Compensatory control in the regulation of human performance under stress and high workload: A cognitive-energetical framework

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Abstract

This paper presents a cognitive-energetical framework for the analysis of effects of stress and high workload on human performance. Following Kahneman's (1973) model, regulation of goals and actions is assumed to require the operation of a compensatory control mechanism, which allocates resources dynamically. A two-level compensatory control model provides the basis for a mechanism of resource allocation through an effort monitor, sensitive to changes in the level of regulatory activity, coupled with a supervisory controller which can implement different modes of performance-cost trade-off. Performance may be protected under stress by the recruitment of further resources, but only at the expense of increased subjective effort, and behavioural and physiological costs. Alternatively, stability can be achieved by reducing performance goals, without further costs. Predictions about patterns of latent decrement under performance protection are evaluated in relation to the human performance literature. Even where no primary task decrements may be detected, performance may show disruption of subsidiary activities or the use of less efficient strategies, as well as increased psychophysiological activation, strain, and fatigue after-effects. Finally, the paper discusses implications of the model for the assessment of work strain, with a focus on individual-level patterns of regulatory activity and coping. © 1997 Elsevier Science B.V.

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1. Introduction

The present paper puts forward the case for a cognitive-energetical framework for research on human performance, emphasising the intimate relationship between behaviour and its biological/motivational context. The central concern of cognitive energetics is that, by neglecting the biological context of behaviour, computational models of human information processing cannot provide adequate accounts of the variability of human performance under stress, emotion, and other conditions that affect the general state of the organism. A cognitive energetics approach argues for the incorporation of energy-based constructs into information processing models, bringing together current cognitive approaches and traditional concerns with the intensity or energising of behaviour (Freeman, 1948; Duffy, 1962). The theory is illustrated through the development of a compensatory control model to account for the different patterns of effects on performance observed under stress and high workload. In addition, however, it provides a framework for the analysis of broader research issues, such as those associated with psychological health, strain, coping, fatigue and individual differences in adjustment, particularly in relation to adjustment to the demands of human work (Hockey, 1993).

A preliminary attempt to provide a forum for discussing these issues was the 1985 workshop held at Les Arcs, France (Hockey et al., 1986). A small group of 30 or so participants spent 5 days discussing how energetical constructs such as effort, activation, arousal, stress, fatigue and resources could be built into computational models of behaviour, and whether such an integration was necessary or desirable. The overwhelming conclusion of the workshop was that the development of an integrative framework was absolutely necessary if the two sets of theories were to remain in contact with each other, though (perhaps understandably) few promising ideas emerged about how this might be achieved. Gopher & Sanders (1984) and Gopher (1986) have tried to integrate the computational structure of processing stages (Sternberg, 1969) with the Pribram & McGuinness (1975) model of energetical mechanisms. In this, arousal is identified with early processing (encoding and feature extraction), and activation with motor adjustment and response preparation. Effort is located centrally as a co-ordinating process, adjusting the balance of input and output operations, and mediating high level feedback from response outcomes, though it is also argued to provide the basis of computational control for central decision processes. Although this approach has much to recommend it, it appears too committed to a particular linear structural model of (simple) performance, and fails to provide a mechanism for changes of strategy and control options. Also in the Les Arcs volume, Wickens (1986) refers to energetical mechanisms in terms of the intensity aspect of information processing, and suggests the inclusion of a gain vector in human information processing models to account for these influences. Again, though, apart from the direct relevance of gain process for manual control and tracking, there seems little opportunity of developing a general model of this kind to handle the complexity of the performance/cost patterns across the broader panoply of tasks, stressors and environmental conditions.
The analysis presented here can be seen as a further attempt to combine energetical processes with information processing models, through the development of a generalised control model. It goes further than previous approaches in providing a mechanism for the dynamic regulatory activity underlying the adaptive response to environmental demands. Unlike traditional activation theory, in which energetical processes are essentially stimulus-driven (Duffy, 1962; Malmo, 1959) the current approach assumes that energetic resources may be allocated and controlled, and subject to strategic resource-management decisions. In this emphasis it builds on the work of Broadbent (1971) and Kahneman (1973), the only major earlier attempts to integrate energetical processes into an information processing model. It differs from these approaches, however, in emphasising the motivational control of action. This assumes that (1) behaviour is essentially goal-directed; (2) control of goal states is normally a self-regulatory process, and (3) regulatory activity attracts costs to other parts of the system.

This approach reflects the insistence by Young (1961) that motivation has to be recognised as more than just a driving or energising force. Instead, it involves the whole cycle of initiation, maintenance and regulation of action. In common with other motivational control models (Carver & Scheier, 1982; Powers, 1973; Schönpflug, 1983) the self-regulatory characteristic of control means that behaviour is modified by reference to internal standards or set points (through negative feedback) so that currently active goals may be maintained, and purposive behaviour promoted. A distinctive feature of the cognitive energetics approach adopted here is to recognise that such regulatory activity may attract costs to emotional and physiological sub-systems, particularly when carried out under conditions of chronic perturbation from stress and environmental load. At a first level of approximation, these costs may be interpreted as an expenditure of mental resources. They are experienced subjectively as mental effort and high levels of subjective strain, and physiologically by increased levels of sympathetic dominance and adreno-medullary activation (Frankenhaeuser, 1986; Kahneman, 1973).

