

Effects of thermal stress on human performance

by Ann E Enander, PhD¹

ENANDER AE. Effects of thermal stress on human performance. *Scand J Work Environ Health* 1989;15(suppl 1):27—33. Experimental evidence indicates that even relatively mild thermal stress may affect human performance. Tasks requiring manual dexterity and muscular strength are clearly impaired by cold exposure, while decrements in vigilance performance and endurance are well documented effects of heat stress. The considerable variation in results regarding the effects of thermal stress may, to some extent, be attributable to complex interactions between exposure conditions, task characteristics, and individual factors. In the present paper the relevance of some of the earlier research work on heat and cold stress is evaluated in the light of the practical and theoretical implications of more recent findings. Current work regarding the nature and extent of the effects of thermal stress on more complex performance is discussed. Attention is also focused on the significance of individual skill and training experience for performance under unfavorable conditions.

Key terms: cold, heat, manual performance, mental performance, physiological reactions, skill, training, vigilance.

Despite advances in technology and protective equipment, people are still required to carry out a wide range of activities under different forms of thermal stress, often in combination with other stressors such as, eg, noise. While the limits of endurance are seldom put to the test in the work environment today, thermal stress can be linked to a wide variety of unfavorable effects, including an increase in unsafe work behavior (1).

Performance measures have increasingly come to be applied in evaluating the effects of environmental stress from both physical and chemical agents (2). The significance of effects on performance can be discussed in a number of different terms, for example, as factors affecting productivity, as potential safety hazards, as factors increasing the physical or subjective cost of effort, or as indicators of a biological effect with possible longer-term consequences for health.

With a historical perspective of the research on thermal stress, it is possible to discern an ebb and flow of work around certain issues. These concentration areas reflect a pragmatic approach to resolving questions of practical importance in applied situations, and the theoretical development has held a lower profile. The unsystematic nature of the work has also created problems in interpreting the results, a fact which has been commented on by several reviewers (3—5). Differences in the methodology used, the definition of thermal stress, and performance measures have contributed to this confusion.

Nevertheless, in more recent work it is possible to discern a phase which might be characterized as one

of reevaluation. There appears to be a revival of interest in some of the stagnated issues regarding the performance effects of thermal stress, and this revival is providing a fresh impetus both in theoretical discussions and in practical applications. One such approach can be noted in the application of theoretical developments from adjacent fields of environmental stress research. This phenomenon can be exemplified by the current reevaluation and discussion of the arousal theory. During one period individual differences were mainly regarded as an unfortunate confounding factor. There now appears to be an increased interest in these differences, particularly in relation to skill, experience, and training.

It is the purpose of this paper to discuss some of the basic issues regarding research on performance during exposure to thermal stress and to consider the current view of effects of cold and heat from the perspective of more recent developments.

How are performance effects related to thermal stress?

One of the basic problems in this research area is that of establishing a relevant measure of thermal stress to which performance effects can be related. Exposure to thermal stress has, for example, been achieved by means of varying air temperature, wind speeds, or physical work or of submerging the body in cold or warm water. The pattern of physiological reactions differs according to the means applied and makes a comparison of the results obtained in different studies difficult. While an environmental stressor such as a noise, defined in physical terms, can at least be regarded as an equivalent stimulus in different studies, situations, and groups of people of normal hearing, the same cannot be said of a certain thermal environ-

¹ Swedish Defence Research Establishment, Karlstad, Sweden.

Reprint requests to: Dr AE Enander, Swedish Defence Research Establishment, FOA 55, Karolinen, S-651 80 Karlstad, Sweden.

ment. The impact of a thermal environment may, for example, vary according to a number of individual characteristics of the subjects, such as age, sex, fitness, etc. Physiological measures provide a more accurate indication of the thermal stress on the individual. Some physical and motor performance criteria appear to be relatively well related to physiological changes. The temperature of the hands, for example, is clearly a limiting factor in the performance of manual tasks in the cold (5, 6).

