

Combined Effects of Heat and Noise on Human Performance: A Review*

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This paper examines the combined effects of heat and noise upon behavioral measures of human performance. Specifically, capabilities on a variety of neuromuscular and mental tasks are reviewed with respect to their vulnerability to joint thermal and acoustic action. The majority of evidence indicates that such stressors do not interact significantly within the ranges experienced commonly in the industrial setting. However, various experimental and methodological inadequacies in the meager data base caution at the present time against a simple interpretation of this apparent insensitivity.

Introduction

Experimentally, the effects of environmental conditions upon human capabilities have been studied most often through the imposition of a single stressor in isolation. Although considerable knowledge has been gained from such research, it is of limited value in an applied industrial setting where multiple sources of stress, which vary in both constitution and severity, act upon the worker. One reason for this lack of combinational studies is that they are expensive in terms of technological facilities⁽¹⁾ and time-consuming with respect to experimental design, where problems of uncontrolled performance transfer across conditions can cloud the interpretation of results.⁽²⁾ Consequently, for practical purposes, the interactions between multiple environmental stressors are often projected rather than derived from direct observation. As there are few theoretical constructs which have been proposed to account for interactive effects, there is only a limited basis from which important combined actions may be inferred.

This paper focuses on the coaction of two stressors which commonly co-occur in the industrial setting: heat and noise. While the individual effects of elevated temperature⁽³⁻⁵⁾ and acoustic level have been well documented,⁽⁶⁻⁸⁾ their combined impact upon performance is much less clear. In the few studies which have investigated heat and noise together, each of synergistic, additive, antagonistic, and negligible interactional effects has been reported.⁽⁹⁻¹²⁾ Understanding these conflicting results depends upon the recognition of differing intrusive factors. Of particular importance is the precise specification of the performance task, whether requiring physical activity, skilled neuromuscular coordination, or simple mental response. Furthermore, the time of exposure, onset order and severity of the respective stressors all exert a powerful influence.⁽¹⁾ In addition to these considerations are the methodological difficulties which beset multiple stress

studies. Among these are problems of asymmetric transfer which are liable to occur when subjects are asked to repeat performance under differing stress conditions.⁽²⁾ Also of concern are the doubtful theoretical foundations upon which many of the studies are based. In the sections which follow, details of individual reports are elaborated, together with the explanatory constructs which have been formed to account for the reported trends.

Experimental Evidence

In previous reviews of research on interactive stressors,^(1,13) it has been projected that four major outcomes are possible. These are: 1) no interactive effect, 2) an additive effect, 3) a greater than additive effect, and 4) a subtractive effect. For

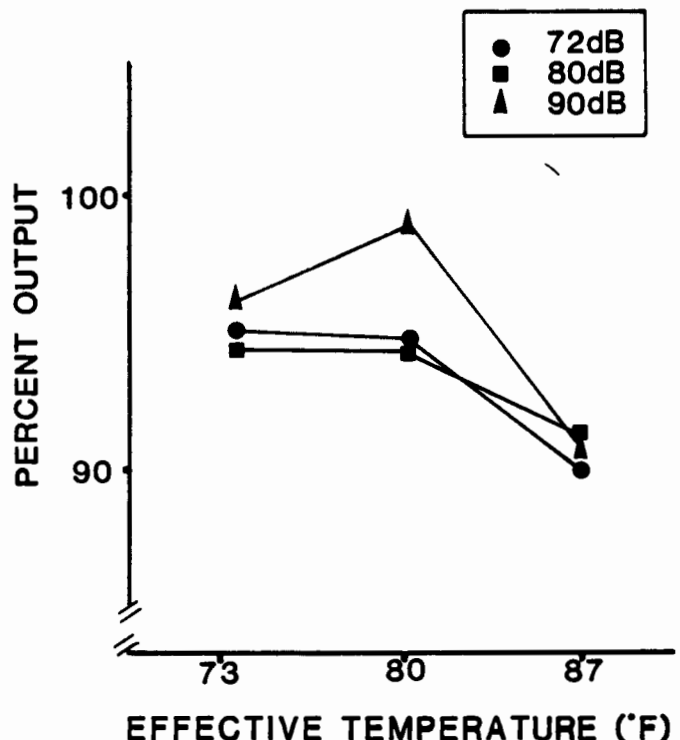


Figure 1—Mean percentage output for seven performance tasks against Effective Temperature and noise conditions.⁽⁹⁾

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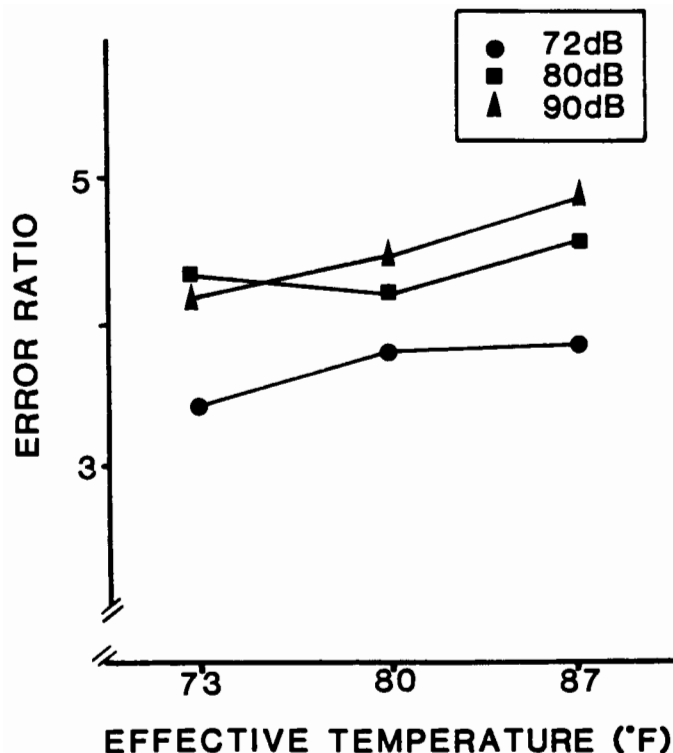


Figure 2—Mean error ratio for six performance tasks against Effective Temperature and noise condition.⁽⁹⁾

the purpose of clarity in this work, these are referred to under three general trends: 1) a negligible effect; 2) a synergistic effect; and 3) an antagonistic effect. As will be discussed later, these represent only an impoverished description of the number of outcomes possible. The rare cases of simple additivity are noted in the text in differing sections according to the overall result of the study examined. For simplicity, the subsequent review section is structured around the trends noted above; although on occasion, results from a single study may be located in more than one category.