1.1. Resources and effort

The construct of resources is central to the development of an integrative model, since it has strong roots in both information processing and energetic theories. From the perspective of human information processing theory, resources have been implicated in all capacity models of attention, memory and dual-task performance. While not denying structural factors (Broadbent, 1971; Kahneman, 1973; Norman & Bobrow, 1975) capacity theories assume that the patterning of human performance cannot be fully understood without reference to a concept of resources. These are conceptualised as the availability of one or more pools of general-purpose processing units, capable of performing elementary operations across a range of tasks, and drawing upon common 'energy' sources (Gopher, 1986; Kahneman, 1973; Wickens, 1984). There may be several such resource pools, as in multiple resource theory (Navon & Gopher, 1979; Wickens, 1984), serving different families of processing needs. To distinguish it from other factors which also limit
multiple performance, the resource construct also implies scarcity (the limited capacity assumption), so that simultaneous mental operations making demands on the same pool of resources must compete for processing units.

In addition to the scarcity criterion, which has dominated research on multiple task performance, resources has also been used in a different sense, to imply the mobilisation of energy; to refer to activities which attract costs and mental effort. It is this effort idea which is most readily identified with resources from the energetical perspective. In many information processing treatments effort and resources have been regarded as essentially synonymous. The widely-use 'processing effort' (Norman & Bobrow, 1975) appears to be deliberately ambiguous with respect to the two meanings. Only in Kahneman's (1973) theory is there any direct discussion of the possible energetical consequences of the allocation of processing effort. Following the important insight by Moray (1967) that central processing capacity may be allocated strategically by higher level (executive) influences, Kahneman identified effort with the action of maintaining a task activity in focal attention, showing that only some activities (rehearsal, comparison, motor control, etc.), now thought of as involving the central executive, depended on effort (resources). Kahneman argued not only that effort provided an increase in overall resources (to meet prevailing demands), but that it attracted costs in terms of sympathetic activation (e.g., pupillary dilation (Beatty, 1982).

As with most other theorists, Kahneman's use of the effort construct is associated chiefly with variations between tasks in processing demands (effort as controlled processing), though he also addresses a second sense of effortful regulation (Kahneman, 1970). This refers to the attempt to maintain a particular task state under stress, overload or external distraction (effort as compensatory control). Whether these two manifestations of effort are really different, as Mulder (1986) implies, or part of the same general mechanism remains to be determined, though both impose a problem resource management. In this paper, stress is considered primarily from the perspective of task performance. Stress states are identified with the occurrence of a mismatch between required and prevailing task states, normally arising from an external disturbance which attracts processing resources. As argued in the regulatory model presented below, an effort-based compensatory control mechanism may be needed not only for maintaining tasks under disturbance from stressors, but for preventing the loss of task goals under all circumstances, including increased processing demands and competition from other tasks. For the present, then, since there are no strong arguments for rejecting parsimony, the two kinds of effort are regarded as different aspects of the same process. We return to this issue in the discussion of the role of effort regulation in compensatory control.

Despite the intuitive appeal of the resource construct, some critics (Navon, 1984) have argued that it has no underlying reality, and has little role to play in the explanation of effects of task difficulty and dual-task interference. The arguments for and against resource theory are complex, and considered in detail elsewhere (Sanders & Koke, this volume). The present discussion is, in any case, focused on the less well-documented application of energetical resources (effort) to the management of performance under stress. Whatever the ultimate value of the resource
construct in the explanation of multiple task performance, this author will argue
that, in the explanation of performance under stress, the more specific energetical
construct of mental effort is difficult to avoid.

1.2. The relativity of performance goals

The focus of the paper is on the role of compensatory effort in the management
of human performance under conditions normally thought to be stressful. The term
'human performance' has come to have a narrow range of meanings within
experimental psychology and human factors. It is normally understood to refer
either to (a) the effectiveness of specific skills in meeting (typically externally-im-
posed) cognitive goals, or (b) the underlying mental operations associated with such
behaviour. Although performance tasks are widely used to provide indirect mea-
sures of underlying mental activity, the logic of these methods is not always
appreciated. From the investigator's point of view, tasks are designed as indicators
of the functional level of underlying processes or mental operations. If the process
is operating less effectively (say, under stress or illness, or because of competition
from other mental operations) the task is assumed to reflect this as a reduced level
of overt performance (assuming that it is sensitive to variations in resource
deployment, rather than operating within what Norman & Bobrow (1975) refer to
as the 'data-limited' range). From the point of view of participants, however, tasks
are essentially externally-imposed goals, requiring them to direct behaviour towards
the achievement of (arbitrary) target outputs over a (typically brief) period of time.
The methodology of performance tasks assumes that the individual is co-operative
and motivated — that goals are internalised and maintained, and afforded a high
level of priority over the required duration of the task. This means continually
refreshing their salience in focal attention, selectively attending to task-relevant
information, avoiding distraction from competing (more relevant, long-term) goals,
etc.

