Chapter 12

HUMAN PSYCHOLOGICAL PERFORMANCE IN COLD ENVIRONMENTS

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INTRODUCTION

Military personnel are expected to perform at optimal levels in all varieties of hostile environments, including cold and extreme cold. The cold can be a potent stressor in field conditions, causing both a deterioration in morale and decrements in performance, including the performance of mission-sensitive duties. This chapter reviews those decrements in human psychological performance that are expectable in mild, moderate, and extreme cold environments in an attempt to provide guidance in framing reasonable performance expectations. In addition, this chapter highlights areas where additional training or pretraining may prove beneficial, including the possible role of acclimatization as a method of attenuating performance decrements. Finally, some attention is drawn to possible central nervous system correlates or determinants of decreased performance in the cold.

An important distinction should be kept in mind in the discussion of the differences in magnitude between exposure to cold air and exposure to cold water. Cold water immersion causes a convective heat loss that is 25 times greater than exposure to cold air at an equivalent temperature, and it places substantially heavier thermoregulatory demands on the body.[1] The thermal conductivity of water has been estimated to be 1,000 times greater than cold air at similar temperatures.[2] In general, the largest performance decrements on psychological measures are seen with individuals immersed in cold water, or wet or partially wet individuals who are also exposed to cold air. Duration and severity of the cold stress are modifiers that will affect performance, as will the presence or absence of turbulence in cold water or wind in cold air.

PROLONGED SEVERE COLD STRESS, HYPOTHERMIA, AND BEHAVIOR

Fig. 12-1. This experimental subject, dressed in full arctic clothing, was exposed to prolonged, severe, cold air stress (–30°F for 3 h) in the Hypothermia and Water Safety Laboratory, School of Medicine, University of Minnesota, Duluth, Minn. Subjects in these conditions demonstrate significant decreases in both core body and peripheral temperatures. Photograph: Mr Dan Schlies, Educational Resources Department, School of Medicine, University of Minnesota, Duluth, Minn.

Cold stress causes a complex set of physiological and psychological responses, often before there is a drop in deep body temperature (ie, rectal or other core body temperature). These responses are dependent on the nature and severity of the cold thermal stress applied. The drop in deep body temperature that follows prolonged cold stress is typically gradual and may exacerbate previous performance decrements or create new ones. When deep body temperature falls below the normal resting range of body temperature (around 37°C), it can be regarded as a beginning stage of hypothermia, but hypothermia is generally defined clinically as a deep body temperature below 35°C (or about 95°F) (Figure 12-1).

The effects of deep body cooling on overt behavior are similar to the effects of general anesthesia. Levels of consciousness and alertness gradually decrease as body temperature drops toward 30°C.[3] Responses become slow and reflexes sluggish; speech becomes slurred and increasingly difficult. Mobility is impaired, and individuals often become drowsy or apathetic.

As will be noted in detail later, there is evidence to suggest some impairment in memory registration, beginning at a core temperature of 36.7°C and progressing to a point at about 34°C to 35°C, at which 70% of information normally retained is lost.[4] Concentration becomes increasingly impaired, although at early stages of hypothermia (34°C–35°C) the impairment appears to be in speed of mental operations rather than accuracy. Although lowered body core temperature also slows the performance of complex calculation tasks, and probably slows performance of reasoning tasks as well, such slowing is not accompanied by any loss of accuracy—provided that adequate time is allowed for the task to be completed. The slowing observed, however, is substantial, with calculations being about 175% slower at a core temperature of 34.2°C.[4]

As the body cools further, casualties of cold stress may become increasingly confused and even incoherent as hypothermia progresses below 34°C to 35°C. Cold stress-induced or hypothermia-induced auditory and visual hallucinations are a not uncommon occurrence as core temperature drops below 35°C and are occasionally reported by individuals exercising in the cold as well.[5,6] Voluntary movements gradually become slower and a simple movement such as touching the nose (normally accomplished within 1 sec when warm) may take a casualty 15 to 30 seconds as his core temperature approaches 30°C. Muscle rigidity, sometimes accompanied by neck stiffness, is often striking at this point, making it difficult to extend the limbs. Gait may become ataxic and deep tendon reflexes may decrease. At a core temperature of 30°C to 31°C the pupils of the eyes may react so slowly that the light reflex may be wrongly assumed to be absent, although it *will* essentially disappear at lower temperature.[3] Consciousness is usually lost between 32°C and 30°C, although there are exceptions to this. At a core temperature of 27°C a casualty may sometimes grunt when questioned, but below about 26°C he usually fails to respond to any stimulus whatsoever, including deep pain. If temperature continues to drop the casualty will lapse into coma.

HYPOTHERMIA AND BEHAVIOR: POSSIBLE MECHANISMS OF ACTION

One factor that might account for slower performance by extremely cold or hypothermic individuals is a direct slowing of synaptic transmission. A fall in central (core) temperature from 37°C to 22°C has been shown to increase the rise time of the end-plate potential in cat muscle to 200% and to increase the fall time to 260% of control values.[4]

The mechanism responsible for cold stress-induced auditory and visual hallucinations is not clear, although there has been some speculation that this may relate to dopaminergic supersensitivity.[5] The hypothesis has been advanced[5] that all hallucinations, and other disturbances of perception, involve the dopamine/5-hydroxytryptamine (5-HT, or serotonin) system and are a result of an overload at a rate-limited step in the degradation pathway of 5-HT. In prolonged heat stress or fever, in which hallucinations can also occur, there is an excessive production of dopamine, which effects a lower body temperature. Dopamine release activates dopaminergic receptors, which cause lowering of the body temperature either directly or via intermediate 5-HT and receptors.[7] During prolonged exposure to cold, dopamine receptors could therefore become supersensitive.

It is possible that at least some of the observed decrements in human performance that occur following prolonged extreme cold stress and during hypothermia may be determined by (*a*) direct or indirect effects of brain cooling, (*b*) changes in brain cerebral blood flow, or (*c*) changes in the electrical activity of the brain[8]; therefore, each of these areas will be reviewed briefly.

Hypothermia and Brain Cooling

Local brain cooling first increases and then decreases neural excitability. The effects of cooling appear to be reversible, and the changes in temperature needed for reported changes in brain function are one Centigrade degree or less in various areas of the nervous system.[9] Spinal and cerebral neurons are reported to become hyperresponsive when only one or two Centigrade degrees below normal.[10] In a series of studies, Hayward and Baker[11] showed a significant amount of nonuniformity in the temperatures in various areas of the brain in dogs, sheep, monkeys, and cats. It is possible that localized brain cooling could occur in humans as well, a possibility of great significance to the military, for localized brain cooling can greatly influence the selective responses of certain areas of the brain, and thus human performance.

As the arterial blood passes through the preoptic-anterior hypothalamus, the temperature of the blood determines the temperature of the brain.[12] In mammalian species that possess internal carotids, cerebral arterial blood temperature oscillations mirror those found in systemic arterial blood. In the monkey, the prototype of the internal carotid species (because monkeys can be subjected to experimental manipulations), accelerated cutaneous and upper respiratory heat losses lead to a sequential and parallel cooling of local venous blood, central venous blood, aortic arterial blood, cerebral arterial blood at the circle of Willis, and various brain sites.[11] We have recently demonstrated similar results in our laboratory using the bypass-cooled dog.[8] From this and other evidence we can conclude that

- the arterial blood removes heat from the brain during hyperthermia,
- venous blood circulation buffers rapid brain cooling during hypothermia, and
- brain–blood temperature gradients are the major determinant of fluctuations in brain temperature.

Effects of Hypothermia on Cerebral Blood Flow

The few studies conducted to date on cerebral circulation and oxidative metabolism during hypothermia indicate that cerebral blood flow (CBF) and cerebral metabolic rate for oxygen (CMRO^2) decrease with body temperature.

We might conclude that progressive reductions in body temperature produce progressively greater decreases in cerebral metabolism. Bering and colleagues,[13] measuring the cerebral metabolic response of monkeys to hypothermia, have demonstrated that this reaction does not occur. Stone, Donnelly, and Frobese[14] confirmed Bering's findings and discovered that in the anesthetized human, the sharpest drop in cerebral metabolism occurs with body core temperature reductions down to 28°C, and that further temperature reductions could not produce a correspondingly greater depression of cerebral oxygen utilization.

During hypothermia, cerebral vascular resistance increases despite elevated arterial carbon dioxide tensions. This increase may be due to two factors:

1. Hemoconcentration in response to hypothermia, reported previously by Prec and colleagues[15] and confirmed by Stone and colleagues,[14] increases blood viscosity and cerebral vascular resistance.
2. Cerebral vessels may constrict in much the same manner as peripheral vessels in a response to hypothermia.

In the absence of shivering, cerebral oxygen consumption is sharply reduced at body temperature of 28°C to 29°C. Ehrmantraut, Ticktin, and Fazekas[16] studied the effects of marked hypothermia on CBF and CMRO^2 in two unanesthetized human adult male victims of accidental hypothermia, one with a core temperature of 30°C and one with a core temperature of 23°C (this patient required bypass rewarming). In both cases, CBF and CMRO^2 decreased when the subjects were hypothermic. When the men were rewarmed, both values returned to normal levels. In light of what is now known of the delicate coupling of CBF and cerebral metabolism,[17] it is likely that CBF was decreased to match the lowered metabolic rate imposed by hypothermia.[12]

Similar results were also reported in humans[14] and in dogs,[18,19] the latter investigators using the radioactive microsphere technique. Anzi and colleagues[20] also utilized this technique to measure CBF in more discrete regions of the brain. A remarkably uniform decrease in regional CBF was noted throughout the brain, ranging from 62% in the brainstem to 82% in the posterior lobe. In another, more-recent study, Steen and Milde[21] studied the effects of prolonged, 24-hour hypothermia and subsequent rewarming in dogs. When the dogs were rewarmed, CMRO^2 increased but CBF increased to only 30% to 40% of normal levels, suggesting some possible metabolic problems in cases of prolonged hypothermia.