Negligible Interactional Effects

One of the first studies on heat and noise effects remains to the present day one of the most comprehensive.⁽⁹⁾ In this work, each of three noise levels — 72, 80 and 90 dB — were combined with three Effective Temperatures (E.T.) — 73° (22.8°); 80° (26.7°); and 87°F (30.6°C)† — to give nine combinations. Tests were run on six subjects, six days a week for seven weeks. Each exposure lasted for four hours and within this period seven performance tests were assessed. The mean results of these exposures are expressed graphically in Figures 1 and 2. Figure 1 illustrates percentage of maximal performance output and Figure 2 shows an error ratio associated with the performance tests. As can be seen in Figure 1, mean performance output for the seven tasks

†The temperature values as shown on this and subsequent pages do not follow the Journal's prescribed form. Rather, the first temperature shown is that expressed by the author(s) as it appeared in the original quoted reference. Its equivalent in Fahrenheit or Centigrade, as appropriate, is shown subsequently in parentheses.

generally drops across the three increasing temperatures with the larger drop between the two most severe exposures. Using performance output alone as a measure, it initially appears that the introduction of noise has a facilitative effect upon overall performance as the 90 dB condition is the most productive of the three acoustic levels tested. When taken in conjunction with the overall error rate, as shown in Figure 2, however, a different interpretation of these data may be realized. The combination of output and error indicates that individuals in the more extreme acoustic exposures gain greater output at the expense of elevated error rate. While this suggests some form of speed-accuracy trade-off, it is not possible to ascertain whether the increased error rate actually offsets the higher performance output. Overall, the mean data for the seven performance tasks would indicate some form of synergistic interaction, but this simple interpretation is not substantiated by a more thorough examination of the results reported. In previous work,⁽⁵⁾ we have argued that combining data from a wide variety of different performance tasks is more liable to mask specific trends than to provide a valid overall indication of stressor actions. Consequently, detailed results from each of the seven performance tasks employed are presented in Figures 3 and 4.

These figures indicate that the general trend toward reduced output across the three performance temperatures is affirmed in most cases. This is most apparent in the Lathe test, with only the mental multiplication test violating this overall trend. It should be noted that the decrement from 73° (22.8°) to 80° (26.7°) is less than that from 80° (26.7°) to 87° F (30.6°C), E.T. This difference may result from individuals generally not being able to compensate physiologically to temperatures exceeding 85°F (29.4°C), E.T. The upper thermal condition in this experiment, which marginally exceeded this limit, would cause an increase in body temperature over the four-hour exposure.^(5,14) This is affirmed in part by the authors, who attempted to conduct a four-hour session at 93° F (33.9°C), E.T., but the experimental participants were unable to complete this series.⁽⁹⁾

While the trend toward reduced efficiency as a function of temperature is exhibited in six of the seven performance tasks, the addition of the acoustic stress in these individual cases does not provide a systematic change in performance ability. For example, the number-checking test produces the best performance with the addition of the highest noise level; however, this pattern is reversed for the Lathe test. As can be seen in Figure 4, error rate was unaffected by the addition of heat and noise, which suggests that most of the performance trends in Figure 3 are not simply an artifact of a speed-accuracy trade-off. Overall, the detailed results of this study indicated the relative independence of the action of the thermal and acoustic stressors, although the result of the manual coordination Lathe test suggests some degree of interaction. Whether this latter effect represents simple additivity or some form of synergy is itself unclear from the data presented.⁽⁹⁾

Another example of relative insensitivity was suggested by a three-stress study examining the effects of light glare and quiet speech in different thermal conditions.⁽¹¹⁾ The cool condition — 69°/64° F (20.6°/17.8°C) — and the hot condi-

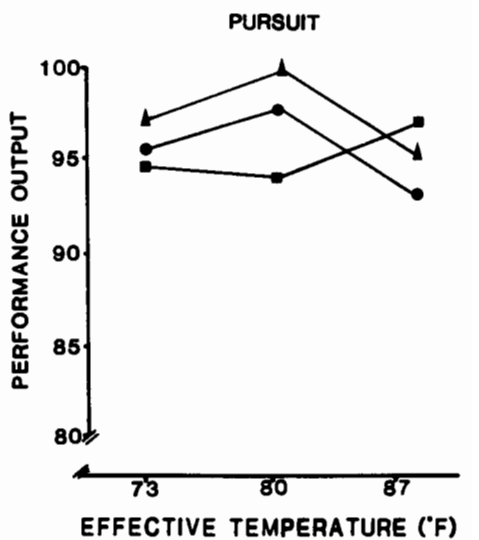
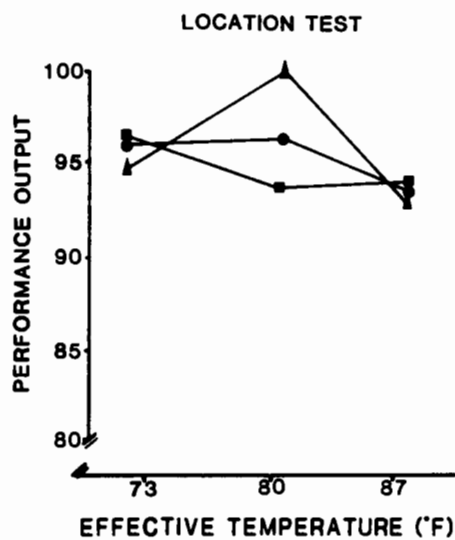
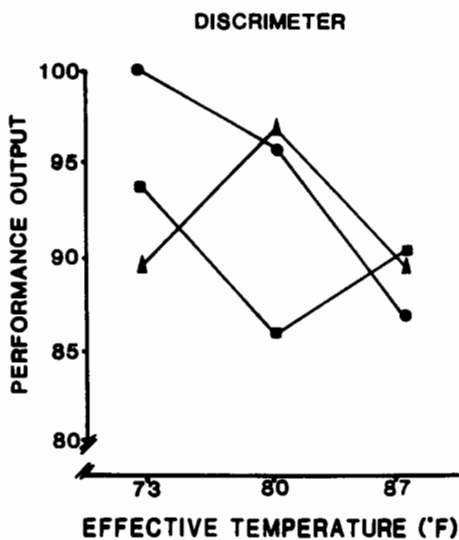
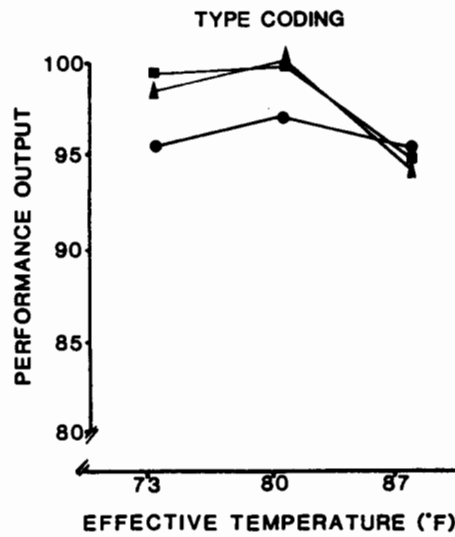
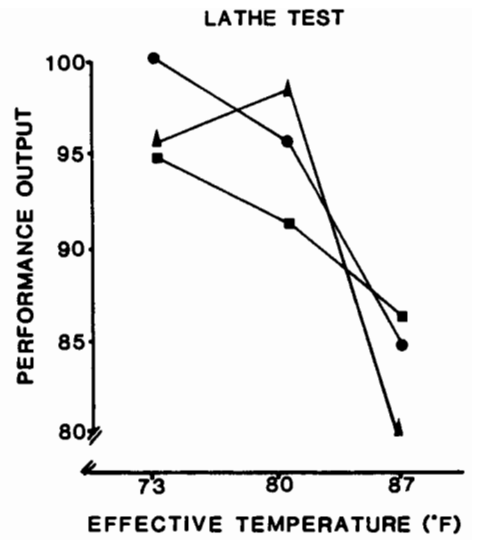
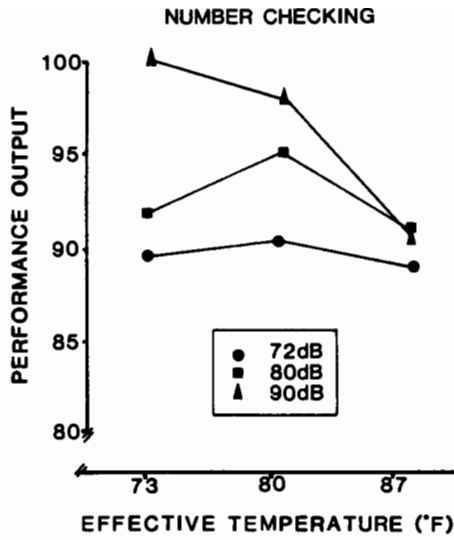
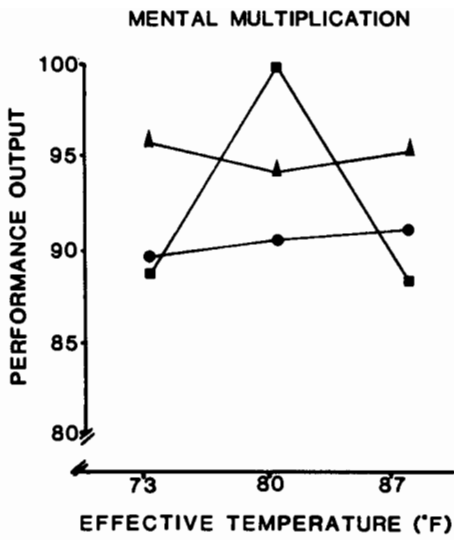