It is sometimes forgotten that a decision to 'perform' cognitive tasks is taken at
the expense of other kinds of behaviour. These may also be cognitive activities,
though with a personal relevance (planning essays or holidays, watching TV,
reading), or determined by more fundamental biological goals (eating or drinking,
expressing emotion, or just resting). In addition, since sustaining an effortful state
is often difficult and subjectively aversive (Kahnean, 1973), carrying out any
demanding mental task may conflict with the more general emotional goal of
maintaining personal well-being and desired affective states. Unlike the vulnerable,
temporary goals that drive task behaviour, the various competing actions that
subserve personal and biological goals are, in many cases, driven by powerful,
self-sustaining motivational systems. Nevertheless, the maintenance of task involve-
ment is not possible without overcoming such competition, and, as Kahneman
(1970) points out, task performance is typically highly reliable and resistant to
distraction. This means that any model of performance must provide a plausible
mechanism for attentional control to be highly effective in the face of competing
activity. It is argued here that maintaining task goals in focal attention is effective
precisely because they are so vulnerable. They require the protection of special purpose mechanisms (usually referred to as selective attention, and experienced as effort or concentration), which need to be continually activated in order to overcome the threat of disruption from concurrent biological and motivational goals.

2. A state regulation model of compensatory control

Before considering the analysis of decrement under stress in terms of patterns of latent decrement, let us consider how such a compensatory control mechanism might operate. The key facts to be explained by an energetical analysis of performance (e.g., Hancock & Warm, 1989; Hockey, 1993; Kahneman, 1971; Teichner, 1968) are (1) That primary task performance is remarkably stable under stress and high demands, and (2) That effective performance under stress is typically accompanied by high levels of physiological activation and subjective strain. It is also apparent (3) that where they occur, overt decrements are normally quite small in magnitude, and more common under laboratory conditions than in naturalistic work settings. The reason for this latter observation has not been formally explored, though it is likely to be related to a high level of motivational control when carrying out real jobs (Hockey, 1993). These may be assumed to encourage more effective control of task performance, because of the greater commitment to work goals and the higher levels of skill.

Over the past 10 years or so (Hockey & Hamilton, 1983; Hockey, 1986; Hockey et al., 1989; Hockey, 1993) we have developed a regulatory-control model to account for the effects of stress on performance. The energetical-control framework argues that the maintenance of performance stability under demanding conditions is an active process under the control of the individual, requiring the management of cognitive resources through the mobilisation of mental effort. Management of effort allows individuals to control the effectiveness of task behaviour in relation to competing concurrent goals, changing demands, and current levels of energetic resources. Essentially, this provides them with the option of adopting a 'performance protection' strategy — to maintain high priority task goals within acceptable limits, though only by incurring extra costs — or of accepting a reduction in overt performance (with no increase in costs). Under most circumstances an increased commitment to task goals is assumed to imply a decrease in the relevance of other personal or biological goals, such as those concerned with leisure, rest or well-being.

2.1. Outline of the model

The broad features of the model are outlined in Fig. 1. It makes a distinction between two levels of control — one associated with lower level, routine regulation (loop A); the other with upper level, effort-based regulation (loop B). In terms of control theory, overt performance is assumed to be driven by internally-maintained
states (determined by both long-term and short-term goals), which determine output criteria for behaviour (how fast to work, how much monitoring of accuracy is required, the order in which actions are executed, and so on): performance output values are continually adjusted to match these (goal-driven) target states. From an energetical perspective, the target state is assumed to be subject to modification in the light of changes in the perceived costs and benefits of alternative states and actions (Hockey, 1993; Schönpflug, 1983). As with all negative feedback systems, control is achieved by comparing target output values with current activity (in this model through an action monitor), and changing the output until the discrepancy is removed (or kept within acceptable limits of error tolerance). The lower loop (A) represents what is often called the 'automatic' control of well-learned skills under the guidance of well-established performance goals. These are typically assumed to require no active regulation or effort, in contrast with controlled or effortful processing, though the energetical model outlined here assumes a continuum of skill-effort levels. The regulation of highly-skilled behaviour is well-represented elsewhere (Wickens, 1992) and is not discussed in detail here. Although performance may be threatened by perturbation from both internal and external events, routine control actions are normally sufficient to maintain stability of output.

2.2. Effort regulation

The routine corrections required for 'automatic' cognitive skills may be assumed to occur without appreciable cost (without effort). It is argued that a second level of control (loop B) is, however, needed to deal with regulation where the discrepancy is too great for low-level corrections to bring it within the target range. A distinction between upper and low levels appears to be the minimum complexity

![Diagram](Fig. 1. Compensatory control model of performance regulation. Loop A represents routine regulatory activity, and loop B effort-based control (see text for explanation).)
needed to account for the data on effects of stressors, attentional demands and performance management (Broadbent, 1971; Rasmussen, 1986; Shallice & Burgess, 1993), and some action theory approaches typically assume a multiple-level hierarchy of regulatory control (Frese and Zapf, 1994). The approach offered here has its origins in the two-level control model of Hamilton et al. (1977), and in Teichner's (1968) hypothesis of compensatory environmental control of stress states, though it has much in common with the explanatory framework developed by Schönpflug (1983). In both cases, the regulation of action is assumed to involve cost-benefit decisions about the use of effort and the relative value of different goals.

