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Processing Resources in Attention, Dual Task Performance, and Workload Assessment

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This report develops the concept of multiple resource theory in dual task performance and describes its relation to the measurement of operator workload. "Structural" and "capacity" theories of attention and time-sharing are contrasted, and the latter are then elaborated to describe the quantitative relation between resources and performance, and the representation of dual task data by the performance operating characteristic within a resource framework. Some deficiencies with a single resource (undifferentiated capacity)

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model of time-sharing are pointed out, and the multiple resources model is introduced. Data are presented supporting a specific model that defines resources by stages of processing, codes of processing, and modalities of encoding. ~~The following sections~~ discuss the relation between multiple resources and operator performance strategies, and different measures of operator workload. The different implications of multiple resource theory on primary task, secondary task, and physiological and subjective measures of workload, and the relations between these are considered.

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Processing Resources in Attention[1]

Christopher D. Wickens

Examples abound of time-sharing that is efficient (e.g., walking and talking; reading while listening to music), as well as time-sharing that is inefficient (e.g., talking while reading, problem solving while listening). The concept of processing resources is proposed as a hypothetical intervening variable to account for variations in the efficiency with which time-sharing can be carried out; the degree to which two tasks can be performed concurrently as well as each can be performed in isolation. Tasks are assumed to demand resources for their performance and these resources are limited in their availability. Therefore, when the joint demand of two tasks exceeds the available supply, time-sharing efficiency drops, and will be more likely to do so as the difficulty of either component tasks increases. For example, conversation with ground control in an aircraft will normally be disrupted if the demands of the concurrent flight task are increased by poor visibility or heavy turbulence. Alternatively, flight performance may degrade as a critical exchange of information is carried out with ground control.

A second intervening variable proposed to explain variance in time-sharing efficiency, is the concept of structure. According to a structural view, two tasks will interfere, because they compete for common processing mechanisms or structures (e.g., stages of processing, modalities of input, requirements for manual response). For example, listening to auditory warning indicators will be more disrupted by the simultaneous requirement to understand a conversation also demanding the auditory channel, than by reading instruments involving visual input.

These two sources of variance in time-sharing performance have been generally associated with two classes of theories of attention: capacity theories (e.g., Knowles, 1963; Moray, 1967; Kahneman, 1973), and structural

[1]A version of this report is to appear in Parasuramian, Davies, & Beatty (Eds.), Varieties of Attention, Academic Press. The author wishes to acknowledge the helpful comments of Major Wm. Derrick, USAF, Dr. David Navon and Dr. Walter Schneider.

theories (Broadbent, 1958; Welford, 1967; Keele, 1973). Both theoretical developments have taken place somewhat independently over the past two to three decades, and each traces its origins to somewhat different historical roots.

Historical Overview

Structural Theories

Experimental investigations of dichotic listening of verbal material in the 1950's and 1960's (e.g., Cherry, 1953; Broadbent, 1958; Moray, 1959; Treisman, 1964), revealed that attention was severely limited when divided between two independent channels of auditory verbal input. These, and a host of other experimental studies, generated classes of theories concerned with the location of the "bottleneck" in human information processing. At what stage of processing did a parallel system, capable of processing separate channels concurrently, "narrow" to a serial system that must handle only one input at a time? A major dichotomy emerged between early selection theories (e.g., Treisman, 1969; Broadbent, 1958) that considered the bottleneck to occur at perception, and late selection theories (e.g., Deutch & Deutch, 1963; Norman, 1968; Keele, 1973) that postulated the serial limitation existing at the point in the processing sequence where decisions were made to initiate a response (either an overt motor response, or a covert response such as storing material in long term memory, or rehearsing it).

In parallel with dichotic listening research, investigations such as those of Bertelson (1967) and Welford (1967), employing the double stimulation or psychological refractory period paradigm, a paradigm in which the subject must perform two independent reaction time tasks in close temporal proximity, (Kantowitz, 1974) and by Noble and Trumbo and their colleagues (Trumbo, Noble, & Swink, 1967; Noble, Trumble, & Fowler, 1967; Trumbo & Milone, 1971), using a dual task paradigm, drew conclusions similar to the late selection theorists that the major limiting bottleneck in the information processing sequence lies at the stage of response initiation. (But see Briggs, Peters, & Fisher, 1972, for time-sharing data in support of an early selection bottleneck.)

According to the view put forth by late selection theories then, attention in task performance becomes nearly synonymous with the availability of a dedicated decision making/response selection mechanism. A subsequent modification of the bottleneck models postulated that there is not a single stage or mental operation that acts as the source of interference, but instead a single limited capacity central processor (LCCP) (Kerr, 1973). Like a single server queue, this processor must be engaged to complete certain mental operations, such as selecting a response, performing a mental transformation, or rehearsing material. According to this view, when the LCCP is in the service of an operation for one task, it is unavailable to a concurrent task that also might require that service, and the performance of the second task will deteriorate. By postulating a number of mental operations that require the LCCP in order to proceed, such a view permits there to be more than a single "bottleneck" within the processing system.

The intent of this section is not to review the vast body of experimental data generated in an effort to choose between early selection and late selection theories, or theories such as the LCCP that amalgamate both positions. Rather, it is to emphasize that the focus of these investigations and subsequent theory has been upon differences in task structure (primarily related to stages of processing) that impact upon dual task performance efficiency. It should be noted that many structural theories, in fact, acknowledge the role of task difficulty (a capacity concept) in generating interference by assuming that more difficult tasks occupy the bottleneck or the LCCP for a relatively longer duration. Yet the emphasis remains upon structure, and the bottleneck or LCCP is conventionally assumed to service only one process or task at a time.

Capacity Theories

An important historical root of capacity theory lies in the human factors concern with the measurement of human operator workload. A paper by Knowles (1963) presented a conceptual model of the human operator as possessing a "pool" of limited capacity resources. As a primary task demands more of these resources (becomes more difficult), fewer are available for a concurrent "secondary" task, and the latter deteriorates. In this manner, primary task workload is inversely reflected in secondary task performance. An implicit characteristic of capacity, in Knowles' paper, as well as in later conceptions, concerns its divisibility and allocation properties. While structures in the structural theories were assumed to be dedicated to one task at a time, the contrasting view holds that capacity can be allocated in graded quantity between separate activities.

In 1967, two papers (Moray, 1967; Taylor,Lindsay & Forbes, 1967), both contributed to the refinement of capacity theory. Moray emphasized the contrast of the capacity view with the on-going debate over early and late selection theories by drawing the analogy between human processing resources and the limited capacity of a time-shared computer. In either the computer or the human information processor, resources can be allocated to any activity, or stage of processing, as dictated by a higher level executive program. With this flexibility available, Moray argued there was no need to assume a given locus of task interference (or bottleneck of attention). The source of interference would depend merely upon the capacity demands at any particular stage of processing. In the same volume, Taylor,Lindsay and Forbes (1967) outlined a quantitative theory of the sharing of capacity between channels of perceptual input, thereby highlighting the sharability, as opposed to the dedicated nature of attention.

While Moray, and Taylor, Lindsay and Forbes were concerned with the allocation of capacity, that aspect of capacity theory that emphasizes the difficulty or intensive aspects of attention has been heavily invoked in two somewhat different domains. Following Knowles' (1963) original paper, many engineering psychologists, concerned with the measurement of human operator workload in applied settings such as the aircraft cockpit or the process control monitoring station, adopted a conceptual model asserting that workload is proportional to the demands imposed by tasks upon the operator's limited capacity (Rolfe, 1971). Thus, great interest has recently been focussed in applied research upon the representation and measurement of available and used capacity, and the relation between capacity-based workload measures and alternative indices relating to subjective scales or physiological parameters (Moray, 1979).

At a more theoretical level, investigators of automatization in perceptual or motor learning, have invoked the concept of capacity as a commodity whose utilization is reduced as learning proceeds (Logan, 1979; Schneider & Fisk, 1980). In a similar vein, the concept of levels of processing in encoding and memory (Craik & Lockhart, 1972) employs the capacity metaphore when describing the amount of processing invested in the encoding process. In either case, investigators often converge on assumptions of capacity usage in performing a primary task (to be learned or remembered), by inferring residual capacity from secondary task "probes" (e.g., Posner & Keele, 1969; Eysenk, 1979; Underwood, 1976). For example, longer reaction times to probe stimuli are presumed to reflect greater capacity demands (lesser automation, deeper processing) of the primary task.

Within the last decade, theoretical treatments by Kahneman (1973), Norman & Bobrow (1975), and Navon & Gopher (1979) have made invaluable contributions to the development of the concept of capacity or resources as an intervening variable in dual task performance. These papers have facilitated the evolution of resources from a loose concept to a quantitative theory, with testable predictions and important implications for the use of the capacity metaphore in workload measurement and learning and memory research. The discussion of resource theory that follows, borrows equally from Kahneman's initial formulation and the subsequent modification and elaboration proposed by Norman & Bobrow and by Navon & Gopher.

Resource Theory

Defining Elements

The terms capacity, attention, and effort have all been used synonymously with resources to refer to the inferred underlying commodity, of limited availability, that enables performance of a task. The term resources is preferred here over the other three because "capacity" suggests a maximum limit itself rather than a variable commodity, attention (as various chapters in this volume attest) possesses a variety of ambiguous meanings, while "effort" suggests a motivational variable that may, but does not necessarily have to, correlate with the commodity enabling performance. Resource theory, as it is loosely conceived, may be described by three basic elements:

1. The performance resource function. Performance is a monotonically non-decreasing function of the hypothetical resources invested in a task. This proposition is manifest in two forms. Under single task conditions if we "try harder" on a task (invest more effort), performance will at least not deteriorate and will probably improve. While this assumption is intuitively appealing, it has received little direct experimental confirmation because practically all performance investigations assume that subject effort is at maximum from the outset. An experimental investigation by Hafter & Kaplan (1977) in which effort has been modulated by payoff and instruction, however, seemingly confirms its validity.[2]

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[2] It may be noted that the Yerkes Dodson Law--the inverted U-shaped function relating performance to arousal (Easterbrook, 1959), predicts that the relation between effort and performance will not be monotonic if increased effort induces increased arousal: trying too hard at a task may induce a deterioration in performance, particularly if the task is complex.