Figure 3—Individual performance output for each of seven tasks shown separately. Efficiency versus Effective Temperature and noise condition.⁽⁹⁾

tion — 100°/90° F (37.8°/32.2° C) — dry bulb/wet bulb temperatures, each had a barely intelligible female voice reading a descriptive passage for 20 minutes, introduced after 10 of the 40 test minutes had lapsed. The immediate task of the 12 participants was to track a moving target with a pointer and to do this as accurately as possible throughout the experiment. The increase in errors of alignment and decrease in pointer movements of the tracking device under quiet speech showed significant changes from the no speech control. Despite the fact that increasing the heat had differing effects on performance, the overall finding, however, was that changes due to quiet speech were independent of the thermal surround. Although the acoustic stressor was not noise by a strict definition, it did represent distracting sound. While quiet speech is different from the traditional notions of excessive industrial noise, the effects of such speech as a stressor may have certain practical applications as, for example, in the office environment. It would be unwise to suggest that this evidence represents anything greater than minor support for the independence of thermal and acoustic stressors.

In a study concerning only display monitoring ability,⁽¹²⁾ performance was undertaken in a relatively constant noise level but with the introduction of sequentially higher heat loads. The noise level between 85 and 95 dB was introduced to simulate actual industrial conditions. The heat level was incremented between a control 29.5/24.5° C (85.1/76.1° F) and an extreme 63/47° C (145.4/116.6° F), dry bulb/wet bulb combination in five sequential steps. As the time in the heat condition covaried with the severity of the stress, it is difficult to assess the effect of environmental heat load; however, the results indicated a decrement in monitoring efficiency as the body temperature of the observer increased. Although noise level of such an intensity does not appear to influence performance on this class of monitoring task,⁽¹⁶⁾ it would be somewhat misleading to deny the possibility of an interaction effect. As the combined impact cannot be specified due to the lack of a comparable quiet condition, results of this study remain somewhat equivocal with respect to combined action. From a previous review on temperature and display monitoring, however,⁽¹⁷⁾ the indication from this study is of a negligible interactive effect for this specific task.⁽¹⁵⁾

While the previous studies have examined the effects of continuous noise on performance against a thermally stressful background, a useful experiment⁽¹⁸⁾ which was undertaken in continuous heat, examined intermittent bursts of noise interpolated in performance. Participants were asked to monitor a 5 × 3 matrix of lights in which 60 light stimuli were presented randomly in each 15-minute session. Four sequential sessions represented one exposure at one heat level, and subjects repeated performance in three heat exposures at 53.5° (11.9°), 66.5° (19.2°) and 89° F (31.7° C), E.T. Four groups of six subjects each went through the experiment with one group acting as a no-noise control. A second group had a one-minute burst of 100 dB noise during the rest break at 30 minutes, a third group had a noise burst of equal intensity and duration at the 45-minute rest break, and the final group had noise during both breaks.

Only the proportion of lights detected was used as a performance measure, and this indicated no effect for either heat, noise or an interaction between the two. Although it was suggested that noise might affect peripheral skin temperature through its vasoconstrictive action, no such evidence was found in the physiological recordings. While the absence of performance change at the extreme 89° F (31.7° C), E.T. appears somewhat anomalous with respect to previous findings,⁽¹⁷⁾ further analysis indicated that 15 of the 24 subjects tested showed distinct individual trends. While five of these latter subjects performed best at the lowest temperature and decreased monotonically in capability as exposure temperature increased, a second group of five subjects performed optimally in the mid-thermal range. A final group of five subjects were best in the highest temperature and were the exact opposite of the first group. These trends tended to cancel each other in the overall results and were responsible for the null mean effect reported. In none of the groups specified, however, was there an interaction with the addition of the brief noise exposures. This latter finding supports the notion of the relative independence of the two stressors.⁽¹⁸⁾

One of the most complete investigational series on stressor interactions was generated in response to the forecast problems of space exploration. In one study,⁽¹²⁾ extremes of both thermal and acoustic stress were imposed in combination. Heat up to 93° F (33.9° C), E.T. was combined with either 70 or 110 dB white noise. Various tasks were performed which simulated pilot or astronaut activity. Among these were object tracking and radar and meter monitoring for irregularly occurring signals for action. Results indicated no interactive effects between heat and noise on any of the 12 performance tasks undertaken. Two examples of these null effects for radar and meter monitoring are presented in Figures 5 and 6. Initially, this appears to be strong support for the notion of the independence of thermal and acoustic action. The results of this study also reported no main effects for heat alone, however, and only one significant main effect for the 12 performance measures when exposed to noise.