In the regulatory control model presented here the upper level is identified with the management of effort (interpreted as the subjective awareness of resource deployment). The effort monitor is assumed to be sensitive to increasing control demands in the lower loop (e.g., a failure to resolve the discrepancy, a slow rate of resolution, high variance of outputs). This is necessary to account for the sensitivity of subjective effort to task-induced increases in demand. Unlike Kahneman (1973), however, we argue that effort is not automatically increased to meet these new demands. Rather, perception of the change in load causes control to be temporarily shifted to the higher level (here called the supervisory controller), where several optional modes of regulation are available. An important implication of the two level model is that the control system requires two separate levels of the effort monitor, both upper and lower set-points. The lower set point is a default for a given task environment (the working effort budget), based on the anticipated resource needs of the task, level of skill, and so on. Increases in demands below this level are not felt as effortful, and control of performance appears automatic (loop A). The upper set point represents an operational maximum for effort expenditure, the difference between the two providing a reserve effort budget for meeting additional demands, unpredictable changes in the demands-resources balance, or the additional burden associated with stressful environments.

The two-level effort system provides a possible solution to the theoretical problem of whether there are two kinds of effort or only one (Mulder, 1986). In terms of the compensatory control model, there is only one kind of effort, but two levels or settings. The lower set point is equivalent to the computational effort associated with task demands. It is determined primarily by an assessment of processing requirements for specific tasks, normally well below the assumed functional limits for effort expenditure, and is likely to be quite stable for a given individual. The upper limit, by contrast, is more clearly motivational in origin, and more variable. It is assumed to be a function of individual differences in the perceived value of tasks goals, in the response to challenge, in the capacity for sustained work, and in the tolerance of aversive states associated with high levels of strain. It is also likely to change more under the influence of short-term factors such as fatigue (Holding, 1983) and prevailing affective states (Ellis & Ashbrook, 1988; Wiethoff & Hockey, 1996). The upper limit of the effort budget may be increased for activities which are more unpredictable or more critical in terms of outcomes (for example, allowing the individual to respond with an increased work-rate to
meet a newly-imposed deadline, or to maintain stable levels of performance in the presence of sudden increases in noise). Correspondingly, the reserve budget may be set quite low when overall capacity has been compromised by recent illness or chronic stress. We would argue that this second level of effort allocation is more strongly associated with patterns of performance degradation under stress and high workload. A small reserve budget will typically give rise to overt decrements under stress, while a larger budget is more likely to be associated with sustained performance and increased costs.

2.3. Modes of control, coping and strain

Different patterns of performance/cost trade-off are hypothesised for the upper and lower settings of the effort control system. At the lower level occasional increases in perceived effort above the set point signal the need for occasional supervisory involvement. More persistent increases may require an upwards adjustment of the working effort budget, to allow routine correction to proceed at a higher level. This would be necessary, for example, when imperfectly-learned skills impose a greater demand than anticipated, or when minor environmental perturbations (noise, or other distractions) are more frequent. Behavioural stability remains high under these conditions, and effort well within reserve limits, though the overall level of mental activity (energy) is increased. We refer to this mode as active coping (or control), broadly corresponding with Frankenhaeuser’s description of challenge situations as involving ‘effort without distress’ (Frankenhaeuser, 1986). Hockey et al. (1996) present a comparison of the two classification schemes. These states are typically associated with an elevated catecholamine response, but no increase in cortisol. In cognitive terms, active control involves increased working memory or executive control (Baddeley, 1986; Shallice & Burgess, 1993), or the use of rule- or knowledge-based levels of responding (Rasmussen, 1986), and may be considered a standard feature of non-routine mental work.

A more serious problem for the effort control system occurs when the perceived level of difficulty is too great to be met by small adjustments to the working effort budget. While there is evidence that subjective limits for maximum effort expenditure are relatively conservative, even for physical tasks (Holding, 1983), operating at higher levels of effort for any length of time is known to be uncomfortable and avoided whenever possible (Wickens, 1986). Such conditions are also regarded as a major source of fatigue associated with cognitive work (Hockey et al., 1989). Within the regulatory model shown in Fig. 1, two broad control options are available for resolving the discrepancy between increasing demands and the upper point for effort expenditure, with different consequences for task performance and energetical costs. In the strain coping mode, the maximum effort budget may be increased still further to accommodate the new level of demand. Target performance criteria can then be maintained, but only at the expense of an increase in energetical costs. This corresponds with the Frankenhaeuser (1986) ‘effort with distress’ pattern of coping. In addition to the affective state features of anxiety and fatigue, it is also associated with high levels of sympathetic dominance, and
increased excretion of both catecholamines and cortisol. Such a state is clearly aversive, though it is unlikely to pose any serious problem for the adaptive process under normal circumstances: the shift to the higher level of effort may be brief, or involve only a moderate increase in the budget.

An alternative response to excessive demands is to adopt a passive coping mode, involving downwards adjustment of performance targets. By leaving the maximum effort budget at its present level this strategy does not incur further costs (which are already high), though it withdraws protection from the disruption of performance. A reduction of goal orientation may be achieved, for example, by reducing required levels of accuracy or speed, by adopting strategies which make less demands on supervisory control, or by paying less attention to subsidiary activities. In critical work tasks, or other situations where a loss of performance standards is personally distressing, the passive mode maps closely onto Frankenhaeuser's 'distress without effort' pattern. This state is associated with increased adrenocortical activity, often found in environmental contexts with restricted instrumental control opportunities (helplessness). An extreme form of passive control is the complete disengagement from the pursuit of task goals. While such a response to the demand for further effort mobilisation is rare in task-oriented contexts, it may be more common in self-managed tasks where time constraints are not normally severe (academic writing, for example?). The activity can be interrupted, and started again when the individual regards him- or herself as being in a 'suitable state'. Even in laboratory tasks, disengagement under stressful work conditions is sometimes observed when further effort expenditure is found not to be effective (or even counter-productive) for maintaining performance (Schultz & Schönpflug, 1982). Where demands are excessive (such that they exceed the set upper limit for effort expenditure), some variant of the indirect strategy would normally be more appropriate. While an active coping response is almost always possible (and necessary in critical emergency situations) it is likely to be maladaptive as an habitual pattern of response to work, or if sustained over a prolonged period (Hockey, 1993).

