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TEMPERATURE-INDUCED CHANGES IN NEUROMUSCULAR FUNCTION: CENTRAL AND PERIPHERAL MECHANISMS[1]

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Summary.—Three series of experimental tests were conducted on subjects under both elevated and depressed thermal conditions. Tripartite series consisted of whole-body immersion excepting the head, whole-body immersion excepting the head and response limb, and immersion of the discrete-response limb. Measures of physiological and behavioural responses were made at sequential .4°C changes during whole-body immersions and approximately 5°C changes of water temperature during the immersion of a limb only. Results suggested that velocity of nerve conduction decreased with thermal depression. Premotor, motor, simple, and choice reaction times varied differentially as a function of the hot and cold conditions. Implications of these differential effects on neuromuscular function are examined with respect to person-machine performance in artificially induced or naturally occurring extremes of ambient temperature.

The human operator is exposed periodically to non-optimal work conditions and on such occasions impinging environmental stressors can radically alter performance capability. Among the most frequently occurring and disruptive stressors are extremes of ambient temperature. Perturbations from normative or comfortable thermal values may be due to geographical location or the artificially generated by-product of manufacturing or storage processes. Depending upon their severity, such extremes may induce variation in either the peripheral or peripheral and deep body temperature of the exposed individual. While the physiological effects and potential thermal health hazards have been fairly well documented, concomitant variation in cognitive and psychomotor performance has remained a largely confused area of investigation. Recently, empirical analyses of these latter effects have been reported, with particular reference to efficiency in person-machine systems (Aird, Webb, & Hoare, 1983; Hancock & Dirkin, 1982). The present paper seeks to extend such research and reports variation of neuromuscular performance under systematically driven increments of both temperature elevation and depression.

The effect of temperature upon simple neuromuscular abilities may be dichotomized into central (CNS) and peripheral (limb) components. The central element includes capacities such as signal detection, information processing, and response selection. Increases in CNS temperature results in enhanced brain blood flow, higher velocity of nerve conduction (CV), and elevated metabolic activity. Moderate changes in CNS temperature are accom-

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panied by heightened behavioural arousal which has been suggested as the mediational process involved in performance enhancement under such thermal conditions (Poulton, 1976). Further deviations from normal CNS temperature require thermoregulatory action, and this process has been postulated as demanding attentional resources. Consequently, less resources are available in thermal extremes for task performance and the capability of the individual suffers (Bell, 1981; Moray, 1967).

The peripheral component of a response mechanism is composed of motor neurons, the neuromuscular junction, and characteristics of the muscle, tendons, and joints of the biokinetic links utilized for action. Velocity of nerve conduction varies as a function of temperature above the blocking threshold noted in the range of 5 to 10°C (Paintal, 1973). In addition to changes in peripheral neural transmission, differences in limb temperature affect components of muscle and associated structures.

The effects of such variation in temperature on components of simple neuromuscular function should be manifest in measureable changes in tasks such as simple and choice reaction time (RT) and movement time (MT). However, because previous research has been of a piecemeal nature, no over-all pattern of results has emerged. Many studies have reported facilitation (Kleitman, Titelbaum, & Feiveson, 1938; Lovingood, Blyth, Peacock, & Lindsay, 1967), decrement (Fraser & Jackson, 1955; Shvartz, Meroz, Mechtinger, & Birnfeld, 1976), and no change (Peacock, 1956) in performance. These rather diverse results are not due simply to experimental error. Rather, they reflect certain complex interactions between differing aspects of an individual, the specific RT task, and the operational environment. In addition, many studies have confounded both temperature and performance variables, making viable cross-study comparison an arduous task. One of the most imporant omissions from many investigations has been the recording of peripheral and core-body temperature changes of the active human respondent.

In consequence, the present study employed an indwelling thermocouple to measure limb temperature as well as temperature at the rectal and tympanic site to index changes in central temperature. In contrast to previous research which has taken limited observations at operator temperatures governed by environmental conditions, the present work utilized a regime whereby observations were taken at increments of deep and peripheral body temperatures across a wide range of the continuum of supportable thermal levels. Four hypotheses concerning performance in such manipulations were advanced. They were first, that either small increases or decreases in core temperature would result in decreased RT and choice RT due to elevated arousal. Second, large changes (greater than 1°C) would be associated with increased premotor and total RT due to the competition for attentional resources from thermoregulation resulting from the stressor. Third, nerve CV will vary with temperature of the response limb and finally, under elevation of limb temperature, motor RT will decrease, while an increase in motor RT will follow limb cooling.