Under dual task conditions, the relation between performance and resources is more easily measurable, but requires greater assumptions concerning the underlying processes. When a subject performs two tasks concurrently, and is requested to allocate attention disproportionally in favor of one task or the other (either explicitly, or implicitly by differential payoff schedules), performance is observed consistently to vary as a function of these instructions (e.g., Wickens & Gopher, 1977; Sperling & Melchner, 1978; Gopher & North, 1977; Navon & Gopher, 1980; Gopher, 1980). Under these circumstances, resource theory infers that the subject is modulating the supply of resources between the tasks, in order to obtain the desired level of differential performance.

A major contribution of Norman & Bobrow's paper was the introduction of the hypothetical construct of the performance-resource function. If two tasks do, in fact, interfere with each other (are performed less well) because they are sharing resources to which each previously had exclusive access, then there must be some underlying hypothetical function that relates the quality of performance to the quantity of resources invested in a task. This function is the performance-resource function, or PRF, an example of which is shown in Figure 1. Maximum single task performance occurs when all resources are invested in the task (point S). Partial diversion of resources to a concurrent task will depress performance accordingly. As more resources are invested, performance will improve up to the point at which no further increase in performance is possible. At this point, the task is said to be data-limited (limited by the quality of data, not by the resources invested). A task might be data-limited either because the measurement scale can go no higher (100% correct on an easy test is achieved with little effort) or because the quality of the data (either perceptual data, or data in memory) is poor (e.g., you cannot understand a faint conversation no matter how hard you "strain your ears"). When performance changes with added or depleted resources, the task is resource-limited.

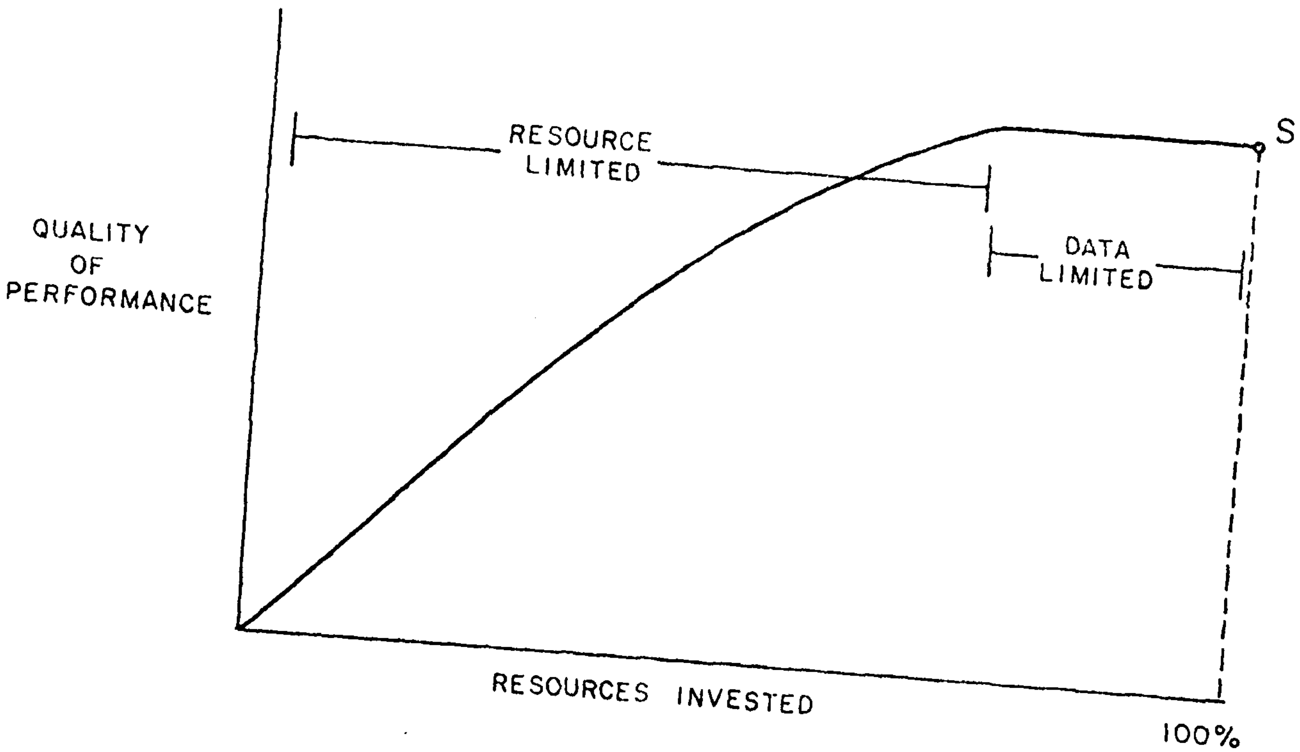


Figure 1. The performance resource function. S = Single task performance.

It is tempting to assume that the actual form of the PRF can be constructed from a dual task experiment in which conditions of variable resource allocation are imposed. An example is the investigation of Wickens & Gopher (1977) in which different priority manipulations called for the subjects to distribute fixed percentages of resources between a tracking anda reaction time task. Performance on two tasks under such a set of allocation policies is depicted in the two PRFs shown in Figure 2a. It should be noted that this representation assumes that(a) subjects actually allocate resources as commanded, (b) the resources deployed in performance of the two different tasks are functionally equivalent. We shall see below that the second assumption may not always be valid.

In theory, it is of course possible to construct a PRF using single task performance data only. A subject performs the task at varying levels of effort, and reports the subjective effort invested in performance at each level. The difficulty here is with the psychological meaning of effort, and the psychophysical scale relating effort to the subject's numerical rating. Nevertheless, an investigation by Wickens & Vidulich suggests that subjects do appear to be able to allocate partial resources to a single task, and to do so in reliable, repeatable graded quantity as dictated by a commanded "percent effort." Furthermore, performance on three qualitatively different tracking tasks, each demonstrated equivalent quantitative relations between the percentage loss in performance, and the percentage of resources commanded.

2. The performance operating characteristics (POC). When two tasks are time-shared and resources are allocated differentially between them, the joint performance of both may be depicted as two separate PRF's, as shown in Figure 2a. Alternatively, these data may be captured by plotting a single point for each condition in a Performance Operating Characteristics, (POC), in which the performance on each task is represented on the two axes (Figure 2b). Such a

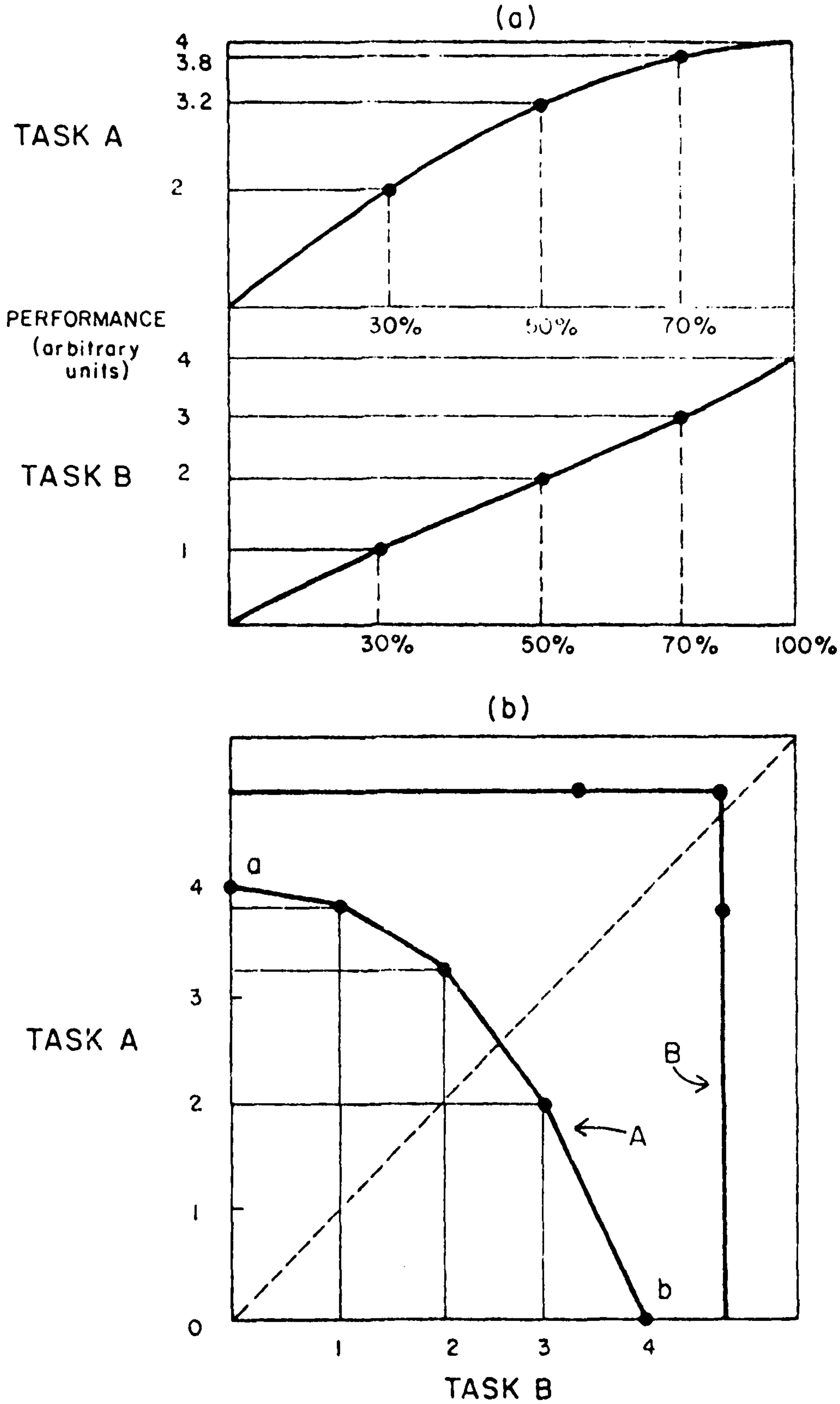


Figure 2. (a) 2 PRF's for two tasks. (b) Data from the 2 PRF's combined in a POC. Curve A: Resource limited. Curve B: Data limited tasks.

representation is quite analogous to the cross plot of hit and false alarm rate, as response bias is varied in the ROC curve of signal detection theory (Green & Swets, 1966), or the cross-plot of RT and error rate in the speed-accuracy operating characteristics (Pew, 1969). In evaluating the POC depicted in Figure 2b, or any other POC, it is important to note certain "landmarks" or characteristics:

(a) *Single task performance* is shown by the point of intersection of the POC with the two axes (a & b). These points may not be continuous with the projection of the function into the axes as shown in Figure 2b. If the single task points are higher (better performance) then there is, in the words of Navon & Gopher (1979), a "cost of concurrence." The act of time-sharing itself may pull resources away from both tasks above and beyond what each task demands by itself. This discrepancy might result from the resource demands of an "executive time-sharer" (Moray, 1967; McLeod, 1977; Taylor,Lindsay & Forbes, 1967), which is utilized only in dual task situations. Its resource demands (and consequent effects on performance) are not then manifest in single task performance. An alternative source of the cost of concurrence results if the requirement to time-share induces a degree of *peripheral interference*. For example, time-sharing two visual tasks, separately displayed in the visual field, may prevent both from achieving simultaneous access to foveal vision. The requirement to perceive through peripheral vision (or to engage in a time-consuming scan pattern) will lower the level of dual task performance on one or both tasks.

