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Auxiliary Heating of the Hands During Cold Exposure and Manual Performance

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Twenty subjects performed five manual tasks barehanded during exposure to a 60°-F ambient temperature control condition, a 0°-F condition, and three ambient temperature conditions of 20°, 0°, and −20° F, in which auxiliary heat was applied to the hands. The tasks consisted of the Purdue Pegboard assembly, block-stringing, Minnesota Rate of Manipulation placing, knot-tying, and screw-tightening tasks and were performed after exposure durations of 0, 60, 120, and 180 min. Exposure to the 0°-F condition without auxiliary heat resulted in significant performance decrements on all tasks. The application of auxiliary heat to the hands resulted in the avoidance or alleviation of impaired performance during cold exposure depending upon the task, ambient temperature condition, and duration of exposure. The differential effects of auxiliary heat during cold exposure across manual performance tasks were related to the effects of auxiliary heat on hand skin temperature. These effects are discussed in terms of differential hand and finger dexterity, strength, and speed of movement requirements across tasks.

INTRODUCTION

The purpose of this experiment was to determine the effectiveness of applying radiant heat to the hands in preventing impaired manual performance during cold exposure. Cold exposure of the hand results in a lowering of hand skin temperature and in decrements in performance on manual dexterity tasks (Bartlett and Gronow, 1952; McCleary, 1953). Performance decrements are related, in part, to the level of hand skin temperature and the type of task being performed. Knot-tying performance was affected when hand skin temperature was lowered to 55° F (Clark, 1961). Hellstrøm (1965) found performance on a task involving the rotation of an object between the thumb and forefinger to be impaired when finger skin temperature was lowered beyond about 68° F and hand grip strength to be reduced gradually when forearm muscle temperature was reduced below about 86° F.

In addition to the level of cooling, performance decrements during cold exposure depend upon the locus and duration of cooling. Le Blanc (1956) found a finger flexion task to be affected by forearm, hand, and finger cooling but found a tapping task to be affected only by cooling of the forearm and hand. An increase in the duration of cold exposure of the hand and forearm resulted in an additional 50% decrease in performance for both the finger flexion task and the tapping task. Clark and Cohen (1961) found greater knot-tying performance decrements for a slow cooling condition (long duration of exposure) than for a fast cooling condition (short duration of exposure). When the hands were rewarmed to a hand skin temperature of 70° F by exposure to normal ambient temperatures, knot-tying performance improved for both conditions, but the difference between conditions persisted. When the hands were rewarmed using an electric muff, the difference between slow and fast cooling conditions was not significant, and the absence

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of a difference between conditions was attributed to the relative effectiveness of radiant heat in raising subsurface temperatures.

Cold-exposure-induced manual performance decrements are assumed to result from a loss of cutaneous sensitivity, from changes in the characteristics of synovial fluid in the joints (Hunter, Kerr, and Whillans, 1952), or from a loss of muscle strength (Hellstrøm, 1965). The relative contributions of these factors to cold-exposure-induced manual performance decrements are dependent upon the locus, level, and rate of cooling and type of manual performance involved.

Based on the above findings, the effectiveness of applying radiant heat to the hands in alleviating decremental manual performance during cold exposure was anticipated to differ across manual tasks, ambient temperature conditions, and duration of exposure. A previous study of auxiliary heat and manual performance found the application of two levels of auxiliary topical heat to the forearms during exposure of the hands to an ambient temperature of -1.3° F not to have an effect on hand skin temperature or on cutaneous sensitivity, as measured by the Mackworth V test. Performance on a pegboard test deteriorated continuously during cold exposure and was not affected by the low level of auxiliary heat applied to the forearm. However, when the high level of auxiliary heat was used, performance improved significantly but was still impaired relative to the control condition. The results suggest auxiliary heat effects during cold exposure are dependent upon the level of heat and type of manual task. In the present experiment, the effect of radiant heat on performance using a battery of five manual tasks was determined for three ambient temperature conditions (20°, 0°, and -20° F) after 0, 60, 120, and 180 min. of exposure. Hand skin temperature was recorded at three points. The changes in manual performance and hand skin temperature with and without radiant heat across manual tasks, ambient temperature conditions, and durations of exposure were analyzed in terms of the differential effects of parameters of cold exposure on components of manual performance.

