-examined. It was suggested that skin temperature was as important as core temperature in an individual's assessment or determination of thermal comfort (5). That study was in agreement with earlier studies of behavioral thermoregulation in primates (23) suggesting that surface and core temperatures contribute to behavioral thermoregulatory responses.

Individual differences exist in cognitive and psychomotor performance during heat exposure (15). Furthermore, "establishing well-defined relationships between climatic conditions and psychological performance has been difficult" (15). In fact, a comprehensive review of the effects of heat exposure on measures of cognitive function, including time estimation, vigilance, tracking and cognitive tasks and found only subtle changes in these parameters during exposure to hot environments (10). Grether (10) suggested that performance is optimal when ambient temperature is 80°F effective temperature, or just above the thermal comfort level.

MILITARY RELEVANCE

Physiological performance and cognitive performance are adversely affected by heat stress. Understanding relationships among physiological systems and psychological/cognitive/behavioral systems during heat exposure is essential to establish guidelines to predict and improve military performance when sustained cognitive performance is required.

If cognitive or physical performance is adversely affected by increased thermal discomfort caused by insufficient heat loss and/or wet skin, one solution might be to intermittently cool the skin surface. Microclimate cooling systems (MCC) have been developed to alleviate heat stress and sustain physical work. These systems are capable of cooling the skin surface (150-325 watts). Unfortunately, soldiers doing light work, such as tank drivers, often turn off MCC. An understanding of the impact of wet skin or high skin temperature at specific skin sites on thermal discomfort and/or specific areas of cognitive performance might direct future efforts to alleviate specific detrimental symptoms of heat stress. If this is the case, possible solutions might be to alter the cooling temperature, the location of air (or liquid) delivered to the body surface or some combination of the two.

This study was funded under US Army Medical Research and Materiel Command STO/STEP TB: *Develop strategies to safely extend heat tolerance and enhance performance during hot weather operations (Risk reduction and performance enhancement).* A DTIC search (SMK50L, 31 Dec 98) was done using the keywords: thermal comfort, thermal sensation, cognition and temperature regulation. A Medline search was done using the same terms. MESH terms were used throughout. No duplicative research was found.

PURPOSE

It was hypothesized that high skin wettedness and elevated skin temperature could be discriminated by the assessment of thermal comfort and thermal sensation. Additionally, it was hypothesized that simple reaction time and selected psychophysical measurements would be negatively affected by a passive four-hour exposure in a hot and humid environment. The hot and hot-humid environments were selected such that the skin of the volunteer would become hot or hot and wet; yet volunteers could tolerate a four-hour exposure.

METHODS

Prior to testing, volunteers were thoroughly familiarized with all experimental techniques. Following informed consent and medical clearance procedures, twelve healthy subjects (ten male and two female) were each tested in three environmental conditions (COND 1, COND 2, or COND 3) for 240 minutes (Table 1).

Table 1. Environmental Conditions for the Study

Description	Condition	WBGT	U.S Army Heat Category
COND 1	28°C/50%rh	70°F	1
COND 2	36°C/50%rh	86°F	2-3
COND 3	36°C/75%rh	90°F	4-5

Testing was done between November and April in Natick, MA. Subjects were not heat acclimated. The mean ($\pm$SD) age was 20.7$\pm$4.4 years, height was 1.75$\pm$0.10 m, mass was 78.3$\pm$13.3 kg, and BMI (body mass index) was 25$\pm$5. They were of average fitness for soldiers of their age and gender. Subjects fasted overnight, and refrained from smoking or drinking alcohol 24 h prior to the experiment. *Ad libitum* water ingestion was permitted until the experiment started. The time of experiments was approximately the same (starting between 0700-0730 h) to control for circadian differences in thermoregulation (21; 22). Environments were presented in a balanced order to minimize any effect of repeated heat exposure. There was minimum of one day between heat exposures. Subjects dressed in shorts, T-shirt, shoes and socks (Summer PT uniform). Core temperature was measured using an ingestible temperature sensor. Briefly, core temperature was monitored using a temperature telemetry pill (HTI Technologies, Inc., Palmetto, FL). The pill continuously transmitted the local temperature to a receiver (BCTM3, FitSense, Inc., Wellesley, MA). On average, the sensor was swallowed 12 to 24 hours before an experiment. However, on some occasions a single sensor was used for multiple experiments. This methodology has been shown effective in accurately measuring core temperature at rest and during exercise (16).