The effects of central core cooling on cerebral CMRO^2, CBF, and glucose substrates may also at least partially account for the observations of slowed mental processing in hypothermic individuals. Most neuroscientists would agree that information treatment in the brain is handled by neurons that transmit the information in the form of action potentials. This in turn leads to potential changes in the target neurons. The synaptic activity, ionic transfers, transmitter synthesis, release and reuptake, formation of second and third messengers, and protein phosphorylation are all energy-demanding processes that deplete energy-rich phosphates. Thus it could be expected that the regional neuronal metabolism should increase during and immediately after regional information processing. Because the local CBF is adjusted to the local metabolic demands, one would also assume that the blood flow would increase. Mental activity—initiated, produced, and evaluated by the brain itself in normothermic individuals—generally also gives rise to CMRO^2 increases in multiple cortical fields and subcortical structures. These short-term metabolic changes are almost exclusively the consequence of increased synaptic activity in locations where the information transformation takes place. The amount of metabolic increase in an active field during mental activity is fully equivalent to the increases in motor or sensory fields during intense voluntary movements or during intense perception.[22] The reduced CBF and decreased metabolic rate that occurs with profound core body cooling, however, may not allow efficient information processing by hypothermic individuals.

Effects of Hypothermia on Evoked Responses

In general, the effects of hypothermia on nerve conduction can be summarized as follows[9]:

1. progressive slowing of axonal conduction,
2. abolition of synaptic transmission prior to conduction failure (postsynaptic activity is abolished at approximately 20°C, whereas axonal conduction does not fail until temperatures lower than 10°C are achieved), and
3. an increased excitability at mild degrees of hypothermia, which precedes the subsequent synaptic depression at lower levels of hypothermia.

Hypothermia also produces several neurophysiological changes such as decreased resting potential, decreased amplitude but increased duration of the action potential, a reduction of nerve conduction velocity, and depression of synaptic transmission due to impaired transmitter release. The changes in evoked responses with hypothermia can be explained by two basic hypothermic effects on neural activity: slowing of the conduction along the axons, and increased synaptic delay. The effect on synaptic transmission appears to be more profound than on the axonal conduction.

Several investigators[23–25] have found that latencies of each component wave of the brainstem auditory evoked response (BAER) progressively increased as a function of decreasing temperature, and that the effect was more profound on the later than on the earlier components. Individual BAER components show a slower rise time and become longer in duration under hypothermic conditions. The latency of BAER component waves and the interpeak latency (IPL) increase exponentially rather than linearly, as a function of decreasing temperature over the entire range of hypothermia (36°C–20°C). We have seen the same pattern of increased latency of the BAER in our laboratory, and it appears to be present with drops in core temperature as modest as one to two Centigrade degrees.

Fitzgibbon and colleagues[26] found a 10% to 20% increase in BAER latency when unanesthetized human subjects are cooled about four Centigrade degrees, which is consistent (in terms of temperature sensitivity) with the data of Marshall and Donchin.[27] These investigators showed latency increases of the auditory evoked response of 6% to 7% during the normal sleep phase of the circadian rhythm when core temperature was about two Centigrade degrees below daytime normothermia.[27] We have observed similar latency increases, again often beginning at one to two Centigrade degrees of core temperature cooling.[8] These studies indicate that evoked responses in humans are slowed during cooling by about 3% to 4% per Centigrade degree. The 10% to 20% increases in latency of peaks in the visual evoked potentials that were observed in some subjects are of the same magnitude as those described by others for evoked responses in a variety of mammals at approximately the same temperature of 33°C to 34°C.

A number of laboratories, including our own, have studied changes in somatosensory evoked responses (SERs) following core body cooling and cold exposure (Figure 12-2). Benita and Conde[28] locally cooled

Fig. 12-2. This experimental subject is exposed to mild cold stress in evoked potential experiments measuring the effect of mild external cold stress (90-min exposure to 7°C air) versus mild internal cold stress (ingestion of ice slurry). Subjects in the mild cold air exposure condition demonstrate increased central nervous system arousal, resulting in decreased latencies in visual evoked potentials and decreased reactions times, in the absence of significant decreases in core temperature.
Subjects in the ice slurry condition demonstrate significant decreases in core body temperature and significant reductions in nerve conduction velocity, accompanied by increased latencies in auditory and visual evoked potentials. They do not demonstrate changes in reaction time. Experiments conducted at the Hypothermia and Water Safety Laboratory, School of Medicine, University of Minnesota, Duluth, Minn. Photograph: Mr Dan Schlies, Educational Resources Department, School of Medicine, University of Minnesota, Duluth, Minn.

a small nuclear region in the brain and found that the latencies of the presynaptic and postsynaptic responses were delayed. The SER in response to induced hypothermia has been studied by several investigators,[29,30] whose results suggest that peripheral and brainstem nerves seem to have comparable behaviors during hypothermia. Our studies with nonanesthetized humans who were internally cooled by ingesting an ice slurry drink also suggest increases in the latency of the SEP response, even at modest levels of core body cooling.

In relation to observations of considerable behavioral alteration in persons who are mildly hypothermic (34°C–36°C) in accidental or experimental situations, these findings suggest that if such behavior is a direct result of brain cooling, then the subtle alterations of electroencephalograms and visual evoked potentials that have been observed here may be correlates of this phenomenon. Minor electrical changes may be associated with detectable impairment of cognitive processes.

Central nervous system mechanisms, in tandem with peripheral physiological effects and more purely psychological effects, may well have an additive effect and produce many of the impairments in human performance that have been observed. Further empirical investigation is needed in this area to delineate the components that are determinants of performance decrements for a given cold stress and a given psychological or psychomotor task.

EFFECTS OF MILD-TO-MODERATE COLD STRESS AND BEHAVIOR

Manual Performance

A number of studies in both cold air and cold water have demonstrated substantial performance decrements in manual performance following cold stress, the magnitude of which appears to be a function of both surface cooling and, with prolonged exposures, deep body cooling (Figure 12-3). When the entire body is cooled, there is likely a local effect at the periphery involving direct interference of sensory-motor functioning, and a general and central effect influencing higher centers that serve to control, direct, and coordinate action.[31] For example, if the hands are preferentially cooled in air to 13°C and the rest of the body is kept warm, then reliable decrements in manual performance are observed, which tend to increase for the first 40 minutes of exposure and change little if at all during the remainder of the first hour of exposure.[32,33] Cooling of the remaining body surface as low as 26°C does not cause further measurable decrement.[34] Alternatively, if the hands are kept warm, then impairments in manual performance are observable when the rest of the body surface area is cooled to 21°C, although this impairment is less pronounced than when the hands alone are cooled to 13°C.[35] If body surface temperatures and hand surface temperatures are simultaneously reduced to 21°C and 13°C, respectively, a greater level of impairment occurs, and if body core temperatures are also dropping, the greatest manual performance decrements occur.

At extreme cold temperatures, losses of sensitivity and manipulative ability are amplified by heavy protective garments worn to buffer heat loss. This decrease in manual performance is further compromised by loss of flexibility in the muscles of the forearm and finger, increase in muscle viscosity of the extensors and flexors of the fingers, and difficulty

Fig. 12-3. This experimental subject, exposed to 0°C air for 120 minutes, is shown completing a standardized dexterity measure, the Grooved Pegboard Test. Following 120 minutes of exposure, the average time to complete this task with the dominant hand increases from 55 to 78 seconds. Experiments conducted at the Hypothermia and Water Safety Laboratory, School of Medicine, University of Minnesota, Duluth, Minn. Photograph: Mr Dan Schlies, Educational Resources Department, School of Medicine, University of Minnesota, Duluth, Minn.

bending joints owing to an increase in joint synovial fluid viscosity.

Tactile Sensitivity

Perhaps the most common noninjurious effect of cold exposure is numbing of the extremities. Possible causes of numbness and the degree of numbness occurring under given ambient conditions have been extensively examined for more than 50 years. Fox[36] and Weitz[37] lowered subjects' forearm skin temperatures 12°C and reported impairment of sensitivity to vibratory stimuli in proportion to the magnitude of cooling. Mackworth[38] reported preliminary data for what he called a "biological index of numbness" related to two components of windchill-air temperature and wind velocity-and much of the later work in this area included the examination of windchill effects (Figure 12-4).

To assess finger numbness, Mackworth developed the "V-test," which has become a standard in numbness assessment. The V-test apparatus consists of a flat wooden ruler cut in half, the two halves laid side by side and joined at one end with a bolt and permanently separated by a one-half inch gap at the other end, forming a V shape with a "gap" that varies in size from 0 to 13 mm. Finger numbness is assessed by laying a finger across the two sides of the V and asking subjects to report when they feel two edges. Tactile discrimination is estimated by the gap size (in millimeters) necessary for the subject to report the presence of two edges. Mackworth[38] reported data on changes in index finger numbness of 35 subjects examined in subarctic Canada using the V-test across two temperature ranges (–25.1°C to –30°C vs –30.1°C to –35.0°C) with varying wind velocities. Each subject was tested while wearing a thick glove with the index finger portion removed. It was found that the rate of increase of numbness in these experiments was largely a function of wind velocity rather than temperature, although this may be an artifact of the narrow temperature ranges used. Higher wind velocities also produced a more prolonged effect with a longer required recovery period. At the coldest temperature sampled and a wind velocity of 6.1 to 10.0 mph, numbness began in 1.2 minutes, versus 2 minutes at the same temperature in winds below 6.0 mph. Later, Mackworth[39] observed a similar pattern of numbness onset in both 4 mph wind conditions and no wind conditions, at ambient temperatures of –16°C and –25°C.

Mills[40] examined pressure sensitivity of bare fingers at –21°C and reported a 4-fold pressure threshold increase in the cold, measured in grams of pressure necessary for subjects to feel the contact from a slowly lowering rod. Morton and Provins[41] examined subjects whose hands were locally exposed to cold but whose bodies were otherwise kept warm (the hand was isolated in a miniature cold chamber). As air temperature to the hand was reduced from 32.5°C to 2.5°C, finger numbness increased in an accelerated fashion. A second study by the same authors[42] investigated isolated cold water stress and finger numbness during a 40-minute immersion of the hand in cold water. Finger sensitivity was reported to be significantly-and essentially equally-impaired in water baths at 6°C, 8°C, 15°C, and 30°C, with some further decrease in the sensitivity only when water baths of 2°C and 4°C were used. Bowen[31] demonstrated substantial impairment of hand tactile sensitivity following a 2-minute exposure to 8°C water, and an enormous 336% decrease in hand tactile sensitivity following a 24-minute exposure.