It has proved more difficult to establish relationships between physiological measures of thermal stress and mental performance. This situation is hardly surprising, since performance on more complex cognitive tasks is the result of an integration of physiological reactions, physical and mental capabilities, and subjective assessments. Thus, while it is, for example, clear that heat stress affects the level of performance on tasks requiring vigilance and sustained attention, the exact nature of the effects has been difficult to ascertain. Although early work indicated a pattern of decrement, later studies have also demonstrated little change (7) or even improvement (8, 9) in performance. A survey of these varied results can be found in a number of reviews on the effects of heat (3, 10, 11). In contrast, the effects of cold on complex mental tasks have received less attention. This lack of interest has variously been attributed to the fact that technology and protective devices have rendered such effects of academic rather than practical significance or that effects of cold may be dismissed as being negligible under less drastic cooling conditions or possibly attributable largely to confounding between mental and manual effects (3, 12).

Two main theoretical approaches have traditionally been favored to explain the effects of thermal stress on complex performance. The classic inverted-U arousal theory hypothesizes an optimal level of arousal for performance of a certain type of task. In principle, a simple task may be facilitated by an increase in arousal, while the optimal level of arousal is lower if the nature of the task is more demanding. An environmental stressor which is hypothesized to increase the level of arousal could be expected to facilitate performance on, eg, vigilance tasks, while causing decrements on more complex tasks. However, in order to accommodate the varied effects of stress on performance, an increasingly elaborate interaction between individual characteristics, task properties, and arousal patterns has been hypothesized (8). While this line of reasoning has significantly contributed to the comprehension of the nature of stress effects, in particular their ability also to improve performance, the serious limitations of indiscriminately using arousal explanations have recently been pointed out by several authors [eg, Bell & Greene (3) and Hockey & Hamilton (13)].

The traditional alternative theory involves the concept of the stressor as a distractor. An early hypothesis (14) proposed that performance is affected nega-

tively when attention is directed away from the task by distracting environmental stimuli. Clearly this theory also encounters difficulties, eg, in explaining an improvement in performance under stress.

More recently there have been developments which may help break the circularity of the arousal-distraction discussion. One is the increased use of more sensitive test and analysis methods that enable researchers to study not only increments and decrements in one total performance measure, but also more subtle changes in, eg, performance strategy. There has also been a shift in emphasis towards describing performance effects in terms of patterns of bodily and cognitive changes rather than in terms of unidimensional arousal-distraction patterns. The development of this approach has been extensively discussed by Hockey & Hamilton (13) as applied to different stress states, such as noise, monotony, etc. In this connection Hockey & Hamilton point out the ambiguity of the heat stress state and do not enter into any discussion of the possible cold stress state. It is beyond the scope of this paper, or indeed of the status of present research results, to fill this gap. The following brief look at recent work does however indicate (i) that effects of cold stress on complex performance, while elusive, may not be negligible and (ii) that a more comprehensive view of the effects of heat is emerging.

Performance during cold exposure

The general effect of cold on the performance of physical and motor tasks is one of impairment. A reduction in core body temperature and muscle temperature generally reduces physical function in a number of ways, eg, muscle strength, duration of exercise, etc (12, 15). The specific effects of cold on the functioning of the hands has been the subject of particular interest. This focus reflects the widely documented problems encountered in attempts to protect the hands from cooling while maintaining unimpaired dexterity (16). Early work indicated that it is the temperature of the hands which is critical for manual performance (17, 18), although severe body cooling and shivering can also affect the performance of some tasks (19, 20). Considerable research has been devoted to establishing the range of temperatures within which performance remains unimpaired. Critical hand and finger skin temperatures have been found for unimpaired tactile sensitivity at 8–10°C (21, 22) and for manual dexterity at skin temperatures of 12–15°C (23, 24).

While the direct relationship between cooling of the hands and a progressive decrement in manual performance is well established, the actual degree of impairment is subject to a number of task and cooling factors. Clearly, tasks involving fine movements of the fingers and hands or the manipulation of small objects are particularly sensitive to the effects of cold (25, 26). Slow cooling, as found in many occupational settings,

is more detrimental to manual performance than rapid cooling to equivalent hand skin temperatures (27, 28). The progressive development of more sensitive techniques of measurement and analysis may tend to result in effects being found at increasingly mild levels of cooling (29, 30).