3. Latent performance decrements under stress

An understanding of the compensatory trade-off between cognitive goals and effort is central to an explanation of performance changes under stress and high workload. Because of this, performance measurement needs to be concerned not only with effectiveness but with the efficiency of behaviour (Hockey, 1996; Schönpflug, 1983). Studies of performance under stress have typically been concerned only with the former — with how well specific output targets are achieved under different conditions. A concern with system efficiency, however, means taking into account the costs of achieving these outputs. This is particularly relevant when comparing conditions in which manifest performance does not differ, since it may indicate that success in maintaining the required standard is achieved at the expense of disruption to other (currently less important) processes. We refer to this as a latent decrement, since it reflects a compromised system state which, although
hidden under normal operational conditions, imposes constraints on adaptability in the face of further or changing demands. Efficiency takes into account the costs of delivering effective action, but also the occurrence of concurrent (or delayed) changes in other system functions, and the capability of the system for absorbing further demands.

A concern with at least some of these issues has been well-established in research on workload and multiple task performance (O'Donnell & Eggemeier, 1986; Wickens, 1992), where primary task decrements are regarded as only one of a number of techniques for detecting differential demands of tasks. Decrements under high load can also be observed indirectly, through the use of secondary tasks, subjective reports and physiological indices (Hockey, 1996). We would argue that the same kinds of considerations hold for the analysis of performance under stress, and that the mechanism of compensatory control has a major role in the patterning of these (hidden) decrements in both domains.

The regulatory control model provides a broad framework for the analysis of performance changes under both kinds of environmental threat: stress and high workload. The compensatory processes involved in system regulation mean that, for detecting effects of performance disruption, we need to consider not only primary (overt) task activity, but also secondary criteria and the costs of increased regulatory activity. Even where primary performance is maintained without loss, the increased strain of performance protection is expected to result in changes in other aspects of overall system performance. In some cases chronic stress or illness may result in a reduction of the maximum effort budget. In others, attention resources may be withdrawn from the central task to deal with perceived threats to emotional stability (e.g., under noise or high state anxiety). In all cases, however, primary goals may be maintained, either by reconfiguration of remaining resources (allowing secondary tasks to incur errors or delays), or by recruitment of additional resources. As we have said, this second option is likely to be associated with increased effort allocation and corresponding metabolic activity, and lead to further indirect costs (e.g., suppression of vagal regulatory processes (Mulder, 1986)). Where reconfiguration cannot achieve the desired effect, or further effortful response is not possible (or desirable), primary task decrements may, of course, be observed. The observed protection of primary performance applies especially to the work environment (Hockey, 1993), because of the external support for task-oriented motivation and the typically high level of task skills. Although degradation (or enhancement) of primary task activity is therefore unusual, the operation of such regulatory processes implies that we should be able to observe changes which reflect increased or decreased costs under different conditions. Four more or less distinct forms of latent breakdown in performance may be identified (Table 1), although they are all argued to be manifestations of the same regulatory process.

3.1. Subsidiary task failures

As observed in workload paradigms, effects of stress states may be detected more readily in less central components of behaviour. Little needs to be said about these,
Table 1
Types of latent decrement associated with performance protection under stress and high demand

<table>
<thead>
<tr>
<th>Type of latent decrement</th>
<th>Characteristics (with examples)</th>
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<tr>
<td>Subsidiary task failure</td>
<td>Selective impairment of (currently) low priority task components</td>
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<td></td>
<td>Neglect of subsidiary activities</td>
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<td></td>
<td>Attentional narrowing</td>
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<tr>
<td>Strategic adjustment</td>
<td>Within task shift to simpler strategies</td>
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<td></td>
<td>Less use of working memory</td>
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<td></td>
<td>Greater use of closed-loop control</td>
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<tr>
<td>Compensatory costs</td>
<td>Strain of active control during performance maintenance</td>
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<tr>
<td></td>
<td>Increased mental effort</td>
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<td></td>
<td>Sympathetic dominance</td>
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<tr>
<td>Fatigue after-effects</td>
<td>Post-task preference for low-effort strategies</td>
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<td></td>
<td>Subjective fatigue</td>
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<td></td>
<td>Risky decision-making</td>
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since their general characteristics are well-known. Effects of stressors on subsidiary aspects of performance are relatively common, though not generally known because of a limited application of the methodology in this area (Hockey, 1996). One of the best-documented forms of secondary task decrement under stress is the narrowing of attention found in dual task spatial displays. Such effects have been found under both laboratory and field conditions for a range of conditions: noise, deep sea diving, threat of shock, fatigue, and many other environmental and work variables (Baddeley, 1972; Broadbent, 1971; Hockey, 1979). For example, Hockey (1970) found that central tracking improved in noise while the detection of peripheral signals was impaired. This effect may also be considered to involve a strategic adjustment (as below), since the detailed pattern of performance depends on the manipulation of priority differences between task components. In the interpretation of this kind of finding we would argue that what is perceived as primary is protected, and everything else is dealt with only where resources permit. The effect does not depend on spatial distribution of attention per se. We have also found such effects in performance of a complex simulation task, based on a cabin air pressure/life support system (Hockey et al., 1993). This required operators to maintain critical cabin parameters (oxygen, carbon dioxide, pressure) within target limits over a continuous 3-h period, while various fault states were imposed on the task. Perhaps surprisingly, they were able to carry out this demanding primary task equally well after a night without sleep, though there was widespread impairment of subsidiary activities: reactions to false alarm probes were slower, the timing of administrative actions more variable, and the diagnosis of fault states less accurate.

