HUMAN FACTORS, 1989, 31(5), 519–537

A Dynamic Model of Stress and Sustained Attention

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This paper examines the effects of stress on sustained attention. With recognition of the task itself as the major source of cognitive stress, a dynamic model is presented that addresses the effects of stress on vigilance and, potentially, a wide variety of attention-demanding performance tasks.

STRESS AND PERFORMANCE CAPABILITY

The influence of stress on human behavior has been a topic of inquiry for many years. Over the last four decades the effect of stress on neuromuscular and cognitive performance has become a major focus of research (Hockey, 1983). Interest in this topic is fueled largely by two factors. The first is the belief that a more profound understanding of human abilities may be garnered from the study of individuals' responses to extreme conditions. The second, allied, reason is the pragmatic requirement of a number of agencies to understand the reactions of their personnel under diverse and arduous operational conditions. These combined influences have generated numerous insights into stress and its effects on the efficiency of operator performance (see Appley and Trumbull, 1986). However, there is no current unified theory that enables a practitioner to predict the effects of different forms of stress on the performance capability of system operators. Although the concept of unitary behavioral arousal has most commonly been used to explain the effects of stress on performance, accumulating evidence has exposed the shortcomings of this simplistic position. And although several alternative approaches have been developed more recently, each has yet to be established as a preferred explanation of stress effects (see Hancock, 1987; Hancock and Chignell, 1985; Hockey, 1986; Hockey and Hamilton, 1983; Sanders, 1983).

Stress is often viewed as a force that degrades performance capability. It is usually considered to be a property of the environment (e.g., Hockey, 1983), though the appraisal and coping mechanisms of the exposed individual (e.g., Lazarus, 1966; Lazarus and Folkman, 1984) and the general response of the physiological system (e.g., Selye, 1956) are seen as equally viable avenues through which to study stress. Giving

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primary consideration to the constituents of the physical environment may be regarded as an *input* approach to stress. In contrast, focus on the appraisal and coping mechanisms of the exposed individual emphasizes the *adaptive* or compensatory aspects of response. The concern of the third approach has been with the *output* of the individual, which typically reflects ongoing changes to different bodily functions. Although this has traditionally meant an examination of physiological processes, the recent emphasis on behavioral capability has expanded the output view to include the analysis of performance efficiency (Hockey, Gaillard, and Coles, 1986).

It has been observed that these three approaches are facets of a single dynamic process (Hancock, 1986b). This implies that a unitary account of stress effects may be possible given the integration of the knowledge from each of the three aforementioned foci (see Figure 1). Input stress represents a description of the physical characteristics of the environment. Within the resolutional power of the methods employed to measure and replicate such conditions, input forms of stress are *deterministic*. Because such input is composed of a constellation of differing sources of which rarely are exactly repeatable, it is best expressed as a stress signature. Adaptive or compensatory processes rely on the response strategies of a number of bodily structures common to all individuals which regulate effects of external change on internal state. Given that these characteristics are similar among all individuals, adaptive actions give a consistent, but not identical, response to repeated exposure to identical input stress. Therefore, examination of adaptive reflections of stress provide *nomothetic* or lawful tendencies compared with the determinism of physical input. Output reflections of stress are dependent on the state and goals of the individual under consideration. Such *idiographic* or person-specific responses make it difficult to generate ubiquitous statements about the action of any equivalent level of input stress on a group of different individuals. Whether viewed separately or as part of a trinity of stress, the input, adaptive, and output foci may be used to describe response at multiple levels of analysis and need not be restricted to the physiological and behavioral domains in which they were founded.

Based on this conceptualization, the principal aim of the present work is to provide steps toward a dynamic model of stress and operator performance. The model describes three modes of operation: one in which dynamic stability prevails, a second in which dynamic instability represents a state of progressive failure toward ultimate collapse, and a third that represents the transition between the other two states. These modes of operation are states of adaptational capacity and also expressions of a common response strategy that is replicated across different levels of operator functioning. In the present form of the model, psychological adaptabil-

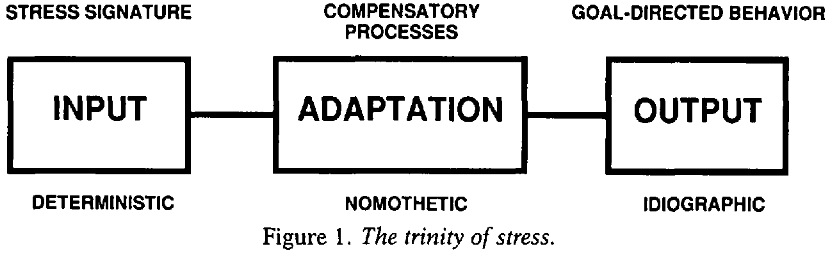

Figure 1. *The trinity of stress.*

ity is closely tied to contemporary notions of operator attentional resource capacity (Gopher and Kimchi, 1989; Kahneman, 1973; Wickens, 1987), whereas physiological adaptivity is related to traditional representations of homeostatic adjustment. It is through a link between such levels of analysis that the model may be elaborated to encompass the effects of stress on a wide variety of attention-demanding tasks, including sustained attention or vigilance, to which it is initially applied here. Vigilance is chosen because it not only represents an environmental source of stress but is also appraised as a stressful task by the performer.