A number of studies have identified skin or extremity temperature as the relevant variable that predicts impairment in manual dexterity and tactile sensitivity (Table 12-1). Mackworth[38] reported very little systematic change in V-test performance until the measured skin temperature reached 10°C to 15°C or below. Morton and Provins[41] were in general agreement with this finding, but noted measurable V-test impairments beginning at hand skin temperatures of 20°C to 25°C. They suggested that the relationship between skin temperature and numbness followed an L-shaped distribution, with relatively little impairment in sensitivity and performance at skin temperatures above 8°C, but a very rapid drop-off in performance below an approximate threshold temperature of 6°C to 8°C. They hypothesized that nerve fibers, skin receptors, or some combination of the two are subject to "cold block," or loss of neural activity below 6°C and 8°C, and therefore are no longer capable of excitation by a new stimulus. Available evidence suggests that the pain threshold for a cold stimulus is also in this range—about 10°C—in all but the most highly acclimatized subjects.[43]

Dexterity

Several researchers have also investigated cold stress and its effects on dexterity (Table 12-2). Springbett[44] was the first experimenter to systematically investigate the effect of local cooling and overall skin cooling on dexterity. Using the Minnesota Manual Dexterity Test, Springbett demonstrated significant impairment in 16 subjects exposed to –4°C for 70 minutes, irrespective of the

Estimated wind speed* (km/h mile/h)	Actual Thermometer Reading (°C/°F)											
	10 50	4.4 40	-1.1 30	-6.7 20	-12.2 10	-17.8 0	-23.3 -10	-28.9 -20	-34.4 -30	-40 -40	-45.6 -50	-51.1 -60
	Equivalent Chill Temperature (°C/°F)											
Calm	10 50	4.4 40	1.1 30	6.7 20	12.2 10	17.8 0	23.3 -10	28.9 -20	34.4 -30	40 -40	45.6 -50	51.1 -60
8 5	8.9 48	2.8 37	-2.8 27	-8.9 16	-14.4 6	-20.6 -5	-26.1 -15	-32.2 -26	-37.8 -36	-43.9 -47	-55.6 -68	-55.6 -68
16 10	4.4 40	-2.2 28	-8.9 16	-15.6 4	-22.8 -9	-31.1 -24	-36.1 -33	-43.3 -46	-50 -58	-56.7 -70	-63.9 -83	-70.6 -85
24 15	2.2 36	5.6 22	12.8 9	20.6 -5	27.8 -18	35.6 -32	42.8 -45	50 -58	57.8 -72	-102.8 -85	72.8 -99	-80 -112
32 20	0.0 32	7.8 18	15.6 4	23.3 -10	31.7 -25	39.5 -39	47.2 -53	-55 -67	63.3 -82	71.1 -96	73.3 -110	86.7 -124
40 25	-1.1 30	-8.9 16	-17.8 0	-26.1 -15	-33.9 -29	-42.2 -44	-50.6 -59	-58.9 -74	-67.7 -88	-75.6 -104	-83.3 -118	-91.7 -113
48 30	2.2 28	-10.6 13	-18.9 12	-27.8 -18	-35.2 -33	-44.4 -48	-52.8 -63	-61.7 -79	-70 -84	-78.3 -108	-87.2 -125	-95.6 -140
56 35	2.8 27	-11.7 11	-20.0 4	-29.4 -21	-37.3 -35	-46.1 -51	-55.0 -67	-63.3 -82	-72.2 -88	-80.6 -113	-88.4 -129	-98.3 -145
64 40	-3.3 26	-12.2 10	-21.1 -6	-29.4 -21	-38.4 -37	-47.2 -53	-56.1 -69	-102.8 -85	-73.3 -100	-82.2 -116	-91.1 -132	-100 -148
	Little Danger (in 5 h with dry skin) Maximum danger is from the false sense of security				**Increasing Danger** Danger from freezing of exposed flesh within 1 min			**GREAT DANGER** Flesh may freeze within 30 sec				
Nonfreezing cold injuries may occur at any point on this chart												

Fig. 12-4. Cooling power of wind on exposed flesh, expressed as an eqivalent temperature (under calm conditions)
*Wind speeds > 64 km/h (40 mph) have little additive effect.
Adapted from US Army Research Institute of Environmental Medicine. *Sustaining Health and Performance in the Cold: Environmental Medicine Guidance for Cold-Weather Operations.* Natick, Mass: USARIEM; July 1922: 37. Technical Note 92-2.

TABLE 12-1

COLD STRESS AND TACTILE SENSITIVITY: SUMMARY OF SEVEN STUDIES

Study	Temperature (°C)	Exposure Time	Results
Weitz (1941)[1]	12°C	*Varied (by forearm skin temp)	Impairment to vibratory stimuli
Mackworth (1953)[2]	–25.1°C to –30°C; –30.1°C to –35°C; plus varied wind	*Varied by hand temp, numbness occurred as early as 1.2 min following exposure at –35°C	Rate of numbness on V-test a function of wind velocity primarily; no impairment until skin temp 2 10°C–15°C
Mackworth (1955)[3]	–16°C; –25°C; + 0 mph; or 4 mph wind	*Varied by hand temp	Similar pattern of numbness both conditions
Mills (1956)[4]	–21°C	21 min	4-Fold pressure threshold increase in cold
Morton and Provins (1960)[5]	Hand temp reduced from 32.5°C to 2.5°C	*Varied by hand temp; numbness typically observed following 3–4 min of exposure	Numbness increased in accelerated fashion when hands cooled but body kept warm. V-test impairments at hand temps of 20°C–25°C, sharp dropoffs at 6°C–8°C
Provins and Morton (1960)[6]	Hand exposed to 2°C, 4°C, 6°C, 8°C, 15°C, or 30°C water temps	40 min	Equal numbness at 6°C, 8°C, 15°C, and 30°C; increased numbness at 2°C and 4°C
Bowen (1968)[7]	Hand exposed to 8°C water temp	2–24 min	Substantial impairment at 2 min; 336% decrease in sensitivity at 24 min

*The criterion was a targeted skin temperature rather than a fixed exposure time.
Temp: temperature
Data sources: (1) Weitz J. Vibratory sensitivity as a function of skin temperature. *J Exp Psychol.* 1941;28:21–36. (2) Mackworth NH. Finger numbness in very cold winds. *J Appl Physiol*. 1953;5:533–543. (3) Mackworth NH. Cold acclimatization and finger numbness. *Proc Royal Soc.* 1955;143:392–407. (4) Mills AW. Finger numbness and skin temperature. *J Appl Physiol.* 1956;9:447–450. (5) Morton R, Provins KA. Finger numbness after acute local exposure to cold. *J Appl Physiol.* 1960;15:149–154. (6) Provins KA, Morton R. Tactile discrimination and skin temperature. *J Appl Physiol.* 1960;15:155–160. (7) Bowen HM. Diver performance and the effects of cold. *Hum Factors*. 1968;10(5):445–464.

temperatures of the rest of their bodies. Leblanc[45] discovered that cooling the structures of the forearm caused an equivalent or even greater decrement in dexterity than local cooling of either the fingers or the hand, a finding later replicated by Clarke, Hellon, and Lind.[46] Gaydos and Dusek[34] replicated the Springbett[44] findings and observed that significant impairments in block stringing and knot tying occurred when hand skin temperature was lowered to approximately 11.5°C, but no decrement was observed when hand temperatures were maintained at 27°C or higher, even when the rest of the body surface was at a lower temperature (25.5°C).

Clark and Cohen[47] identified a criterion hand skin temperature of 16°C as the minimum temperature at which no significant decrements in dexterity performance on a complex knot tying task occurred, whereas substantial errors occurred at hand skin temperatures at and below 13°C. They also reported that a greater decrement of performance occurred when the subjects' hands were cooled slowly as opposed to quickly, that a sizable decrement in performance persisted even after rewarming in subjects who had been cooled slowly, and that the rate of rewarming was directly related to the rate of cooling.

Bowen[31] demonstrated 20% decrements in four measures of hand manipulative functioning following 20-minute exposure to 22°C water, 25% decrements following 20-minute exposure to 17°C water, and 45% decrements following 20-minute exposure to 8°C water. Kiess and Lockhart[48] demonstrated that local hand warming is capable of preserving some dexterity, despite moderate lowering of skin body

TABLE 12-2

COLD STRESS AND DEXTERITY: SUMMARY OF EIGHT STUDIES

Study	Temperature (°C)	Exposure Time	Results
Springbett (1951)[1]	–4°C air	70 min	Significant impairment on Minnesota Manual Dexterity Test, whether body was warm or cooled
Leblanc (1956)[2]	Forearm and/or hand cooled	Varied, up to 10 min	Cooling forearm caused equal or greater impairment than cooling fingers or hand
Gaydos and Dusek (1958)[3]	11.5°C to 27°C skin temps	Varied according to skin temp	Dexterity (knot tying/block stringing) impaired at low temperature; effect related to hand-skin temperatures
Clark and Cohen (1960)[4]	Hand in water; hand temps from < 13°C and > 16°C	—?	Hand-skin temperature of 16°C identified as minimum temp below which impairments in dexterity occur
Bowen (1968)[5]	Hand in water at 8°C, 17°C, or 22°C	20 min	20% decrements in 22°C water; 25% decrements in 17°C water; 45% decrements in 8°C water
Bensel and Lockhart (1974)[6]	–7°C; 16°C	180 min; 180 min	Decrements in six manual tasks at –7°C; greatest decrement with fastest rate of cooling
Davis et al. (1975)[7]	5°C water (whole body)	35–50 min	17% decrement in dexterity immediately, but not progressive
Enander (1987)[8]	5°C	90 min	13% decrement in hand dexterity

—?: Unknown

Data sources: (1) Springbett BM. The effects of exposure to cold on motor performance. Toronto, Ontario, Canada: Defense Research Board of Canada; 1951. (2) Leblanc JS. Impairment of manual dexterity in the cold. *J Appl Physiol*. 1956;9:62–64. (3) Gaydos HF, Dusek ER. Effects of localized hand cooling vs total body cooling on manual performance. *J Appl Physiol.* 1958;12:377–380. (4) Clark RE, Cohen A. Manual performance as a function of rate of change in hand temperature. *J Appl Physiol.* 1960;15:496–498. (5) Bowen HM. Diver performance and the effects of cold. *Hum Factors*. 1968;10(5):445-464. (6) Bensel CK, Lockhart JM. Cold-induced vasodilatation onset and manual performance in the cold. *Ergonomics*. 1974;17:717–730. (7) Davis FM, Baddeley AD, Hancock TR. Diver performance: The effect of cold. *Undersea Biomed Res.* 1975;2(3):195–213. (8) Enander A. Effects of moderate cold on performance of psychomotor and cognitive tasks. *Ergonomics.* 1987;30(10):1431–1445.

temperature. Bensel and Lockhart[49] examined performance on six different manual dexterity tasks and—in contrast to Clark and Cohen[47] — concluded that the greatest rate of performance decrement in their sample occurred with the fastest rate of cooling, independent of the absolute final temperatures achieved. In contrast to the Bowen results, Davis, Baddeley, and Hancock[50] reported a 17% deterioration in dexterity in wet suit-clad scuba divers, who were tested following 35 to 50 minutes of exposure to 5°C water; the deterioration was not progressive but rapid, following initial cold water immersion. This disparity in findings may be caused by the nature of the tasks sampled in these two studies, with knot tying requiring a higher degree of very fine motor movements that may deteriorate faster in the cold. Enander (1987)[51] reported a 13% decrement in manual dexterity in a sample of 24 subjects clad in lightly quilted jackets and pants exposed to 5°C air for 55 to 90 minutes.