METHOD

Subjects

Two right-handed adult male subjects aged 27 and 30 yr. volunteered to participate in the study.

Design

Subjects were exposed to three experimental manipulations in both hot and cold water. First, whole-body immersion (A_iB_i, arm in, body in) in a water-filled tub. Second, whole-body immersion except the right arm (A_oB_i, arm out, body in), and finally, immersion of the right arm only (A_iB_o). Each subject had a unique order for the six different immersions, which were carried out over a 2-wk. period. This resulted in a 2 × 3 (temperature by type of immersion) repeated-measures design. Five pilot immersions were necessary to determine the relationship between rate of change of body temperature and water temperature necessary to cause such a change.

Procedure

All procedures took place at the Environmental Physiology Unit, Simon Fraser University. Subjects, clothed only in swimming trunks, were instrumented in a pre-experimental room, where ambient temperature ranged from 20 to 22°C. In whole-body immersions, the subject sat in a cedar tub 121 cm in depth, which was water-filled to a level of 100 cm. In the first condition (A_iB_i), the whole body was immersed to neck level. In the second condition (A_oB_i) the response arm was not immersed but remained outside the tub and was maintained at pre-immersion temperature by the use of a warm or cool cloth. Discrete-limb immersion (A_iB_o) was achieved in a ceramic coated steel sink with a depth of 21 cm.

During whole-body immersion (A_iB_i), physiological and behavioural measures were taken at 0.4°C increments of deep body temperature as recorded at the rectal site. When the limb only was immersed (A_iB_i), measures were taken at every 4°C change in warming and every 5°C change in cooling (49°C maximum and 12°C minimum). The following measurements were taken in all conditions: temperatures (rectal, tympanic, muscle, skin, and water), reaction time, movement time, and heart rate. In addition, nerve CV was measured both pre- and post-immersion. Rectal temperature was recorded from a YSI thermistor inserted 15 cm past the anal sphincter and tympanic temperature was recorded from a tympanic thermistor positioned alongside the tympanum. Intramuscular temperature was taken by a wire thermocouple inserted to a depth of 12 mm beside the extensor digitorum longus in the forearm of the response limb, while skin temperature was derived from a mean of four measures at chest, arm, thigh, and calf (Ramanathan, 1964). Similar measures were elicited in the condition which required immersion of only the discrete limb.

The RT/MT task consisted of response to a visual stimulus by a 35-mm extension movement of the right index finger in both a simple and choice (two alternative) situation. Subjects' hands rested on an aluminum bracket at chest height. The index fingers rested on pressure sensitive switches spaced 60 mm apart. Two light-emitting diodes (LEDs) were positioned at eye level one metre in front of the subject. For simple reaction-time measures 10 trials were recorded. Each trial consisted of an auditory warning stimulus, a random foreperiod (.5 to 1.5 sec.) and the imperative stimulus. In the choice situation, the procedure was similar, however, the right or left LED was randomly presented until 10 trials with the right finger were recorded. Movement times were determined by the closure of a microswitch by the responding finger. In addition, electromyographic recordings were taken for each reaction time trial. Surface electrodes (Beckman Ag-AgCl) were placed over the extensor digitorum, and recorded on FM tape. Subsequent analysis using a microcomputer (A/D at 1000Hz) and custom software allowed for the determination of EMG onset. This allowed for the determination of the subcomponents of the response (Weiss, 1966), namely, pre-motor reaction time (defined as time from onset of stimulus to onset of EMG activity) and motor reaction time (onset of EMG to initiation of movement). Measures of premotor and motor reaction time were taken at each of the measurement intervals defined above.

For the measure of velocity of nerve conduction (CV), stimulation was applied to the ulnar nerve at the wrist (styloid process) and elbow (proximal to the internal humeral condyle). The action potential of the adductor pollicus was observed on a storage oscilloscope. Electromyographic (EMG) recordings from adductor pollicus were utilized for this measure.

RESULTS

Physiological Measures

Deep body temperatures followed patterns typically expected in cold- and hot-water immersion. In the cold condition, a period of inertia in rectal temperature was followed by an approximately linear decrease until termination at the 35°C level. Inertia was less evident in hot immersion where rectal temperature rose progressively to the 39°C termination level. The alternate measure of deep-body temperature at the tympanic site followed this general pattern but exhibited slightly higher absolute values and contained an apparent lag with respect to the rectal measure during cold immersions. Similarly, during hot immersions, tympanic temperature exceeded rectal temperature. In immersions of a discrete limb, there was no change in either of the measures of deep-body temperature.