This paper begins with an examination of the effects on vigilance of different forms of input more commonly recognized as environmental stresses. The confusion that surrounds the effects of acoustic stress or noise on sustained attention is contrasted with the patterns that emerge from examining the influence of thermal variation—particularly heat stress—on vigilance. Reasons for such a difference are elucidated. In the section that follows it is argued that an integrated view of stress and performance must consider the task itself as a primary influence in the generation of stress. The evidence that sustained attention generates such stress is briefly considered. These observations are used as one element in the construction of a dynamic model of stress effects. The strengths and limitations of this model are examined in a summarizing section.

PATTERNS OF VIGILANCE PERFORMANCE UNDER STRESS

The traditional approach to stress research has pursued investigations principally on the basis of environmental sources of disturbance. This strategy has been elaborated upon most recently by Hockey and Hamilton (1983), who have advocated the use of two research strategies that they label *narrow-* and *broad-band* approaches. Narrow-band investigations examine the effects of a variety of stresses on a single task, whereas the broad-band approach looks at multiple distinct tasks under the influence of a single source of stress. With respect to the vigilance task, two forms of environmental stress have generated the greatest interest: noise and temperature. This is not to say that other sources (e.g., vibration; Wilkinson and Gray, 1974) have not been examined (see Davies and Parasuraman, 1982; Hancock, 1984b; and Poulton, 1977, for reviews). Rather, the most extensive knowledge about the effects of stress on sustained attention concerns the impact of thermal and acoustic stimuli (Loeb and Jeantheau, 1958; Loeb, Jeantheau, and Weaver, 1956; Mackworth, 1950/1961). It is important to ascertain why the effects of noise seem so complex (Koelega and Brinkman, 1986; Loeb, 1980) whereas those for temperature generate a clearer picture (Hancock, 1986c). In the latter case sustained attention is degraded as thermal homeostasis of the observer is disturbed. Significant breakdown in capability occurs when deep body temperature exceeds the bounds of dynamic compensability. Performance is unaffected with no variation in deep body temperature and is facilitated when the observer is established in a static hyperthermic state.

With any two discrete areas, such as noise and vigilance, there may be no substantive interaction. There may be a weak interrelationship, but the quality of existing knowledge is such that a convincing case has yet to be established adequately. Alternatively, it is possible that interactive effects are so contingent upon specific circumstances that broad generalizations about any interrelationships become meaningless. In their recent review of the literature concerning the effect of varying noise, describing how the characteristics of the acoustic signal change during the period of exposure, Koelega and Brinkman (1986) favored the latter interpretation. Indeed, such was their conviction on the subject that they concluded:

> The present authors are pessimistic as to the usefulness of future reviews on "noise and vigilance." Referring to the aforementioned confusion in the literature of both noise and vigilance, and illustrated by this analysis of variable noise on vigilance performance, we even believe that further attempts to find order in the effects of "noise" in general, or in the results of "vigilance tasks" in general, should be abandoned. (P. 478)

However, Koelega and Brinkman (1986) offered the comment that the *microstructure* of vigilance performance may be the locus in which to search for noise effects (see also Kryter, 1970) and that such an approach may reveal nuances in the variation of efficiency which remain masked by grosser measures. In their experimental work Koelega, Brinkman, and Bergman (1986) reported data that support such an inference, though no systematic pattern was found for the effect of noise even there.

As acknowledged in their paper, Koelega and Brinkman (1986) elected to examine one of the most complex stress and performance-related circumstances. In view of the number of factors involved in the study of variable noise effects on vigilance and the size of the data base used to address the matrix of potential response patterns, the failure to observe consistent effects is not entirely unexpected. However, for a more parsimonious stress (i.e., temperature) such a general pattern appears to be forthcoming (see Hancock, 1986c). The frustration expressed implicitly by Koelega and Brinkman (1986) is one example of conditions that result when theory fails to assume a leading role in knowledge development (Kantowitz, 1987).

Whereas studies of varying noise have not uncovered systematic effects on vigilance performance, results from experiments employing continuous noise have produced such effects (see Lysaght, Warm, Dember, and Loeb, 1984). Lysaght's (1982) framework (reproduced in Hancock, 1984b) differentiated the effects of continuous noise by the use of three separate dimensions: (1) information-processing demands of the task, (2) noise level, and (3) acoustic quality, which differentiated white and varied noise. In general performance is degraded by a high level of white noise (above 90 dB SPL) when processing demands are high. Performance remains unchanged when processing demands are low whether the level of white noise is above or below the 90 dB level. However, performance on low-demand tasks is facilitated in the presence of low-level varied noise. Information about the other combinations of Lysaght's three dimensions is insufficient to determine any clear trends, but this is largely because of a lack of experimental evidence rather than a demonstrable absence of consistency.

Koelega and Brinkman (1986) argued that continuous noise is rare in the real world, and so for purposes of ecological validity their survey was confined to variable noise. This category includes intermittent noise (periods of so-called quiet may be interpolated with the acoustic stress). The introduction of this temporal uncertainty in regard to the presence of noise generates considerable complexity, and excluding the results from continuous noise may eliminate information on which certain consistencies might be founded. In addition, there is a variety of operational conditions (e.g., space shuttle operations) in which tasks must be performed against a background of noise that does not vary in any significant manner, so the argument concerning ecological validity is not one that excludes continuous noise as a source of stress.