The term peripheral interference refers to situations in which dual task performance deteriorates due to *physical constraints* on the processing system. Thus, the eyeball cannot be in two locations at once. A given finger cannot simultaneously depress two keys nor can the mouth utter two words at once. Physical characteristics of the basilar membrane may cause the masking of acoustic stimuli associated with one task, by stimuli associated with another.

Peripheral interference here is distinct from the concept of "structural interference" that has been invoked to account for such instances as the difficulty in simultaneously performing two independent motor acts. (Rubbing the head, patting the stomach is a classic example.) While related to the similarity of demands on the motor system, this type of interference is not due to its physical constraints, and therefore is one that may be overcome with practice.

(b) The time-sharing efficiency of the two tasks is indicated by the average distance of the curve from the origin, (0) of Figure 2b; obviously the farther from the origin, the more nearly dual task performance is close to single task performance (efficient time-sharing).

(c) The degree of a linear exchange between the two variables in the POC function indicates the extent of shared or exchangeable resources between the tasks. A POC such as curve I shown in Figure 2 indicates that a given number of units of resources removed from task A (thereby decreasing its performance) can be transferred to and utilized by task B (improving its performance). A discontinuous or rectangular POC (curve II) suggests that one of two states exist: either (i) the resources are not interchangeable between tasks, so that withdrawing resources from task A (and thereby decreasing A's performance) cannot be used to benefit performance on B, or (ii) one of the tasks are in a data-limited region for the range of the POC in question. In this case, withdrawing resources from task A (the data-limited task) will not deteriorate its performance, but can improve B's performance. In either case, performance change in one task will not occur concurrently with a change in the other, and so the POC will be parallel to one of the axes.

(d) Bearing in mind that the POC is actually a series of points, each one collected in a different time-sharing trial, then allocation bias is indicated by the proximity of a given point on the POC to one axis over the other. A point on the positive diagonal indicates an "equal allocation" of resources between tasks. This latter assumption, however, can only be made if the two tasks employ the same performance metric. If they do not, then a problem arises concerning how many units of decrement of task A, employing one variable, are equivalent to a given unit of decrement of task B. Equivalence here is assumed to reflect the loss of performance induced by the removal of an equal quantity of resources. If tasks were time-shared under the explicit instructions to divide attention equally between them, then the 50/50 point by definition could define the equal allocation axis. However, in the absence of such a landmark, other assumptions need be made in order to quantitatively map the performance variable of the two tasks onto the common hypothetical variable of "resources." One approach is to assume that equal variability of the two measures (across replications and/or across subjects), reflects equal units of resources. This Fechnerian assumption, in essence translating raw performance into normal deviate scores, has been made by Gopher & North (1977), in presenting performance feedback to subjects in a dual task paradigm, and by Wickens (1980) and Wickens, Mountford & Schreiner (1981) in comparing dual task decrements across tasks.

3. Automation and task difficulty. An important characteristic of resource theory is its ability to treat the effects of practice and task difficulty as different manifestations of the same underlying construct--the marginal efficiency of resource investment, or the gain in performance achieved per invested unit of resources.

Figure 3 shows the PRFs underlying two tasks, A and B. B demands fewer resources to reach equivalent performance levels to A (and, in fact, B contains

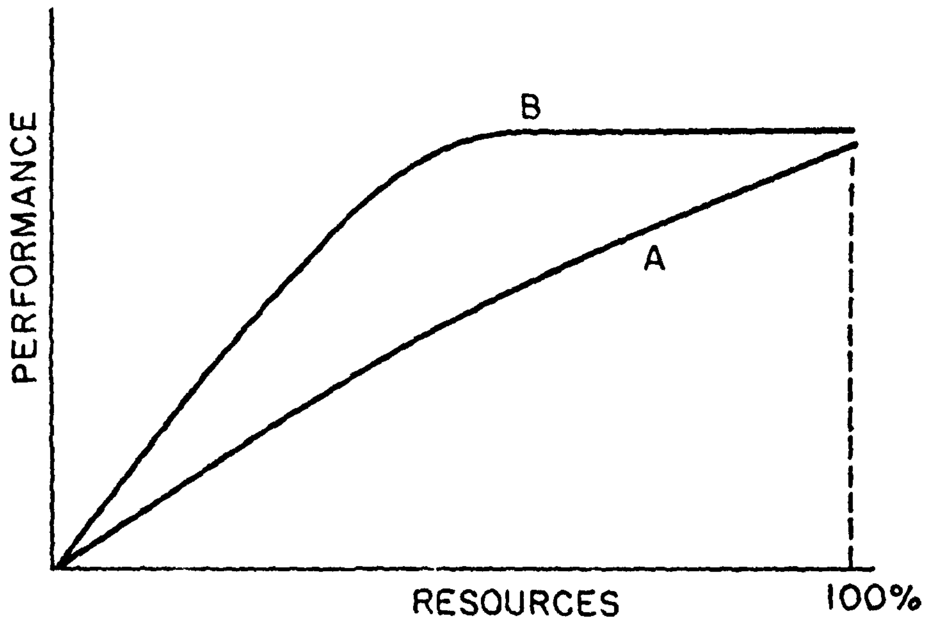


Figure 3. The PRF for a practiced or easy task (B), and a novel or difficult task (A).

a greater "data-limited" region). B then differs from A by being of lesser difficulty and/or having received more practice (more automated). Note that B may not necessarily be performed better than A (at 100% resource investment into A), but can simply be performed at that maximum level with more "spare capacity." Thus, characteristics such as the "automaticity" of perception of words or letters need not be viewed as qualitatively different from attention-demanding perceptual activities (e.g., Kerr, 1973), but merely as resulting from a quantitative change in the PRF. In this manner, Schneider & Shiffrin's (1977) distinction between automatic and control processes assumes a difference in the data-limited region of the underlying PRF (Schneider & Fisk, 1980).

In terms of a POC representation, the easier or more practiced version of a task yields a POC that is farther from the origin than the POC of the more difficult task. The separation of the two POCs increases as allocation priorities emphasize the task whose difficulty (practice) is varied. This contrast is shown in Figure 4. Curve I depicts time-sharing performance with the easier version of task A, while II is with the more difficult version. As described above, it is also likely that the more practiced (or easier) version contains a greater data-limited region, and therefore will show a larger stretch of the POC that is parallel to the abscissa.

The representation shown in Figure 4 makes an important point relevant to investigators who use performance on a secondary task to infer the resource demands of the primary task. Suppose two versions of a primary task A (1 & 2) were time-shared with a secondary task (B). If B time-shared with A_2 (B_2) yielded better performance than B time-shared with A_1 (B_1), as shown on the abscissa of Figure 4, then the investigator might conclude that A_2 is the easier version of the primary task. Yet as we look at the shape of the underlying POC, we see this is not the case. It is only because the subjects

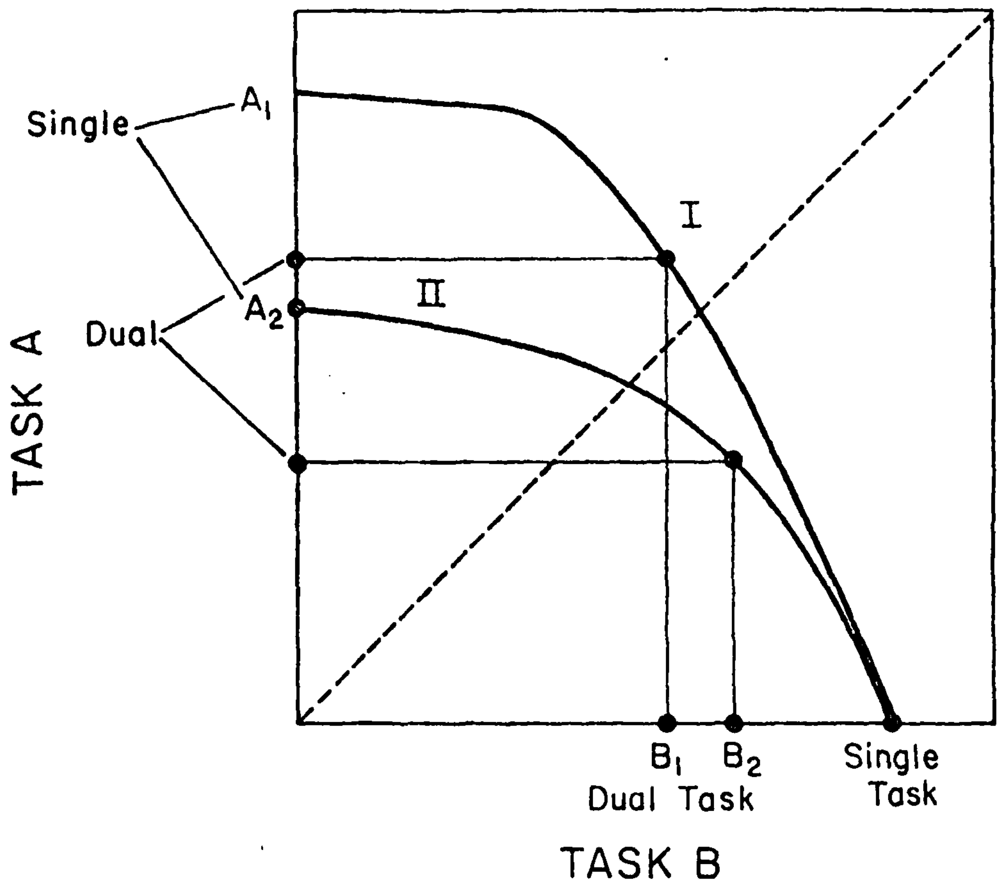


Figure 4. Two POC's generated by time-sharing task B with an easy (A_1) and difficult (A_2) version of Task A. When time-shared with A_1, subject allocates in favor of A. When time-shared with A_2, allocation is in favor of B.

allocated in favor of task B when paired with A_2, to a greater extent than when paired with A_1, that we obtained this spurious result. It is important then to represent dual task results in a POC space (even if only one allocation policy is used), rather than reporting only "secondary task performance decrements." In this way, the investigator can present a more informative picture of how the subject is allocating resources in different conditions.

