

## On the Economy of the Human-Processing System

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An approach to human performance based on economic concepts is described. It elaborates on the view that the human system employs utility considerations to decide on allocation of its limited resources. The efficiency of those resources for performing a task depends on parameters characterizing the task and the performer. This approach is first used to discuss various models and interpretations for dual-task performance and their predictions, subject to the assumption that there is a single pool of resources. An expansion of this approach is then presented that hinges on the idea that the human-processing system incorporates a number of mechanisms, each having its own capacity. Those capacities can at any moment be allocated among several processes. Empirical evidence relevant to this idea and new interpretations for phenomena of dual-task performance suggested by it are presented.

In this article we draw an analogy between a person performing one or more tasks and a manufacturer producing one or more products. For this purpose, we try to give interpretation to the microeconomic theory within the domain of human performance. We hope to bring forward a broad framework in which many powerful ideas suggested by previous authors can be placed and related to each other.

In the first section we delineate the definitional framework of our approach, elaborate on ideas suggested by previous authors, especially Kahneman (1973) and Norman and Bobrow (1975, 1976), elaborate on a technique proposed by Norman and Bobrow, and present a theory of resource allocation adopted from microeconomics. In the second

section, we discuss dual-task performance within the proposed framework, uncover some of the hidden assumptions in previous analyses, and examine what happens when those assumptions are violated. The suggested framework is expanded in the third section to incorporate a view of the source of limitation of human performance that has hitherto been neglected. More specifically, we introduce and discuss a notion of multiple capacity. In the fourth section we reexamine dual-task performance in the light of this theoretical possibility. The fifth section is a general discussion of applications and implications of our suggestions and of their relations with some other ideas and theories of human processing.

### Some Basic Concepts

#### *Resources*

Let us first postulate the idea that the human system possesses at any moment a finite amount of processing facilities, which we call by the name coined by Norman and Bobrow (1975) *resources* (sometimes referred to as effort, capacity, attention, etc.; see e.g., Kahneman, 1973; Kerr, 1973; Moray, 1967; Posner & Boies, 1971; Shiffrin, 1976). Nor-

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mally, performance of a task is positively related to the amount of resources available to it.

### *Subject-Task Parameters*

For a given individual at a certain moment, a task is characterized by several parameters, such as sensory quality of stimuli, predictability of stimuli, availability and completeness of relevant memory codes, stimulus-response (S-R) compatibility, response complexity, and amount of practice. Norman and Bobrow (1975) subsumed all those parameters under the title *data quality*. The connotation of this term, however, is too limited; we prefer the term *subject-task parameters*. Subject-task parameters may characterize the task (e.g., response complexity), the environment (e.g., signal-to-noise ratio), or the permanent or changing properties of the performer (e.g., finger dexterity, level of practice), so they constitute a description of a situation in terms of many different variables (cf. the distinction made by Garner, 1974, between state limits and process limits and the distinction made by Norman & Bobrow, 1975, between signal- and memory-data limits). The feature of these parameters is that they are the constraints imposed on the system by the task (or more precisely, by the encounter of a specific task and an individual subject). Within those constraints, the system is usually free to mobilize its resources to perform the task.

### *Performance Functions*

Performance is determined by the *amount* of resources invested and by their *efficiency*. In other words, overall performance may be considered as a product of the amount of resources invested and the average contribution of a unit of resources to performance (*average efficiency*). An increase in amount of invested resources yields a performance gain that equals the increase in resources times their marginal contribution (*marginal efficiency*). The average efficiency of re-