When faced with a particularly complex problem, it is often useful to consider evidence from companion areas of investigation. For a number of reasons temperature is the more parsimonious form of stress. One principal difference is in the history of each of these sources of physical disturbance. Whereas temperature, as a component of climate, has been a continuous influence during human evolution, noise is largely a new stress that originated in the Industrial Revolution (Jones, 1983; Loeb, 1986). Both high and low temperatures are stressful, but in noise-related investigations low levels of sound (i.e., quiet) are taken for control, or no-stress, conditions. Therefore, noise may be considered unidirectional in effect, whereas temperatures can be characterized as a bidirectional influence. In addition to the foregoing differences, temperature is a property of the environment but is also a physiological attribute of the human operator. It is the direct connection between physiological status and level of thermal stress in the environment that allowed Hancock (1986c) to differentiate the performance effects of temperature on sustained attention. Clearly acoustic stress possesses no direct physiological analogue, and so any similar search would have to be founded on the diverse patterns of physiological response that the noise elicits. This means a much more arduous and complex search.

Finally, body temperature is the major entraining physiological rhythm. A number of functions of the human system are captured and synchronized to the temperature rhythm (Kleitman, 1939/1963; Moore-Ede, Sulzman, and Fuller, 1982). As a representation of the action of the dominant endogenous oscillator, temperature has a widespread influence that is apparent in both physiological and behavioral activity. In addition, a direct connection has been drawn between change in body temperature and the perception of duration. Whereas increasing body temperature speeds apparent duration, decreased body temperature slows it (Baddeley, 1966; Hancock, 1984a). It has been suggested that this influence underlies performance variation on a number of tasks including sustained attention. With noise, no such simple connections among the level of environmental stress input, the physiological or adaptive response adaptation, and the proceeding performance or stress output are evident. Therefore, although temperature effects provide useful indications in the search for general patterns concerning stress, the complex acoustic influences remain much more obscure. These major reasons are responsible for the difference between the conclusions on consistency of Hancock (1986a), who examined temperature, and of Koelega and Brinkman (1986), who evaluated the impact of variable noise.

SUSTAINED ATTENTION AS A SOURCE OF STRESS

The foregoing observations concern the traditional but somewhat divisive approach to stress and its influence on task performance. Stress is seen as an independent agent and, commonly, as a property of the external environment. An individual's performance on the task is viewed as a separate control condition against which the effect of stress is evaluated. An alternative approach to examining how stress affects performance stems from the recognition that the task itself is a significant form of cognitive stress (Hockey et al., 1986). This concept is suggested by recent studies in sustained attention. Although traditional vigilance tasks have been thought to place a relatively low demand on the monitor, recent data suggest otherwise. For example, Gluckman, Warm, Dember, Thielmann, and Hancock (1988) found uniformly high workload response to both simultaneous and successive sustained attention tasks. This finding was confirmed by Galinsky, Dember, and Warm (1989), who, in addition, found that the powerful effect of event rate in vigilance was directly reflected in the perception of mental workload (Hancock and Meshkati, 1988). The vigilance task itself illustrates how powerful the stress of an informationally impoverished display combined with a highly demanding discrimination task may be (see Gluckman et al., 1988). The mere need to maintain a vigil is sufficient to produce a stress response, and subjects in vigilance experiments have reported increased levels of stress following completion of the vigil.

The stress response of an individual during vigilance performance as part of a wide spectrum of behavioral situations has been monitored through the measurement of the amount of catecholamines, adrenalin, noradrenalin, and corticosteroids released by the adrenal glands (Parasuraman, 1984; Wesnes and Warburton, 1983). During a vigil catecholamine and cortisol output increases in subjects, indicating that vigilance demands effort and elicits a stress response (Frankenhaeuser, Nordheden, Myrsten, and Post, 1971; Frankenhaeuser and Patkai, 1964; Lundberg and Frankenhaeuser, 1979). Studies of the subjective responses of participants also indicate that vigilance is more draining to an individual than was previously assumed. Specifically, subjects who were asked to rate themselves on five mood dimensions before and after a vigilance task reported they were more strained and less attentive after the vigil compared with the pretest measures (Thackray, Bailey, and Touchstone, 1977). The subjects also perceived themselves to have less energy and became increasingly more bored and irritated as a result of performing the vigilance task. Interestingly, individuals who reported smaller shifts in mood and, presumably, perceived the vigil as less stressful performed more effectively than did subjects with greater mood shifts.

Ratings for similar subjective responses to vigilance performance have been reported by Warm and his associates (Hovanitz, Chin, and Warm, 1989; Lundberg, Warm, Seeman, and Porter, 1980; Warm, Rosa, and Colligan, 1989) using Thackray et al.'s (1977) scales on completion of a vigil. Subjects reported higher levels of fatigue and drowsiness after the task than they did before the task. A similar study confirms that monitors become more drowsy and feel fatigued following a vigil, according to their subjective ratings (Macomber, 1987). Thackray (1981) postulated that the stress resulting from vigilance stems from having to maintain a high level of alertness during a monotonous situation while at the same time having no control over the events that may occur. Control appears to be a particular influence on response to stress because of its role in both the appraisal and coping processes (Frese, 1987). For example, Karasek (1979) has observed that the most stressful condition is one that combines extremes of demand and low control, whereas the stress of varying demand may be ameliorated by increasing the performer's decision control.

THEORIES OF STRESS AND VIGILANCE

Collectively the foregoing observations lead to the most important point that permeates the whole argument concerning stress and vigilance: the role of theory. There has been a collective failure of theories that seek to explain vigilance performance (see Loeb and Alluisi, 1984). This failure is also true for theories of stress in general, which with few exceptions have exhibited similar stagnation. It is noteworthy that the only theoretical construct that spans the two areas is the concept of behavioral arousal. In their paper Koelega et al. (1986) observed, "But arousal theory can explain any results, post hoc, and lacks predictive power. The position on the inverted-U curve can only be specified after the experiment, so arousal theory, in its present form, is not amenable to rigorous experimental testing" (p. 588). They are assuredly correct. This and additional limitations of the unitary behavioral arousal theory have been elaborated in detail by Hancock (1987). Failure to find consistencies in the noise and vigilance data is consequently a specific case of the general failure of theoretical integration both within and across two respective areas. One way to arrive at a coherent theory is to reduce the imposed demands of both the task and the stress to some common elementary components. For this, consideration of the performance task as the primary source of stress is a central premise. From the brief overview of existing theories in the next section it is clear that such an approach has not yet been explored.