Strength

The available evidence suggests that cold exposure-particularly cold water exposure-causes substantial decrements in hand strength and impairs the ability to sustain a submaximal upper extremity muscle contraction (Table 12-3). Craik and Macpherson[52] reported in 1943 that immersing the hand in 7°C water for 15 minutes reduced mean grip strength 21%, and reduced the strength of finger-thumb opposition 44%. In 1947, Horvath and Freedman[53] reported an average decrease in grip strength of 28% in heavily clothed subjects who were

TABLE 12-3

COLD STRESS AND STRENGTH: SUMMARY OF FOUR STUDIES

Study	Temperature (°C)	Exposure Time	Results
Craik and Macpherson (1943)[1]	7°C water (hand)	15 min	21% decrease in mean grip strength; 44% decrease in finger-thumb opposition
Horvath and Freedman (1947)[2]	–25°C air (whole body)	180 min	28% decrease in mean grip strength
Clarke et al. (1958)[3]	27°C water (forearm)	Varied by skin temp, 30–120 min total exposure	60% decrease in grip strength at 2°C forearm skin temp
Bowen (1968)[4]	8°C water	24 min	14% decrease in hand strength

Temp: temperature
Data sources: (1) Craik KJW, Macpherson SJ. *Effects of Cold Upon Hand Movements and Reaction Times*. London, England: Medical Research Council Military Personnel Research Committee; 1943. Report BPC**.** 43/196. (2) Horvath SM, Freedman A. The influence of cold on the efficiency of man. *J Aviation Med*. 1947;18:158–164. (3) Clarke RSJ, Hellon RF, Lind AR. The duration of sustained contractions of the human forearm at different muscle temperatures. *J Physiol.* 1958;143:454–473. (4) Bowen HM. Diver performance and the effects of cold. *Hum Factors*. 1968;10(5):445–464.

exposed to –25°C air for 3 hours without exercising. In 1958, Clarke, Hellon, and Lind[46] isolated forearm muscle temperature as a critical determinant of hand strength decrements by cooling forearm muscle to 27°C via a water bath and observing a progressive deterioration in hand grip, which approached a 60% decrement at 2°C. Bowen[31] demonstrated a 14% impairment in hand strength following a 24-minute exposure to 8°C water. Similar results have been reported in sustaining a submaximal contraction by Coppin, Livingstone, and Kuehn,[54] and by Clarke, Hellon, and Lind.[46] The available evidence to date suggests that local cooling of the muscles, particularly forearm muscles, to a muscle temperature at or below 27°C is likely to impair limb strength and decrease the length of time that a submaximal muscle contraction can be maintained.

Motor Speed

Relatively little work has been done to investigate the effects of cold stress on motor speed, in part because most motor speed measures have a confounding component of manual dexterity as well. The available evidence, however, suggests some likely decrements in motor speed with significant cold exposure (Table 12-4). In 1970, Stang and Weiner[55] reported increased time to complete underwater work tasks in their sample of 12 experienced wet suit-clad scuba divers exposed to 16°C and 10°C water for 90 minutes, although some of the reported difficulty may be attributable to fine motor task demands in their simple assembly tasks (eg, attaching a plate to a work bench frame with wing nuts, attaching two plates together with wing nuts, transferring small nuts and screws

TABLE 12-4

COLD STRESS AND MOTOR SPEED: SUMMARY OF TWO STUDIES

Study	Temperature (°C)	Exposure Time	Results
Stang and Weiner (1970)[1]	10°C to 16°C water (whole body)	90 min total	Increased time to complete underwater assembly tasks, although some tasks had a dexterity or strength component
Enander (1987)[2]	5°C air (whole body)	Varied, 55–90 min	Decrements in tapping speed beginning after 20 min of exposure and increasing in severity with longer durations of exposure

Data sources: (1) Stang PR, Wiener EL. Diver performance in cold water. *Hum Factors*. 1970;12(4):391–399. (2) Enander A. Effects of moderate cold on performance of psychomotor and cognitive tasks. *Ergonomics.* 1987;30(10):1431–1445.

TABLE 12-5

COLD STRESS AND VIGILANCE: SUMMARY OF SEVEN STUDIES

Study	Temperature (°C)	Exposure Time	Results
Mackworth (1950)[1]	21°C to 36°C	Varied by skin temp	Optimal vigilance efficiency and minimal signal omissions at 26°C
Kissen et al. (1964)[2]	4°C	60 min	Progressive deterioration in vigilance to visual matching display
Poulton et al. (1965)[3]	–2.2°C to 1.7°C	30 min	Decreased vigilance of shipboard lookouts at decreased oral temperatures, but some uncontrolled variance due to rain and wind
Teichner (l966)[4]	12.8°C; 26.7°C	40 min; 40 min	No difference in visual detection between two temperatures sampled
Baddeley et al. (1975)[5]	4.4°C water (whole body)	60 min	No decrements in an underwater visual vigilance task
Vaughan (1977)[6]	4.5°C water; 15.5°C water	180 min	Increase in average visual detection times at both temperatures for immersed scuba divers.
Angus et al. (1979)[7]	0° to 5°C	16 d	Decrements in vigilance task following outdoor sleeping, further decrements due to REM sleep deprivation

REM: rapid eye movement

Data sources: (1) Mackworth NH. *Researches on the Measurement of Human Performance*. London, England: Medical Research Council; 1950. Report Series 268. (2) Kissen AT, Reifler CB, Thaler VH. Modification of thermoregulatory responses to cold by hypnosis. *J Appl Physiol.* 1964;19:1043–1050. (3) Poulton EC, Hitchings NB, Brooke RB. Effect of cold and rain upon the vigilance of lookouts. *Ergonomics.* 1965;8:163–168. (4) Teichner WH. Individual thermal and behavioral factors in cold-induced vasodilatation. *Psychophysiology*. 1966;2:295–304. (5) Baddeley AD, Cuccaro WJ, Egstrom GH, Weltman G, Willis MA. Cognitive efficiency of divers working in cold water. *Hum Factors*. 1975;17(5):446-454. (6) Vaughan WS Jr. Distraction effect of cold water on performance of higher-order tasks. *Undersea Biomed Res.* l977;4(2):103–116. (7) Angus RG, Pearce DG, Buguet GC, Olsen L. Vigilance performance of men sleeping under arctic conditions. *Aviat Space Environ Med.* 1979;50(7):692–696.

from one side of a plate to the other) or decrements in strength (eg, loosening torqued nuts and bolts with wrenches, removing bolts with a speed wrench). Using a purer measure of motor speed, Enander[51] reported in 1987 substantial decrements in tapping speed using a simple, handheld counter in a sample of 24 subjects exposed to 5°C air, which occurred following approximately 20 minutes of cold exposure and increased in severity with longer durations of cold exposure.

Vigilance

Since 1950, several investigators have studied the effects of cold exposure on vigilance tasks, but the body of literature in this area remains markedly smaller than companion studies of heat stress effects on vigilance, attention, and concentration (Table 12-5). Mackworth[56] reported optimum vigilance efficiency and minimal signal omissions for artificially acclimatized subjects at 26°C air temperatures versus either 31°C, 36°C, or 21°C. Pepler,[57] using naturally acclimatized subjects in Singapore, was able to confirm Mackworth's findings in part, and the results of these two studies led to speculation that there is an optimal level for vigilance in the range of 27°C to 32°C,[58,59] and that vigilance exhibits an inverted U-shaped distribution with lowered vigilance at both higher and lower temperatures.

Kissen, Reifler, and Thaler[60] reported a progressive deterioration in visual vigilance in lightly clad subjects exposed to 4°C air for 1 hour, who were required to distinguish randomly displayed matched pairs of a visual pattern from unmatched pairs. They observed a decrease in the number of correct identifications as cooling progressed, coincident with decreases in body core temperature, although commission errors did not vary with increased exposure time. Poulton, Hitchings, and

Brooke[61] examined vigilance of shipboard lookouts at –2.2°C and 1.7°C cold exposures and reported decrements in lookout vigilance coincident with decreased oral temperatures, although there were methodological problems in these studies owing to the uncontrolled variance attributable to wind and rain during some watch periods. Teichner[62] investigated prolonged visual detection at 12.8°C and 26.7°C air temperatures, which were accompanied by minimal decreases in body core temperature. There were no observed consistent differences between these two temperature conditions in mean percentage detection or average response speed.

In an early review paper, Grether[63] hypothesized that optimal vigilance is observed at 26.7°C on the Effective Temperature (E.T.) scale, an index of perceived warmth that combines dry and wet bulb temperatures with air velocity. In 1975, however, Baddeley and colleagues[64] reported no decrements in visual vigilance (detecting the onset of a faint peripheral light during the performance of a two-man pipe assembly task) in a sample of 14 acclimatized divers following a 60-minute exposure to 4.4°C water, despite a mean drop in rectal temperature of 0.72°C. In contrast, Vaughan[65] reported in 1977 an increase in the average time to detect peripherally displayed targets in a sample of US Navy–qualified, wet suit–clad scuba divers exposed for 180 minutes to 4.5°C and 15.5°C water. In 15.5°C water, detection speed slowed to 3.6 seconds in the first hour, to 4.2 seconds in the second hour, and to 7.2 seconds in the third hour. However, at 4.5°C water exposure, detection speed was initially much slower at 7.8 seconds, improved in the second hour to 4.8 seconds, and deteriorated again in the third hour to 8.4 seconds.