While the absence of change under acoustic stress is not unexpected,⁽¹⁶⁾ the null effect of increased temperature is in direct contrast to the majority of previous observations at this high temperature level.^(4,5) The reason for this discrepancy appears to lie in the temporal duration of the exposure. In the experimental procedure, participants were exposed to the combined stress for only 30 minutes of which, only the latter 20 were used to assess performance.⁽¹²⁾ This time was insufficient to disturb the body temperature of the individuals, as shown in Figure 6. Consequently, initial exposure periods may represent a time during which the subject is able to use the novelty of the environment to combat the adverse effects of the unpleasant conditions. There is evidence to suggest that it is only with disturbance to deep body temperature that performance on such tasks is degraded.⁽¹⁷⁾ Overall, this work indicated the ability of subjects to withstand the effects of heat and noise in combination in acute or short-term exposures. Although this work is considered to show negligible interactive effects, due to the

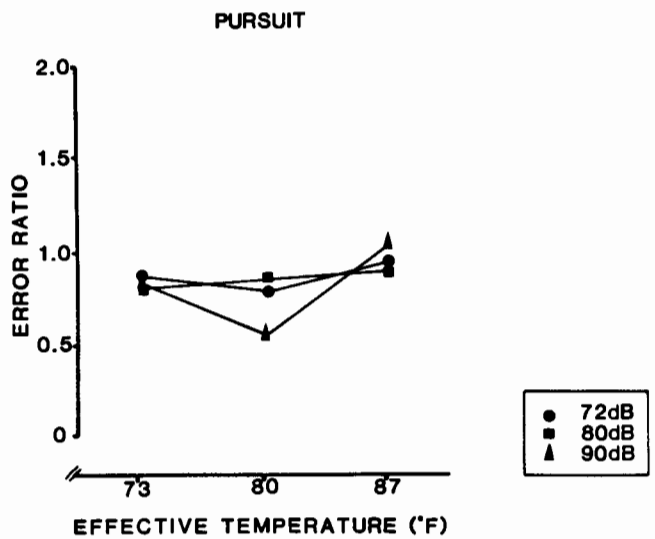
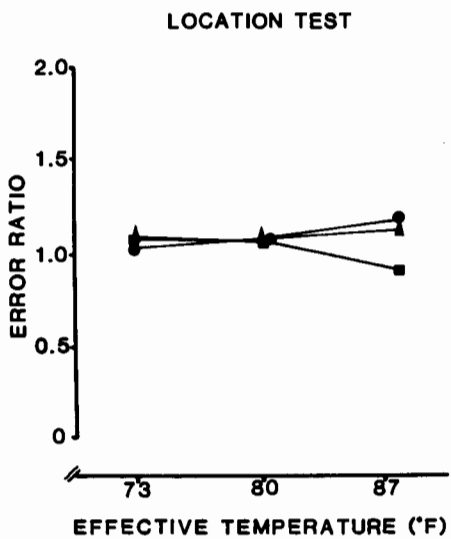
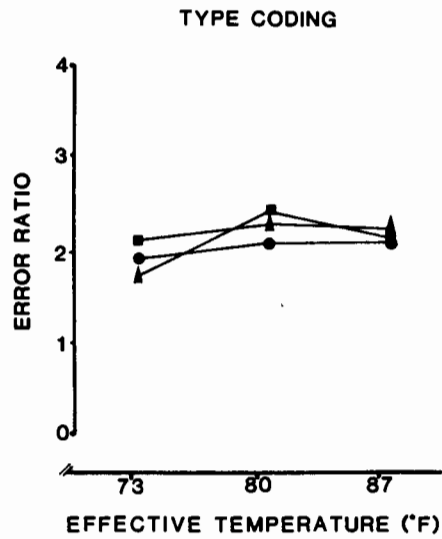
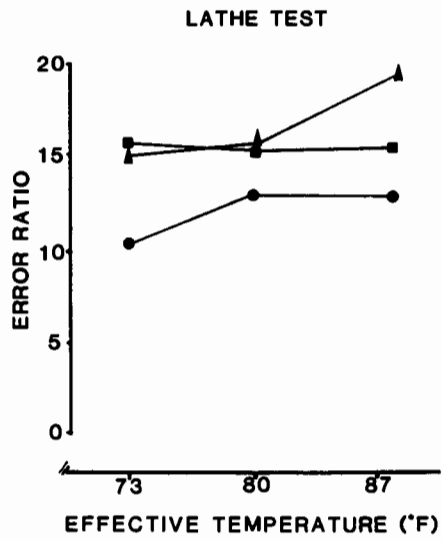
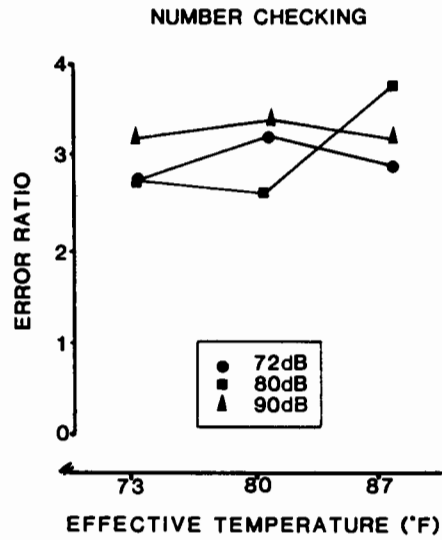
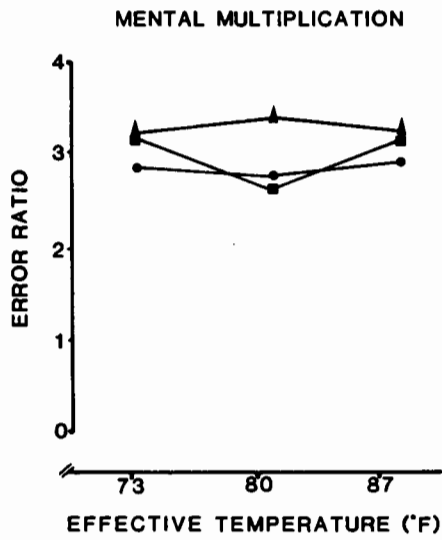


Figure 4—Individual error ratio for each of six performance tasks shown separately. Error ratio as a function of Effective Temperature and noise condition.⁽⁹⁾

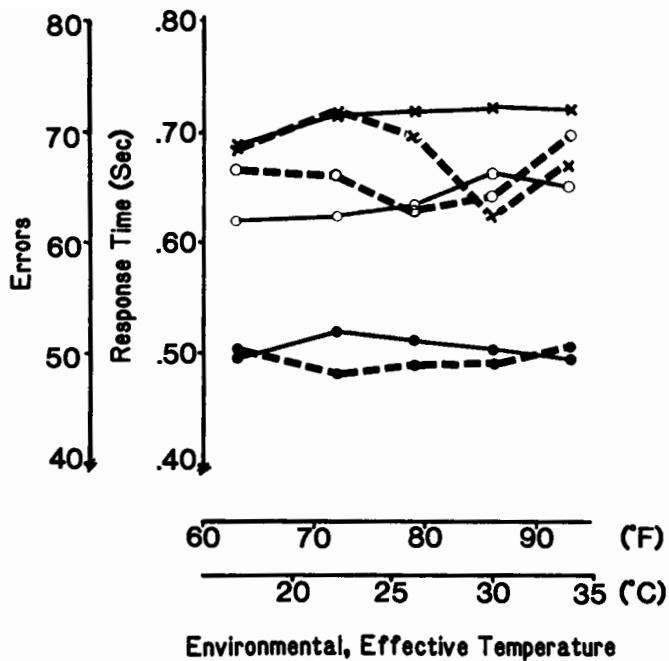


Figure 5—Errors of omission (crosses), errors of commission (open symbols) and response time (closed symbols) as a function of Effective Temperature and noise. Data for radar monitoring in 70dB (—) and 110dB (····) shown.⁽¹²⁾

short work period involved, this is not evidence of worker invulnerability to these levels of stress, either singly or in combination.