METHOD

Subjects

The subjects were 20 volunteer enlisted men assigned to the Climatic Research Laboratory of the U.S. Army Natick Laboratories. The subjects ranged in age from 20 to 25 years and had previous experience with cold exposure.

Apparatus and Tasks

The tasks were performed at a 5-X-5-ft. table in a wind tunnel. Placed over the table were three Chromolox, 3000-w. infrared heaters, each with a heated length of approximately 66 in. The heaters were placed so as to heat all tasks and were between 22 and 28 in. above the table top. The output of the heaters was continuously controlled between 5 and 95% of their output.

The tasks employed were the following: knot-tying, block-stringing, Purdue Pegboard assembly, Minnesota Rate of Manipulation placing, and screw tightening. For the knot-tying task, each subject was required to tie 15 standard knots (overhand and bight) on pieces of rope hanging from a rotatable circular disc. Block-stringing consisted of stringing 20 blocks with a hole in each face onto a needle and string. For the pegboard assembly task, each subject constructed six pin-washer-collar-washer assemblies. The placing task consisted of picking up 44 circular blocks with the preferred hand and placing them in a wooden frame. Screw tightening consisted of tightening and loosening six vertically mounted screws with a screw driver. All tasks except the placing task required both hands.

Procedure

Prior to the experiment, each subject had five days of practice on each task at 70° F. All subjects received three practice trials a day on the screw-tightening task. Ten subjects received four trials a day on the remaining tasks. Ten subjects with previous experience on the tasks received either two or three trials a day. All subjects wore the standard Army fatigue uniform during the practice days.

During the experiment, each subject served at five ambient temperature conditions: a control condition at 60° F; ambient temperatures of 20°, 0°, and –20° F with auxiliary heat; and 0° F ambient temperature without auxiliary heat (the cold-exposure condition). Subjects were run in groups of four. Each group was exposed to one condition a week over a five-week period. Five presentation orders for the temperature conditions were employed. Each group of four subjects received a different temperature condition sequence.

Under all ambient temperature conditions, the subjects wore insulated arctic boots, summer underwear, field trousers with liner, wool shirt, field jacket with liner, pile cap, arctic parka with liner, and arctic hood. Each subject was permitted to ventilate as necessary for personal comfort. Between testing periods, subjects wore arctic mittens except in the control condition. In addition, the subjects wore a ten-point copper constantan thermocouple harness used for measuring mean weighted skin temperature. Body skin temperature was sampled from the ten points on the body and automatically integrated by a Leeds-Northrup Speedomax Recording System (Iampietro, 1961). Hand skin temperature was recorded from thermocouples on the volar surface of the little finger, the forefinger, and the dorsum of the nonpreferred hand. Mean weighted skin temperature was recorded and printed every 336 sec., and hand skin temperature was recorded and printed every 24 sec. Rectal temperatures were recorded from rectal catheters. However, difficulty was encountered in keeping rectal catheters in place, and the rectal temperature data were not analyzed. If hand skin temperature dropped below 39° F, the subject was removed from the test chamber, and testing was discontinued for that subject for that session.

Upon entering the chamber, each subject immediately performed three consecutive trials on each of the tasks (test period 1). After completing the tasks, the subjects put on the arctic mittens and rested until the next test period. The time required to complete the entire task series was approximately 20 min. The task series was replicated on test periods two, three, and four after 60, 120, and 180 min. of exposure, respectively. Total exposure time was approximately 3 hr. 20 min. On each task series, the order of performing the tasks was varied for each subject.