In 1979, Angus and colleagues[66] reported substantial decrements in performance on the Wilkinson visual vigilance task over the course of 16 days of exposure to 0°C to 5°C arctic temperatures, with a marked decrement in performance following the initial cold exposure. Although there was an observed gradual improvement in vigilance on subsequent exposure days, there was deterioration in performance on days following especially cold nights when rapid eye movement (REM) sleep was disrupted, suggesting partial adaptation of vigilance ability during prolonged cold exposure, modified somewhat by the effects of REM deprivation.

In an attempt to account for the disparity in findings from different laboratories in this area of investigation, Hancock[67] argued in 1984 that substantial vigilance decrements occur only during dynamic shifts in body core temperature and are not likely to occur at steady state temperatures, suggesting that fully acclimatized subjects would be unlikely to exhibit vigilance decrements even at very cold ambient temperatures.

Reaction Times

Investigations completed thus far suggest minimal decrements in simple reaction time (except in the most extreme conditions) but marked changes in more complex reaction-time tasks (Table 12-6).

Simple Reaction Time

In 1942, Williams and Kitching[68] tested both simple and choice visual reaction time (motor response to a visual stimulus) in three subjects following 60-minute exposures to environmental chamber temperatures of –18°C and –45.5°C The authors concluded that although body temperatures dropped, there was no direct relationship between reaction time and body temperatures, and that the observed variations in reaction time that occurred at temperatures of –45.5°C were explainable as due to discomfort-induced distraction. In 1947, Horvath and Freedman[53] reported no deleterious effects of cold exposure to visual choice reaction time in a sample of 22 subjects housed in temperatures of –29°C for 8 to 14 days and tested three times per day. Forlano, Barmack, and Coakley[69] in 1948 and Teichner[70] in 1954 reported that simple reaction time was unaffected by cold air exposures as severe as –45°C. In a follow-up study of 640 men exposed to cold air temperatures as low as –37°C, Teichner[71] reported in 1958 that linear decrements in reaction speed were observed in subjects beginning at an ambient temperature of –26°C with a wind speed of 10 mph or greater. Mild exercise caused a small recovery in reaction speed.

At wind speeds of 5 mph or less, no effect of temperature on reaction speed was observed. These results were apparently not related to measured skin temperatures and were instead believed to be due to increased distractibility and discomfort in windchill conditions, leading to the coining of the term “psychological cold tolerance” and the speculation that these effect of cold and windchill on simple reaction time might not be seen in highly acclimatized individuals. Since that time, Pease, Ludwig, and Green[72] in 1980 and Goodman, Hancock, Runnings, and Brown[73] in 1984 have demonstrated decrements in mean reaction time to moderate to severe cold stress, although not without extreme cooling of the responding arm. In 1987, Enander[51] reported no decrement in simple visual

TABLE 12-6

COLD STRESS AND REACTION TIME: SUMMARY OF EIGHT STUDIES

Study	Temperature (°C)	Exposure Time	Results
Williams and Kitching (1942)[1]	–18°C; –45.5°C air	60 min	Decrements in simple and choice RT at –45.5°C
Horvath and Freedman (1947)[2]	–29°C air	8–14 days	No difference in visual choice RT
Teichner (1954)[3]	–45.5°C air	45 min	Simple RT not affected in air temps as low as –45°C
Teichner (1958)[4]	–37°C air + wind	Varied, 45–63 min	Linear decrements in RT at –26°C when accompanied by 10 mph wind
Stang and Weiner (1970)[5]	10°C to 21°C (water)	90 min	0.5% slower visual choice RT in 16°C water; 23% slower visual choice RT in 10°C water
Ellis (1982)[6]	–12°C water	90 min	Increase in errors of 200%–300% in serial choice RT; no effect on simple RT
Ellis et al. (1985)[7]	–5°C air	Varied; fast cooling 60 min; slow cooling 180 min	Increase in errors on serial choice RT when rapidly cooled, but not if slowly cooled
Enander (1987)[8]	5°C air	Varied, 55–90 min	Replicated Ellis (1982)[6]

RT: reaction time

Data sources: (1) Williams CC, Kitching JA. The effects of cold on human performance, I: Reaction time. *Misc Canad Aviat Rep.* Toronto, Ontario, Canada: Banting and Best Department of Medical Research; 1942. (2) Horvath SM, Freedman A. The influence of cold on the efficiency of man. *J Aviation Med*. 1947;18:158–164. (3) Teichner WH. Recent studies of simple reaction time. *Psychol Bull.* 1954;51:128–149. (4) Teichner WH. Reaction time in the cold. *J Appl Psychol.* 1958;42(1):54–59. (5) Stang PR, Wiener EL. Diver performance in cold water. *Hum Factors*. 1970;12(4):391–399. (6) Ellis HD. The effects of cold on the performance of serial choice reaction time and various discrete tasks. *Hum Factors*. 1982;24(5):589–598. (7) Ellis HD, Wilcock SE, Zaman SA. Cold and performance: The effects of information load, analgesics, and the rate of cooling. *Aviat Space Environ Med.* 1985;56(1):233–237. (8) Enander A. Effects of moderate cold on performance of psychomotor and cognitive tasks. *Ergonomics.* 1987;30(10):1431–1445.

reaction time in a sample of 12 men exposed to air temperature of 5°C for 90 minutes.

Choice Reaction Time

In 1970, Stang and Wiener[55] reported decrements in visual choice reaction time in their sample of 12 experienced scuba divers exposed to water at temperatures of 16°C and 10°C. When compared with their task performance in 21°C water, subjects responded 10.5% slower when exposed to 16°C water, and 23% slower than that when exposed to 10°C water.

In 1982, Ellis[74] reported significant decrements in serial choice reaction time in subjects exposed to air temperatures of –12°C for 90 minutes. The serial choice reaction time task used in these experiments consisted of the serial visual presentation of a series of digits between 1 and 8 that were to be classified by the subject as either odd or even by depressing one of two control buttons. Immediately after either button was pressed, a next digit was randomly selected and presented, and the cycle continued for 500 trials. Despite an increase in serial choice reaction time errors of 200% to 300% for these cold-stressed subjects, there was no accompanying decrement in simple reaction time in the cold (immediate pressing of a button when the number "0" appeared on the screen). These errors were directly proportional to observed reductions in mean skin temperatures and reported to be largely independent of any fall in rectal (core) temperatures.

Ellis, Wilcock, and Zaman[75] demonstrated in 1985 reliable decrements on the 8-choice visual choice reaction-time task in eight lightly clad male subjects rapidly cooled by exposure to –5°C air for 60 minutes, but decrements on the same 8-choice visual choice reaction-time task were not observed with a subsample of six male subjects cooled slowly by a 180-minute exposure to 8°C air. This has led to speculation that rapid cooling via mild cold air stress may affect complex reaction-time primarily by increasing discomfort and distraction rather than by a direct effect due to changes in body surface or core temperature. In 1987, Enander,[51] using a very similar visual choice reaction time task, was able to replicate Ellis's[74] 1982 results in a sample of 12 lightly clad women exposed to 5°C air for 55 to 90 minutes. There were increases in the number of errors, speed of incorrect responses, and number of false alarms, leading to speculation that for more complex tasks reaction time may be compromised by a decreased ability to inhibit incorrect responses.

Target Tracking

The programmatic study of the effect of cold stress on manual pursuit tracking began more than 50 years ago (Table 12-7). In 1947, Blair and Gottschalk[76] found that manipulation of a metal tracking control by thumb and forefinger was impaired during cold air exposure. The initial exposure of men fully dressed in arctic clothing (including arctic mittens) to air temperature of –25°C produced a 19% reduction in performance from that found at 23°C, and a further reduction in temperature to –41°C produced an additional 21% decrement, although some of the observed decrement may have been attributable to numbness and surface cooling of the fingers on the bare metal apparatus. In 1954, Teichner and Wehrkamp[77] reported results of multiple trials of pursuit rotor tracking at air temperatures of 13°C, 21°C, 29°C, and 38°C. Performance of their subjects deteriorated both above and below 21°C, but that performance appeared to fall off more rapidly at 13°C than it did at 29°C or 38°C. A follow-up study of the effects of longer-term cold exposure on pursuit rotor performance was reported by Teichner and Kobrick in 1955.[78] Their six subjects lived in a constant temperature environmental chamber for 41 days, and their pursuit rotor tracking ability was tested daily (15 trials per day). For the first 16 days the chamber temperature was held at 24°C, the next 12 at 13°C, and at 24°C for the remaining 13 days. Visual-motor tracking performance was markedly and immediately impaired in the cold and recovered gradually, but only to the approximate level of performance obtained at the beginning of these experiments, essentially eliminating the beneficial effects of practice on this task that had been observed over the course of the first 16 days.