In a recent experiment, based upon the notion of division of attention during performance of two concurrent tasks, the effects of either 55 or 95 dB (A) were tested in combination with 22° (71.6°), 29° (84.2°) or 35°C (95° F) dry bulb temperature.⁽¹⁹⁾ One initial problem is that noise was presented for 1-9 sec at random intervals of 1-9 sec and, although humidity was reported as constant between 40-50%, other specifications of the thermal surround were left undefined. On a central task, subjects were required to track a target, and results indicated no main or interactional effects for heat and noise on this task. For the concurrent secondary task, numbers were presented aurally above the noise level and subjects had to decide if the numbers were higher or lower than their predecessors. While both heat and noise individually exerted a significant detrimental effect upon the number of errors committed in this secondary task, there were no interactional effects between heat and noise.⁽¹⁹⁾

While the studies described found mostly negligible interactive effects on performance, there are several studies which have looked at multiple stressors' effects but which have not reported explicitly on heat and noise in combination. Two studies^(20,21) examined heat, noise and vibration together. The first of these demonstrated that the three-way combined stress condition was less interruptive than the effect of the single greatest individual stress, which most often turned out to be vibration. As the three-way combined stress condition was compared only to the action of single stressors, the separate interactive effect of heat and noise could not be determined. Although the second study⁽²¹⁾ was somewhat more comprehensive, the interactive effect of heat and noise

could be recognized only by comparing the effect of vibration alone with the multiple stress condition. As with the previous study, there is the suggestion that the addition of heat and noise has a slightly antagonistic effect upon the action of vibration alone. Due to the restricted number of experimental conditions, however, the actual combined effects of heat and noise only could not be assessed directly from the reported data.

A further study which has examined multiple stress effects used a variety of acceleration, turbulence, noise, heat and illumination levels in an aviation-related experiment.⁽²²⁾ As with the previous investigations, it was shown that multiple stress conditions adversely affected manual tracking although, in accord with the above works, no combined heat and noise effects were available for direct examination.

Synergistic Interactive Effects

While the previous collection of studies reported little in terms of interactions, there are some reports suggesting more positive experimental results. The first of these studies⁽¹⁰⁾ was not conducted in the laboratory but in a vehicle moving through a desert environment. A control condition, in which performance was examined at night in a stationary mode, was compared with a daytime stationary and moving exposure. The results of the monitoring task showed little effect for the introduction of 125° F (51.7° C) dry bulb temperature. However, as this result depends upon comparing day with night performance and as time of day appears to exert an effect on this form of vigilance, this null effect for heat has been questioned.⁽²³⁾ Overall response times suggest some synergy between heat and the 125 dB noise and random vibration. As the multiple stress results were compared

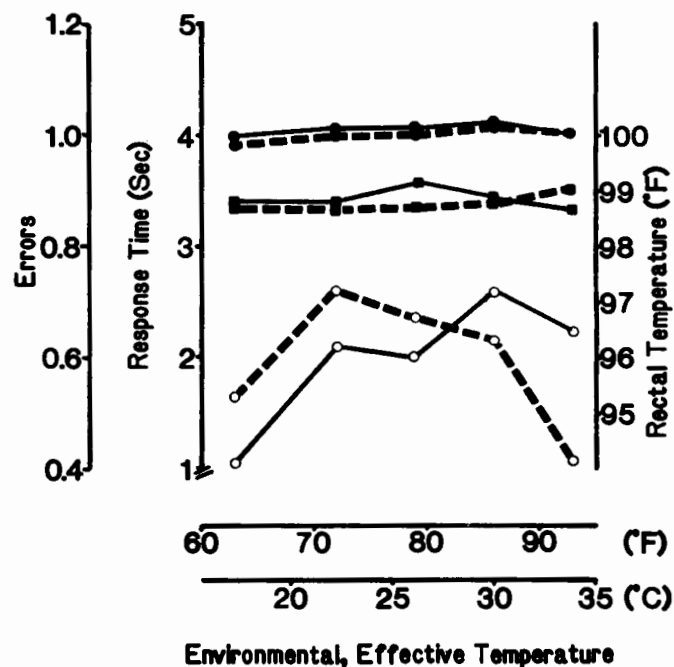


Figure 6—Errors of commission (open circles) and response time (closed circles) for meter monitoring as a function of Effective Temperature and 70 dB (—) and 110dB (····) noise. Data for rectal temperature variation (closed squares) also shown.⁽¹²⁾

only with the heat and control exposures, the interactive effect between heat and noise was not distinguished specifically. Like other multiple stress reports,⁽²⁰⁻²²⁾ it is difficult to decide whether the observed synergy is due to the addition of noise, vibration or an amalgamated action of the two.

This is not true of a later study,⁽²⁴⁾ in which eight combinations of four Effective Temperatures — 72° (22.2°), 78° (25.6), 84° (28.9) and 90° F (32.2°C) — and four noise levels — 41, 80, 90 and 100 dB (A) — were employed. The 12 male subjects were exposed to the differing combinations for 1½ hrs of which the latter 30 min were used to test capability on a five-choice serial reaction task. Response was measured by the total number of reactions, errors committed, relative errors and gaps in response. Heat significantly affected the latter measure, which increased 18% between the 72° and 90° F, E.T. Noise also impacted performance in that 5% fewer responses were recorded at 90 dB as compared to 41 dB. The interactive effect for heat and noise was observed on gap scores where the effect due to heat was dependent upon