For the auxiliary heat conditions, the temperature at the workspace for the various tasks was not uniform and varied with the distance of the task from the heaters. A sampling of temperatures taken from points on the task where the subject would be expected to work gave the following means and standard deviations for the ambient temperature conditions with auxiliary heat: 103.4° F ± 20.0° at 20° F, 110.4° F ± 30.8° at 0° F, and 89.8° F ± 42.6° at –20° F. The wind speed in the tunnel was approximately 3 mph, but the workspace was shielded from the wind.

RESULTS

Mean Weighted Skin Temperature

The mean weighted skin temperatures for the control condition varied from 90.0° F upon entry to 91.8° F during the fourth test period. For the other conditions, all mean weighted skin temperatures dropped over the four test periods from approximately 88° F to 86.1°, 83.3°, 81.0°, and 80.5° F for the 20°, 0°, and –20°-F auxiliary heat conditions and the 0°-F cold-exposure condition, respectively.

Hand Skin Temperature

The means and standard deviations of the hand skin temperature for each recording point on the hand at each test period and ambient temperature condition are presented in Table 1. The hand skin temperature varied with the recording point on the hand and with ambient temperature. For the auxiliary heat conditions and the cold-exposure condition, hand skin temperature changed little from the third and fourth test periods. For all

TABLE 1

Mean Hand Skin Temperature (HST) and Standard Deviations (SD) as a Function of Ambient Temperature and Auxiliary Heat Conditions in Degrees F.

Ambient Temperature Condition		*Little Finger*		*Middle Finger*		*Back of Hand*	
		HST	*SD*	*HST*	*SD*	*HST*	*SD*
60°	Test 1	88.8	5.2	88.1	4.3	84.9	2.8
	Test 2	87.9	5.5	86.7	6.0	84.7	2.7
	Test 3	84.7	8.3	85.1	7.3	83.5	3.5
	Test 4	82.8	8.9	83.4	7.8	82.7	3.5
With Auxiliary Heat							
20°	Test 1	81.4	9.7	83.3	8.6	87.1	6.0
	Test 2	73.5	9.4	77.5	8.5	87.9	5.7
	Test 3	68.7	9.1	73.8	7.0	86.8	5.5
	Test 4	69.0	8.2	73.8	7.4	84.8	6.6
0°	Test 1	75.6	10.3	78.0	8.9	86.8	5.2
	Test 2	65.5	7.5	70.3	7.2	86.9	6.9
	Test 3	62.8	8.2	67.8	7.8	84.3	6.7
	Test 4	62.7	7.5	67.8	7.1	83.2	6.8
– 20°	Test 1	67.7	10.4	70.8	9.8	83.6	6.0
	Test 2	56.8	6.5	60.3	6.8	79.7	7.1
	Test 3	57.3	7.5	60.1	7.7	78.1	8.0
	Test 4	57.8	6.8	60.7	7.4	76.9	8.6
Without Auxiliary Heat							
0°	Test 1	61.9	12.5	61.5	12.3	69.6	7.7
	Test 2	52.2	7.4	52.2	7.1	57.6	7.8
	Test 3	51.8	6.7	51.7	6.5	52.9	6.8
	Test 4	50.2	5.1	50.1	5.0	52.9	6.3

ambient temperature conditions, auxiliary heat acted to raise hand skin temperature relative to that for the cold-exposure condition. The effect was greatest for hand skin temperatures at the back of the hand.

Several subjects had to be removed from the test because of cold hands during the cold-exposure condition. One subject was removed during test period two, and three subjects were removed during test period three. At –20° F, one subject was removed during test period three and one was removed during test period four because of cold feet. In addition, one subject was not tested in this condition for medical reasons.

Task Performance

Two separate analyses were performed on the task data. The first analysis (the auxiliary heat analysis) assessed the effects of auxiliary heat at ambient temperatures of 20°, 0°, and –20° F compared to the 60°-F control condition. In the second analysis, (the cold-exposure analysis) the effects of exposure to 0° F with and without auxiliary heat were compared to the 60°-F control condition. For the analyses, the performance scores for each subject on each task were analyzed according to a mixed analysis of variance design with sequence of temperature condition as a between-subjects factor and ambient temperature conditions and test periods as within-subjects factors. In instances where subjects were unable to complete the experimental conditions, the degrees of freedom in the analyses were correspondingly decreased. In both analyses, the ambient temperature and test period main effects were significant for all five tasks.