Much work in the human factors domain is directed toward operations in the face of multifaceted and multioriginating forms of stress. At present no satisfactory theoretical account is available to predict the action of discrete or interactive stresses that occur in real-world settings (see Hockey et al., 1986). This situation has emerged from a continued adherence to the notion of behavioral arousal and poor reflection on the insightful efforts of early researchers (for example, see Broadbent, 1963). Simplistic and inaccurate interpretation of the observations of Hebb (1955) and Lindsley (1951), among others, has fostered many contemporary problems. Uncritical acceptance by some investigators of the unitary arousal "explanation" of otherwise inexplicable findings has produced post hoc accounts rightly criticized by Koelega et al. (1986). This predominance has not been offset by the sporadic but important notes of caution sounded by more critical theoreticians. For example, Naatanen (1973) reviewed the evidence concerning the inverted-U relationship between activation and performance and concluded that the descending arm of the inverted U was an artifact of distraction from other sources of stimulation and the inappropriate nature of many of the experimental manipulations designed to test predictions from the inverted U. Naatanen (1973) proposed that when the performer remains focused on the task at hand, behavioral efficiency increases as a negatively accelerated function of activation. Only when the individual disperses efforts to other sources of stimulation does the inverted-U function appear as was observed initially by Yerkes and Dodson (1908) and which continues to be invoked in various forms to the present day (Moody, Joost, and Rodman, 1987).

The promise of solutions inherent in the work of the early 1960s has not been realized. Although neurophysiologists have continued to make progress in this area (see Robbins, 1986), comparable efforts in behavioral research have enjoyed less success. The demise of the unitary arousal theory left little in the way of a satisfactory behavioral account of stress effects. A number of interesting hybrid models have been developed which address not only stress but also the way in which energetic aspects of behavior in general may be integrated into the linear information-processing models of human capability (see Hockey et al., 1986). One approach, formulated by Hockey and Hamilton (1983), distinguishes a number of differing cognitive patterns of stress states. This position, based on careful analysis of a spectrum of experimental evidence, specifies differing arousal patterns that are dependent on the characteristics of the task and the stress under consideration. This fractionated arousal account has a powerful appeal in that the results of numerous studies that have employed an arousal explanation can be readily fitted within this new structure. In addition, the established connection with a neurophysiological substrate remains tacitly intact. One weakness lies in this construct's relative lack of predictive capability, which is also essentially a residual characteristic of its parent unitary arousal position.

An alternative perspective has been presented by Sanders (1983). In his model he links the concepts of arousal, activation, and effort, as envisaged by Pribram and McGuiness (1975), to a linear stage model of information processing. Sanders's hybrid addresses the differential effects of stress on sequential stages of processing by examination of choice reaction time responses. This construct has the potential for extension beyond the limited realm of reaction time response in which it is founded and may prove an efficacious avenue through which to pursue a predictive structure for general effects. At this stage, however, a number of constraints prevent this from becoming a general theory.

Concerning both of these alternatives, it should be noted that fractionation and hybridization increase the range of behavior that can be adequately explained. However, this power is gained at the expense of added degrees of explanatory freedom. Only a more substantial experimental data base can distinguish whether this latter tactic is appropriate in this realm of investigation.

A third alternative that we have pursued focuses on the commonalities that exist between the functioning of physiological systems in response to environmental perturbation and the behavioral actions designed to accomplish the same aim. In principle, our postulate is that there is a common strategy that subsumes each of these levels of activity. However, behavioral response is initiated earlier and exhausted earlier than are accompanying physiologically compensative processes. Further, we suggest that there is a strong link between these embedded envelopes of defense, such that physiological compensation is initiated at the point at which behavioral response reaches the exhaustive stage. This model has developed through a series of stages (see Hancock, 1986b; Hancock and Chignell, 1985; Hancock and Rosenberg, 1987) and is presented here in full.

A DYNAMIC MODEL OF STRESS AND SUSTAINED ATTENTION

In navigating through a dynamic environment, which presents a series of challenges and opportunities, the individual encounters a number of perturbing conditions that threaten or constrain goal-directed activity. These interfering conditions occur at all levels of operation, and we have referred to them generically as sources of input stress. Minor levels of input stress are readily absorbed by adaptive capability; they do not disturb steady-state functioning and so are not reflected as output stress, manifest in change of behavior. However, as input stress level increases through change in intensity, prolongation of exposure time, or both in combination, output is eventually affected. Stated more formally, the effects of an input stress are propagated through the system when the buffering capability of adaptive capacity is exceeded. The level of input stress that can be tolerated indefinitely by an individual without subsequent output disturbance defines a region of *maximal adaptability*. For working operators the primary source of input stress is task demand. Output is reflected in performance efficiency. However, multifaceted environments provide more than one form of input, and the more traditional forms of stress impinge on both psychological and physiological capabilities. Although response *strategies* across physiological and psychological systems are proposed as identical systems, the region of maximal adaptability is larger for physiological functioning. Physiological and psychological responses are linked in a formal way, which we explore later in this paper for specific examples. However, one immediate consequence of this relationship is that input forms of stress that appear to solely affect psychological processes, such as task demand, produce indirect reflections propagated throughout the physiological system, a relationship exploited, for example, in attempts to derive physiological indices of mental workload (see Hancock, Meshkati, and Robertson, 1985; Wilson and O'Donnell, 1988). The reverse is also true, and as is clear in the work on circadian variation (see Colquhoun, 1971; Kleitman, 1939/1963; Moore-Ede et al., 1982), endogenous physiological state influences performance capability (see also Hockey, 1986).