Upon arriving at the laboratory for each of the three experiments, body weight was measured and a Polar "Favor" heart rate monitor (Polar CIC Inc., Port Washington, NY) to measure heart rate was attached. An Actiwatch Alert (MiniMitter Co. Inc., Bend, OR) was attached to the non-dominant wrist. The volunteer was then moved into the climatic chamber and seated in a comfortable chair (blood drawing chair). A DynaPulse 5000A blood pressure monitor was placed on the upper arm for the measurement of systolic, diastolic and mean blood pressure (auscultation; automated by PulseMetric Inc., San Diego, CA). Surface heat flow disks were placed at eight skin sites (forehead, chest, back, upper arm, forearm, hand, thigh and calf) to measure skin temperature and local heat flow. Mean skin temperature was calculated as:

$$T_{sk} = 0.07(\text{head})+0.175(\text{chest})+0.175(\text{back})+0.07(\text{upper arm})$$
$$+0.07(\text{forearm})+0.07(\text{hand})+0.19(\text{thigh})+0.20(\text{calf}) \quad (19).$$

Mean heat flow was calculated from the eight sites as described above. Positive heat flow in these studies represents heat lost from the body to the environment. Dew point sensors were attached to 3 sites (chest, arm and calf) (9). Skin wettedness was calculated from the skin dew point, the skin temperature and the ambient dew point as:

$$w = [P_{s,dpl} - P_w] / [P_{s,sk} - P_w]$$

where: $P_{s,dpl}$ and $P_{s,sk}$ are the saturated vapor pressure at the local dew point and local skin temperature respectively, and P_w is the ambient water vapor pressure (17).

Mean wettedness was calculated as:

$$w_x = 0.39(\text{chest}) + 0.16(\text{forearm}) + 0.45(\text{calf})$$

Whole body sweating was determined from the change in body weight from pre- to post-experiment corrected for water ingested. Each subject was given 190 ml of water before the initial body weight and again at 120 minutes of exposure.

Following instrumentation, each subject sat passively in the environmental chamber at the specific temperature combination for that day's experiment for 240 minutes. Subjects were required to remain seated and awake during the entire four-hour experiment. They were also allowed to bring in reading material to read while seated in the chamber. Core and surface temperatures were recorded every minute. Heart rate and arterial blood pressure were recorded each 15 minutes. Magnitude estimation of thermal discomfort and thermal sensation were measured according to Gagge (6; 7). Thermal sensation was assessed on a scale of cool to neutral to warm (see Appendix). Similarly, thermal comfort was assessed on a scale of discomfort to comfort (see Appendix). These measures were taken at 30-minute intervals. Simple reaction time was assessed at 15-minute intervals using the Actiwatch Alert. An audible alarm would randomly sound during each 15-minute period. The time to respond was recorded by the device. The USARIEM Environmental Symptoms Questionnaire (ESQ) (20) was administered at the termination of each heat exposure session. The ESQ was worded in the past tense to assess individual subjective responses relative to the daily testing session. The ESQ indices for well-being, tiredness, cardiopulmonary discomfort and subjective heat were calculated and scored according to standard procedures described by Sampson et al., (20). At the end of each experiment, the subject was hydrated back to baseline body weight with water and/or Gatorade™ prior to being released for the day.

All data (core and surface temperatures, heart rate, heat flow, mean arterial pressure, reaction time, thermal comfort, thermal sensation, skin wettedness and ESQ) were analyzed by analysis of variance techniques with repeated measures (environmental condition by time). Tukey's critical difference was used to discriminate

significance for all variables except for the Environmental Symptoms Questionnaire for which the Duncan multiple range test was used.

RESULTS

The mean (±SD) mean skin temperature and mean heat flow for the twelve subjects for all three conditions are shown in Figures 1A and 1B.