Again, the analogy with signal detection theory is direct. In signal detection the investigator reports both hits and false alarms, and interprets these in terms of an efficiency index (d') and a cognitive bias (beta). In dual task performance, both primary and secondary task decrements are reported, and interpreted again in terms of an efficiency index (the "distance" from the origin of the POC), and an allocation bias (the distance from the positive diagonal). However, the theoretical models underlying these distance measures are far more primative in the POC case.

Limitations of Single Resource Theory

The preceding presentation of resource theory has assumed that only a single reservoir of undifferentiated resources exists within the human processing system, equally available to all stages of processing or mental operations. It is important to contrast this conception of the mechanism underlying time-sharing phenomena with alternative conceptual viewpoints. As we shall see below, capacity theory has been expanded in two directions in an effort to account for four basic experimental phenomena in dual task research, each of which presents some difficulties for a single resource model. These four phenomena, difficulty insensitivity, perfect time-sharing, structural alteration effects, and difficulty-structure uncoupling, each relate to the structural aspects of the tasks.

<u>Difficulty insensitivity</u>. Several examples may be cited in which increases in the difficulty or demand of one task, presumably consuming more resources (as allocation is held constant), fail to influence the performance of a second task. In a study by North (1977), subjects time-shared a tracking task with a discrete digit processing task. The discrete task required subjects to perform mental operations of varying complexity on visually displayed digits, and indicate their response with a manual key press. In the simplest condition, subjects merely pressed the key corresponding to the displayed digit. A condition of intermediate demand required the subject to indicate the digit immediately preceding the displayed digit in time--a running memory task. In the most demanding condition, subjects were required to perform a classification operation on a pair of displayed digits. These three operations apparently imposed different resource demands, as indicated by their single task performance level and their interference with simple digit cancelling. However, when the digit tasks were performed concurrently with the tracking task, all three had equivalent disruptive effects on tracking performance. Analogous examples of difficulty insensitivity may be found in investigations by Kantowitz & Knight (1976), Isreal, Chesney, Wickens, & Donchin (1980), and Wickens & Kessel (1979). (See Wickens (1980) for a summary of such studies.)

<u>Perfect time-sharing</u>. An example of perfect time-sharing is provided by Allport, Antonis, & Reynolds (1972) who demonstrated that subjects could sight-read music and engage in an auditory shadowing task concurrently, as well as they could perform either task by itself. Wickens (1976) observed the same finding when an auditory signal detection task was time-shared with a response-based force generation task.

It is possible that both difficulty insensitivity and perfect time-sharing could be accounted for within the framework of undifferentiated capacity theory, if it is assumed that one or both tasks, in either case possess large data-limited regions. In the case of difficulty insensitivity, this would allow the added resource demands of the more difficult version of a task, to be met by diverting resources from the concurrent task, without sacrificing the latter's performance. In the case of perfect time-sharing, both tasks must have considerable data-limited regions, so that an appropriate allocation policy can be chosen to produce perfect performance for both tasks while sharing resources.

While a data-limited explanation can, in theory, account for difficulty insensitivity and perfect time-sharing, it appears doubtful that the examples described above involved heavily data-limited tasks. Neither North's (1977) tasks nor those of Allport, Antonis, & Reynolds were predictable or repetitive in a manner that might easily give rise to automation. All tasks furthermore appeared to involve a relatively heavy time pressure, either through forced pacing, or through a self-paced schedule in which performance was measured in terms of the number of responses made (North's tasks).

Structural alteration effects. Structural alteration effects refer to instances in which the change in a processing structure (modality of display, memory code, modality of response) brings about a change in interference with a concurrent task, even when the difficulty (demand for resources) of the changed task has not been altered. Such examples have been observed with regard to input modality (e.g., Isreal, 1980; Treisman & Davies, 1973; Martin, 1980; Rollins & Hendricks, 1980), response modality (e.g., Harris, Owens, & North, 1978; McLeod, 1977; Wickens, 1980), and codes of central processing (verbal versus spatial) (Hellige & Cox, 1976; Wickens, Sandry, & Micalizzi, 1981). If the difficulty of the altered task truly remains unchanged (and performance or subjective ratings of single task controls must guarantee this), then the resource demands should be very similar or identical across tasks. No change in interference with the concurrent task therefore should be predicted under an undifferentiated resources assumption. (When input or output structures are altered, it is important also that the investigator guard against interference changes due to peripheral interference. Consderable care was taken in this regard in the investigations cited above.) It should be noted that in many of these investigations, the magnitude of the change in interference is sometimes small, relative to the absolute size of the time-sharing decrements.

The uncoupling of difficulty and structure. The uncoupling of difficulty refers to instances in which the more difficult of two tasks, paired with a third task, actually interferes less the third task than does the easier one. This effect was noted by Wickens (1976), where tracking was paired with an auditory signal detection task, and an open-loop force generation task. The signal detection task was assessed by subjects to be the more difficult and therefore, presumably it demanded more resources. Yet signal detection interfered less with tracking than did the force task.

Multiple Resource Theory

It is evident from the last two examples that some restructuring of the undifferentiated resource view is required. This has proceeded in two directions. Kahneman (1973), in modifying the presentation of undifferentiated capacity theory in his early chapters, acknowledges the potential role of structural factors in contributing to interference between tasks. The model which emerges is one in which competition between tasks for the general pool of resources proceeds in conjunction with competition for more or less dedicated satellite structures (e.g., modalities of encoding and response). An alternative modification, which is in many ways quite similar to Kahneman's proposal, yet entails a few fundamentally different assumptions, postulates the existence of multiple resources (Kantowitz & Knight, 1976; Navon & Gopher, 1979; Sanders, 1979; Isreal, Chesney, Wickens, & Donchin, 1980; Wickens & Kessel, 1980; Wickens, 1980). According to the multiple resource view, there is more than one commodity within the human processing system that may be assigned resource-like properties (allocation, flexibity, sharing).

The implications of this view for time-sharing are threefold: (a) To the extent that two tasks demand separate rather than common resources, they will be time-shared efficiently; (b) To the extent that tasks share common resources, a relatively smooth POC can be generated between them; (c) A change in the difficulty of a task is defined as increasing the demand for one or more of the resources upon which its performance depends. If part of those resources are also required for performance of a concurrent task, the concurrent task will be affected. If, on the other hand, the resources affected by the difficulty manipulation are not used in performance of the concurrent task, the latter will remain unaffected. These relations are shown in Figure 5.

According to the multiple resources conception, difficulty insensitivity arises in this latter case. Here, additional resources cannot be transferred from the concurrent task to compensate for the added demand imposed on the manipulated task (or if resources are transferred, performance of the manipulated task cannot benefit from their availability). Perfect time-sharing results when the two tasks demand entirely non-overlapping sets of resources. Structural alteration effects occur when the change in task structure brings about less overlap in resource demands. Finally, difficulty-structure uncoupling will result when two tasks that place heavy resource demands on separate pools are compared with two tasks of lesser demands imposed on a common pool.

If resources do, in fact, reside in separate reservoirs,[3] then it is important to identify the functional composition of these reservoirs.

[3]The reader should be cautioned from interpreting the hydraulic metaphore to literally.