3.2. Strategic adjustment

Under some circumstances, serious disruption to primary task outputs may be minimised by a change in the way the task is carried out. Where flexibility of output
criteria is possible, strategy adjustments may take the form of less effortful modes of processing under stress. This enables the operator to cut back on control requirements (for example, by reducing the time spent on monitoring of feedback or on checking the effectiveness of decisions, or processing information in larger chunks (Wickens, 1992)). Even in simple tasks such as choice RT, conditions such as noise, time pressure or state anxiety have sometimes been found to cause a shift in the speed-accuracy trade-off function, towards a faster but less accurate mode of responding (Hockey & Hamilton, 1983). In more complex tasks a reduction of effort often takes the form of reduced involvement of working memory or a shift towards a less resource-intensive mode of control; e.g., from knowledge-based to rule-based in the Rasmussen (1986) taxonomy, or from open-loop to closed-loop control (Bainbridge, 1978). This reduces the dependency on demanding cognitive processes such as working memory, but may make performance vulnerable to sudden increases in demand. Despite their obvious diagnostic value, such indirect measures of degradation have not been widely used, within either workload or stress research.

A good example of this kind of change is the well-known study by Sperandio (1978). He found that air traffic controllers adopt a more routinised work pattern when the number of aircraft contacts increased beyond their ‘comfortable’ workload level, switching from a strategy of individual routing for each contact to a fixed procedure for all. This reduction in planning complexity reduces the load on the vulnerable working memory system, preserving the primary goal of safety, while compromising secondary goals such as airport scheduling and passenger comfort. Similar kinds of strategy changes have been found in the simulation study referred to above (Hockey et al., 1993). In addition to the decrement in secondary task activities, performance protection for the primary task was achieved through a simplification of control strategies. Operators carried out less monitoring of the current status of system parameters under sleep deprivation, instead relying on manual interventions to correct the system when parameters drifted out of range. This is consistent with observations by Sheridan (1972) that active sampling of displays is an effort-demanding process, and suggests that sleep-deprivation imposes an additional burden on effort mobilisation. A final example of strategy changes under stress is the innovative series of studies by Schönpflug and his colleagues, using simulated office tasks (Schönpflug, 1983; Schultz & Schönpflug, 1982). In a stock control task, participants responded to stressors such as time pressure and loud noise by making more frequent checks of computerised reference information about stock holdings and unit prices. Whereas under normal conditions this information was much more likely to be held in memory while making a series of decisions, under stress subjects tended to check the lists before making each decision. Since decision errors did not increase in the stressful conditions, the results show that reducing the load on memory helped subjects to protect the primary task goals, though at the expense of increased time costs.
3.3. Compensatory costs

The compensatory control model predicts that, under the (high effort) direct coping mode, the mobilisation of further resources should be revealed as increased activation of physiological systems involved in 'emergency' reactions (e.g., sympathetic and musculo-skeletal responses, neuroendocrine stress patterns). There are also likely to be effects on mood states reflecting the affective response to emergency and sustained coping effort. While these are not direct measures of the latent breakdown of performance, they can be thought of as the unwanted side-effects of the compensatory behaviour helping to maintain primary performance under extreme conditions. This compensatory effect of effort is illustrated in an early study of sleep deprivation (Wilkinson, 1962) in which decrements in arithmetic computation were smaller for subjects who showed increased muscle tension (interpreted as effort to combat sleepiness and maintain orientation towards the task). The performance-cost trade off is seen more clearly in two recent studies of noise effects, using more meaningful psychophysiological measures. Lundberg & Frankenhaeuser (1978) found two patterns of arithmetic performance and costs under noise in different studies; either a decrement with no changes in adrenaline and subjective effort, or maintained performance with increased levels of adrenaline and effort. Veldman (1992) also found that the maintenance of performance under noise (on various memory and search tasks) was accompanied by marked increases in heart rate and blood pressure. In a recent field study (Rissler & Jacobson, 1987) an absence of performance decrements during an intense period of office change was, again, accompanied by a compensatory increase in adrenaline and cognitive effort. Such effects illustrate the role of compensatory regulation in the protection of performance, and may be seen as a trade-off between the protection of the primary performance goal and the level of mental effort that has to be invested in the task. These and other more recent studies (Hockey, 1993) indicate that the regulation of effort is at least partially under the control of the individual, rather than being an automatic feature of task or environmental conditions.