Research on the effects of cold on more complex tasks has, as has already been pointed out, been meager. A study of shipboard lookouts by Poulton et al (31) is often cited as indicating effects of cold on vigilance, although the interpretation of the results was complicated by confounding wind and rain under the control conditions.

Interest in the effects of cold on complex mental functions has been stimulated by several studies of divers working in cold water. The discussion as to the applicability of these results to other forms of cold exposure being laid aside, this work has shown effects of cold on a number of complex tests (32, 33). Support for the concept of cold as a distractor is found in a study of divers exposed to cool (15.5°C) and cold (4.5°C) water conditions (34). The results from this study showed that performance on two complex tasks was significantly poorer in the cold water only during the first of the 3 h of exposure. During the second and third hours of exposure performance did not differ between the cold and moderate water temperatures, in spite of increasing differences in the degree of physiological cooling between the two conditions. The results during the first hour were attributed to the greater distracting effect of the cold environment, an effect independent of deep body cooling.

Two studies of cold air exposure (35, 36) demonstrated an increase in errors on a serial choice-reaction time test, but no increase in the number of lags registered. Increasing the complexity of the choice in the test (36) led to a relative increase in errors made in the cold. Taken together, the results of these two studies were interpreted in terms of the arousal theory. The increase in errors was hypothesized to result from a change in strategy caused by a cold-induced increase in cortical arousal.

Recent work (37) has demonstrated significant increases in the number of errors, speed of incorrect response, and number of false alarms on two computerized tests during mild cold exposure of a group of women. These effects were only obtained in tests designed to require continuous rapid accurate responding with minimal opportunity to inhibit erroneous reactions. It is interesting to note that an increase in rapid errors on a serial choice-reaction time task was recently reported at lower levels of noise than noted previously. This result was obtained following a task modification to minimize hand movement, and thereby the response latency and the time allowed for correcting erroneous reactions was also decreased (38, 39). An increased number of responses to blank trials during cold exposure, previously noted in flicker-fusion threshold determination (40), may be interpreted as

demonstrating a similar effect of erroneous response. Thus there is evidence that at least one effect in the possible pattern of cold stress might be a decreased ability to inhibit erroneous responses.

Performance during heat exposure

The general relationship between physiological changes in response to heat stress and physical performance is held to be relatively clear and predictable. There is little initial effect on physical strength, but the gradual accumulation of heat in the body during longer and more intense exposures gradually builds up fatigue and a corresponding decrease in endurance. The importance of the time factor is reflected also in the discussion of applicable limits for mental and psychomotor tasks of various kinds (10, 41, 42).

Many of the studies investigating the more complex effects of heat have used tasks involving sustained attention and vigilance. There is evidence of a nonlinear relationship between a rise in body temperature and performance. Mild heat exposure appears to impair performance on vigilance tasks, while further heat stress may induce improvement. For more complex mental tasks the effect is the reverse, initial facilitation followed by impairment. The overall picture is, however, confusing since the effects may vary according to factors such as the duration and severity of exposure, the characteristics of the task, and the characteristics of the individual. A complex pattern of arousal has been proposed to account for these effects, invoking an initial stimulating effect, followed by a sequence of decreased arousal associated with adaptation, increased arousal in response to rising body temperature, and a final decrease as exhaustion is approached (8). In view of the lack of reliable independent measures of arousal this theory, while elegant, is clearly open to criticism in view of its post hoc nature.

Recently Hancock has conducted comprehensive reanalyses of the work on sustained attention under heat stress in relation to body temperature changes (11, 43, 44). He makes a clear distinction between conditions under which body temperature is undergoing a dynamic increase and those under which body temperature is unchanged or established in a static hyperthermic state. According to Hancock's analysis, dynamic temperature change is associated with performance decrement, while subjects in a stable state show no change or even improvement in performance. While emphasizing the descriptive rather than explanatory nature of this relationship, Hancock points out the practical applications if inertial intervals during which body temperature remains stable can be used to calculate safe tolerance periods for tasks requiring sustained attention (44).