Mean task performance and the 95% confidence intervals over periods for all ambient temperature conditions are presented in Figures 1 through 5 for all tasks. For all tasks,

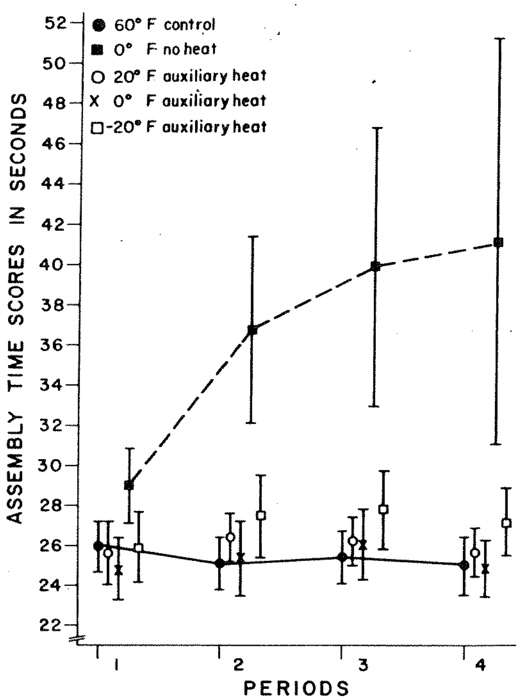

Figure 1. Purdue Pegboard assembly time scores across four periods.

the cold-exposure condition resulted in significantly impaired performance relative to that for the 60°-F control condition on periods two through four. Only pegboard assembly performance was impaired significantly during the first period in the cold exposure condition. Performance was improved slightly on

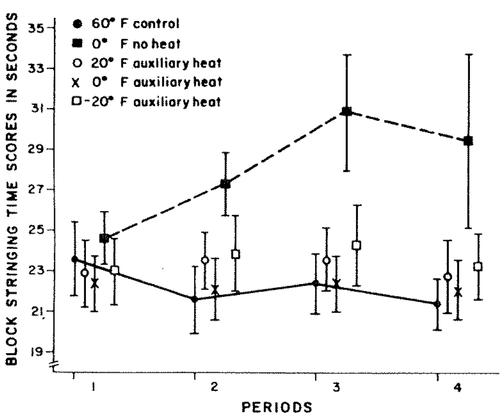

Figure 2. Block-stringing time scores across four periods.

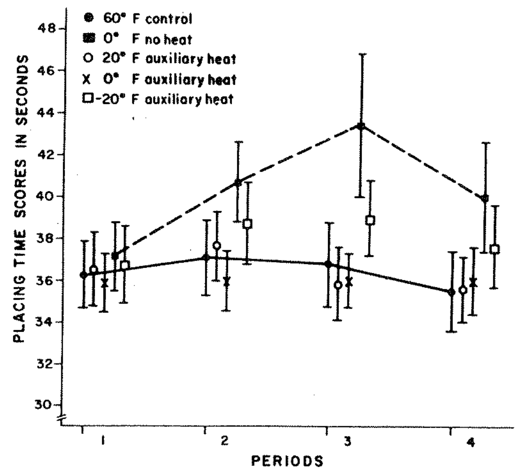

Figure 3. Minnesota Rate of Manipulation placing time scores across four periods.

the fourth period relative to that for the third period for the block-stringing, placing, and screw-tightening tasks. For all tasks, intersubject variability increased after the first period at 0° F without auxiliary heat.