The costs of commitment to high priority goals are presented normally only in terms of normative patterns of response to stressors, though such effects are subject to considerable individual differences. Some individuals are more likely to react by clinging strongly to task goals, while others may be indifferent to the challenge provided by the prevailing stress conditions. To predict such differences we would need to establish the goal hierarchies for the sample, and the degree to which primary goals are perceived to be under threat. For example, Vogel et al. (1959) compared students with a higher commitment either to academic achievement or social affiliation. The former showed increased psychophysiological responses only under the stress of academic performance being assessed, and the latter only when they were being evaluated by their peers. Similarly, Bergman & Magnusson (1979) found elevated adrenaline levels in academic testing to be much higher for 'over-achievers' (with a stronger commitment to the primary goal) than for their classmates. These differences in goal commitment do not appear to have been explored in the context of task performance under stress. At least in field studies of
real jobs, however, we would expect to see stronger psychophysiological responses (and better performance protection) in individuals who were more committed to their work goals.

3.4. Fatigue after-effects

Finally, since compensatory activity attracts costs, which are aversive, the model predicts a shift to a low effort mode of control whenever changes in task demands permit. This is most strongly expected as fatigue after-effects, in the form of decrements on probe tasks presented at the end of exposure to the stressor or demanding work. Such effects have been studied very little, and then normally within a classical workload/fatigue paradigm (Broadbent, 1979; Holding, 1983), though they are equally appropriate as a response to working under stressful environmental conditions (Hockey, 1993). Because of its widely-recognised importance, work fatigue has been studied extensively since the early days of psychology, though the search for a sensitive test of the carry-over effect of sustained mental work to the performance of new tasks has proved elusive (Broadbent, 1979). Holding (1983) argued that there are methodological difficulties in the analysis of this apparently straightforward problem: subjects in fatigue experiments appear to be able to raise their level of effort for brief periods to respond to the challenge of the probe test, so that performance appears unimpaired. This is, of course, the same problem as we have observed in measuring the direct effects of stressors: by responding to the new task with further effort, subjects effectively compensate for any underlying inadequacy in functional processing capacity. Holding showed that fatigue effects could be observed by providing subjects with alternative task strategies. Following prolonged work they were more likely to choose a task method requiring low effort, even though it entailed more risk of error. A similar finding was obtained by Meijman et al. (1992), in a study of driving examiners workload. Examiners were observed to make less effort on cognitive probe tasks (in terms of both subjective effort and reduced suppression of heart rate variability) after more demanding work days. This approach to fatigue reveals it to be a state in which there is a shift towards preferring activities requiring less effort, or less use of high level control actions. It may be apparent from previous discussions of compensatory control that, where no options are available (as is more usual in fatigue studies), we would expect to see increased costs associated with maintained performance in the post-work probe tests. There do not appear to be have been any direct measurements of such effects.

4. Applications to the analysis of work strain

The different patterns of performance observed under stress and high workload can be interpreted in terms of the compensatory control options available for maintaining stability of the system in response to the changing balance of goal priorities and environmental flux. Maintenance of primary task goals requires an
active compensatory process to protect vulnerable cognitive goals from disruption by (stronger) emotional and biological goals. Although primary performance is typically maintained under stress, this compensatory activity normally results in disruption to secondary or auxiliary features of the integrated system performance, and to increased involvement of energetic resources (compensatory effort).

Adjustment to adverse environmental or internal conditions (through the choice of coping mode) must take into account not only external performance goals but also the need to satisfy personal goals, and to maintain an adequate state of general well-being. While the postulated control process allows individuals considerable flexibility in the choice of coping mode, many work environments, through their intolerance of errors and slow rates of work, naturally encourage the adoption of direct coping. In cases where effort demands are already very great (hospital doctors, nurses, air traffic controllers), chronic use of this high strain mode may be maladaptive, since there is little opportunity for recovery from the fatigue associated with such coping activity of this type. Such jobs may reveal strong carry-over effects from one shift to the next, and very high levels of psychological morbidity (Hockey & Dawson, 1995). Maintaining performance under high effort attracts a significant cost in terms of discomfort and sustained sympathetic activation, and also in affective indicators of strain.

4.1. Dimensions of affective strain.

The most common way of assessing strain in such contexts is through the use of subjective reports of affective state (moods). In the cognitive energetical framework proposed here, two (functionally independent) dimensions of affective strain are distinguished. Based on the widely-supported analysis of mood states, such as the Watson & Tellegen (1985) dimensions of positive and negative affect (PA and NA), strain is defined as a combination of anxiety and fatigue. This is broadly equivalent to high NA and low PA, although the latter is more strongly identified with states such as depression, which have a stronger emotional content. This terminology is preferred to the undifferentiated ‘good–bad’ analysis of mood states, which can lead to ambiguity. For example, Frankenhaeuser (1986) uses the term ‘distress’ to refer to both strain and passive modes: although anxiety may be a common feature, the two modes differ strongly in their implications for the development of fatigue.

Within the context of the compensatory control model outlined above, these two strain indicators have a specific metacognitive function. Anxiety is assumed to be an output of the action monitor. It is the principal indicator of primary appraisal (Lazarus & Folkman, 1984), signalling the extent of perceived demand or threat to current goals by environmental events. Increases in subjective fatigue are more complex, but appear to reflect the coping strategy used to manage demands under stress. Within the context of performance, fatigue is hypothesised to indicate the integrated regulatory effort over the period of the task (the extent to which the active control mode has been adopted). In the short-term, fatigue of this kind is a natural consequence of effective coping, but not when it is associated with chronic
strain. Fatigue may also reflect a baseline reduction in adaptive capacity (e.g., through illness). The general sensitivity of fatigue to heavy work demands, stress, and most kinds of illness indicates that it may have a general adaptive role in shifting behaviour towards less effortful modes of response.