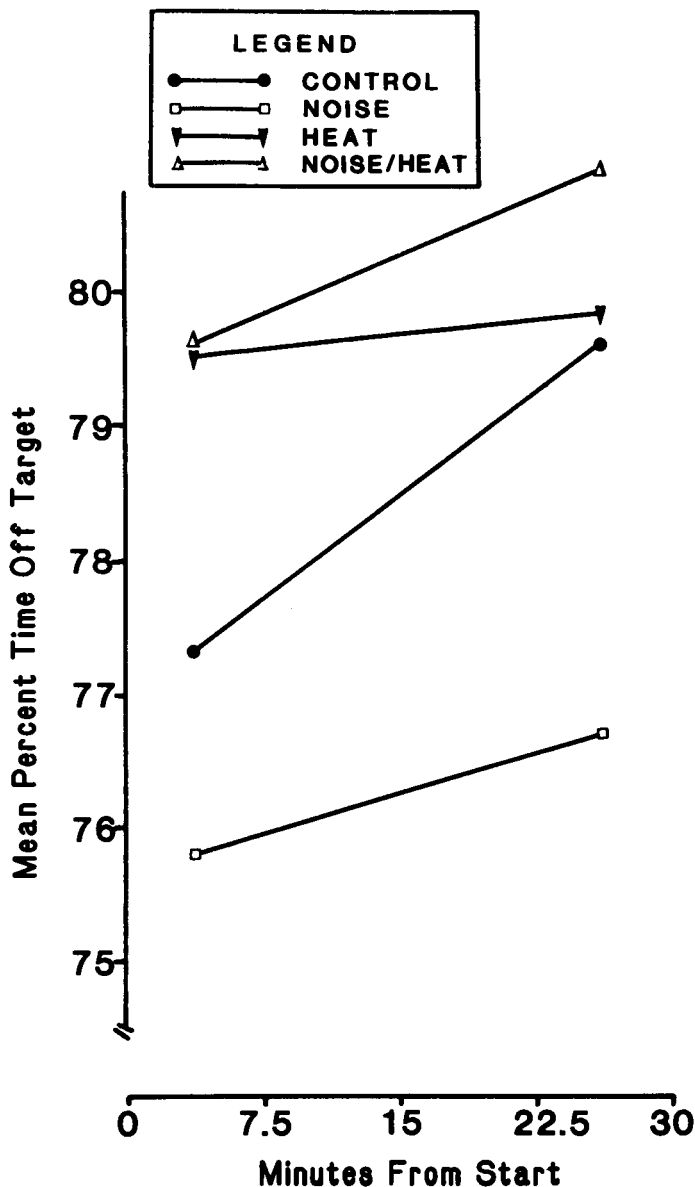


Figure 7—Mean percent time off target as a function of temporal exposure in heat and noise exposures.⁽²⁵⁾

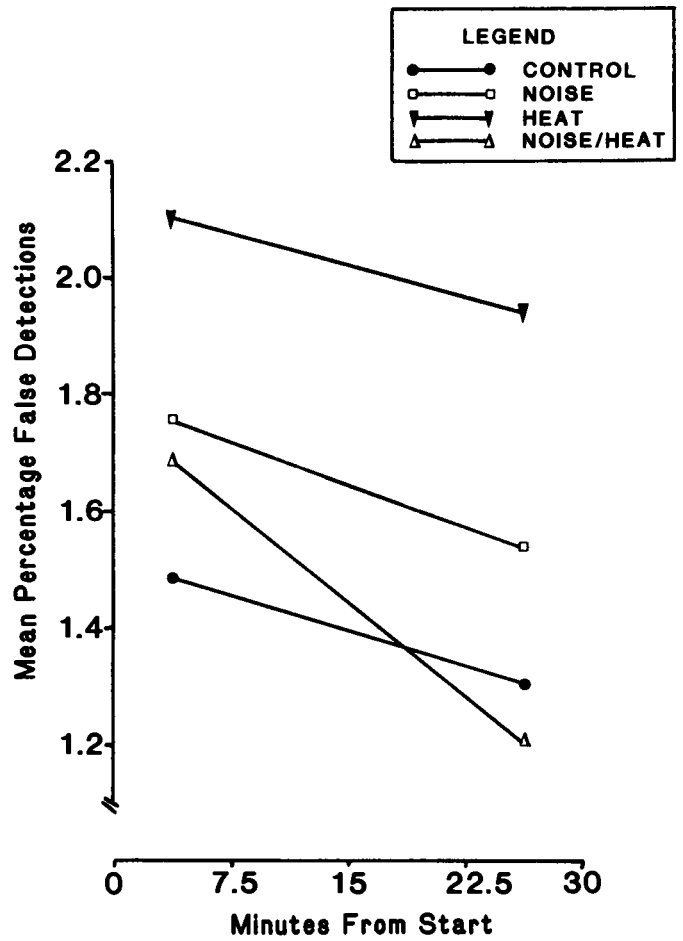


Figure 8—Mean percentage of false detections as a function of temporal exposure. Data for heat and noise conditions shown.⁽²⁵⁾

the ambient noise level. These data indicate a degree of synergy, but notably only for one of the four performance measures employed.⁽²⁴⁾

A synergistic interaction was reported in an additional experiment in which only heat and low-frequency noise were studied. Participants were exposed to 34.4° C (94° F) E.T. and 102dB noise, weighted on the C scale, both singly and in combination. The control conditions were 19° C (66.2° F) E.T. and approximately 80 dB (C) in the “quiet” exposure. Two of the three performance tasks reported time-related changes in efficiency. These were manual coordination on a pursuit tracking apparatus⁽¹¹⁾ and visual monitoring or vigilance, both 30 min in duration. The data for pursuit rotor tracking, which are reproduced in Figure 7, indicate a slight synergy for the combined condition when compared to performance under either stress singly. Over the total exposure time, the performance deteriorated in each condition with the no stress control declining more than either of the stressors singly or together. It should be noted that even though such changes can be distinguished reliably, they represent overall fluctuations of only 4-5% in absolute efficiency. For the mean number of false detections in the visual vigilance task a similar synergistic tendency appears, but for this performance parameter, efficiency improves with time on task rather than being degraded as in the above tracking

example. While each of noise, heat, and the control condition appears to improve uniformly, the combined condition improves more rapidly, as illustrated in Figure 8.

Thus, each of these two tasks suggest heat and noise interact synergistically, but such interactions induce diametrically opposing tendencies with progressive time on actual performance. As with the tracking task, absolute changes in performance are small and the percentage of false detections less indicative of an overall measure of vigilance efficiency than, for example, signals detected. Data for this latter measure of performance as reported in the study are elaborated in the following section. The authors⁽²⁵⁾ considered the possibility that reported interactions were functions of a range effect due to the use of a repeated measures design.⁽²⁾ If such is the case, then these results are largely artifactual rather than fundamental findings.