Figures 1A and 1B: Mean Skin Temperature and Mean Heat Flow.
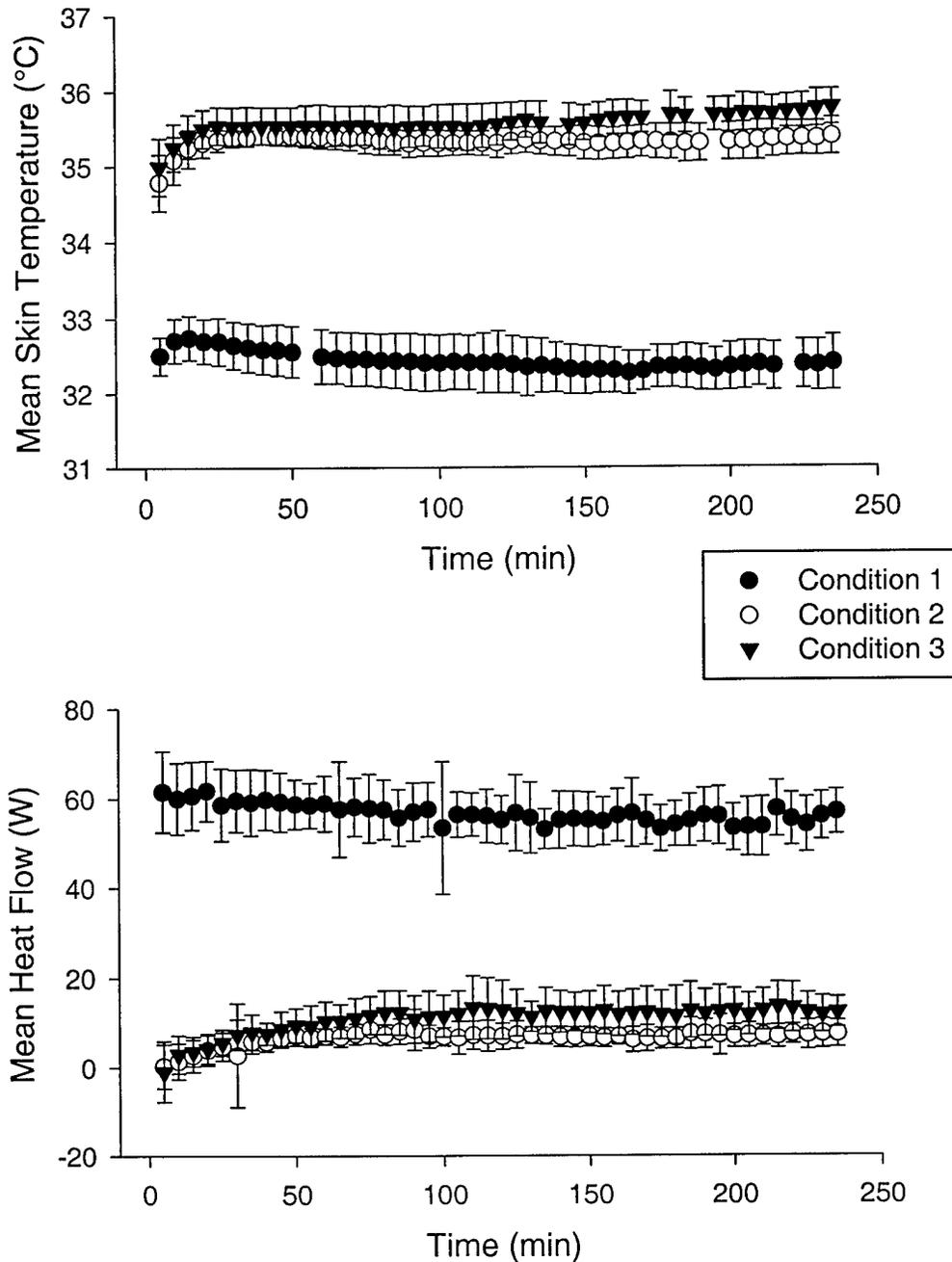
As expected, the ambient dry bulb temperature "fixed" skin temperature and subsequently heat flow in the specific environmental conditions. Mean skin temperature

was lower in COND 1 (32.4 ± 0.12°C), than COND 2 (35.3 ± 0.10°C) and COND 3 (35.6 ± 0.13°C) during the four-hour experiments (p<0.05). Mean heat flow was higher in COND 1 (57 ± 2 W), than COND 2 (6 ± 2 W) and COND 3 (11 ± 5 W) during the four-hour experiments (p<0.05). Both COND 2 and COND 3 limited dry heat loss by design as the gradient between skin temperature and ambient temperature was 0.4-0.7°C.

Core temperature (mean ± SD, T_c) averaged over the final hour of the four-hour exposure for the three conditions is shown in Figure 2. In this Figure and Figures 3 and 4, the conditions go from left to right COND 1, COND 2 and COND 3.