With the exception of the screw-tightening task, the use of auxiliary heat in preventing performance decrements during exposure to 0° F was successful. Performance differences between the 60°-F control condition and the 0°-F condition with auxiliary heat for the remaining four tasks were small and not statistically significant. However, screw-tightening performance was impaired at periods three

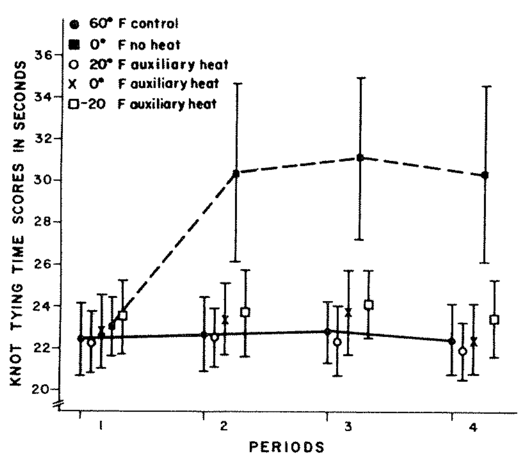

Figure 4. Knot-tying time scores across four periods.

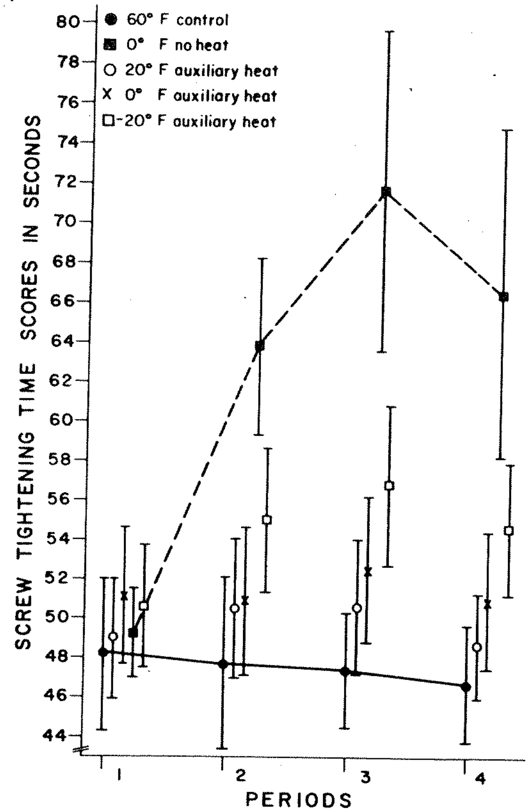

Figure 5. Screw-tightening time scores across four periods.

and four for the 0°-F auxiliary heat condition.

The use of auxiliary heat may have been successful in preventing decrements in knot-tying performance at –20° F compared with performance for the control condition. Although the temperature effect was significant in the auxiliary heat analysis ($F(3,44) = 7.03$, $p<.001$), the comparison between extreme scores involved those at 20° F and at –20° F. Mean knot-tying performance for the –20° auxiliary heat condition was not significantly different from that for the control condition at each period. For the remaining tasks, the use of auxiliary heat at –20° F did not prevent impaired performance relative to that at 60° F. However, performance decrements were alleviated relative to those of the cold-exposure condition. Block-stringing and pegboard-assembly performance, although impaired relative to scores at 60° F for periods two through four, was far superior to performance for the cold exposure condition. Performance during periods three and four on the placing task at –20° F with auxiliary heat was poorer than performance at 60° F and better than performance in the cold-exposure condition. For the –20°-F auxiliary heat condition on periods two through four, screw-tightening performance was impaired relative to performance for the control condition and for the 20°-F and 0°-F auxiliary heat conditions and was superior to performance for the cold-exposure condition.

Pearson product moment correlation coefficients were calculated between the time scores for all five tasks and hand skin temperature at each of the three recording sites for each period and temperature condition. While only 45 of 300 correlation coefficients were significant at $p = 0.05$, many of the significant coefficients form at least one of two patterns. One pattern is the relationship between surface temperature at the back of the hand and task performance for the cold-exposure condition. These correlation coefficients are presented in Table 2. Nine of the 12 coefficients were significant in the comparison of hand skin temperature at the back of the hand with pegboard-assembly, block-stringing, and screw-tightening performance for the cold-exposure condition. The significant negative correlation coefficients reflect the occurrence of lowered skin temperature with long time scores and of shorter time scores with higher surface temperatures.