In 1957, Russell[79] investigated a manual tracking task in six ambient temperatures ranging from –10°C to 40°C. The test task involved using a manipulator control to actuate a stylus, which was used to track a laterally moving ink line on a moving chart paper. The manipulator was configured to respond to either slight pressure or to actual movement. Russell found that duration of exposure had no significant effect on performance, but that performance on both types of tracking tasks declined steeply when

TABLE 12-7

COLD STRESS AND TARGET TRACKING: SUMMARY OF SIX STUDIES

Study	Temperature (°C)	Exposure Time	Results
Blair and Gottschalk (1947)[1]	23°C; –25°C; –41°C	Varied with skin temp	19% reduction in manipulation of a metal tracking control at –25°C; additional 21% reduction at –41°C
Teichner and Wehrkamp (1954)[2]	13°C to 38°C	30 min	Pursuit rotor tracking deteriorated above and below 21°C, but more rapid falloff at 13°C
Teichner and Kobrick (1955)[3]	13°C to 24°C	41 days	Visual motor tracking markedly and immediately impaired at 13°F
Russell (1957)[4]	–10°C to 40°C	73 min	Decrements in tracking at 10°C; pressure tracking deteriorated faster than movement tracking
Payne (1959)[5]	4°C; 13°C; 21°C	200 min; 200 min; 200 min	Decrement in complex tracking task at 4°C
Enander (1987)[6]	4°C to 20°C	60 min	Significant increase in errors, speed of incorrect response, and number of false alarms on two computerized tracking tests at 4°C

Temp: temperature

Data sources: (1) Blair EA, Gottschalk CW. *Efficiency of Signal Corps Operators in Extreme Cold.* Fort Knox, Ky: US Army Medical Research Laboratory; 1947. AMRL Report 2. (2) Teichner WH, Wehrkamp RF. Visual–motor performance as a function of short-duration ambient temperature. *J Exp Psychol.* 1954;47:447–450. (3) Teichner WH, Kobrick JL. Effects of prolonged exposure to low temperature on visual–motor performance. *J Exp Psychol.* 1955;49(2):122–126. (4) Russell RW. Effects of Variations in Ambient Temperature on Certain Measures of Tracking Skill and Sensory Sensitivity. Fort Knox, Ky: US Army Medical Research Laboratory; 1957. AMRL Report 300. (5) Payne RB. Tracking proficiency as a function of thermal balance. *J Appl Physiol.* 1959;14:387–389. (6) Enander A. Effects of moderate cold on performance of psychomotor and cognitive tasks. *Ergonomics.* 1987;30(10):1431–1445.

subjects were exposed to ambient temperatures below 10°C, and that pressure tracking deteriorated sooner than movement tracking, suggesting that subtleties of motor control might deteriorate faster in the cold than more pronounced motor movements.

In 1959, Payne[80] examined tracking performance of lightly dressed subjects at 21°C, 13°C, and 4°C on a complex task requiring attention to several controls at once for accurate performance. Payne reported that performance on this task was directly related to ambient temperature, with the poorest performance occurring at 4°C, a condition also reported by subjects to be quite stressful. Recent work by Enander[51] (1987) has demonstrated significant increases in number of errors, speed of incorrect response, and number of false alarms on two computerized tracking tests completed by female subjects during mild cold exposure. These effects, however, were only obtained when tests were constructed that required continuous rapid accurate responding, with minimal available opportunity to inhibit error responses.

Memory and Recall

It has been known for some time that extreme cold stress can induce confusion and impaired consciousness, and a series of studies have examined the effects of cold water immersion and pronounced cold stress on memory and memory registration (Table 12-8).

In 1959, Keatinge[81] reported that two of his subjects experienced complete amnesia for the last few minutes of 20-minute immersions in 5°C water, during which time they experienced core temperature decreases to 34.2°C and 35.1°C. In 1968, Bowen[31] reported a 22% decrement in performance on the Clock Test, a measure of short-term memory, in subjects exposed to 8°C water. In 1970, Stang and Weiner[55] reported decrements on an arithmetic test

TABLE 12-8

COLD STRESS AND MEMORY: SUMMARY OF EIGHT STUDIES

Study	Temperature (°C)	Exposure Time	Results
Keatinge (1959)[1]	5°C water (whole body)	20 min	Reported complete amnesia in two subjects for the last few minutes of immersion, at body core temperatures of 34.2°C and 35.1°C
Bowen (1968)[2]	8°C water	Varied, typically less than 25 min	22% decrement in performance on the Clock Test, a measure of short-term memory
Stang and Weiner (1970)[3]	10°C water	90 min	Decrements reported on an arithmetic test, attributed to lapses in concentration
Egstrom et al. (1972)[4]	4.4°C water	50 min	Impairment in divers' ability to recall material learned underwater
Baddeley et al. (1975)[5]	4.4°C water; 25.6°C water	50 min	Impairment of the recall of short paragraphs
Davis et al. (1975)[6]	5°C water; 20°C water	35–50 min	Memory recognition impaired after exposure to 5°C water
Coleshaw et al. (1983)[7]	15°C water	Varied, 45–60 min	70% decrement in memory registration at core body temp of 34°C–35°C
Thomas et al. (1989)[8]	5°C air	60 min	Decrement in delayed matching to sample visual memory

Temp: temperature

Data sources: (1) Keatinge WR. *The Effect of Work, Clothing and Adaptation on the Maintenance of the Body Temperature in Water and on Reflex Responses to Immersion*. Cambridge, England: University of Cambridge; 1959. Thesis. (2) Bowen HM. Diver performance and the effects of cold. *Hum Factors*. 1968;10(5):445–464. (3) Stang PR, Weiner EL. Diver performance in cold water. *Hum Factors*. 1970;12(4):391–399. (4) Egstrom GH, Weltman AD, Baddeley WJ, Cuccaro WJ, Willis MA. *Underwater Work Performance and Work Tolerance*. Los Angeles, Calif: University of California, School of Engineering and Applied Sciences; 1972. UCLA-ENG-7243. Biotechnologic Laboratory Technical Report 51. (5) Baddeley AD, Cuccaro WJ, Egstrom GH, Weltman G, Willis MA. Cognitive efficiency of divers working in cold water. *Hum Factors*. 1975;17(5):446–454. (6) Davis FM, Baddeley AD, Hancock TR. Diver performance: The effect of cold. *Undersea Biomed Res*. 1975;2(3):195–213. (7) Coleshaw SRK, Van Someren RNM, Wolff AH, Davis HM, Keatinge WR. Impaired memory registration and speed of reasoning caused by low body temperature. *J Appl Physiol*. 1983;Jul 55(1 Pt 1):27–31. (8) Thomas JR, Ahlers ST, House JF, Schrot J. Repeated exposure to moderate cold impairs matching-to-sample performance. *Aviat Space Environ Med*. 1989;60(11):1063–1067.

during exposure to 10°C water for 90 minutes, with errors attributable to momentary lapses in concentration.[65]

In 1972, Egstrom and colleagues[82] reported impairment in divers' abilities to recall material learned underwater when tested after 50 minutes of exposure to 4.4°C water, although no impairments were noted in vigilance, reaction time, or reasoning tasks. The authors speculated that this result might represent reduced attentional capacity. In 1975, Baddeley and colleagues[64] examined the performance of subjects exposed for 50 minutes to water at 4.4°C and 25.6°C. Although no impairment was found on reasoning tasks or vigilance tasks, there was impairment in the recall of short paragraphs. No decrement in recognition memory was observed. Also in 1975, Davis, Baddeley, and Hancock[50] compared performances on tasks involving simple arithmetic, logical reasoning, digit span, word recall, and memory recognition during 35- to 50-minute exposures to water at 5°C and 20°C. Only the memory tests were significantly affected by differences in exposure temperature. Although decrements in word recognition performance were highly correlated with body cooling, word recall scores were not, implying an effect not solely attributable to the result of direct central (core body) cooling.

In 1983, Coleshaw and colleagues[4] reported significant impairment of auditory memory registration following immersion in 15°C water. At core body temperatures of 34°C to 35°C, loss of about 70% of the data that could normally be retained was observed. There was no observed impairment in previously learned data, however, implying an effect of deep body cooling on new learning and concentration, or attention, or both.

In 1989, Thomas and colleagues[83] reported a clear decrement in delayed matching to sample visual memory performance in a sample of six subjects exposed to 5°C air for 60 minutes, and this impaired level of performance persisted at the same level in two subsequent exposures to 5°C air, each occurring 1 week apart. Each subject in this experiment was lightly dressed and seated in front of a computer terminal, which visually displayed a target matrix of 16 squares colored either red or yellow. Subjects responded to seeing the target matrix by pressing a button on the console; the target matrix was then immediately removed from the screen and after a 3-second delay, two comparison matrices were displayed on the screen. One matrix was identical in pattern to the sample matrix, the other differed by one cell only, and the subject was required to choose the identical matrix. During the exposure to 5°C air, the number of errors increased relative to pretest performance in 22°C ambient air, response times following the presentation of the target stimulus were shorter, and response times prior to selecting the comparison matrix were longer. These data were unrelated to central body cooling effects and generally were interpreted as a decrement in performance related to increased arousal rather than distraction.

Complex Cognitive Functioning

The available evidence in this area suggests that decrements in cognitive functioning due to cold stress are for the most part directly related to task complexity. In 1966, Baddeley[84] studied the effect of cold water immersion on the ability to estimate time by having 20 scuba divers count up to 60 at what they considered to be a 1-second rate while immersed in 4°C sea water. Subjects consistently counted at a slower rate while immersed, which was correlated with decreases in oral temperatures (median rank-correlation = 0.50). Rate of counting was not correlated with pulse rate, predive anxiety, or effects of the order of the tests. It should be noted that the face was directly exposed to cold water in these experiments, resulting in oral temperature measurements that are probably gross underestimates of deep body temperatures.

In 1968, Bowen[31] reported a 12% decrease in accuracy on a symbol processing task completed by subjects immersed in 8°C water. This task consisted of a subject's reading an entry that listed, in sequence, a code number and four colors. The subject was then required to visually scan a 10 X 10 table (10 colors by 10 numbers) to find a numerical value for each color. Each subject then selected a problem from a problem chart array, which provided four sequential numbers. The subject paired each of these sequential numbers with the previously derived numerical values for each of the four colors, multiplied each pair, summed the products, and checked off the correct number with a grease pencil on an answer slate. Subjects also experienced fewer successfully completed items on a problem-solving set—exceptions test when immersed in 8°C water. This test involved having the subjects visually scan five numbers presented horizontally and deciding which four of these numbers had the same arithmetic common denominator (ie, which numbers could all be evenly divided by the same number) and excluding the one that did not by checking it with a grease pencil. The increased performance decrement on both of these tasks was not believed to be related to decrements in motor speed or dexterity.

In 1977, Vaughan[65] reported significant decrements in navigation problem-solving tasks completed by eight US Navy-qualified scuba divers during the first hour of immersion in 4.5°C water, but noted that performance on these same tasks during the second and third hours of immersion were not significantly different-whether immersed in 4.5°C water or 15.5°C water. The navigation problem-solving task involved a display console in an underwater simulator, which presented information about the vehicle's position with reference to its intended track. The console additionally displayed real time, across-track error, and distance traveled along-track. Given the displayed data (which were varied remotely for each navigation problem), divers were asked to plot successive positions of the vehicle, draw a vector triangle, and determine set and drift of the current, vehicle speed, vehicle course over the bottom, and a new heading for the vehicle that corrected for current vector effects. Observed decrement on this navigation task during the first hour of immersion was interpreted by Vaughan as due to distraction rather than as secondary to core or peripheral cooling.