One reason for the apparent disparity in results regarding heat stress may lie in the use of the general

term "heat stress" to cover a variety of different stress states. Closer attention to both the level and direction of physiological reactions may help clarify the picture. This approach is also strongly advocated by Allan and his associates (45) on the basis of a series of experiments indicating that direction and rate of change in both core and skin temperatures may be important determinants of performance.

Effects of thermal stress in relation to training and skill

Given that, in some cases, the possibilities of modifying the environment or the task are limited, a central question is whether people can be trained to withstand the negative effects of that environment. While physiological acclimatization to heat is a widely accepted phenomenon and may increase the capacity for physical work, the evidence of a corresponding improvement in psychological performance is ambiguous (9). The position as regards cold exposure is still less clear-cut and has been widely debated. While local acclimatization effects, in the form of increased finger temperature and rapid onset of cold-induced vasodilatation, have been found among habitually cold-exposed subjects (46–49), the relationship between such effects and performance has not always been clear (50). Conversely, while instances of improved manual performance have been demonstrated among subjects familiar with cold exposure, concomitant physiological changes have not necessarily been established (51).

Irrespective of the existence of physiological changes in response to repeated exposure to thermal stress, the general view seems to be that familiarity breeds, if not contempt, then at least competence. This view would seem to imply the concept of the stressor as a distractor. With increased familiarity the impact of distracting stimuli, which divert attention from the task at hand, should decrease.

There are indications that subjects accustomed to cold exposure experience less discomfort than unaccustomed subjects at equivalent skin temperatures. In a study of reactions to local hand cooling (52), meatcutters and office workers were compared with regard to physiological and psychological responses during both cold stimulation and a passive recovery phase. No differences were found between the groups as regards hand skin temperature measurements, but the meatcutters were found to experience significantly less cold and discomfort particularly under the conditions in which room temperature was set at 10°C, the normal work environment temperature of the meatcutters. This result might be interpreted as indicating a decreased impact of situation-specific sensory stimuli among the accustomed workers. Similar results have been obtained in heat exposure (53). However, a direct connection between reduced discomfort and im-

proved performance is not self-evident. Indeed, it might be suggested that a reduction in discomfort with no equivalent reduction in physiological reaction may in fact constitute a hazard as regards decreased sensitivity to significant sensory warning signals.

There is also a general view that practice under thermal stress enables the individual to develop a more adequate behavior pattern. The positive effects of training in the cold are often cited, generally with reference to an early study by Clark & Jones (54). In this study manual performance during cold exposure was studied as a function of the thermal conditions of training. Briefly the results indicated that a change in thermal conditions after a period of practice resulted in a relatively greater decrement in performance, irrespective of the direction of the change. Thus subjects who learned the task under neutral conditions performed worse under cold conditions than subjects who had experienced cold during the practice sessions. The data also indicated that subjects training under cold conditions were inferior to comparison groups when tested under neutral conditions. The authors stressed the importance of varied thermal experience early in training and suggested that the thermal conditions under which a task is performed may become part of the stimulus complex to which the correct manual response is connected over a period of training. Consequently any change in these thermal conditions causes a disruption in performance.

More recently there has been a revival of interest in the possible effects of training on performance. I recently conducted a study of manual performance training in a group of women unfamiliar with manual work or cold exposure (55). The results differed to some extent from those of Clark & Jones, since they do not indicate any advantage of practice under cold conditions for subsequent performance in the cold. Indeed, practice under neutral conditions tended to be more advantageous for a task involving complex manual manipulations, in this case a screw manual dexterity task. It should be noted that in my experiment the group was female and completely untrained, while in the formerly cited study the group was made up of male military personnel, presumably relatively skilled in manual work, who also had some opportunity for practice with warm hands. A recent study (56) of relatively inexperienced male military personnel practicing manual tasks under different thermal conditions also revealed results resembling those of my study. When tested in the cold, the group who had practiced under normal thermal conditions was found to perform somewhat better than the group who had practiced in the cold.