The correlation coefficients between pegboard-assembly performance and hand skin temperature for the cold-exposure condition and the –20°-F auxiliary heat condition are presented in Table 3 and represent the second pattern of relationships. For the cold-exposure condition, pegboard-assembly scores correlated significantly with hand skin temperature at the back of the hand for each of four periods and with hand skin temperature at the little finger and middle finger for periods one and two. When auxiliary heat was applied to the hands at –20° F, pegboard-assembly scores on periods two through four correlated signifi-

TABLE 2

Correlation Coefficients between Task Performance and Hand Skin Temperature at the Back of the Hand for the Cold Exposure Condition

Tasks	Period 1	2	3	4
Pegboard Assembly	−0.644*	−0.636*	−0.648*	−0.536*
Block Stringing	−0.249	−0.699*	−0.549*	−0.703*
Minnesota Placing	0.015	−0.352	−0.496	−0.475
Knot Tying	−0.382	−0.466	−0.592*	−0.395
Screw Tightening	−0.034	−0.379	−0.599*	−0.582*

*$p = 0.05$

TABLE 3

Correlation Coefficients between Purdue Pegboard Assembly Performance and Hand Skin Temperature

	Ambient Temperature Condition					
	0°F., No Heat			−20°F., Auxiliary Heat		
	Skin Temperature Locus			Skin Temperature Locus		
Period	Little Finger	Middle Finger	Back of Hand	Little Finger	Middle Finger	Back of Hand
1	−0.641*	−0.547*	−0.644*	−0.294	−0.179	−0.079
2	−0.546*	−0.498*	−0.636*	−0.456*	−0.481*	−0.206
3	−0.220	−0.290	−0.648*	−0.504*	−0.481*	−0.241
4	−0.307	−0.290	−0.536*	−0.528*	−0.573*	−0.393

* $p = 0.05$

cantly only with hand skin temperature at the little and middle fingers.

DISCUSSION

The mean weighted skin temperatures in the present experiment dropped to a low of 80.5° F. In a previous study, Kiess and Lockhart (1970) found body cooling, the lowering of body surface temperature while maintaining hand skin temperature above 85° F, to affect manual performance only when body surface temperature was lowered to 70° F for a fast-cooling-rate condition and to 74° F for a slow-cooling-rate condition. It is concluded that, for the present experiment, local cooling of the hand and forearm is the determining factor for manual dexterity in the cold.

In the present experiment, exposure of the unprotected hand to a 0°-F ambient temperature condition resulted in (1) lowered surface temperatures which were similar for three recording sites on the hand and (2) impaired performance on five manual tasks. The application of auxiliary heat to the hands during cold exposure, while not effective in maintaining hand skin temperature above 85° F, did affect both hand skin temperature and manual performance. The effect of auxiliary heat on hand skin temperature differed across recording site and ambient temperature condition. At 20° F and 0° F, hand skin temperature at the back of the hand during test periods was higher than corresponding hand skin temperatures at 60° F. However, surface temperature decreased with decreasing ambient temperature and with diminishing surface area until, for the little and middle fingers at −20° F, hand skin temperature was only slightly higher than hand skin temperature at 0° F without auxiliary heat.