In 1993, Giesbrecht and colleagues[85] reported decrements in the performance of complex tasks requiring mental manipulation (backward digit span) and mental processing and analysis (Stroop Color-Word Test) following the immersion of swimsuit-clad subjects in 8°C water once central cooling of 2°C to 4°C had occurred, suggesting a greater effect of cold on tasks that (*a*) are complex or perceptually demanding and (*b*) require significant concentration or short-term memory. In their sample of six subjects, cold water immersion had no significant effect on less cognitively demanding tasks such as auditory attention, visual recognition, and forward digit span.

Learning

Although several investigators have demonstrated deleterious effects of cold stress on components of the learning process (attention, concentration, vigilance, and memory), there has been relatively little work examining direct effects on learning. To date, the effect of high temperatures has been more extensively examined than low temperatures. In 1968, Pepler and Warner[86] examined the learning efficiency of 72 male and female college students who studied a programmed text once a week for 6 weeks (3 h/d) while lightly dressed and housed in an environmental chamber at ambient temperatures of 17°C, 20°C, 23°C, 27°C, 30°C, or 33°C. The lowest mean error rate and lowest mean rating of perceived effort occurred in the 27°C condition. The highest mean error rate occurred at 17°C: the students changed their learning style and worked more quickly, they experienced higher levels of effort, and they made errors at a faster rate. Although far more work is obviously needed in this area, these data are in general agreement with Enander's[51] report of significant increases in number of errors, speed of incorrect response, and number of false alarms during mild cold exposure.

Thermal Sensation Versus Thermal Perception

In cold environments, an individual's behavioral responses to the cold are often a function of his or her subjective assessment of cold and thermal discomfort rather than of actual exposure time, physiological status, prior acclimation to the cold, or deep body temperature.

Some evidence suggests that perceived thermal intensity (*a*) depends solely on signals from peripheral thermal receptors and (*b*) is independent of the stimulation of central thermal receptors. This is consistent with the observations of Benzinger[87,88] in a series of experiments published in 1970 and 1978 on the role of surface temperature on cold perception. These studies suggest that central thermoreception in the homeostatic range from 36.1°C to 37.8°C appears to make no demonstrable contribution to cold perception at its threshold. In contrast, the thermal comfort experiments using perfused gloves done by Cabanac and colleagues[89,90] and published in 1971 and 1972, suggest that the behavioral response to cold stress strongly depends on internal body temperature. A third position is represented by the work of Mowrer,[91] who concluded in 1976 that thermal intensity depends solely on signals from peripheral thermal receptors, and that thermal pleasantness or comfort is the result of an interaction of signals from both central and peripheral receptors. One explanation of this disparity may be that central cold receptors contribute to the conscious sensation of cold primarily at lower central temperatures. In 1970, Benzinger[87] demonstrated the apparent absence of a central component for temperatures in the range above 36°C central temperature.

In a series of experiments by Gagge and colleagues[92] published in 1967 and Hardy and colleagues[93] in 1971, a marked drop in skin temperature and heart rate was observed following exposure to 17.5°C air.

Initial reactions to these changes were an intense sensation of cold and discomfort, which were followed by both (1) a temporary reduction of the estimates after vasoconstriction had developed and (2) a slight increase in internal body temperature. During the following 2-hour period body cooling was essentially passive, and reports of discomfort and cold sensation were relatively stable and increased only slightly. During the final hour, there was little, if any, correlation between reports of discomfort and thermal sensations of cold with mean skin temperature. Similarly, Hardy[94] found in another series of cold air experiments in 1970 that neither mean skin temperature nor internal body temperature appeared to be related in any quantitative sense to sensory responses; like most of the experiments reported in this section, cold sensation was found to be related to discomfort or pain. These sensory responses increased on entering the cold—before any appreciable change in body temperature—and decreased rapidly on leaving the cold—before any significant recovery of the 2.8°C decrement in body temperature that had been incurred during the exposure. The sensors were thus "leading" the body temperature changes and their effects were anticipatory, suggesting that cold sensation may be a type of sensory response related to the rate of change of skin temperature.

In 1989, Hoffman and Pozos[95] examined subjective estimates of cold and temperature at multiple body sites in 12 subjects immersed in 10°C water for an average of 112 minutes while wearing flotation suits. Subjects were unable to reliably assess how cold they actually were, with .51 being the highest correlation observed between perceived temperature and actual temperature.

The results of these studies suggest that although subjects exposed to mild-to-moderate cold air may be able to reliably assess thermal intensity and body temperatures, individuals who are rapidly cooled in cold water may have considerable difficulty separating feelings of pain and discomfort from feelings of cold, which could have serious consequences in cold weather survival situations and demonstrates the somewhat subjective and variable nature of cold perception.

Arousal Versus Distraction Models of Complex Behavior

Two theoretical models have been generally proposed to explain the effect of cold stress on human performance, although neither has satisfactorily accounted for the observed patterns of performance decrement. The first, the theory of general arousal, predicts effects dependent on the degree of physiological stimulation in relation to task difficulty and subject experience.[51] This model is described as having a U-shaped distribution, such that the performance of a simple task may be facilitated by an increase in arousal (eg, a mild cold stress), whereas the optimal level of arousal needed to facilitate performance is lower if the nature of the task is more complex. Using such a model, therefore, an environmental stressor such as mild cold stress would be expected to facilitate performance on simple tasks such as vigilance and degrade performance on more complex tasks such as choice reaction time or delayed matching to sample tasks. To date, however, this model has been found to have serious limitations: it does not adequately explain some performance decrements in mild cold stress conditions despite attempts to build more complex arousal models; and it also does not well address the majority of performance decrements observed during moderate-to-severe cold stress.[96]

The second theory, that cold stress has a distraction effect, was first proposed in 1958 by Teichner[71] as a way to explain the apparent lack of consistent relation between measures of physiological cooling and human performance. According to the distraction model, cold stress is believed to cause momentary switches of attention from the primary task, resulting in performance decrement. Although this model would to some extent account for decrements in attention, concentration, and reaction time in some cases of mild cold stress, there is no room in this model to address observed facilitation of performance in modest cold stress, nor have investigators observed the pattern of missed signals that this model would predict.[51,75]

Training and Acclimatization

Although there have been several reports of both naturally occurring and experimentally induced acclimatization altering the cooling rates of fingers and hands, relatively few reports have included an examination of resultant changes in hand skills, dexterity, and strength. In 1952, Yoshimura and Iida[97] reported a significant attenuation of finger vasoconstriction and earlier cold-induced vasodilation in a sample of cold-acclimatized Chinese and Mongolian subjects versus non–cold-acclimatized Japanese subjects. In 1955, Meehan[98] described similar differences between Athabascan arctic Indians and caucasians. Krog and colleagues[99] described similar differences in 1960 between Norwegian and Laplander fishermen and controls; Nelms and Soper[100] in 1962 between British fish filleters and laboratory technicians; and Hoffman and Wittmers[43] in 1990 between male arctic explorers and a comparison group matched for gender, age, and finger size. In addition, Enander, Skold-strom, and Holmer[101] noted in 1980 that a cold-acclimatized group of meat cutters experienced significantly less cold and discomfort (increased psychological cold tolerance) when exposed to 10°C air, compared with a sample of office workers, despite no significant differences in measured hand temperature.

In 1960, Krog and colleagues[99] additionally investigated the effect of cold habituation (acclimatization) on the motor responses of Norwegian and Laplander fishermen. They reported that their cold-acclimatized subjects had a faster finger-tapping rate and greater grip strength than a matched, nonacclimatized control sample. This result was reported to be correlated with an altered cold-induced vasodilation (CIVD) response in the acclimatized subjects' fingers, such that their fingers did not get as cold as the control samples' fingers before their fingers began to rewarm spontaneously. (For further information on CIVD, please see Chapter 13, Prevention of Cold Injuries, and Chapter 14, Clinical Aspects of Freezing Cold Injury.)

In 1962, Clark and Jones[33] trained subjects for 3 weeks on a standard manual task in either a hands-cold training condition or a hands-warm training condition, and later assessed the subjects' abilities to perform this task in the cold. One day of cold-hands training reduced significantly the size of the performance decrement usually associated with cold exposure, but continued cold experience did not. Skill level on the task was not reported to interact with the cold-induced performance decrement.

Much further work should be done in this area, although these preliminary studies appear to indicate at least some beneficial effects of cold-climate training on manual skills. Yet to be adequately addressed is the issue of cold-weather training on those tasks that appear to be vulnerable to distractions, effects that are attributable to the cold. If there is a substantial distraction effect due to cold stress, this distraction should be attenuated by previous cold exposures, acclimatization, or both. Also as yet inadequately addressed is whether phased training is beneficial to combined training in attempting to reduce performance decrements in the cold. Phased training refers to training on a task in the absence of a stressor (in this case, the cold) and retraining that same task in the presence of the stressor, versus combined training in which the task is initially learned in that stress environment in which it is likely to be performed. The available literature in the field of psychological stress effects suggests that there may be no measurable differences between the two types of training in terms of stress coping,[102] but this possibility should be empirically tested in cold-stress training environments. The only evidence in this regard was the observation by Clark and Jones[33] in 1962 that whether a subject initially practiced a manual task with cold hands or warm hands, a switch to the alternate condition led to an initial performance decrement, suggesting a component of state-dependent learning. This effect was not observed, however, in subsequent studies by Enander in 1986.[103]

PRACTICAL APPLICATIONS AND MILITARY CONSIDERATIONS

The performance decrements following cold exposure that have been demonstrated in controlled laboratory environments have important implications for personnel in the field as well. In some circumstances, cold-induced decreases in performance can lead to significant impairments in mission-critical tasks, putting both cold-affected individual and the group at risk. The following are practical suggestions for military operations in the cold.