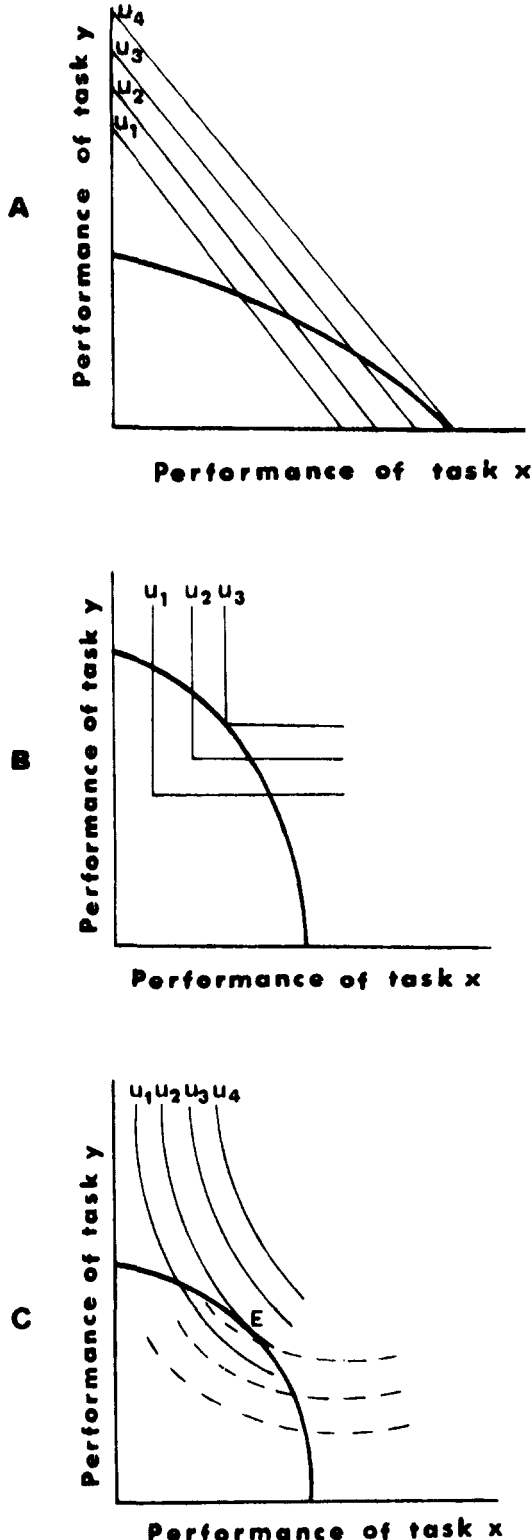
sources over the entire domain (to which we later sometimes refer as task difficulty) is determined by the subject-task parameters. Thus, performance can be viewed as a function in several arguments: subject-task parameters that are imposed on the system and resources that are controlled by it. Let this be called a *performance function*. Let the term suggested by Norman and Bobrow (1975), *performance-resource function*, denote the section of this function relating performance to amount of resources, holding all parameters constant. The slope of the latter function corresponds to the efficiency of resources, given the parameters.

### *Demand*

When certain subject-task parameters are given and a certain level of performance is intended, the amount of resources required to achieve this level under the circumstances can be derived from the performance function. This theoretical quantity can be called the *demand* for resources. It is clear that demand is a function of subject-task parameters and level of intended performance; that is, a task demands more processing resources the more difficult it is and the higher the criteria for successful performance are. A tracking task, for example, is more demanding the less regular the motion of the target is and the more stringent the level of tolerance for mean square error is. Note that according to this definition of demand, demand is not an invariant property of a task, as implied by the analyses of some previous authors (see, e.g., Kerr, 1973); it is rather defined for a specific task and a specific level of performance.

Sometimes what we call demand is referred to as difficulty (e.g., Kantowitz & Knight, 1978). This usage of the term *difficulty* is consonant with one natural language sense of this word, denoting the subjective feeling of strain accompanying involvement in demanding tasks. However, in this article we reserve the term *task difficulty* for the average efficiency of resources determined just by the





combination rather than over the single tasks, because the worth of combinations may not be directly derived from the worth of single-task performance of the two tasks.

#### *Performance Operating Characteristics*

Given the structure of the tasks and the capabilities of the system, some levels of joint performance are feasible and some others are not. When the system is free to allocate its resources in any proportion, it can achieve every combination  $(P_x, P_y)$  that can be given by the performance functions of  $x$  and  $y$  subject to the constraint that  $R_x + R_y \leq R^L$ , namely, that the amount of resources used by both tasks together is still within the capacity of the system. The set of combinations that can be produced when the system operates at its full capacity (when  $R_x + R_y = R^L$ ), can be represented as a curve of the type called by Norman and Bobrow (1975) *performance operating characteristics*. (See illustrations in Figure 1.) A performance operating characteristic (POC) traces the bound of joint performance. All combinations are feasible that are either on it or on the area enclosed by it and the two axes. All other combinations are beyond the reach of the system; for example, when the POC is Curve 3 in Figure 1,  $C_1$  and  $C_2$  are feasible, but  $C_3$  is not.