Impaired manual performance during cold exposure was either alleviated or prevented by the application of auxiliary heat to the hands depending upon the duration of exposure, ambient temperature condition, and task. The differential effects of auxiliary heat during cold exposure across tasks are interpreted in terms of specific cold exposure effects on aspects of manual performance. As mentioned previously, Clark (1961) found knot-tying performance to be impaired when hand skin temperature was lowered to 55° F, and Hellstrøm (1965) found the rotation of an object between the thumb and forefinger and hand-grip strength to be impaired when hand skin temperature was lowered beyond about 68° F and when forearm muscle temperature was reduced below about 86° F, respectively. It is assumed that screw-tightening performance is related to hand and arm strength, and that pegboard-assembly and block-stringing performances are related to fine finger dexterity requirements similar to the rotation of an object between the thumb and the forefinger. The presence and absence of performance decrements for these tasks across periods and auxiliary heat conditions are related to the level of hand skin temperature at different recording sites using an 86°-F hand skin temperature the above cutoff level for unaffected performance. Although forearm muscle temperature was not recorded in the present experiment, the level of hand skin temperature at the back of the hand for the auxiliary heat conditions after the first period corresponds with the presence and absence of screw-tightening performance decrements. This is based on the 86°-F hand skin temperature cutoff level for unaffected performance. Loss of cutaneous sensitivity is assumed not to be implicated in the impaired performance during cold exposure. The lowest mean hand skin temperature (50° F) during cold exposure was higher than the critical hand skin temperature (46° F) for impaired cutaneous sensitivity (Fox, 1967).

Although attempts to correlate performance and digital temperature during cold exposure have not been notably successful (Teichner, 1957), there was some evidence in the present experiment for patterns of relationships between performance and hand skin temperature at different recording sites. During cold exposure, block-stringing, screw-tightening, and pegboard-assembly performances were correlated significantly with hand skin temperature at the back of the hand. The relations between individual variations in surface temperature at the back of the hand and impaired pegboard assembly performance due to ambient temperature are complex. The hand skin temperatures at all three recording sites for periods one and two of cold exposure were significantly correlated with performance. Individual variations in surface temperatures at each point may reflect individual variations in either surface or subsurface temperatures. However, for periods three and four during cold exposure, hand skin temperature dropped to similar levels across periods for all three recording sites and only the surface temperatures at the back of the hand were related to individual variations in performance. For these latter periods, individual variations in hand skin temperature at the back of the hand are assumed to reflect individual variations in subsurface temperatures in terms of the capacity of the hand to supply heat to the extremities. With the application of auxiliary heat, hand skin temperatures at the fingers, but not at the back of the hand, are assumed to reflect individual variations in subsurface temperatures in terms of the heat received from the larger surface area. It is proposed that pegboard-assembly performance is dependent upon the temperatures at finger joints and muscles and that the above relationships between hand skin temperature and performance occur when variations in surface temperature reflect corresponding changes in subsurface temperatures.

The results of the present experiment demonstrate the effectiveness of the application of auxiliary heat to the hands in alleviating performance decrements during cold exposure and support several conclusions. Severe cold exposure affects manual performance, reduces the receptivity of the skin surface, affects the muscular control of the fingers, hands, and arms, and reduces the mobility of the joints. These latter effects of cold exposure on the hand depend upon parameters of cold exposure, such as level, rate, and locus of cooling. The application of auxiliary heat to the hands during cold exposure had a differential warming effect on parts of the hand across ambient temperature and a differential effect on manual performance across tasks. Based on the assumption that manual tasks differ in their relative dependence on the unimpaired function of the hands and arms, the differential effects of auxiliary heat on manual performance were analyzed in terms of the susceptibility of specific tasks to specific impairments.

While the present analysis was based, in part, on the effects of level of hand skin temperature, duration of cold exposure, and locus of cooling on different manual tasks reported in the literature, a recent review of human performance in the cold (Fox, 1967) continued to emphasize a critical hand skin temperature (between 54° F and 61° F) for impaired manual dexterity. However, greater emphasis must be based on aspects of manual dexterity and additional parameters of cold exposure. The present application of auxiliary heat was successful in, at least, alleviating manual performance during cold exposure even though the hand skin temperature (58° F) at −20° F was below the critical hand skin temperature. In addition, screw-tightening performance at 0° F with auxiliary heat was impaired relative to that for the control condition even though the hand skin temperature (63° F) was higher than the critical hand skin temperature. Further study of the effects of parameters of cold exposure on aspects of manual performance should suggest additional techniques for alleviating cold-impaired performance or set limitations to the types of tasks that can be performed during cold exposure.

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