A formal illustration of these modes of operation and the relationships among stress, adaptability, and response capacity are shown in Figure 2. An input stress (represented on the abscissa in Figure 2) can vary between extreme values of underload and overload, which are labeled *hypostress* and *hyperstress.* A zone of comfort is located at a central position on this continuum. It is possible that the zero level of a stress may fall within this region of comfort. In these cases stress generates only one side of the two-sided picture given in Figure 2. This unipolar representation is applicable to the influence of noise. Such a differentiation between unipolar (one-sided) and bipolar (two-sided) representations may result in the failure to find either the respective ascending or descending arm of the typical inverted-U description (see also Weiner, Curry, and Faustina, 1984).

The comfort zone is included within a larger region where psychological adaptability remains stable. As the level of stress progresses toward extremes, increasing discomfort is followed by a rapid decrease in psychological adaptability (the dotted line). Input stress drains adaptive capability at each level of the system. At the behavioral level stress drains psychological adaptability, which in Figure 2 is equated with attentional resources. In the present work attentional resources are taken to represent the global capacity notion as first advanced by Kahneman (1973). Although there have been a number of developments of this proposal (see Wickens, 1987), the more parsimonious unitary capacity conception is used as an initial connection to stress effects. A multiple attentional resource structure may be used, but the present level of information is insufficient to distinguish potential stress effects on differential attentional resources (see Kantowitz, 1985, for further discussion on the problems of ambiguity and operationalization of the capacity concept). Until the controversy concerning multiple resource theory is clarified (see Wickens, 1987), the simpler unitary capacity notion is adopted as a starting point for integration of stress and attentional characteristics.

For the effects of temperature, genesis of the failure in task efficiency occurs at the point when complete physiological compensation to the environment is no longer possible and dynamic stability is superseded by transition to dynamic instability (see Hancock, 1986c). Eventually loss of psychological adaptability is followed by a similar decrease in physiological adaptability. In this event homeostatic response mechanisms are overcome by the stress and the regulatory system changes mode of operation from steady-state negative feedback to positive feedback operation. This is represented for both physiologi-

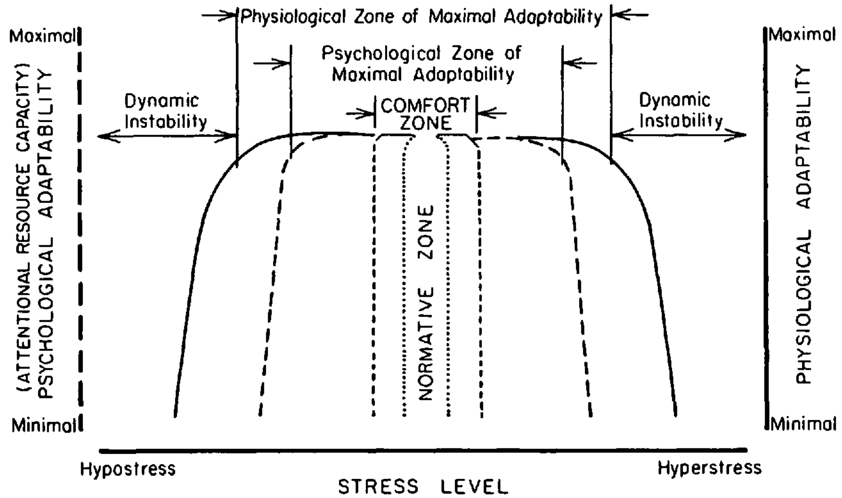

Figure 2. *Physiological adaptive capability (solid lines) and psychological adaptive capability (outer dashed lines: equated with attentional resource capacity) as functions of stress level. Embedded in these zones is a region of comfort sought by the active operator. A central normative zone describes a region in which compensatory action is minimized, as environmental input is insufficient to demand appreciable dynamic response. Within zones of maximal adaptability, negative feedback predominates. Outside stable limits, positive feedback induces dynamic instability that proceeds toward the breakdown of adaptive response and eventually functional failure.*

cal and psychological processes as the region of dynamic instability in Figure 2.

In other work (Hancock and Chignell, 1987) we have suggested that the manner in which cooperative human-machine systems may fail could replicate the changes of state noted earlier for the individual operator (see also Hancock and Chignell, 1988). This should be regarded not as a simple failure of the human element embedded within the larger system but as a change in system mode of operation. For example, in a typical vigilance task it is possible to increase signal intensity and to provide multimodal signal presentation when it becomes clear that the human monitor is missing critical signals (Warm and Jerison, 1984; Weiner, 1973). Within such adaptive systems it is possible that the change of state from stable, through transitional, to failure modes of operation remains a reasonable approximation of the breakdown process under the stress of an external driving influence.