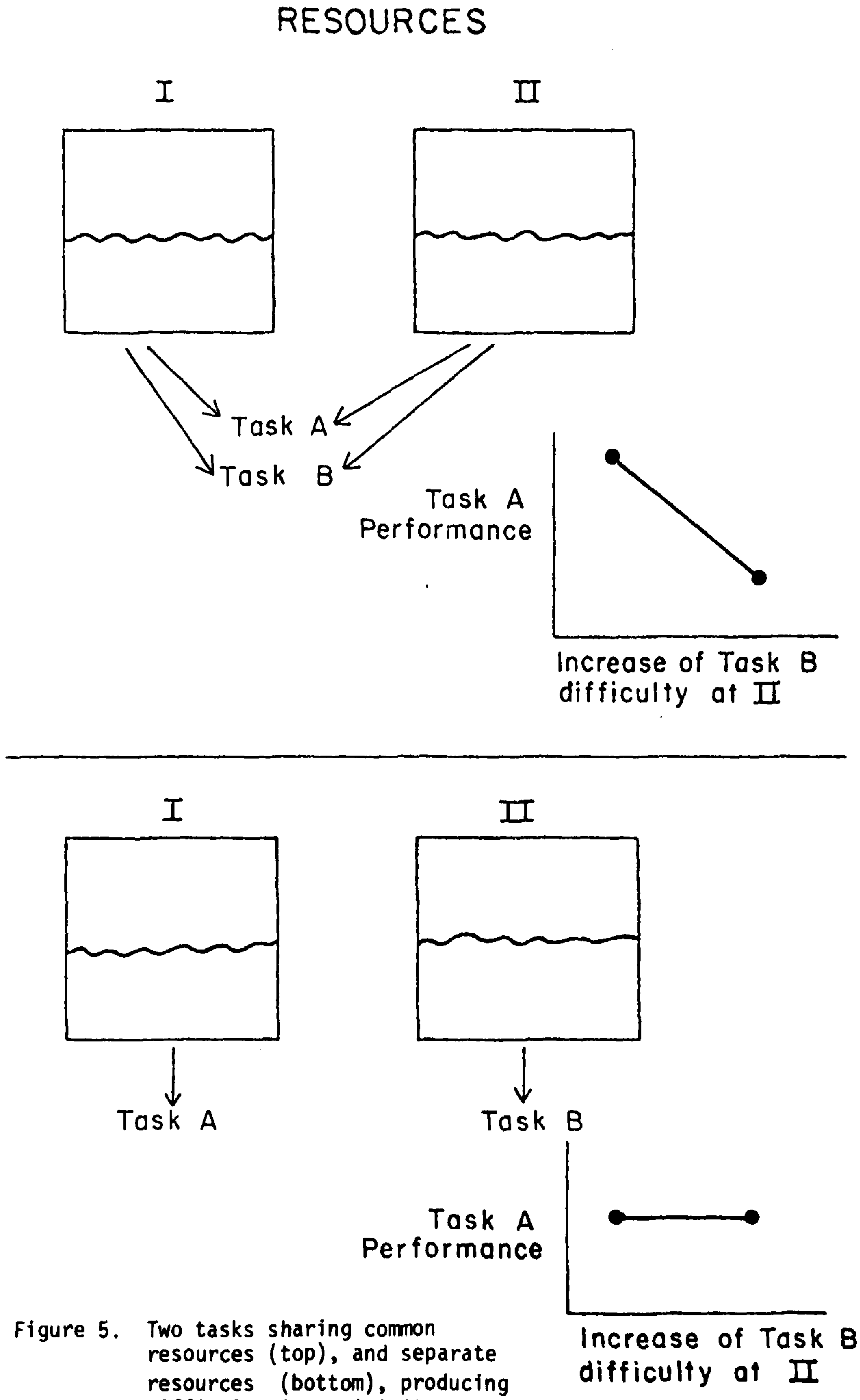


Figure 5. Two tasks sharing common resources (top), and separate resources (bottom), producing difficulty insensitivity.

Examining a large number of dual task studies which produced structural alteration effects and difficulty insensitivity, Wickens (1980), has argued that resources may be defined by a dimensional metric consisting of stages of processing (perceptual/central vs. response), modalities of input (visual vs. auditory) and response (manual vs. vocal), and codes of perception and central processing (verbal vs. spatial). It is possible that the response modality dimension is similar to the coding dimension, assuming that manual responses tend to be those that are spatially guided. If this is so, then the "structure" of resources may be conceptually depicted in the heuristic representation of Figure 6.

Stages. The argument that stages define resource pools posits that perceptual and central processing resources are functionally separate from those underlying response processes. Supportive evidence is provided when the difficulty of responding in a task is manipulated, and this manipulation does not affect performance of a concurrent task whose demands are more cognitive or perceptual in nature (or the converse). Such evidence has been provided by the difficulty insensitivity demonstrated in experiments of Isreal, Wickens, Chesney, & Donchin (1980) and Isreal, Chesney, Wickens, & Donchin (1980). In these experiments, subjects perform a task of discriminating between target and non-target auditory stimuli presented in a Bernoulli sequence, and maintaining a mental count of the targets. Event-related brain potentials (ERP) elicited by the stimuli are recorded, and ERP amplitude is inferred to reflect processing of the discrimination task. The ERP amplitude, assumed to depend upon perceptual and central processing resources, is influenced by manipulations of display load of a concurrent task (Isreal, Wickens, Chesney, & Donchin, 1980), but is unaltered by the requirement to generate manual responses or by manipulations of the bandwidth of a concurrent tracking task (Isreal, Chesney, Wickens, & Donchin, 1980). Presumably the latter manipulation influences the difficulty of selecting and executing responses.

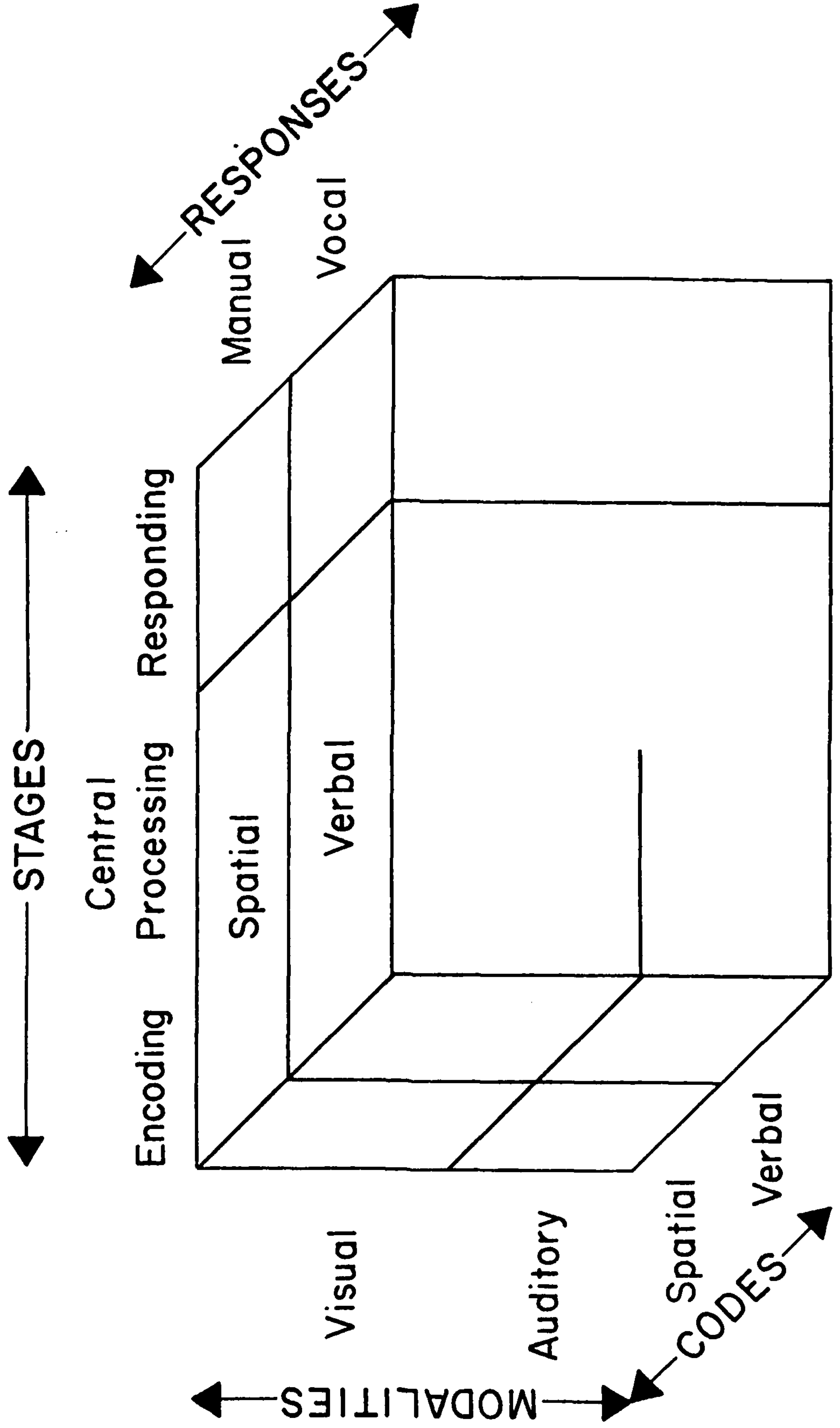


Figure 6. A heuristic representation of the structure of processing resources.

The demonstration by Wickens (1976) of difficulty-structure uncoupling when the signal detection and force generation tasks are time-shared with tracking also provides evidence for stage-defined resources. The more demanding signal detection task requires perceptual resources different from the response-related resources entailed in tracking and force generation. Other evidence for stage related resources is provided by difficulty insensitivity findings of Kantowitz and Knight (1976) and Wickens and Kessel (1980). Finally, Shaffter (1971) has argued from a close analysis of transcription skills such as typing, that perceptual,translational, and response processes can all proceed effective in parallel.

Processing codes. The notion that spatial and verbal processes may each draw upon functionally separate resources, and that these may be anatomically related (in most subjects) to the right and left cerebral hemispheres, respectively, is supported by the research and theory of Kinsbourne and Hicks (1978). They observed greater interference of a verbal task with dowl balancing when the latter was performed with the right hand (controlled by the hemisphere engaged in verbal processing) than with the left (controlled by the unused "spatial" hemisphere). McFarland and Ashton (1978) observed that this handedness asymmetry of interference was reversed when a spatial memory task was substituted for the verbal task. Brooks (1968) has obtained evidence that imaging tasks that require spatial working memory are performed more efficiently if their response is verbal and vocal than if it is manual, while verbal imaging tasks are performed better with a spatially guided manual response than a verbal one. These are presumably conditions in which processing and response functions are under the control of separate, rather than common, hemispheres. Similar conclusions have been drawn from reaction time-tasks, The longer response latencies are observed when the hemisphere of stimulus processing is the same as that controlling the response (e.g., Allwitt, 1981; Dimond & Beaumont, 1972;

Green & Well, 1977). Other demonstrations of "code-specific" interference experiments is provided by Baddeley and his colleagues (Baddeley, Grant, Wight, & Thompson, 1975; Baddeley & Lieberman, 1980). Further, Moscovitch and Klein (1980) observed that recognition performance was more impaired when two spatial targets were presented simultaneously (a face and a random polygon), rather when a spatial and a verbal target were presented.

An assertion that separate resources underlie verbal and spatial central processing (as well as encoding and response) could plausibly account for the results of Allport, Antonis, and Reynolds (1972) in which perfect time-sharing was observed between two information processing tasks at all stages (music sight-reading and verbal shadowing). This explanation assumes that musical sight-reading involves some degree of right hemispheric processing (Nebes, 1977) along with its visual input and manual output, while the verbal shadowing is assumed to require left hemispheric processing, along with auditory input, and vocal output.