Learning to perform a task in the cold may thus be less advantageous. However, a study of visuomotor performance (57) indicated that cold affects the level of performance rather than learning, since rapid recovery to the expected practice level was found on returning to warm conditions. Differences in the type of task,

or again in level of skill, may contribute to the conflicting evidence. There is little evidence regarding the practice and learning of cognitive tasks in the cold. However, memory registration has been shown to be progressively impaired with decreased core temperature from a level of about 36.7°C, while recall of previously learned data proved highly resistant to effects of lowered body temperature (58). Impaired memory registration may have hazardous consequences, eg, for divers memorizing a safe return route in cold water (58).

The significance of level of skill has been pointed out with regard to the effects of heat on vigilance performance (59, 60). There is evidence that skilled subjects are better able to maintain performance under thermal stress. In his analysis of the conflicting evidence with regard to vigilance performance, Hancock cited two studies in which no effects of heat on performance were found. He pointed out that in both these studies the task was such that highly practiced subjects, as used in these cases, could achieve a high degree of automation in their performance and thereby reduce sensitivity to the effects of environmental stress. However, a study by Wenzel & Ilmarinen (61), of one highly practiced subject exposed to heat, indicates that unimpaired performance may be achieved at the cost of greater effort, as measured by a superelevation in heart rate.

In regard to learning and practice it is interesting to note the work by Poulton & Freeman, who studied transfer effects in experimental studies (62). The authors cited several examples of experiments in which subjects exposed to an experimental stressor perform poorly and then continue to perform poorly in later tests under more optimal conditions. One interpretation may be the adoption of inadequate methods of work under stress, the inadequate methods then persisting even when the stress is relieved. Even if the practical significance of such possible effects cannot at present be assessed, they are certainly of note for the design of repeated measures experiments.

In view of the significant practical applications, it is clearly important that the effects of different practice and training models be clarified. A few tentative conclusions may be drawn from the evidence presented. The effects of practice conditions may differ at different stages in the skill acquisition process. Thus acquiring a certain level of skill under optimal conditions prior to an encounter with adverse conditions may be advantageous during the early stage of learning. This approach has been advocated in connection with other types of psychological stressors (63). Similarly, a high level of practice on some tasks of, eg, sustained attention may promote a performance strategy less amenable to negative influence. Experience of adverse conditions may, however, enable more suitable strategies to be developed at a later stage in the learning process.

Concluding remarks

The ultimate aim of applied research in this area is to reduce the negative effects and possible risks associated with work under thermal stress and to increase effectiveness. Broadly speaking, the thrust of such endeavors can be aimed in two directions, towards the environment and the situation or towards the individual. By improving clothing and protective equipment, redesigning the tasks to be performed and the tools with which to perform them, and using different technical solutions to minimize the impact of the environment, one can create conditions favoring improved performance. Some thermal stress situations will, however, still remain less amenable to the achievements in technology and protective equipment, due, eg, to the unpredictability of the weather and the elements, the conflicting thermal demands of people and the products and processes with which they are working, and economic factors.

A complementary approach is to regard the individual and to consider how the faculties of withstanding the impinging influence of environmental stress can be optimized in a specific situation. Further work on the significance of training and skill is required to clarify how this possibility may be accomplished.

In order to attain genuine improvement in performance under thermal stress, actions must be based on a theoretical understanding of the nature of the effects. Some advances in this direction seem to be under way in providing models which can account for the diverse effects observed. As always, there is a need for more data of a systematic nature. Detailed experimental planning and analysis of the data are also necessary to expose not only the possible increments or decrements in total performance, but also shifts in strategy, transfer effects, and interactions due to individual differences. In this connection noneffects are also of interest when the patterns are established, although it has been observed that such effects may be less likely to be reported (3).

Finally, in interpreting research results, one should perhaps recall that they are often achieved by selected groups of healthy young men who are highly motivated and subject to relatively brief periods of exposure. The everyday occupational situation may differ considerably. While this is hardly an original observation, nor exclusive to the domain of thermal stress, it may bear repeating.

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