Skin temperature also followed an expected pattern, whereby during whole-body immersions average skin temperature rapidly stabilized to within 1 to 2°C of the water temperature. There was agreement between the four skin-temperature sites, all values within 1.0°C. As might be expected, intramuscular temperature also tended to approach water temperature in both the hot and cold conditions. However, this tendency was less marked than that for skin temperature but more pronounced than the pattern for core-body temperature. In the immersion of a discrete limb in all cases save one, there were no noticeable differences in either core or skin temperature at the various sites. Intramuscular temperature of the immersed limb followed the temperature of the water with approximately a 2°C lag.

Although some difficulties were encountered in measuring heart rate, the pattern for each individual was fairly consistent. Heart rate was responsive to hot immersion, averaging 50 to 60 beats higher at the end of the exposure compared to pre-immersion levels. In cold exposures, heart rate increased initially,

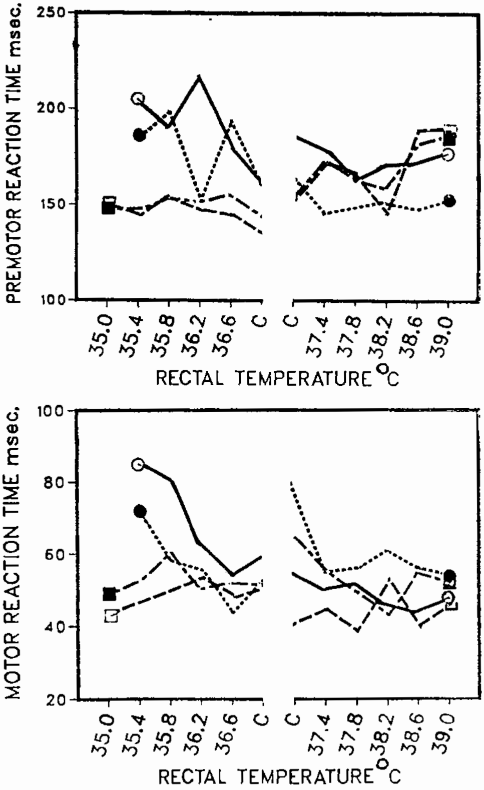

FIG. 1. Simple premotor and motor reaction times for the body in conditions as a function of rectal temperature: ● A_1B_1—S1, ○ A_1B_1—S2, □ A_0B_1—S1, ■ A_0B_1—S2

approximately 10 beats per minute and returned toward pre-immersion levels as rectal temperature was reduced below 36°C. Velocity of nerve conduction was measured at the pre- and post-immersion stages. Pre-immersion values averaged 50 m/sec., although there was a relatively large range (38 to 88 m/sec.) across a relatively small range of limb-temperature values. Post-immersion CVs were obtained for a much larger range of limb temperatures. In the cold exposure, intramuscular temperature varied between 15 and 17°C with a mean CV of 44 m/sec., while in the hot condition values ranged from 40 to 45°C and a mean CV of 54 m/sec. The relationship obtained is much less pronounced than might be expected from previous research. However, there was a general tendency for velocity of nerve conduction to decrease as limb temperature was reduced.

Behavioural Measures

Premotor and motor RT in both the simple and choice situations are

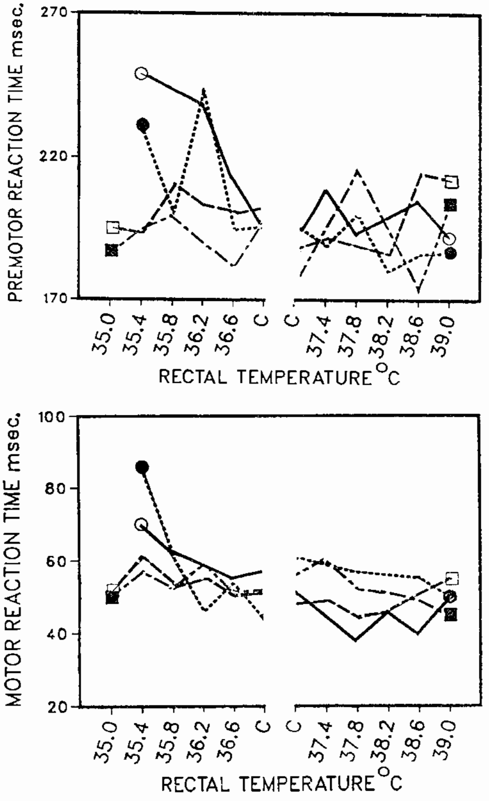

FIG. 2. Choice premotor and motor reaction times for the body in conditions as a function of rectal temperature: ● A_1B_1—S1, ○ A_1B_1—S2, □ A_0B_1—S1, ■ A_0B_1—S2