Figure 2: Core Temperature for Three Conditions during Hour Four.
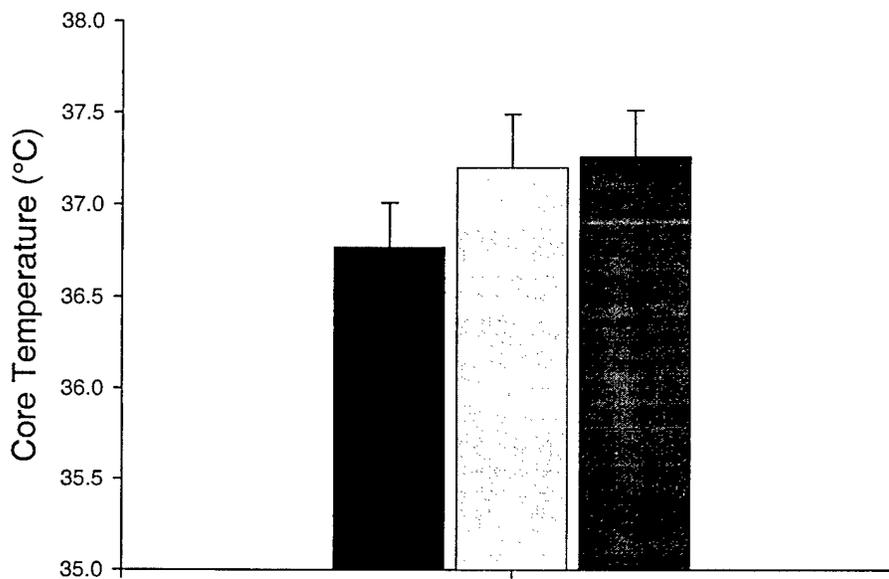
T_c increased approximately 0.5°C during the four-hour exposure in COND 2 and COND 3 and remained unchanged in COND 1. T_c was significantly higher in COND 2 (37.2 ± 0.3°C) and COND 3 (37.3 ± 0.3°C) compared to COND 1 (36.8 ± 0.2°C) during the four-hour experiments (p<0.05). Water loss from sweating was significantly greater in COND 2 (0.6±0.2 kg) and COND 3 (0.6±0.2 kg) than COND 1 (0.1±0.1 kg) (p<0.05). Mean arterial pressure (Figure 3A) was unchanged during the four-hour experiments and was not different between environments due to heart rate compensation (Figure 3B). MAP was 86 ± 6 Torr in COND 1, 87 ± 8 Torr in COND 2 and 85 ± 6 Torr in COND 3. Heart rate was significantly higher in both COND 2 (74 ± 12 b·min^{-1}) and COND 3 (78 ± 9 b·min^{-1}) than in COND 1 (60 ± 6 b·min^{-1}) in the last hour of the four-hour experiments (p<0.05).