The boundaries of the zones of maximal adaptability of physiological and psychological response may be continuous, requiring a statistical definition as in the concept of a psychophysical threshold. Alternatively, the boundaries may themselves represent discontinuities. In the latter case the point of discontinuity may be detected using a form of trend analysis for the case of a single stress source of increasing intensity. However, in many industrial environments the operator is exposed to the effect of multiple stress sources. In this multidimensional case in which interactions occur, the point of discontinuity can be represented as a cusp on a topological manifold. The type of cusp will depend on the nature of the interacting stress sources and may be described using the tenets of catastrophe theory (see Zeeman, 1977), though the simplistic application of this concept to behavioral phenomena should be approached with caution. For critiques of the use of catastrophe theory see Gardner (1983) and Sussmann and Zahler (1978), and for alternative arguments see Stewart and Peregoy (1983) and Kugler and Turvey (1987).

Figure 3 illustrates an extension to Figure 2 whereby the base axes have been subdivided into two differing characteristics. The axes are composed of information rate, which is the temporal flow of the environment, and information structure, *structure* being a nonpejorative term connoting *meaning* sought by the individual perceiver. Among other influences, meaning is contingent on previous experience with both task and stress (Hancock, 1986a) and also on expected future actions that depend on the aims and goals of the individual operator. As different individuals seek different meanings in a common environmental display, stereotypical behavior should not be expected at mild levels of stress, when many avenues are open to achieve desired goals. However, under extremes of load, the number of solution paths with respect to goal achievement diminishes. Therefore, it is at extremes of stress, when constraints are greatest, that common behavior across indi-

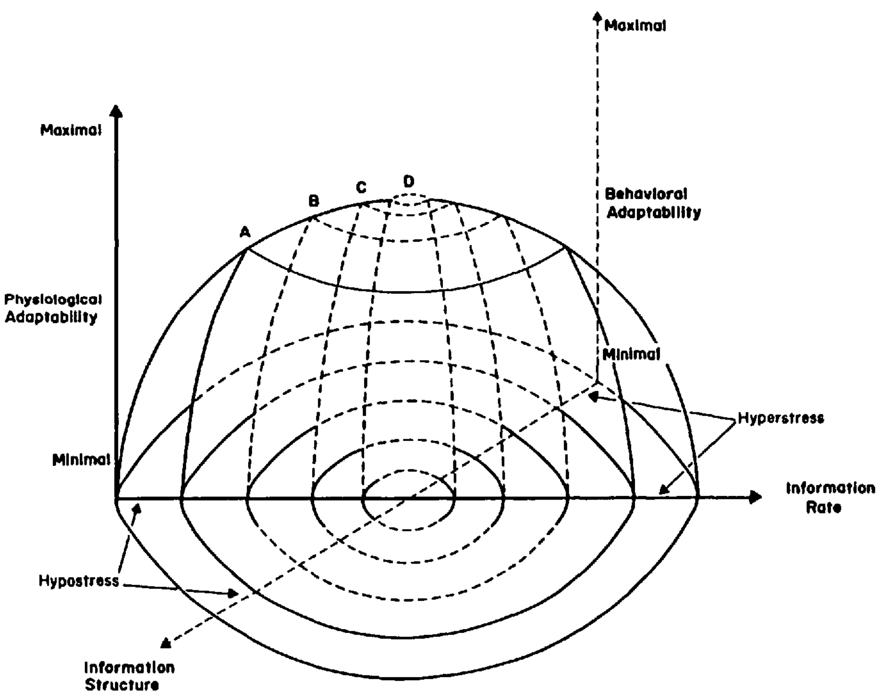

Figure 3. *Physiological and psychological adaptability as functions of hypostress and hyperstress expressed on the dual axes of information rate and information structure. Multiple stresses can be represented as summated scalars plotted as a single vector on the two-dimensional base. The necessity for costly adaptive response can be minimized by behavioral strategies that navigate the overall manifold around the perturbations presented by the environment and so avoid stressful conditions. The introduction of machine prosthetics greatly magnifies the range of tolerable environmental conditions through augmentation of human adaptability. Protective structures can either cushion or isolate the operator from large perturbations and thus obviate the need to engage in costly adaptive activity on behalf of the operator.*

viduals should be expected. The end point of such a continuum is a situation in which a single solution represents survival behavior, and within these constraints is therefore stereotypic.

The number of solution paths with respect to any task or assembly of tasks is constrained by the information in the environment. An information-rich environment allows numerous possibilities for successful outcomes, which are diminished in more arid, sterile solution spaces. Stress acts in a similar constraining manner to reduce the strategies available to the operator to successfully meet the task demands presented. With increases toward extremes on the respective stress axes, solutions become progressively stereotypical until, at the highest tolerable levels of stress, survival defines the single solution. These base axes are not strictly independent or orthogonal in that the content of information affects perceived flow, and vice versa (Doob, 1971; Hancock and Rosenberg, 1987). Thus it is commonly (though not universally) the case that low information rate provides less meaning to the perceiver and higher information rates provide greater meaning. This results in a deformation of the base axes at the circumferential periphery of adaptability, as illustrated in Figure 3.

The vertical axes of adaptability indicate that individuals *seek* to retain an optimum information flow via the available actions that can modify perceived rate and structure. This seeking strategy is manifest in behavior such as attentional narrowing, in which, under increasing stress, the perceiver narrows attention to cues of perceived greatest (meaning) salience (see Cornsweet, 1969, Easterbrook, 1959, and Wickens's 1987 review). It is also present in the load augmentation represented by stimulus hunger and magnification under conditions of sensory and perceptual deprivation whereby the absolute level and patterning, respectively, of environmental stimuli are reduced drastically (Zubek, 1964). If a task is performed with the necessity for little or no attentional resource dedication, as appears to be the case for "automatic"-type processes (see Schneider and Shiffrin, 1977), then little effect on performance should be expected with increasing levels of input stress. Experimental evidence appears to confirm this postulation (see Hancock, 1986a).