illustrated in Figs. 1 and 2.[2,3] These indicated differential effects for the hot and cold conditions when the body was immersed. In general, premotor RT remained constant in the hot conditions as core-body temperature increased. In the cold conditions, however, premotor RT increased markedly as core-body temperature decreased only when a limb was immersed. When the limb was kept at a normal temperature of 34°C, premotor RT did not change (see Fig. 1). Motor RT exhibited similar effects. In particular, during heated body conditions, motor RT decreased slightly when the arm was immersed and remained constant with the arm at normal temperature. Similarly, no change in motor RT was found with cooling when the arm was not immersed. However, cooling the limb greatly increased motor RT (see Fig. 2).

When the body was immersed, changes in total RT for both simple and choice measures were dependent on limb immersion and temperature. The same effect was exhibited in MT. In cold immersions, RT increased with

TABLE 1

REACTION AND MOVEMENT TIMES FOR BODY-IMMERSED CONDITIONS

Condition	Temp(r)	Simple RT	Simple MT	Choice RT	Choice MT
Hot Arm In Body In	Control	240	55	250	61
	37.4	216	50	251	49
	37.8	211	44	245	48
	38.2	215	43	241	46
	38.6	210	44	243	43
	39.0	216	42	240	43
Hot Arm Out Body In	Control	208	59	234	59
	37.4	223	55	249	60
	37.8	209	58	250	55
	38.2	200	58	239	54
	38.6	234	51	245	50
	39.0	236	50	258	57
Cold Arm In Body In	Control	213	56	246	55
	36.6	237	67	259	78
	36.2	244	94	294	88
	35.8	265	79	283	97
	35.4	275	128	318	128
Cold Arm Out Body In	Control	190	58	251	53
	36.6	200	56	242	55
	36.2	202	53	253	54
	35.8	209	50	257	52
	35.4	196	60	253	59
	35.0	195	60	242	51

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[2] Due to mechanical failure, FM tape recordings of the 35.0°C Arm in, Body in condition were unavailable for analysis.

[3] One of the subjects, on immersion of the limb in the 48°C water broke into a profuse sweat, and skin temperature at all sites rose approximately 1.5°C.

core-body temperature when the limb was cooled because changes occurred in motor RT. Time to complete the movement (MT) also increased as temperature decreased when the limb was immersed (see Table 1).

For immersions of a limb only, the results for premotor and motor RT were quite similar to those for the conditions of body immersion. When the limb only was cooled, premotor RT decreased with the fastest times at the peak of thermoreceptor sensitivity (20-25°C). Motor RT, however, increased as the limb was cooled. When the limb was heated, premotor RT remained constant while motor RT decreased. In general, the results of heating and cooling the limb only showed that task performance is often largely a consequence of peripheral function.

DISCUSSION

The physiological reactions of the individuals in the present study are highly consistent with previously observed reactions in similar circumstances (Hardy, Gagge, & Stolwijk, 1971). In cold-water exposures, inertia of core-temperature was augmented by vasoconstriction and shivering thermogenesis to offset heat loss to the surrounding liquid. This was slowly overcome and core temperature gradually decreased with progressive exposure. In hot-water exposures, heat was progressively stored by the body despite thermoregulatory actions such as peripheral vasodilation and sweating. These latter effects accompany an increase in heart rate as observed in the present work. In total immersion as indicated, the only possible heatsink is the non-immersed head, however, effector action at this location is insufficient to rid the body of heat from the water and core temperature rapidly rises. Skin temperatures tend to asymptote toward the ambient water temperature, while intramuscular temperature exhibits the same tendency but less dramatically due to overlying subcutaneous tissue.

Velocity of nerve conduction appeared to decrease as muscle temperature was depressed. This followed the general hypothesis. However, at elevated limb temperatures this tendency was less obvious. Such equivocality questions the validity of the measurement technique applied to the ulnar nerve or alternatively suggests readings from the thermocouple inserted in the extensor digitorum longus were not truly reflective of ulnar nerve temperature. In either case this indicates the necessity to pursue more elegant measures of velocity of nerve conduction *in vivo* during such thermal variations.