Antagonistic Interactive Effects

In the previous study,⁽²⁵⁾ two examples of synergy in performance were presented for two differing performance mea-

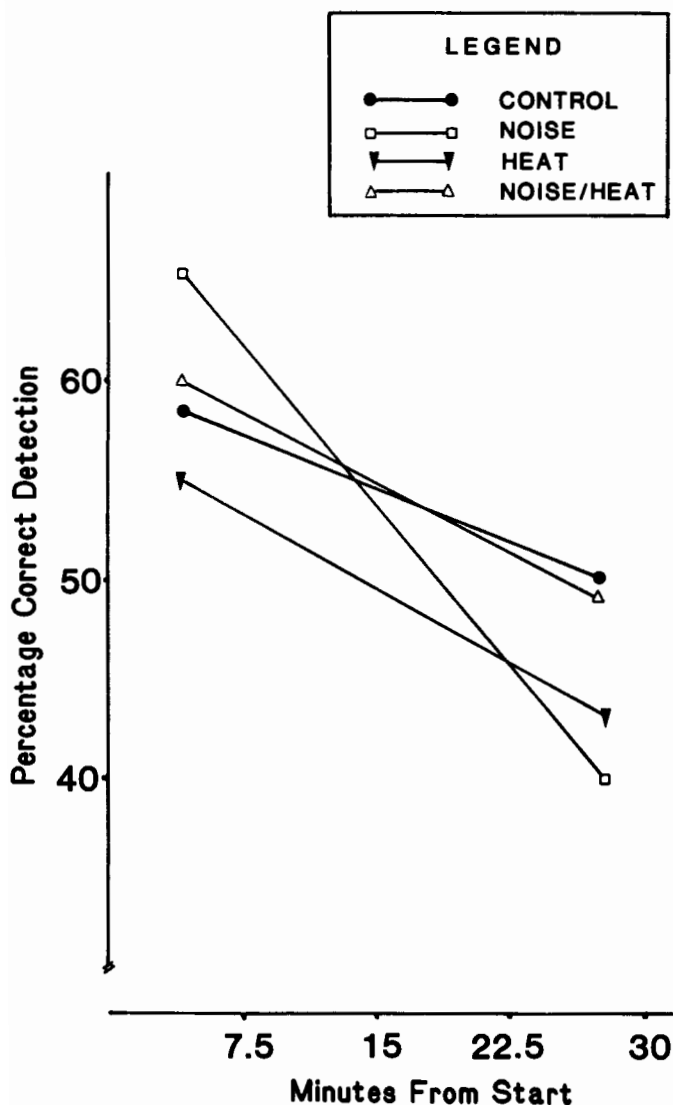


Figure 9—Percentage Correct Detections versus temporal exposure, data for heat and noise conditions shown.⁽²⁵⁾

ures. For the latter visual vigilance task, however, a further measure of efficiency includes absolute level of signal detection. Data for this particular measure are presented in Figure 9, which shows that the separate declines in detection over time for both heat and noise are partly offset when the stressors are combined. Indeed, such a combination brings overall performance level close to that of the no stress control. In such vigilance tasks it is common to construct a sensitivity metric d' , through the combination of the detection efficiency and the percentage of false detections. As reproduced from the original report, Figure 10 indicates that sensitivity or d' is reduced least under the dual stress condition compared to the control and particularly to each single stress exposure. This also suggests a degree of antagonism between heat and noise for the overall monitoring task. Because of the methodological difficulties noted by the authors, however,⁽²⁵⁾ these results should be interpreted with considerable caution.

Further evidence of interactive effects was produced in a study specifically designed to examine working industrial conditions.⁽²⁶⁾ An 85 dB (A) industrial noise condition was compared to a 50 dB (A) quiet condition in either 22° (71.6°) or 30° C (86° F) air temperature. Workers were required to perform both psychomotor and vigilance type tasks for a period of one hour for each task. The use of a portable test facility enabled the investigators to use an actual sample of industrial workers who performed the experiment at their place of employment. The first 30 min of any exposure formed an acclimation period to the ambient thermal condition, after which subjects were given a five-minute practice period followed by a 30 min performance period. The design also allowed for comparison of employees by sex and race. Although individual heat and noise effects were reported, only details of the interactive effects are considered in the following.

For the white female employees, there were no main or interactive effects on any of the performance tasks for the two stressors imposed. For the white male employees, only errors in a five-choice response time task proved vulnerable to the effect of stress; however, this increase in errors was *magnified* by the introduction of the second stressor condition, and indicates some form of additive effect. These overall effects are dependent upon between-subject comparisons with a total of only ten individuals in each group. For the black male workers, the addition of heat significantly elevated the total number of responses in the serial choice reaction task compared to the trends when performed in noise alone. This antagonistic effect was also seen for hesitation errors, or gaps of greater than 1.5 sec in response, in the sequential choice reaction task for the black, male employees. For this group also, the significant reduction in rate control errors in a tracking type task when heat was introduced was offset by the addition of noise. Although this latter result gives an example of synergistic type action, the authors noted that due to the small number of subjects in each of the respective groups these interactive effects cannot be established unequivocally.⁽²⁶⁾

Discussion

As can be seen from a summary of evidence presented in Table 1, most of the reports support the notion of a relative insensitivity between the action of thermal and acoustic stressors. As noted by the authors, even those accounts with interactional effects are beset by methodological problems, which cast doubt on the positive results found.^(25,26) The suggestion of independence of action was first voiced by Broadbent.⁽²⁷⁾ He examined a number of studies in which differing stressors had been applied to comparable participants who performed a common task. From these comparisons he suggested that while noise and sleep loss address some common mechanism, the effect of heat is separate and acts on a different mechanism altogether. These observations were offered in response to the typical arousal position which had been proposed to account for combined stressor action. This position indicates that extreme heat and noise are both arousing in their action, and therefore their combined action should be at least additive, if not synergistic, in nature. This overarousal should produce a decrement in the performance of the workers. As is apparent from Table 1, however, the loose prediction of the arousal position is not borne out in experimental observations. A fuller treatment of arousal is to be found in the work of Poulton.⁽²⁸⁾

It has been suggested⁽²⁹⁾ that one way to decipher the interactive effect of heat and noise on performance would be to examine their combined effect on physiological functioning. There have been at least two attempts to address this issue framed within performance experimentation. Each of these suggestions relies on the observation that noise may induce peripheral vasoconstriction. The first account⁽¹⁸⁾ argued that such vasoconstriction would increase the physiological strain through elevating the difference between core and skin temperature. As a result, the effect on performance should be one of additivity or, more probably, synergy in reducing efficiency. A second account⁽¹²⁾ employed the same rationale concerning the action of noise, but suggested that as the vasoconstriction would induce a subjective cooling effect, noise should exercise an antagonistic effect with respect to heat impact. Unfortunately, there is little support in the physiological data of either of the experiments to support the contention of vasoconstrictive effects.^(12,18) Indeed, it was suggested that the immediate response to noise was somewhat short-lived and, consequently, the expected effects were not observed.^(12,30)

The consensus of the current experimental data therefore suggests that the actions of heat and noise are largely independent. This is not to suggest, however, that the evidence at the current time is in any way conclusive. First, the reports have been tabulated under three major possible effects; however, this is an impoverished set of possibilities that occur from only the interaction of two stressors. There may be a subtractive effect, or the stressors may be independent throughout their ranges, a tendency referred to as iso-insensitivity. Finally, the stressors may be antagonistic in such a manner that performance remains constant throughout the range from a normative to an intolerable level yielding a zero sum effect. Added to these major effects, perfor-