Upon the two base axes we have superimposed a topological manifold that expands on our previous formulations (see Hancock and Chignell, 1985). The center of the four sections represents a normative zone (Figure 3, point D). This is a location that demands no adaptive action, as input stress is insufficient to initiate compensatory activity by the individual. Considering that stress is an almost ubiquitous property of work conditions, residence in this zone is transient and inherently unstable, as task and environmental demands rapidly induce transgression of the zonal threshold. This normative zone is surrounded by a comfort zone. The concept of comfort has been variously defined, but, in this work we take the point of comfort violation to represent *the cognitive recognition of the failure of the current action of the dynamic adaptive process to counteract the impinging, multivariate matrix of input stress sources* (Figure 3, point C). This matrix is represented for the present purpose as a summated single vector of input stress the origin of which is the current location of the individual on the base axes. Vector direction represents the nature of overall stress action, and vector length represents the intensity of the input stress experienced. This concept is discussed in more detail later. It is on this vector representation, which is expressed in terms of energy-bound information available to the perceiver, that the actions of a number of stress sources with common paths of physiological action may be combined.

The individual has some degree of freedom with respect to manipulating the location of the manifold on the base. This freedom can be used in adapting to the various sources of stress as they occur. The use of freedom in this context is similar in conception to the factor of control, as referred to earlier from the work of Karasek (1979). Essentially this is the ability to navigate among the number of solution paths available. However, with progressive increase in stress, the individual sequentially violates comfort, performance, and, finally, physiological tolerance limits (Figure 3, points C, B, and A, respectively). It is suggested that the dynamic stability, as represented by the apex of each cylinder, may be modeled as a negative feedback form of control (Hancock, 1981). This form of control underlies successful action in each respective zone. In addition, the rapid failure as given by the side of each cylinder can be viewed as an expression of positive feedback. Thus while the transition from success to failure in each zone varies according to the level of stress experienced, the strategic adaptive action is replicated at each stage. This strategy transcends level of measurement focus whereby action at differing levels can also be modeled by the manifold presented (see Hancock, 1986b; Miller, 1978). In other work we have examined the use of principles of catastrophe theory to represent this series of progressive state transitions (see Zeeman, 1977). This application is not developed here, though efforts to derive quantified predictions from this construct are in progress (Hancock and Pierce, 1989). At the psychological level we view this seeking strategy as related to attentional resource utilization. This is an important behavioral trait in that we expect workers to attempt to optimize their information flow even in the face of considerable variation in the level of input stress.

Each input stress can be represented as a vector within the multidimensional space of Figure 3. A region centered on the origin of this space represents the comfort zone. The orientation of the vector will reflect the qualitative nature of the stress. The length (magnitude) of the vector will vary with the intensity of the input stress. Vector summation techniques can be used to predict interactions among stresses. Ekman and Lindman (1961) developed a vector model of multidimensional scaling and similarity judgments. In an analogy close to the present model, the length of the vector represented its intensity whereas the orientation of the vector referred to its qualitative character. The description of stresses within a vector model allows the quantitative assessment of stress interactions and prediction of the location of points of maximal adaptability for multiple stress combinations. A multivariate array of stresses can be replaced with a single vector that represents their summation. This vector will then define a point on a multidimensional manifold (as illustrated in Figure 3), which will in turn specify the levels of psychological and physiological adaptability and response capability.

The vector model is a convenient way of thinking about multiple stress interactions and the interaction between stress and the imposed demands of a particular task or group of tasks. However, quantification of stresses in terms of vector orientations and magnitudes is difficult. Stress scaling accuracy is dependent on the quality of existing knowledge, much of which has been shown to be poor and inadequate. Much of the relevant research has focused on sources of stress taken singly rather than in multivariate combinations. Factor analysis or multidimensional scaling (Kruskal, 1977; Davison, 1983) can be used to transform physical specifications of stresses into a reduced set of latent factors (dimensions), provided that sufficient data about similarities or correlations in the effects of different forms of stress are collected. Alternatively, canonical correlation analysis (Harris, 1975) might be used, though the resulting canonical variates are often difficult to interpret without further analysis (Bentler and Huba, 1982).

Initially, exploratory investigations of the relationship between stress and adaptability are likely to be most useful. In the absence of detailed information on how task demands and sources of stress interact, even an approximate scaling would be helpful in developing a model of the relationship between stress and adaptability. Such a model would indicate the progress of an exposed individual toward regions of dynamic instability. Intuitively an episode of exposure to multiple forms of stress would trace a path on the surface of the multidimensional manifold. Breakdown in physiological or psychological adaptability would correspond to leaving the plateau of the manifold, where in this stable region adaptability is not impaired significantly by the environmental stresses.

At this point we can address why the effects of temperature on vigilance provide patterns that can be captured simply, whereas those of variable noise remain essentially unresolved. Quite simply the three components of stress—input, adaption, and output—and their interconnection can be thoroughly documented for thermal effects. The input value may be described by a number of known indices; the compensatory processes of adaptation culminating in an eventual rise in core body temperature are established physiological sequences. The effect on output or goal-directed behavior thus presents clear consistencies (Hancock, 1986c). It is important to note that these consistencies were expressed in continuous exposures to the thermal stress, not pulsed or intermittent exposures. Our knowledge of the effects of exposure to essentially variable heat, are, like that of variable noise, similarly incomplete.

For noise the connection across the sequence of physical input (described in such terms as dBA), to adaptive response, to output behavior is much less clear, principally because we do not have a clear grasp of the pattern of physiological and behavioral compensatory actions undertaken to combat the effects of noise. This stems from a number of factors considered earlier, such as the relatively recent occurrence of noise as a stress on the organism, resulting in no acoustic analogue of body temperature. Without such knowledge the links among stable, transitional, and failure modes may not be distinguished, as they can be for temperature.