<u>Modalities</u>. It seems apparent that we can sometimes divide attention between the eye and ear, better than between two eyes or two ears. This is obviously true (and of trivial theoretical interest) if peripheral interference is allowed to dominate in the intra-modality conditions. Most studies have not carefully controlled for this factor, but four that have (Treisman & Davies, 1973; Isreal, 1980; Rollins & Hendricks, 1980; Martin, 1980), suggest that there is indeed still an advantage to crossmodal presentation. Treisman and Davies observed more efficient cross-modal detection of both spatial-temporal patterns and semantic targets than intramodal detection. Rollins and Hendricks & Martin replicated this result even when the depth of semantic processing of the auditory stimuli was systematically varied. Isreal replicated the greater effect of intra- versus cross-modality interference between tracking and reaction time when the modality of both tasks was manipulated orthogonally and the sources of peripheral inter-

ference (masking and visual scanning) were tightly controlled.

Considering response modalities, investigations by McLeod (1977), Harris, Owens, & North (1978), Wickens, Sandry, Vidulich & Schiflett (1981), and by Wickens & Harris (Wickens, 1980) have all shown the greater time-sharing efficiency of tracking with a discrete task that used vocal as opposed to manual responses. Wickens and Harris furthermore showed that this gain in efficiency was additive with, and independent from, the gain obtained by using separate, rather than common input modalities. As such, this latter effect provides indirect evidence for stage-defined resources, since manipulations of resource competition at the earlier processing stages are independent in their effect from manipulations of resource competition at response.

Contrast between Models of Time-Sharing

Multiple vs. single resources. Careful scrutiny reveals that there really are not major differences between the multiple resource model, and Kahneman's model that assumes an undifferentiated resource with competition for satellite structures. Both predict that time-sharing will be less efficient if two tasks share common structures. According to Kahneman's conception, this results from direct competition for the structures. According to a multiple resources conception, it results from competition for the resources which enable the structures to function. Like multiple resource theory, an undifferentiated resource view can also account for difficulty insensitivity, as long as the concept of data limits is invoked. However, the undifferentiated resource view really cannot easily accommodate the examples of perfect time-sharing of two resource demanding tasks, such as Allport, Antonis, & Reynolds' (1972) demonstration with piano playing shadowers. It is possible in this model to assume that two tasks can be efficiently (but not perfectly) time-shared, if their input and output structures (encoding and response) are separate. But if both tasks demand some degree of central processing (decision making, memory, or translatory operations), interference must occur if the tasks are not heavily data-limited. If they are not, one must assume that there are separate resources at a central level to explain perfect time-sharing.

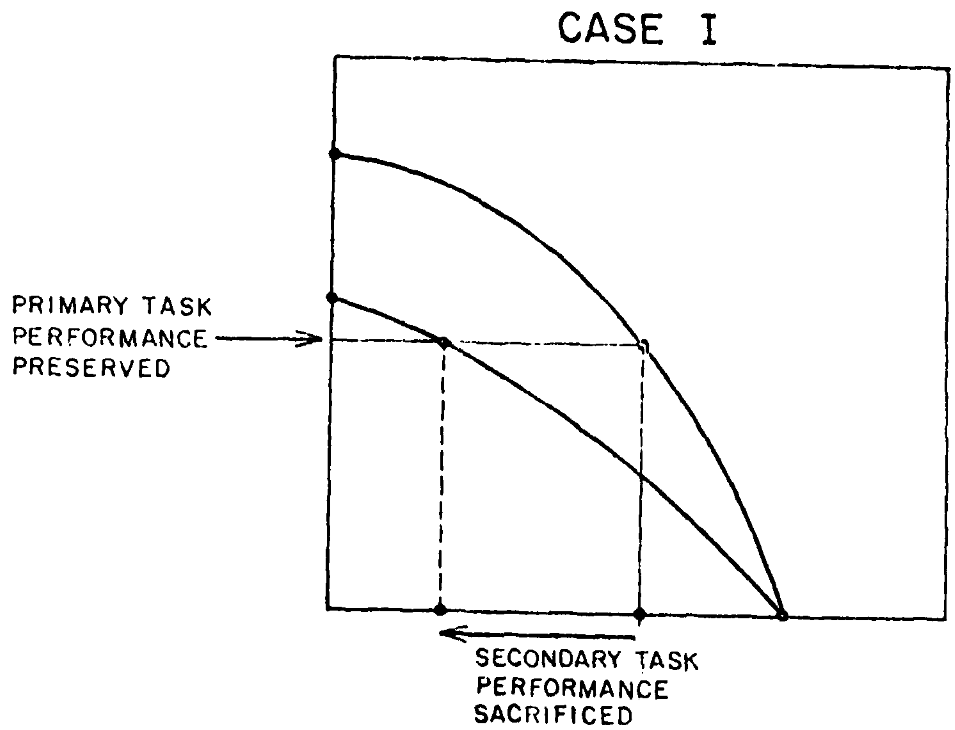
Perhaps the clearest difference between the two models relates to the fact that the undifferentiated capacity model postulates only a single commodity with resource-like properties (sharability and flexibility under different allocation policies), while the multiple resource view postulates more than one such commodity. To establish the latter assertion empirically, requires one of two experimental techniques: 1) One must identify a smooth exchanging POC between two tasks, both of whose major demand is imposed upon the potential resource in question. For example, Sperling and Melchner (1978) observed that continuous POCs could be generated between detection of the outer and inner rings of a display of letters and digits, even as these were presented tachistoscopically, so that no differential fixation could be utilized. Since the major demands of this task are perceptual, we might assume that the process of encoding possesses resource-like properties. In order to establish that the identified resource is indeed perceptual, and not of an undifferentiated nature, it would be necessary to demonstrate that a smooth POC cannot be generated if a response loading task is substituted for one of the detection tasks.

2) One must demonstrate that the cost of increasing the demand of one task (the manipulated task) within the structure or resource pool in question, can be borne by a concurrent task that also requires that resource but not by a concurrent task that does not. In the first case, this would be accomplished if resources were reallocated in graded quantity from the paired task to the manipulated task within the specified resource pool, preserving performance on the manipulated task while sacrificing that of the paired task.

In the second case, no such transfer would be possible. Figure 7 presents hypothetical POCs for the two cases in question.

An experiment by Wickens & Derrick (1981) has demonstrated such an effect when a tracking task was paired with an easy and difficult version of a Sternberg Memory Search Task (Sternberg, 1969). The difficult version of the latter required subjects to initiate a complex double response to indicate the outcome of their decision. The cost of this double response, observed in RT under single task conditions, was eliminated in dual task conditions and was instead borne by tracking task error. These data would suggest that tracking utilizes response related resources which are sharable with the output stages of the Sternberg task. When the central processing demand of the Sternberg task was increased, however, by increasing the size of the memory set, the Sternberg RT measure bore the cost of the increased resource demand, not the tracking task. Assuming that subjects could not shift the burden of higher memory load to tracking performance, this would suggest that separate resources were involved. Wickens, Tsang, & Benel (1979) have also demonstrated an instance in which the reallocation strategy cannot be applied, when separate resources are apparently involved. Performance on a tracking task, whose difficulty was manipulated (and inferred to influence response resource demands), could not benefit from resources transferred from a concurrent signal detection task. Similar examples have been provided by Gopher, Brikner, & Navon (1980). For an excellent discussion of testible discrimination between theories, the reader is referred to Navon & Gopher (1979, pp. 247-249).

Resources versus the dedicated central processor. As noted previously, an important defining property of resources concerns the sharable properties governing their allocation. Through careful modeling and experimental design, Long (1976) and Tulving & Lindsay (1967) have concluded that in detection and recognition tasks processing truly is shared simultaneously between auditory and



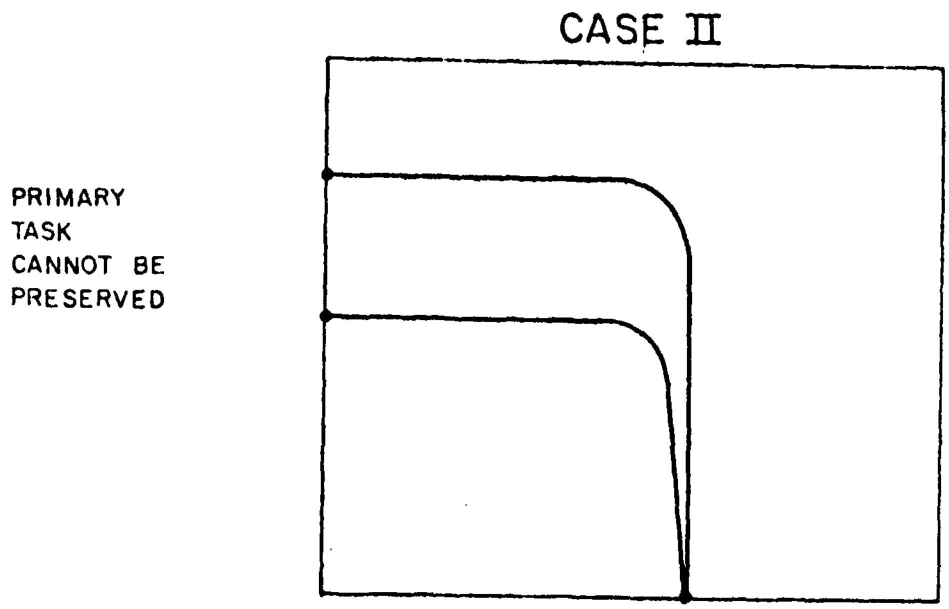


Figure 7. Case I: Shared resources. Primary performance can be preserved with difficulty increase.

Case II: Separate resources. Primary task performance must fall.

visual signals, rather than switched discretely. This demonstration of "shared capacity" relates closely to the issue of parallel versus serial processing (e.g., Taylor, 1976; Townsend, 1974), and as such, provides a point of convergence between the limited capacity central processor view and the resource view (whether undifferentiated or multiple). Clearly the dedicated processor, of a bottleneck or LCCP model can be made to mimick the sharable qualities of a resource if: a) the processor can switch sufficiently rapidly between tasks or channels of information; b) the processor is capable of adjusting the "dwell time" proportionately according to operator strategies and task priorities. At lower frequencies of sampling--such as those involved in visual fixation strategies, the latter is clearly an available strategy, and furthermore, can be easily validated by objective measurement (e.g., Senders, 1964).