Figure 3A and 3B: Mean Arterial Pressure and Heart Rate during Hour Four.
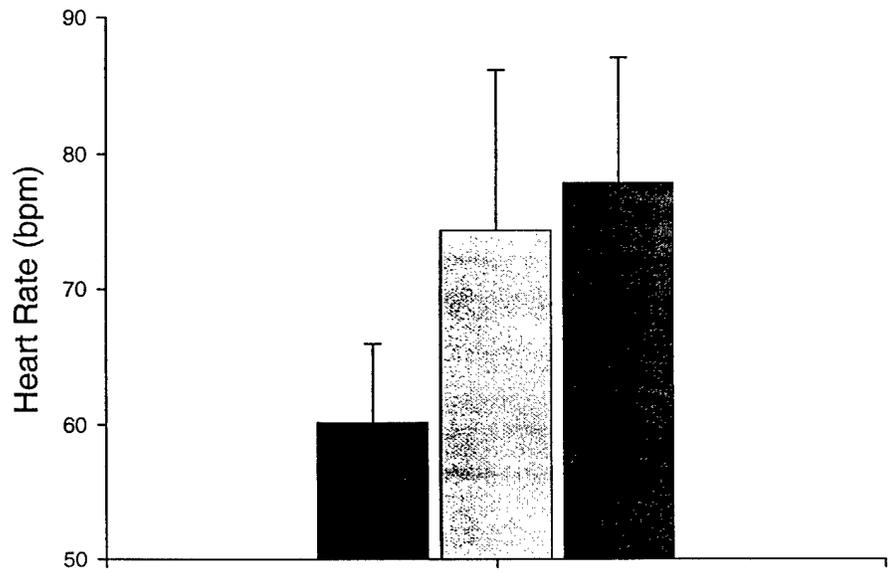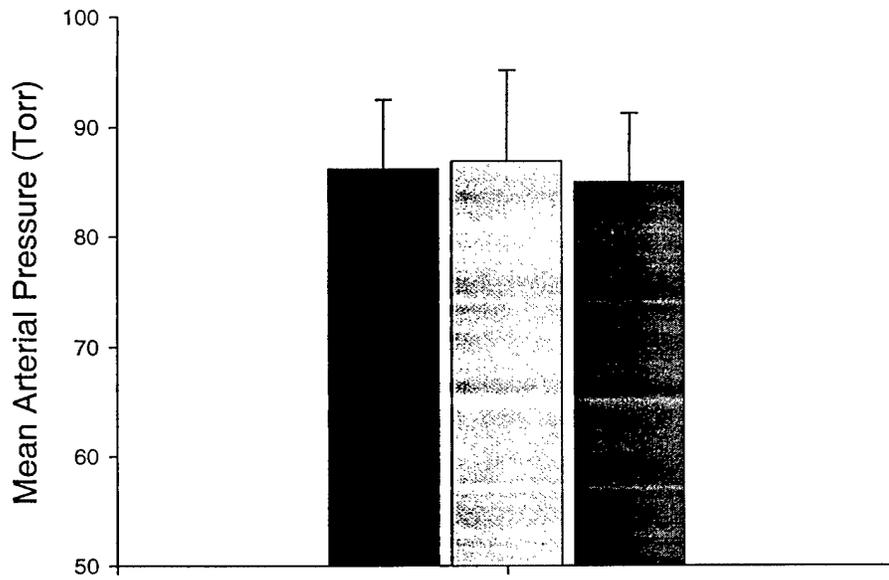
Figure 4: Simple Reaction Time during Hour Four.
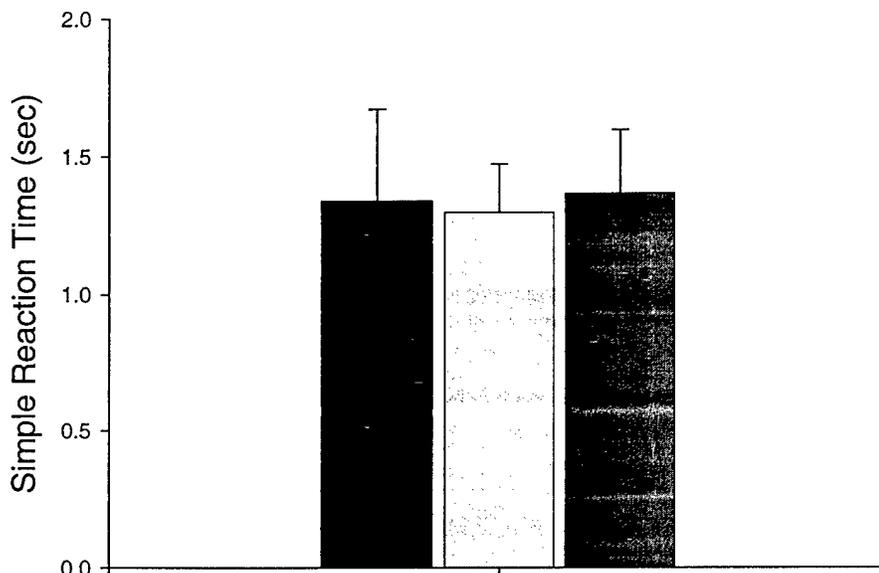
Simple reaction time averaged over the final hour is shown in Figure 4. There was no difference in simple reaction time at any time during the four-hour exposure between or among conditions. Simple reaction time averaged 1.3 ± 0.3 sec in COND 1, 1.3 ± 0.2 sec in COND 2 and 1.4 ± 0.2 sec in COND 3 during the four-hour experiments.