As our knowledge of the patterns of stress responses grows (Hockey and Hamilton, 1983), our ability to predict the action of recent and more complex stresses such as variable and intermittent noise improves. However, the difference between continuous exposures, in which time-based effects are cumulative, and intermittent exposures, in which elements such as submaximal recovery, acclimation, and fatigue enter the picture, will always be one of greater complexity. In reality the model is useful in predicting continuous exposure to simple forms of stress, as it involves essentially the imposition of a single vector on the base axes of Figure 3. However, the summation of multiple vectors, many of which have not yet received even cursory examination, essentially defeats preliminary attempts at quantification and prediction at the present time. This is no real criticism of the model but an acknowledgment that accurate quantification must precede prediction if the latter is not to be essentially meaningless. On a brighter note, information on continuous noise does appear to present a number of consistencies that may enable the distillation of a stress-related response pattern.

CONCLUSIONS

In order to achieve an integrated approach to stress and performance, it is essential to consider the type of demands imposed by a particular task or group of tasks. It has been argued most cogently that sustained attention or vigilance is a growing component of the job demands of many contemporary system operators (see Adams, 1987; Parasuraman, Warm, and Dember, 1987; Weiner, 1987; also see Moray, 1986, for related work on supervisory control). In performing these vigilance tasks individuals face an ever-widening spectrum of task-related and environmentally generated stresses. Added to these trends is the increasing requirement for high-speed and "error-free" performance in complex systems whose failure, or even periodic disruption, has serious societal consequences. Thus there is a growing need to understand the effects of stress in general and its effects on sustained attention in particular. These patterns, like many others in the stress literature, do not follow simple and expected trends (see Gluckman et al., 1988). Such incongruities emphasize the need for a comprehensive program of experimentation.

Currently the most widely accepted theoretical avenue for explaining stress effects on human performance is the notion of behavioral arousal. Although arousal has served a number of useful functions in developing interest and argument in the stress arena, its lack of predictive capability is a serious drawback. In addition, concerns over its descriptive clarity and its nature as a unitary construct have generated considerable concern. Further, the connection between physiological descriptions of arousal and behavioral correlates of performance is much more complex than the simple inverted-U curve implies. These criticisms and potential solutions have been elaborated elsewhere (see Hancock, 1987; Hockey and Hamilton, 1983; Naatanen, 1973).

In contrast to the arousal formulation, the present model is based on the concept of adaptability in both physiological and psychological terms and is tied to recent theories of human attention (Fisk, Ackerman, and Schneider, 1987; Wickens, 1987). Research findings concerning performance in the face of heat stress suggest that significant breakdown in capability is associated with the point at which thermoregulatory action is no longer capable of maintaining a state of dynamic stability (Hancock, 1986c). It is postulated that this isomorphism between physiological action and psychological response holds for the action of other sources of stress, though, as we have seen, the application of such a construct applied to the more complex effects of variable noise requires a much clearer understanding of the physiological effects of acoustic stress (see Koelega and Brinkman, 1986).

The concept of maximal adaptability can be extended to combinations of multiple tasks in the presence of numerous sources of stress. Spatial models of interactions will be useful in describing the relation between stress and human adaptability, but considerable experimental work is still needed. The effect of stress is seen in a reduction of available attentional capacity (psychological adaptability) and an increase in physiological strain that has to be compensated for by regulatory systems (physiological adaptability). This conception allows initially for the development of more precise tolerance limits to discrete sources of stress which are therefore based on physical parameters of the environmental or input stress. However, as the task itself is considered a primary form of stress—and vigilance clearly presents an impoverished display that still demands a difficult discrimination—then interactions between tasks and between combinations of tasks and environmental stresses can also be projected onto the base of the manifold as represented in Figure 3.

At the present stage of development it would be overly simple to suggest that the current model can provide complete solutions to the numerous problems posed by the effect of both single and multivariate sources of stress on operator performance. Of particular concern is the quantitative identification of the numerous factors that, together with the sources of stress, should be integrated to provide the vector representations as inputs to the model, as illustrated in Figure 3. Further, prediction implies a knowledge of the goals and skills of the individual performer. Such questions of individual differences remain to be adequately addressed for veridical simulation of response to be realized (but see Fisk et al., 1987).

However, the model does provide insight into the failure of an operator under the driving influences of stress. Further, a number of potential avenues are opened through which solutions to the complex challenge of stress and performance might be posed. The model has the advantage of being generated specifically for stress effects and is not the result of applying a conception derived from weakly related areas of research. With specification of the sources of stress it provides testable propositions that, if confirmed, would provide the predictive capacity so clearly absent in the behavioral arousal conceptualization. The model implies some fundamental commonalities across all forms of stress and suggests that the physiological and cognitive response strategies that meet such perturbations are companion expressions of a single response strategy. The model therefore provides a general architecture from which the clearly needed theoretical structure to explain the actions of stress on operator capability can emerge.

ACKNOWLEDGMENTS

This work was supported by Grant NCC 2-379 from the National Aeronautics and Space Administration. Sandy Hart was the technical monitor for the grant. The views expressed are those of the authors and do not necessarily represent those of the named agency. The authors would like to thank Dr. R. Parasuraman, Dr. M. H. Chignell, Dr. M. Vercruyssen, Tina Mihaly, and six anonymous reviewers for their critical and helpful comments on earlier versions of this work.

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