If higher frequency switching is postulated, however, it appears nearly impossible to distinguish between whether processing resources or structures are truly shared between tasks, or are modulated by rapid switching. Indeed, it does appear that at some levels of processing, discrete attention switching is clearly an identifiable phenomenon (LaBerge, Van Gelder, & Yellott, 1971; Kristofferson, 1967). The position argued here is that the critical bandwidth, above which discrete switching is referred to as shared resources, is somewhat arbitrary. Very rapid intertask (or interchannel) switching may, for all intents and purposes, be labelled as shared resources.

A Hierarchical Structure of Resources

The structure of multiple resources presented in Figure 6 suggests a series of independent, non-overlapping reservoirs. If taken literally, the implications of this representation are: a) tasks demanding completely non-overlapping resources will always be perfectly time-shared; and b) if two tasks utilize partially separate resources, their degree of interference (on non-interference) will be unaffected by the "functional distance" (within the matrix of Figure 6) between the non-overlapping resources. As an explicit example of these implications we may consider the resource composition of a perceptual task, by looking in detail at the encoding stage of Figure 6--a 2 x 2 matrix of resources defined by modality (auditory-visual) and code (spatial-verbal). It is clear that two tasks within a single cell (e.g., two auditory verbal tasks) will interfere to a greater extent than two tasks in adjacent cells (auditory-verbal and visual-verbal) (e.g., Treisman & Davies, 1973). The data do not support the assertion, however, that two tasks demanding adjacent cells will be perfectly time-shared. Indeed, in Treisman & Davies' experiment, the authors observed that the cross model (auditory-visual) conditions demonstrated considerable interference. Correspondingly, a spatial and verbal visual detection task may be expected to show some degree of interference, albeit less than two verbal, or two spatial tasks. (Moscovitch & Klein, 1980).

These considerations suggest that human processing resources may be defined hierarchically. One example of such a scheme proposes that there exists some degree of separate auditory and visual resources, each one exclusive to the specific modality. These cannot be transferred to the other modality to facilitate performance. In addition, there exists a pool of general verbal perceptual resources, sharable between modalities, but not between codes. Above this level in the hierarchy exists a pool of general perceptual/ central resources, available to both spatial and verbal processing of either auditory or visual information, but not available to response processes. Finally, at a most general level, there might, indeed, exist a pool of "undifferentiated resources" which is available to and comp eted for by all tasks, modalities, codes, and stages as required. These general resources may be assumed to represent that which is conventionally labelled attention, consciousness, the bottleneck, or the LCCP of the structural theories.

Acknowledgement of its existence does not, however, in any way, obviate the explanatory value of the multiple resource concept.

The hierarchical representation described above, while accounting for increasing interference as a function of the increasing proximity of tasks within the resource space, is not entirely adequate. The problem is that the hierarchy described explicitly proposes a dominance ordering of dimensions that places modalities below codes and codes below stages. According to this representation, a given structural alteration effect will only be observed within the level of a shared structure above it in the hierarchy. More specifically, the specific scheme described predicts that the effect of shared versus separate modalities in time-sharing will only be observed if both tasks share a common code of processing (e.g., both are spatial). Likewise, the effect of shared versus separate codes will only be observed if a common stage of processing is employed. Brooks' (1968) demonstration of the interaction between spatial and verbal working memory tasks and response modalities provides evidence against this interpretation.

While some degree of dominance ordering between dimensions may in fact exist (e.g., it may make more of a difference in time-sharing efficiency to employ separate modalities than to employ separate codes), it is unlikely that this ordering is unidirectional. That is, it is probable that separate codes will improve time-sharing efficiency over shared codes, even if separate modes are also used. Specification of the precise effects of shared versus separate resources (levels) on one dimension, as a function of the overlapping resource demands on a different dimension, is a thorny problem that will require considerable experimental, theoretical, and analytical ingenuity to solve.

On the Relation between Resources and Strategies

The relation between resources and the strategies adopted by subjects in dual task performance may be articulated at levels both within and between tasks.

At a within task level, it is clear that different performance strategies can be employed that may increase or decrease the resource demands of component tasks. Shifts in the speed-accuracy tradeoff of reaction time, in control and response timing in tracking, or in rehearsal strategies in memory tasks, can easily have an impact upon the total resources demanded by a task as well as upon the locus of task resource demands. Two specific examples may be cited: First, tracking a system with sluggish dynamics may be accomplished either by a perceptual strategy that focusses on extracting the higher derivatives of the error signal as a means prediction and anticipation, or by a response strategy--in which impulse control is delivered to correct a deviation in error position (Wickens, Derrick, Gill & Donchin, 1981). The different strategies would shift the locus of resource demands between early and late stages, and one strategy would presumably be advantageous over the other depending upon the nature of a paired task. Second, encoding or rehearsal of verbal material may differ in the "depth of processing" (Craik & Lockhart, 1972), and this would presumably alter the emphasis upon phonetic as opposed to semantic codes (Posner, 1978). Such a shift, in turn, would vary the relative interference with tasks that differed in their dependence upon verbal versus auditory resources. (Martin, 1980).

At a between task level, strategies may be employed in adopting a particular allocation policy between tasks. As an example, if one of two time-shared tasks had a large data-limited region, such that perfect performance could be achieved at only 30% resource investment, while the other task was resource-limited across the entire range of performance, a 50/50 allocation policy would clearly be non-optimal. Instead, a strategy of investing 30% or fewer resources in the data-limited task would generate a higher level of combined performance. Correspondingly, the slope of the two PRFs dictates the particular operating point that will generate maximum dual task performance efficiency. As an example, Schneider & Fisk (1980) demonstrated that the efficiency of time-sharing two detection tasks--one a highly automated task of detecting "consistently mapped targets" (Schneider & Shiffrin, 1977) and the other a resource-limited task of detecting variably mapped targets, was influenced by the strategy of resource allocation adopted by the subject. Only when the subject was instructed to emphasize the resource-limited task, did the time-sharing efficiency of the two tasks approach maximum.

A related demonstration of the importance of allocation strategy in dual task performance was provided by Gopher & Brikner (Gopher, 1980). Subjects practiced in a dual task paradigm either under fixed or variable priority allocation conditions. When both groups were transferred to a different time-sharing paradigm, in which tasks of various difficulty levels were shared, the variable training group performed better. Presumably the skills in resource allocation that they had acquired proved useful in optimally adjusting the resource supply to tasks that varied in their resource demand.

What are Resources?

In the discussion presented above, the concept of resources has been invoked as an inferred quantity and hypothetical intervening variable to account for differences in time-sharing efficiency. Does this variable possess a physically identifiable counterpart? Various candidates appear plausible. Beatty (1980) has marshalled convincing evidence that pupil dilations mimic very closely changes in processing that correspond to increased resource mobilization (e.g., increase in task difficulty). His arguments that this response represents a direct manifestation of reticular activation system activity suggests that the latter may, indeed, be a candidate for a resource. Other intriguing evidence has correlated performance changes with blood flow changes to various areas of the brain

(Gur & Reivich, 1980), or with the brain's metabolism of Gluco proteins (Sokoloff, et al., 1977). However, the response time of both of these measures appear to be somewhat slow when compared with the bandwidth of performance change under resource mobilization (Wickens, Tsang, & Benel, 1979).

While the above representations suggest resources to be a generalized commodity, an alternative conception presented by Kinsbourne & Hicks (1978) considers resources to reflect the actual competition for a functional cerebral "space." Two tasks with demands in close proximity within this functional space share resources--neural processing mechanisms--and will interfere. Where this space contains discontinuities, as between cerebral hemispheres, or processing modalities, adoption of a multiple resources conception becomes quite plausible.

A final caution is in order. The concept of multiple resources has been invoked as a means of accounting for empirical phenomena in dual task performance. In the representation presented here, the resource dichotomies are defined across boundaries (stages, codes, and modalities) for which independent evidence suggests there to be a major discontinuity in processing. I do not intend to argue that there are not other discontinuities that define resource pools (e.g., Navon & Gopher, 1980, have argued that tracking in horizontal versus vertical axes is enabled by separate computational-perceptual resources), nor that proximity along other dimensions of processing (e.g., perceptual feature similarity or proximity of responding fingers) will not increase the degree of interference between tasks. I propose, however, as a note of caution that the explanatory and predictive power of the multiple resources concept, may be greatly diminished as the number of dimensions of separate resources proliferate (see Navon & Gopher, 1979, p. 249, for compatible views). Future research will, it is hoped, identify those categorical distinctions that account for the greatest variance in time-sharing efficiency, designate these as resources, and acknowledge that further variance in time-sharing efficiency remains due to other aspects of task similarity (e.g., perceptual features, response digits). It is with this parsimony in mind that the structural configuration in this chapter has been presented.

Applications of Multiple Resource Theory

Developing systems are becoming increasingly complex. The trend toward automating functions in many aviation, computer, and process control systems has not really unburdened the human operator/supervisor, but has often merely shifted the qualitative nature of processing load from output to perception and understanding (Wickens & Kessel, 1979; Danaher, 1980). The desired goal of a reduction in system error has not seemingly been achieved. The tremendous load imposed upon the human operator is relevant to our preceding theoretical discussions of attention and multiple resources in two contexts. (1) Exploiting multiple resources in task integration to increase the potential information processing characteristics of the human operator, (2) the measurement of operator workload.

Task Integration

The representation of Figure 6 suggests that the processing capacity of the human operator may be greatly influenced by the choice of task demands imposed upon an operator in dual task situations. Indeed Allport, Antonis, & Reynolds' demonstration of "perfect time-sharing" provided such an example. Often system requirements leave the designer little choice as to what resources demands a task will impose. For example, the aircraft pilot must navigate the aircraft through space. This is inherently a spatial task, just as storage of numerical information concerning required instrument settings seems to be inherently verbal. Yet considerable flexibility is also available. With increasing computer technology available in the areas of voice recognition and synthesis, choices may be made about whether to "display" instrument information visually or auditorily; or whether to accept commands by discrete manual action, or by voice command. In the input mode options often exist to display information verbally (e.g., digital meters), on spatially (analog symbology). At a central processing level some potential seemingly exists for training subjects to utilize either a spatial or verbal code for certain computational and problem-solving operations.