- Loss of hand dexterity and loss of tactile sensitivity in extreme cold can lead to measurable loss of feedback as to what the hands are doing if tasks are done without adequate visual inspection (eg, tasks performed in the dark or in very low light conditions requiring the manipulation of switches, buttons, or component parts or repair tasks done primarily by feel). Individuals may need the provision of aids that may not have been needed in temperate environments, such as extra lighting via flashlights or penlights, additional inspection mirrors, the use of glow tape or luminescent dots, adaptation of unimanual tasks to become bimanual tasks, or the provision of special tools. Tasks traditionally done by touch, such as some calibration tasks, may need to be done by visual inspection or by the use of specialized tools.
- Attempting to keep the hands as warm as possible to minimize changes in hand dex-

terity and tactile sensitivity raises the problem of bulky gloves, which decrease dexterity but may retain hand heat, versus thinner gloves or bare hand performance, which may initially preserve dexterity until the fingers become numb, at which point dexterity decreases. This dual need for warmth and dexterity may require task-specific gloving or electrically heated gloving to decrease bulk, suggesting the need for specialized clothing issue for individuals with mission-critical cold weather tasks. Ergonomic redesign of controls may be required to allow gloves-on task performance, and metal surfaces of controls and tools that contact the hand may need to be covered with plastic or rubber to decrease heat conductivity and decrease heat loss from the hands.

- Ironically, problems also result from gloves that are too warm (or clothing that is too warm), especially following exercise or work that generates sweat, which creates faster recooling rates due to evaporation and increases the risk of freezing or nonfreezing cold injury. This may require a rethinking of customary work-rest cycles to avoid excess heat generation, combined with layered clothing or the use of "clothing systems" that will allow the rapid adding or subtracting of clothing layers in response to changes in ambient temperature and activity level. The military should pay close attention to gloving design, especially the use of absorbent inner-gloving liners to wick away moisture and breathable outer microfilament fabric to allow moisture to leave the interior of the glove but also accommodate a relative vapor barrier to impede moisture from the outside. There may also be a supply need for additional issue of multiple pairs of gloves for troops in the field to avoid having individuals with wet gloves. These same considerations would apply to socks, boots, and to a lesser extent, outerwear. Ideally, some provision would be made for the rapid drying of garments in the field as well, although some of the quicker-drying microfilament fabrics may make this concern moot.
- Weapons tracking systems that are hydraulically controlled will have increased damping in extreme cold and operate at different rates than those that operators are accustomed to, causing potential performance decrements. At extreme temperatures, oils and lubricants may become less efficient and more viscous, causing binding of component parts and consequently a lag between initiating a task and the response of the component equipment. The same is true for cabled control and flight surfaces, which may cause systems to respond at different (and sometimes varying) rates. Combined with potential manual dexterity decrements and decrements in vigilance, increased operator errors may ensue. These types of operator errors may be minimized with training in similarly cold environments or, when practical, local heating of component parts.
- Component mission tasks may need to be divided into either subtasks that can be performed by individuals working shorter periods of time and pausing to rewarm their hands, entire body, or both, or by assigning tasks to teams and consistently rotating warm troops from warm shelters to cold work sites. This requires a recognition that some tasks that may be easily accomplished in temperate environments by a single individual (such as equipment repair tasks or the operation of some weapons systems) may take much longer in extreme cold or be accomplished with greater errors and potential injury. This may require the sort of cross-training of individuals on multiple tasks familiar to those in special operations so that task-switching can occur in extreme cold environments, rather than training individuals on a small number of very specialized tasks.
- Decreases in hand strength in extreme cold environments, coupled with sometimes balky mechanical controls, may require the ergonomic redesign of specialized tools to increase leverage, specialized pretraining to increase hand strength, or the redesign of controls or tasks (eg, local heating of controls via circulating hot air, heated shelters for operators, and heat coils or heated shelters for equipment, if practical).
- Impairment in vigilance at extreme cold temperatures suggests the need for much more frequent changes of sentries and sailors on watch if not sheltered from the elements than would be expected in temperate climates. This would also hold true for

divers, and suggests the need for shortened dive times in cold water missions when practical. In like manner, the available evidence of possible decrements in memory recall following cold water immersion suggests the need for either briefer exposure times or the use of written notes taken at the time or direct, on-line communication.

SUMMARY

In an attempt to provide guidance in framing reasonable performance expectations for military personnel, this chapter reviews the scientific evidence for decrements in human performance that are expectable in mild, moderate, and extreme cold environments. In addition, areas are highlighted where additional training or pretraining may prove beneficial, including the possible role of acclimatization as a method of attenuating performance decrements. Finally, some attention is drawn to possible central nervous system correlates or determinants of decreased performance in the cold.

The effects of deep body cooling on overt behavior are similar to the effects of general anesthesia. Levels of consciousness and alertness gradually decrease as body temperature drops toward 30°C. Responses become slow and reflexes sluggish; speech becomes slurred and increasingly difficult. Mobility is impaired, and individuals often become drowsy or apathetic. Some evidence suggests a degree of impairment in memory registration beginning at a core temperature of 36.7°C. Concentration becomes increasingly impaired, although at early states of hypothermia (core temperatures of 34°C–35°C) the impairment appears to be in speed of mental operations rather than accuracy. Lowered core temperature also slows the performance of complex calculation tasks, and it probably slows performance of reasoning tasks, as well. As the body cools further, individuals may become increasingly confused and even incoherent as hypothermia progresses below 34°C or 35°C. Voluntary movements gradually become slower, and a simple movement such as touching the nose may take an individual 15 to 30 seconds as his core temperature decreases to near 30°C. Muscle rigidity is often striking at this point, making it difficult to extend the limbs, and is sometimes accompanied by neck stiffness. Gait may become ataxic, and deep tendon reflexes are decreased. Consciousness is usually lost at core temperatures between 32°C and 30°C, although there are some exceptions to this.

One factor that might account for slower performance by extremely cold or hypothermic individuals is a direct slowing of synaptic transmission. Local brain cooling first increases and then decreases neural excitability. The effects of cooling appear to be reversible, and the temperature changes needed for reported changes in brain function are one Centigrade degree or less in various areas of the nervous system. Venous blood circulation offers a buffering of rapid brain cooling during hypothermia, and brain–blood temperature gradients appear to be major determinants of fluctuations in brain temperature. The effects of core temperature cooling on cerebral CMRO^2, CBF, and glucose substrates may also at least partially account for the observations of slowed mental processing in hypothermic individuals. In general, the effects of hypothermia on nerve conduction are summarized as follows:

1. progressive slowing of axonal conduction,
2. abolition of synaptic transmission prior to conduction failure (postsynaptic activity is abolished at approximately 20°C, whereas axonal conduction does not fail until temperatures of < 10°C are achieved), and
3. an increased excitability at mild degrees of hypothermia that precedes the subsequent synaptic depression at lower levels of hypothermia.

A number of studies in both cold air and cold water have demonstrated substantial decrements in manual performance following cold stress, the magnitude of which appears to be a function of both surface cooling and, with prolonged exposures, deep body cooling. When the whole body is cooled, there is likely a local effect at the periphery involving direct interference of sensory-motor functioning, and a general effect influencing higher centers of the central nervous system that serve to control, direct, and coordinate action.

At extreme cold temperatures, loss of sensitivity and manipulative ability is amplified by heavy protective garments worn to buffer heat loss. This decrease in manual performance is further compromised by loss of flexibility in the muscles of the forearm and finger, increase in muscle viscosity of the extensors and flexors of the fingers, and difficulty in bending joints because of increased viscosity in the synovial fluid. A number of studies have identified skin or extremity temperature as the relevant variable that predicts impairment in manual dexterity and tactile sensitivity. Available evidence suggests that the relationship between skin temperature and numbness follows and L-shaped distribution, with relatively little impairment in sensitivity and performance at skin temperatures above 8°C but a very rapid drop-off in performance below an approximate threshold temperature of 6°C to 8°C. The pain threshold for a cold stimulus is also in this range, about 10°C in all but the most highly acclimatized subjects. Substantial errors in dexterity occur at hand-skin temperatures at and below 13°C. A greater decrement of performance occurs when subjects' hands are cooled slowly, as opposed to quickly; a sizable decrement in performance persists even after rewarming in subjects who are cooled slowly; and the rate of rewarming is directly related to the rate of cooling.

The available evidence suggests that cold exposure—particularly cold water exposure—causes substantial decrements in hand strength and impairs the ability to sustain a submaximal upper-extremity muscle contraction. The available evidence, however, suggests some likely decrements in motor speed with significant cold exposure.

Although cold exposure clearly affects vigilance, substantial vigilance decrements are likely to occur only during dynamic shifts in core body temperature and are not likely to occur at steady state temperatures, suggesting that fully acclimatized subjects would be unlikely to exhibit vigilance decrements even at very cold ambient temperatures. Investigations completed thus far suggest (1) minimal decrements in simple reaction time except in the most extreme conditions, but (2) marked changes in more complex reaction time tasks. On computerized tracking tests completed during mild cold exposure, recent work has demonstrated significant increases in the number of errors, the speed of incorrect responses, and the number of false alarms. These effects, however, are only obtained when tests were constructed that required continuous rapid, accurate responding, with minimal opportunity available to inhibit error responses.

The fact that extreme cold stress can induce confusion and impaired consciousness has been known for some time, and a series of studies has examined the effects of both cold water immersion and pronounced cold stress on memory and memory registration. Decrements have been observed in divers' abilities to recall material learned underwater, impairment in the recall of short paragraphs, and delayed matching to sample visual memory. The available evidence in the area of complex cognitive functioning suggests that decrements in cognitive functioning owing to cold stress are, for the most part, directly related to task complexity.

Finally, individuals who are rapidly cooled in cold water may have considerable difficulty separating feelings of pain and discomfort from feelings of cold, which could have serious consequences in cold weather survival situations and demonstrates the somewhat subjective and variable nature of cold perception.

Preliminary studies appear to indicate at least some beneficial effects of cold climate training on manual skills. Yet to be adequately addressed is the issue of whether cold weather training has an effect on the tasks that appear to be vulnerable to distraction that is attributable to the cold. If there is a substantial distraction effect due to cold stress, then this distraction should be attenuated by previous cold exposures or acclimatization, or both. Also as yet inadequately addressed is whether phased training is beneficial to combined training in attempting to reduce performance decrements in the cold. Some practical advice is offered relative to minimizing the effects of cold in the field.

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