Indices (mean $\pm$ SD) of thermal comfort and thermal sensation are shown in Figure 5A and 5B for the three environmental conditions of the study. These data are shown as a proportion of the entire scale from "comfort to discomfort" or "cool to neutral to warm" for thermal comfort and thermal sensation respectively. The ordinate was anchored at each end (see test instrument in Appendix) by these adjectives. Immediately upon exposure to COND 3, subjects perceived more discomfort than comfort and this remained relatively constant for the four-hour exposure (61 ± 5 ND). COND 1 was comfortable for the entire four-hour exposure (16 ± 2 ND). Exposure to COND 2 was not different from COND 1 initially, but over the time course of the exposure (44 ± 7 ND), subjects perceived increasing thermal discomfort. By the beginning of the third hour of exposure, thermal discomfort was not different between COND 2 and COND 3 and both COND 2 and COND 3 indicated more discomfort than COND 1 ($p<0.05$).

Immediately upon exposure to the 36°C (COND 2 and COND 3) environments subjects reported a sensation of warmth (Figure 5B) that remained unchanged throughout the four-hour exposure (COND 2 = 74 ± 2 ND and COND 3 = 81 ± 3 ND). These values were significantly higher than COND 1 (35 ± 3 ND, $p<0.05$).

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Figure 5A and 5B: Thermal Comfort and Thermal Sensation.
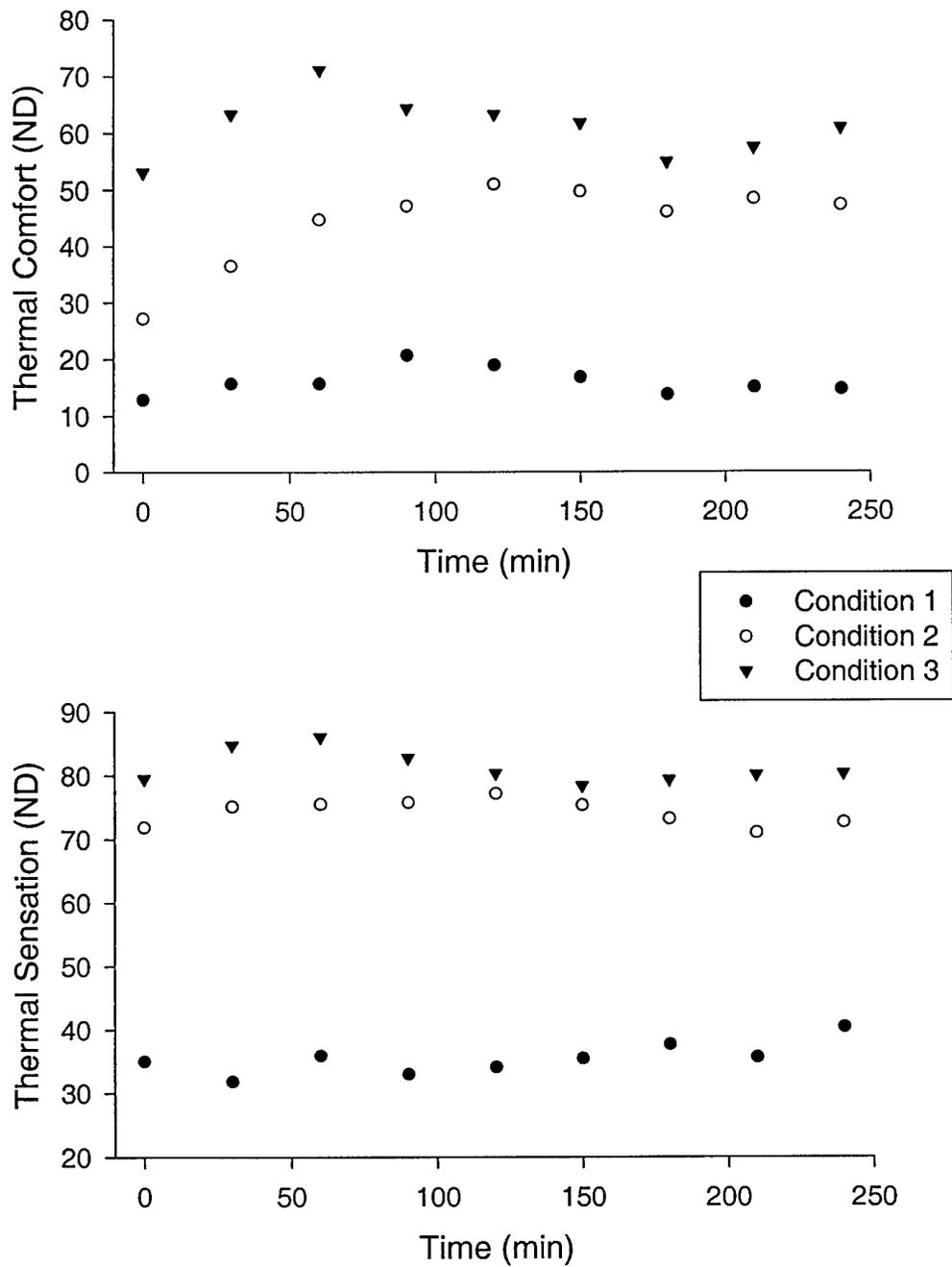
Figure 6: Skin Wettedness.
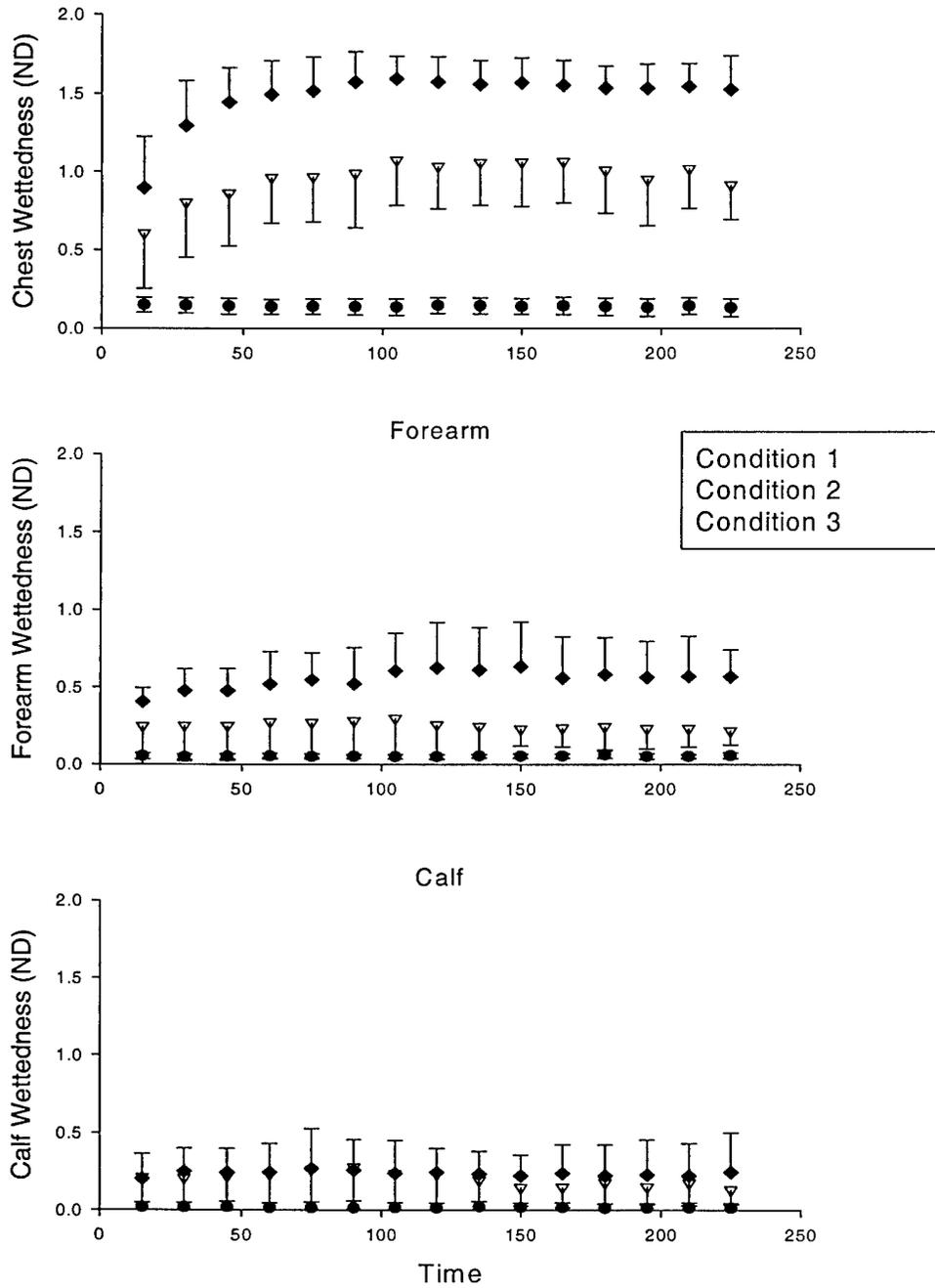
Figure 7: Skin Wettedness and Thermal Comfort.
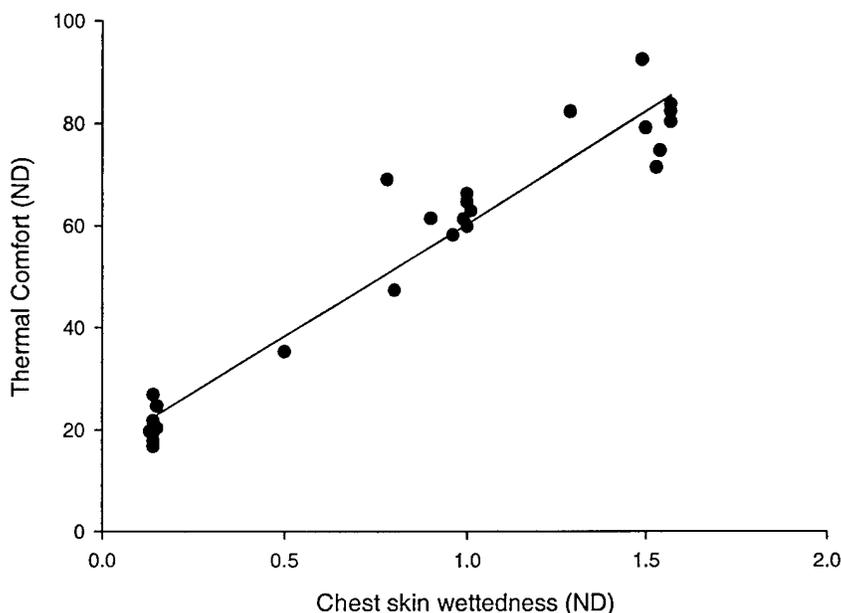
Skin wettedness on the chest, forearm and calf in the three environmental conditions studied is shown in Figure 6. The skin on the chest was fully wet after five minutes in COND 3 and averaged 1.47 ± 0.20 for the remainder of the four-hour exposure. The skin is fully wet when this value reaches 1.00 (or 100%). The skin on the chest was fully wet starting the second hour of exposure in COND 2 (0.94 ± 0.29). Chest skin was minimally wet in COND 1 (0.14 ± 0.05) and was significantly drier than COND 2 and COND 3 (p<0.05). Forearm and calf wettedness were not as high as observed on the chest. Forearm wettedness was higher in COND 3 (0.55 ± 0.21) than COND 1 (0.05 ± 0.01) and COND 2 (0.25 ± 0.18) (p<0.05). Calf wettedness was higher in COND 3 (0.24 ± 0.19) and COND 2 (0.20 ± 0.20) than COND 1 (0.02 ± 0.03) (p<0.05). Skin wettedness averaged over the entire body surface was related to thermal comfort (Figure 7; R^2 = 0.94). This relationship shows as the skin surface becomes wet with un-evaporated sweat, the perception of discomfort increases in a linear fashion.