The general tendency of reaction time and movement time suggest that an intricate relationship between central and peripheral temperatures and performance exist. Previous accounts of such results with the body immersed and the limb at normal temperatures for premotor RT suggest that there is no competition for attentional resources from thermoregulation. However, when the limb and body are immersed, attention is directed toward thermoregulation as evidenced by the increase in premotor RT. Increments and decrements in simple and choice RT are also elicited with immersions of limb only. If the arm is heated, RT decreases as intramuscular temperature rises because there is decrement in motor RT. In contrast to heating, cooling the limb causes an increase in RT with an increment of premotor RT. Accurate description of behavioural changes to temperature stress can only be achieved by examining both the central and peripheral components of a response.

In sum, the present study extends some recent work (Aird, Webb, & Hoare, 1983; Hancock & Dirkin, 1982), which has begun to examine performance variation in more controlled circumstances. The experiments reported provide a method for the examination of task performance through a systematic change in temperatures, with peripheral and deep-body temperature independently manipulated (Hancock, 1983). Measurement of behavioural responses at systematic changes of such temperature provided information regarding the contribution of central and peripheral temperatures to performance variation. These results are important to those concerned about the design and use of complex systems in which the human operator is vulnerable to the effects of the thermal environment which induces change in either deep and/or peripheral body temperature.

REFERENCES

AIRD, J. W., WEBB, R. D. G., & HOARE, J. Heat exposure-induced changes in motor outflow component of reaction time. *Perceptual and Motor Skills*, 1983, 56, 699-706.

BELL, P. A. Physiological, comfort, performance, and social effects of heat stress. *Journal of Social Issues*, 1981, 37, 71-93.

FRASER, D. C., & JACKSON, K. F. Effect of heat stress on serial reaction time in man. *Nature*, 1955, 176, 976-977.

HANCOCK, P. A. The effect of an induced selective increase in head temperature upon performance of a simple mental task. *Human Factors*, 1983, 25, 441-448.

HANCOCK, P. A., & DIRKIN, G. R. Central and peripheral visual choice-reaction time under conditions of induced cortical hyperthermia. *Perceptual and Motor Skills*, 1982, 54, 395-402.

HARDY, J. D., GAGGE, A. P., & STOLWIJK, J. A. J. *Physiological and behavioral temperature regulation.* Springfield, IL: Thomas, 1971.

KERSLAKE, D. M. K. *The stress of hot environments.* Cambridge: Cambridge Univer. Press, 1970.

KLEITMAN, N., TITELBAUM, S., & FEIVESON, P. The effect of body temperature on reaction time. *American Journal of Physiology*, 1938, 121, 495-501.

LOVINGOOD, B. W., BLYTH, C. S., PEACOCK, W. H., & LINDSAY, R. B. Effects of d-amphetamine sulfate, caffeine, and high temperature on human performance. *Research Quarterly*, 1967, 38, 64-71.

MORAY, N. Where is capacity limited? survey and model. *Acta Psychologica*, 1967, 27, 84-92.

PAINTAL, A. S. Conduction in mammalian nerve fibres. In J. E. Desmedt (Ed.) *New developments in electromyography and clinical neurophysiology.* Basel, Switzerland: Karger, 1973. Pp. 19-41.

PEACOCK, L. J. A field study of rifle aiming steadiness in serial reaction performance as affected by thermal stress and activity. *Army Medical Research Laboratory Report*, No. 231, Fort Knox, KY, 1956.

POULTON, E. C. Arousing environmental stresses can improve performance—whatever people say. *Aviation, Space and Environmental Medicine*, 1976, 47, 1193-1204.

PROVINS, K. A., GLENCROSS, D. J., & COOPER, C. J. Thermal stress and arousal. *Ergonomics*, 1973, 16, 623-631.

RAMANATHAN, N. C. A new weighting system for mean surface temperature of the human body. *Journal of Applied Physiology*, 1964, 19, 531-533.

SHVARTZ, E., MEROZ, A., MECHTINGER, A., & BIRNFELD, H. Simple reaction time during exercise, heat exposure, and heat acclimation. *Aviation, Space and Environmental Medicine*, 1976, 47, 1168-1170.

WEISS, A. D. Premotor and motor components of reaction time. *Journal of Experimental Psychology*, 1966, 71, 9-15.

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