There are a number of human engineering factors that ideally should contribute to the system designer's decision as to which of these flexible options are selected and implemented in a particular system (Wickens, Vidulich, Sandry, & Schiflett, 1981). Important, for example, is the compatibility of a particular form of information to be relayed through visual versus auditory channels, given the parallel and serial aspects of the two modalities, respectively. However, in light of the previous data a factor that should be of great importance is a design criterion that seeks to minimize the overlap of demands on common resources for tasks that will, or should be performed simultaneously. It is dubious that "perfect" time-sharing will ever be achieved (or objectively measurable) outside of the idealized laboratory conditions, but it is possible that judicious selection of input and output and codes, so as to distribute demands across resources, can reduce the critical probability of human error.

Workload Assessment

We noted earlier in this chapter that the measurement of human operator workload represented a strong impetus for the development of resources. In early treatments (Rolfe, 1971; Knowles, 1963), the workload of a task was conceived as inversely related to the percentage of "residual capacity" not allocated to a primary task. In recent years the concept of human operator workload has benefitted from a resurgence of both theoretical and applied interest, as witnessed by the growing number of volumes and conferences addressing the subject (Moray, 1979; Ergonomics, 1978; Roscoe, 1978; Wierwille & Williges, 1978; Williges & Wierwille, 1979; Wierwille, Williges & Schiflett, 1979; Wierwille & Williges, 1980; Odgen, Levine & Eisner, 1979; Shingledecker, 1981). While the number of proposed measures of operator workload has proliferated--Wierwille and Williges (1978) have enumerated some 28 different techniques -- there is still a lack of any clear consensus of just what workload is, and whether the various measures are tapping the same, or different, constructs. Probably the only statement that can be made for which there is universal consensus is that workload is multidimensional (Wickens, 1979; Moray et al., 1979; Hartman, 1980). The following pages will consider the implications of the multiple resources concept to four major classes of workload measures: primary task parameters, secondary task performance, physiological measures and subjective ratings.

Primary Task Parameters. A major goal of workload research is to enable the system designer to predict what effect a particular design innovation (conceptually, a change in a parameter of a primary task) will have on the workload experienced by the operator when performing the task. Will the innovation increase or decrease operator workload? If either, then by how much? This consideration makes pertinent an important distinction between task workload, task difficulty manipulations and performance. A laboratory investigator may manipulate a particular task parameter under the assumption that workload is being increased -- for example in detection by degrading a target, by placing more targets on a screen, or in tracking by increasing the frequency of required corrections. Yet whether or not (or by how much) workload actually is increased is critically dependent upon the operator's response to the manipulation. If he continues to respond identically as before, therefore ignoring the added information imposed by the manipulation (in the case of the added display elements, or the increased tracking frequency) it is doubtful that the experienced or measured workload will have increased. The parameter change will be manifest as a greater decrement between obtained and desired (i.e., perfect) performance, but the investigator should not expect any concurrent workload measures to reflect this manipulation, nor fault the measures if they do not so respond. In order to accurately specify workload effects from primary task manipulations, it is necessary to include a description both of the nature and magnitude of a manipulation of primary task difficulty, and the change (or lack of change) in primary task performance.

Within the context of multiple resources theory, primary task performance constitutes one of two examples of vector measures. An accurate specification of the workload imposed by a task or a task manipulation must account for the dimension of resources outlined in Figure 6 (or for the dimensions of whatever other multiple resource model might be proposed). At least, optimally the measure should reflect resources imposed by task performance on both encoding/central processing and responses, of a verbal and spatial nature.

When assessing the workload imposed by a task, in contrast with the workload change induced by a task manipulation, a useful primary task workload measure is the <u>primary task workload margin</u>. In deriving the workload margin, a criterion level at which a task is to be performed must be specified. In applied contexts, this criterion is often supplied by a systems engineer -- for example the maximum allowable deviation off of a glide slope in an approach to landing an aircraft, or the allowable error rate and typing speed for a clerk typist. A primary task parameter is then chosen that will deplete resources of a particular nature, and this parameter is manipulated until it reaches a level such that performance falls below the criterion. For example in the aviation example, a small dynamic instability in the actual flight control surface could be gradually increased until performance error is sufficiently deviant (Jex & Allen, 1979). This level (the magnitude of the parameter manipulation) is the workload margin, as it provides an index of how much additional demand from the initial task conditions the resource in question can bear before performance becomes unsatisfactory. The workload margin is a vector measure since one such dimension should be supplied for each postulated resource.

The Secondary Task Technique. Imposing a secondary task as a measure of residual resources not utilized in the primary task is an oft employed technique closely related to the primary task workload margin (Rolfe, 1971; Ogden, Levine & Eisner, 1979). Rather than "absorbing" the capacity by increasing the difficulty of the original activity, resources are absorbed by a new activity, the secondary task. Secondary task performance is thus, ideally, inversely proportional to the primary task resource demands. Like the workload margin, as a vector quantity the secondary task technique must also account for the dimensionality of resources. Workload differences attributable to a manipulation of a primary task variable can be greatly underestimated if a mismatch between the resource demands of the primary task manipulation and those of prominent importance in the secondary task is obtained. An example of such a mismatch might be provided by the use as a secondary task of an auditory word comprehension or mental arithmetic task (auditory, verbal, perception/central), to assess the workload attributable to manipulations of tracking response load (visual, spatial, response). While some competition will be expected for any "general" resources within the system, the structure-specific contributions to resource demands will be underestimated.

A problem often encountered with the secondary task technique is the interference and disruption that it often causes with the primary task. It is interesting that one of the solutions offered to this problem is to choose highly dissimilar secondary tasks from the primary task. The preceding discussion suggests that this remedy may be employed only with a potential cost -- a reduced sensitivity to resource-specific attributes of primary task workload. The ideal secondary task technique would then logically be one that employs a battery of secondary task measures, a suggestion offered by Kahneman (1973). In cases where one level of a dimension can be easily discounted as not contributing to primary task performance, the dimensionality of the battery may be reduced accordingly. For example a verbal processing task with no spatial components need not be assessed with a spatial secondary task. However, in cases in which an activity is performed that potentially engages all "cells" of Figure 6, a secure workload measure should involve a battery that also incorporates those cells.

Physiological Measures. From the standpoint of multiple resource theory, physiological indices of workload, along with subjective ratings, represent a class of scalar measures. The term "scalar" is adopted because for any given physiological index (e.g., heart rate, EEG, pupil diameter, GSR [see Williges and Wierwille, 1979, for a comprehensive summary]), there is probably a many-to-one mapping from the demands imposed upon the separate resources to variance in the particular measure in question. The challenge to the investigator of these measures must be to establish the nature of this mapping. Does a given measure reflect variation on only certain dimensions, in which case it is somewhat diagnostic and adopts the more vector properties of a secondary task? Does it reflect variation in only the most demanded resource from any pool? Or does it reflect the aggregate demands imposed upon all resources, in which case its diagnosticity is sacrificed for greater total sensitivity. There is some evidence in this regard that pupil diameter may be equally responsive to manipulations of response load (e.g., the frequency of response corrections in tracking; Jiang & Beatty, 1981) as well as to encoding/central processing load (Beatty & Kahneman, 1966). A similar status is suggested by heart rate variability measures (Derrick, 1981). These measures then reflect the total resource demands imposed on the system but are undiagnostic with regard to the locus of demand. On the other hand the event related brain potential (Isreal, Chesney, Wickens & Donchin, 1980; Isreal, Wickens, Chesney & Donchin, 1980), sacrifices this global sensitivity for greater diagnosticity of the earlier processing stages. Absolute heart rate (as opposed to its variability) seems to show diagnosticity at later stages.

Subjective Measures. Subjective ratings of task difficulty represent perhaps the most acceptable measure of workload from the standpoint of the actual system user, who feels quite comfortable in simple stating, or ranking, the subjective feelings of "effort" or attention demands encountered in performing a given task. Some have argued (Sheridan, 1980) that these measures come nearest to tapping the essence of mental workload. Yet subjective ratings must accept the same status as scalar measures as physiological indices because of the difficulty that people encounter in actually introspectively diagnosing the source of resource demands within a dimensional framework (Nisbett & Sims, 1976). When asked to rate "response load" for example, people will encounter difficulty in separating the mental workload in response selection and programming from the physical muscular workload of execution. In addition to the common psychophysical problems associated with subjective scaling and response biases, there still is too little data available to make strong assertions concerning the degree of sensitivity of subjective effort to the dimensions of resource demand.

Concluding Remarks. If all measures of workload demonstrated high correlation with each other, and residual variance was due to random error, there would exist little need for further validation research in the area; the practitioner could adopt whichever technique is methodologically simplest and most reliable for the workload measurement problem at hand. However, such an ideal is not the case, and systematic instances of lack of correspondence between measures are readily available. For example, Derrick (1981) obtained data suggesting that subjective measures were relatively more sensitive to the number of competing activities, while primary task performance reflected to a greater extent the difficulty of a given single task activity. Another example is an experiment of Herron, 1980, in which a target aiming innovation, subjectively preferred by users over the initial variant generated reliably poorer performance than the original. When such dissociation of measures appears, the question of which is the "best" measure clearly depends upon the use to be derived from that information. If workload is to predict performance margins or "residual attention" to cope with failures in critical operational environments it seems wiser to adopt a system that manifests greater residual attention by primary or secondary task measures, despite the fact that it may demonstrate higher subjective ratings of difficulty. If, on the other hand, the issue is one of consumer useability, of setting work-rest schedules or of job satisfaction,and variations in performance are relatively less critical, then greater weight should be provided to the subjective measure. That such dissociations between measures occur should not be viewed as a source of discouragement, but rather as one more testimony as to the complexity of the human's attentional mechanisms, and as an instigation for more, fundamental and useful research into the relations between the subjective, objective and physiological realms of human performance.

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