The USARIEM Environmental Symptoms Questionnaire (ESQ) index scores for well-being were unable to discriminate between any of the conditions tested in this study. Similarly, the ESQ tiredness index was unable to discriminate between the three environments tested. However, the ESQ cardiopulmonary discomfort index scores indicated an elevated cardiopulmonary discomfort for COND 3 compared to COND 1 and COND 2 (p<0.05). Finally, the subjective heat index was higher for COND 2 and COND 3 compared to COND 1 (p<0.05).

DISCUSSION

We used an experimental paradigm that compared physiological responses and some psychophysical measurements in two environmental conditions that were more stressful than ambient conditions where deficits in cognition appear (15). This allowed the assessment of subtle differences in thermal comfort and thermal sensation during four-hour exposures in three distinct environments (11; 14). As expected from the experimental design, a range of thermal comfort and thermal sensation responses was observed. Our measurement of skin wettedness predicted thermal comfort effectively in all environments tested. In addition, the subjective assessment of thermal comfort discriminated between all environments. This study supports the observation that a four-hour heat exposure did not affect simple reaction time.

As stated in the INTRODUCTION, individual differences exist in cognitive and psychomotor performance during heat exposure (15) and these individual differences obscure the subtle changes in these parameters during exposure to hot environments (10). The establishment of "well-defined relationships between climatic conditions and psychological performance has been difficult" (15) and has not been further delineated by the current study. The selected psychophysical tasks that were used in this study addressed perception, simple reaction time and symptomatology during prolonged exposures to hot and hot and humid environments.

We were able to demonstrate a very strong relationship between thermal comfort and wet skin using the paradigm designed for this study (Figure 7). Under these conditions, significant portions of the skin surface were wet with unevaporated sweat and this sustained skin wettedness contributed to decreasing thermal comfort. These results are not novel and are in agreement with earlier studies (1-3; 6-8; 23). The thermal comfort, thermal sensation and subjective indices all show the two hot conditions were very similar during the final two hours of exposure. That is, there were no significant differences between the hot and the hot-humid conditions on any of these measurements during the final two hours of exposure. These findings are supported by the physiological data as well. Even though it appears the skin was less wet (Figure 6) in COND 2 than COND 3, from a physiological perspective there is no difference between the conditions. The skin is fully wet when the wettedness value approaches 1.00 or 100%. It is obvious that this occurred for chest skin in both of the hot environments.

The thermal neutral zone for lightly clothed human volunteers ranges from 28-31°C (11; 14). Women are more prone to reside at the top end of the thermal neutral zone and men at the bottom (12; 13). Our thermoneutral "control" environment was set to the low end of this window. Our thermal sensation results of less than "neutral" and a slight lowering of the core temperature (0.1°C) over the four-hour exposure support this assessment.

The USARIEM Environmental Symptoms Questionnaire was utilized to determine index scores for well-being, tiredness, cardiopulmonary discomfort and subjective heat illness (20). The well-being index and tiredness index were not able discriminate between any conditions tested in this study. This was not surprising because subjects were passively sitting during the entire four-hour exposure, and there was little demand for energy expenditure. The cardiopulmonary discomfort index scores indicated an elevated cardiopulmonary discomfort for the two hot environments.

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This index was supported by an elevated heart rate (14-18 b·min^{-1}) during the four-hour exposure to the heat. Even at rest, the hot environments "forced" a redistribution of the cardiac output to the cutaneous blood vessels in an attempt to dissipate heat. Mean arterial pressure was maintained during this redistribution of the cardiac output through the increased heart rate in the two hot conditions. However, the environmental conditions prevented radiative and convective heat loss from the skin surface as ambient temperature was slightly higher than skin temperature (Figure 1). So the increased blood flow to the skin surface increased cardiovascular strain without heat dissipation. To further complicate attempted heat loss, the water vapor pressure gradient between the skin and the ambient air was not favorable for evaporative heat loss from the skin surface to the environment (9 Torr in COND 3 and 20 Torr in COND 2). The result was that core temperature increased during the four-hour exposure in both environments. This finding, and the elevated skin temperature and sustained wet skin, explain the elevated subjective heat index, derived from the Environmental Symptoms Questionnaire, in the hot conditions of the study.

CONCLUSIONS

This research provided evidence that skin wettedness predicted thermal comfort effectively in all environments tested. The subjective assessment of thermal comfort discriminated among all environments and the heat index derived from the USARIEM Environmental Symptoms Questionnaire discriminated between the neutral and the two hot environments. Unfortunately, several indices derived from the Environmental Symptoms Questionnaire had limited utility to discriminate among significantly different environments. The environmental paradigm developed may be more effective when combined with more complex cognitive tasks or when used before and after other interventions, such as heat acclimation, to determine changes or benefits from those interventions.

RECOMMENDATIONS

This study was the first in a series to characterize the relationships among physiological and psychophysical variables under controlled laboratory environmental conditions. The paradigm developed has utility in other research scenarios. Additional studies are required to understand the relationships between complex cognitive function(s) and the physiological variables studied because physiological performance and cognitive performance are adversely affected by heat stress during exercise and work in personal protective equipment. Issues of hydration-dehydration-rehydration affecting cognition and complex mental tasks need to be addressed. The interaction(s) of increasing work intensity, work rest cycles and personal protective equipment and cognition and complex mental tasks need to be addressed. Continued understanding of relationships among physiological systems and psychological/cognitive/behavioral systems during heat exposure remains essential to establish guidelines to predict and improve military performance when sustained cognitive performance is required.

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APPENDICES

THERMAL COMFORT

COMFORT   **DISCOMFORT**

| |
_____

Indicate along the line how you feel right now.

THERMAL SENSATION

COOL   **NEUTRAL**   **WARM**

Indicate along the line how you feel right now.