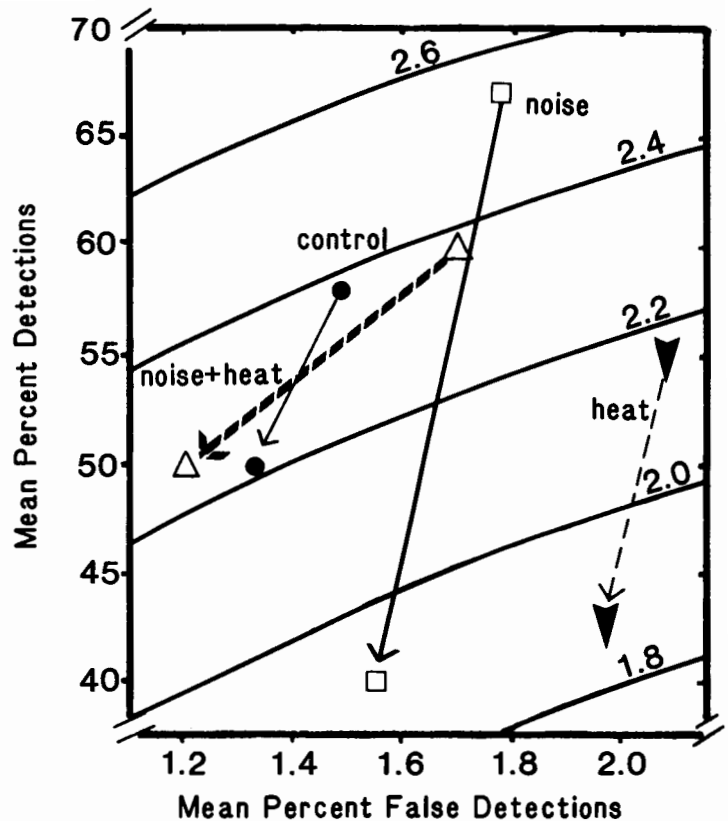


Figure 10—Signal detection metric d' change over time for control, heat alone, noise alone and a combined condition. Diagonal lines represent contours for the value of d' shown at right. Reproduced from⁽²⁵⁾ Copyright 1974 by the American Psychological Association. Reprinted by permission of the author.

mance may fluctuate between trends according to the level of each stressor. This makes even the interaction between two stressors a somewhat complex problem to unravel, and the apparent insensitivity as expressed in this paper may dissolve under more detailed scrutiny.⁽³¹⁾

There are two points of major concern which should also be recognized. First is the problem of precise specification of the stressors involved. In several of the studies, insufficient detail is provided concerning the elements of the thermal and acoustic surround. Without such information, the referenced studies are essentially unreplicable and consequently of somewhat limited value. The omission of such specification may be due to several factors. However, in order to construct a viable overall picture of combined effects, it is necessary to integrate such results with more contemporary evidence. In the absence of the numerical values which prescribe the physical constituents of the noise and heat, such an integration cannot be achieved.

The second problem, of possible greater practical importance, concerns the temporal exposure of the experiments examined. Almost without exception the studies discussed have used short-term exposures of less than a single working day in total. While this may give some ideas as to acute effects, it cannot represent a viable evaluation of the long-term impact of repeated exposure on multiple occasions, as experienced in many industrial conditions. If environmental

TABLE I
Summary of Studies on Combined Heat and Noise Effects

Study	Heat Level (°C)	Noise Level (dB)	Exposure Time (min)	Specific Tasks	Combined Effect
Viteles and Smith ⁽⁹⁾	22.8 ^B 26.7 30.6	72 ^C 80 90	240	Mental multiplication Number checking Lathe test Type coding Discriminator Location test Pursuit test	No consistent interactions. Suggested interaction only for the lathe test. Potential example of synergy.
Pepler ⁽¹¹⁾	20.6 ^A 37.8	Barely ^C intelligible voice	20	Pursuit tracking task	No interaction or addition effects observed.
Bell, Provins and Hiorns ⁽¹⁵⁾	29.5 ^A 63.0	85-95 ^C Simulated	Varied by subject	Visual monitoring	Lack of a noise control precludes precise interaction assessment.
Arees ⁽¹⁸⁾	11.9 ^B 19.2 31.7	One-minute ^C bursts at 100dB at 30/45 min into task.	60	Visual monitoring	No effect for either heat, noise or combination on mean detection efficiency.
Dean and McGlothen ⁽¹²⁾	21.1 ^A 26.7 32.2 37.8 43.3	70 ^C 110	30	Radar/meter monitoring ten other performance tasks.	No main effects. No interactive effects.
Bell ⁽¹³⁾	22 ^A 29 35	Random bursts ^D of 1-9s duration at 1-9s intervals 55 95	33	Primary task-pursuit tracking Secondary task-response time	No main or interactional effects for primary task. Suggestion of additivity for secondary task decrement.
Renshaw ⁽²¹⁾	22.2 ^B 25.6 28.9 32.2	41 ^D 80 90 100	90	Five-choice serial reaction task	Indication of synergy for measure of response gaps.
Grether <i>et al.</i> ⁽²¹⁾	20 ^B 31	80 ^C 105	60 35	Tracking Choice reaction time Voice communication Mental arithmetic Visual acuity	Presence of vibration prevented discrete effects of heat and noise being distinguished.
Grether <i>et al.</i> ⁽²¹⁾	21 ^B 31	80 ^C 105	60 35	As above with a telephone test substituted for voice communication	Combined heat and noise effects not distinguished separately.
Bowman and von Beckh ⁽²²⁾	24 ^A 51	66 ^D 85	60	Tracking Response time	Presence of acceleration buffed and low light obscured heat and noise effects.
Loeb and Jeantheau ⁽¹⁰⁾	52 ^A	125 ^C	225	Visual monitoring	Heat, noise and vibration in combination, no distinguishable effect of heat and noise alone.
Poulton and Edwards ⁽²⁵⁾	19.0 ^B 34.4	80 ^E 102	90	Tracking Visual monitoring	Some statistical indications of both synergy and antagonism. Possible artifact of methodological approach.
Wyon <i>et al.</i> ⁽²⁶⁾	22 ^A 30	50 ^D 85	30	Serial choice response Visual vigilance task	Some indications of synergy and antagonism in selected groups but small number of subjects per cell in study.

^A Dry bulb temperature
^B Effective temperature
^C Noise scale not reported
^D dB (A)
^E dB (C)

stressors have both specific and non-specific physiological effects, as evidence suggests they do,⁽¹⁶⁾ then the long-term impact of the combined non-specific actions may be those which are of critical importance to worker health and safety. Such effects would not be manifest in the short-term exposures reported on in this review.

In conclusion, although evidence favors the independent action of heat and noise in the level commonly experienced in the industrial environment, this should not be taken as a mandate in setting potential standards. Indeed, the more conservative course of action would be to regard these stressors as slightly synergistic in combined effect and to act accordingly. These recommendations are made with respect to recognition that studies examining interactive environmental stressors are currently beset with both theoretical and methodological inadequacies which invalidate in part a number of the research findings.⁽³²⁾ Until the problems of stressor interactions are approached systematically, the intrinsic problems of highly complex workplace environment may not be unravelled.

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