4.2. Longitudinal analysis of work strain.

Most of our evidence on patterns of work strain come from cross-sectional analyses of demands and outcome variables, or from brief experimental studies. Yet, such relationships are essentially dynamic, shifting in critical cases from active to strain modes or from strain to passive, depending on the coping experience of individuals. A paradigm-shift towards longitudinal methods is implicated, in order to observe these developmental changes in the patterning of strain states, and to permit more clear-cut interpretations of the correlational data available in most cases (Frese, 1985). A true longitudinal study of work and health will require at least 12 months between first and last sampling, to allow time for symptoms to develop from changes at work. In the short term, however, multiple-occasion sampling using diary methods can be used to assess patterns at the within-individual level. This method has the additional advantage of providing data on intra-individual styles of adjustment to work demands.

A 3-month study of coping and work demands in 32 young doctors (Wiethoff & Hockey, 1996) showed that, whereas anxiety was correlated with day-to-day changes in work demands in all participants, fatigue was predicted by demand level only for those who used a characteristic active coping style (preferring to use effortful strategies to overcome problems). Those who adopted a passive style (not dealing with problems as they occurred, preferring to let them take care of themselves or putting them off until later) showed little relationship between fatigue and workload, but had a higher baseline level of fatigue — probably due to the cumulative effects of unprocessed demands over successive days. In a second, 6-week, study of adjustment to daily work demands (Hockey et al., 1996), the overall coping pattern was found to be different for two doctors faced with demanding work situations (high load with limited control opportunities); one exhibited a strain mode (high effort, high fatigue, increased adrenaline) and the other a passive mode (low effort, low fatigue, increased cortisol). However, when they encountered enabling situations at work (days in which both involvement and control were high), they both showed the familiar active mode of coping (high effort, high energy, increased adrenaline). While this supports the postulated existence of three adjustment modes, broadly equivalent to those proposed by Frankenhaeuser (1986) and in the present paper, it implies that different individuals may typically make use of only a sub-set of these. A more detailed analysis of these strain patterns is currently being undertaken, using a very large sample (n = 160) of nurses and secretarial staff, with daily measures over 6–9 weeks for each. These will allow us to test this hypothesis directly by examining demand-strain correlations at the within-individual level, for people identified as using different coping styles and having varying levels of chronic mental and physical ill-health.
4.3. Methodological requirements for a test of the compensatory control model.

The analysis of intra-individual patterns of demand/well-being relationships within demanding jobs promises to provide important insights into the role that energetical regulation plays in the management of work performance. However, a full test of the compensatory control model, requires the measurement of adjustment at all levels of the system. It will need to be able to identify a range of alternative coping modes (patterns of performance/cost trade-offs), as well as differences between individuals in characteristic coping styles (sub-sets of modes). This can be done by various data-reduction techniques (e.g., canonical correlation, multiple regression), carried out on the aggregated de-trended data for individual participants (Hockey et al., 1996). To provide stable solutions of the multivariate data set, however, such studies will need to measure not only affective state, but ongoing performance (including secondary tasks or the possibility of measuring strategy changes), and relevant psychophysiological parameters (notably the stress hormones and cardiovascular variables, all of which have been shown to reflect shifts in effort and performance protection). There are enormous barriers to achieving such an ideal study. A multiple sampling methodology imposes heavy demands on participants (e.g., daily measures for several months), so that subjective reports are often the only kind of data that may be possible. Where psychophysiological measures can be obtained, as in the two studies reported above, there is a natural trade-off (given a fixed research effort) between the number of participants tested and the frequency of sampling. Measurements are often intrusive (e.g., the collection of body fluids for hormone analysis), particularly if repeated over many occasions. Some form of automatic or self-monitoring may be helpful in some cases (e.g., ambulatory recording of autonomic variables for later analysis). However, where timing of sampling is critical (as in performance or self-report procedures), such methods are likely to depend unrealistically on the reliability of self-administered testing in the context of busy professional lives.

In addition, it will not be enough to identify coping modes, or differences between individuals in the characteristic deployment of such modes. We will also need to consider dynamic changes in regulatory behaviour, in relation to environmental and motivational changes. Since performance protection is under the control of the individual we would expect to observe systematic shifts in the use of different coping modes. Furthermore, these shifts of regulatory activity should be predictable from the temporal structure of demands and coping mode, changes in goal orientation, reported energy levels, etc. Although the compensatory control model is expressed in terms of general cognitive-energetical properties of state regulation, the parameters of control are identified with factors which operate at the individual level. This means that meaningful comparisons may be made between individuals in the way in which regulatory activity is managed over time, and in the transitions between coping modes. For example, take two individuals identified as having characteristic passive or active coping styles, both observed to be operating in a strain mode for a period of three (very busy) days. Because of the match between their characteristic and operational modes, we would predict that the first
would shift to the less demanding passive mode before the second. The analysis of state transitions is also important in testing assumptions about the possible restorative value of the passive state. Even in highly active individuals, the strategic use of the passive coping mode (e.g., following periods of heavy strain) may be expected to be associated with generally higher levels of functional health and well-being, and more stable long-term demand/well-being relationships. This may provide the basis of a real understanding of long-standing problems such as the development of chronic fatigue, both at work and outside it.

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**References**