The POCs may have various shapes. Later in this article we discuss some determinants of the shape of a POC. The negative of the slope of a POC at a given point,  $-\Delta P_y / \Delta P_x$ , may be called *objective substitution rate*, which represents the amount of improvement in one task that can be gained by sacrificing one unit of the other task. This rate equals the ratio of the partial derivatives of the performance functions of  $x$  and  $y$  with respect to the amount of resources invested in

*Figure 2. Illustrations for three types of indifference curves: Panel A describes perfect utility trade-off; Panel B describes complete lack of trade-off; Panel C describes partial substitution. (Each of the two sets of curves in Panel c, the solid curves and the dashed ones, corresponds to a different situation or subject. The bold curve is a performance operating characteristic.)*

each task,<sup>2</sup>  $(dP_y/dR_y)/(dP_x/dR_x)$ , subject to the condition  $R_x + R_y = R^L$ . In other words, this rate reflects the relative efficiencies of resources for the two tasks: A unit of resources moved from Task  $y$  to Task  $x$  leads to a decrease in performance of  $y$  by the marginal contribution to  $y$  and to an increase in performance of  $x$  by the marginal contribution to  $x$ . Thus, the objective substitution rate is inversely related to the relative demands of the tasks per unit of performance improvement. The less that Task  $y$  demands with respect to Task  $x$ , the larger is the negative slope of the POC.

The POC comprises a set of alternative combinations only one of which is realized in a particular situation. If the system can voluntarily control the selection among the alternative combinations, it will probably consider their utility. Thus, we now turn to discuss the motivational aspect of joint performance.

### Indifference Curves

When there is a finite level of intended performance, then  $D_x$  and  $D_y$  sum up, and the sum constitutes the load applied on the system by both tasks together. The system will supply resources as long as they are available. However, what happens when the supply cannot meet the demand? To analyze this case, let us assume that utility is a nondecreasing function of performance, at least up to the intended level.

The performer must have preferences among different mixtures of outputs of the tasks performed. Those preferences can be represented by means of what economists call *indifference curves* (or equal-utility contours), each of which is a locus of all combinations among which the person is indifferent (in other words, combinations that have the same subjective utility). Figure 2 illustrates various maps of indifference curves.<sup>3</sup> Note that when utility is continuous, each map consists of an infinite number of curves. The negative of the slope of an indifference curve corresponding to utility  $u$  at a given point  $(- \Delta P_y^u / \Delta P_x^u)$  may be called *subjective substitution rate*. It represents the utility trade-off of the tasks, namely, how

much improvement in  $P_y$  is needed to compensate for deterioration of  $P_x$  in terms of utility, namely, to maintain utility at the same level  $u$ . The subjective substitution rate equals the ratio of the partial derivatives of the utility function with respect to  $P_x$  and to  $P_y$ ,<sup>4</sup>  $(\partial U / \partial P_x) / (\partial U / \partial P_y)$ . In other words, the subjective substitution rate is inversely related to the relative importance of the tasks.

Indifference curves may assume various shapes. Two extreme cases that reflect perfect utility trade-off on one hand and complete lack of trade-off on the other hand are presented in Panels A and B of Figure 2, respectively. However, realistic psychological examples for these two extreme cases must be rare. For most task pairs, outputs appear to be *partly substitutive*, as illustrated in Panel C of Figure 2. This case is intermediary between the first two and it exists whenever degradation of  $P_x$  can be compensated for by some improvement in  $P_y$  (or vice versa), yet the subjective substitution rate is not constant. Some degree of performance in both tasks is very important, but the utility gained by improving performance progressively diminishes. Therefore, the results of deterioration in performance of either one of the tasks get more and more severe, whereas the impact of the concurrent improvement in performance of the other task gets less and less beneficial. Hence, to compensate for the deterioration, more and

<sup>2</sup> A decrease of  $\Delta P_y$  in  $P_y$  releases  $-\Delta P_y / (dP_y/dR_y)$  resources, which multiplied by  $dP_x/dR_x$  yields an improvement of  $\Delta P_x$  in  $P_x$ . Hence,

$$\frac{-\Delta P_y}{\Delta P_x} = \frac{dP_y/dR_y}{dP_x/dR_x}$$

<sup>3</sup> While revising this article for publication, an article by Rachlin and Burkhard (1978) was brought to our attention; they borrowed economic terminology to analyze behavior in instrumental conditioning studies. Many concepts introduced in this section were presented by Rachlin and Burkhard in greater detail.

<sup>4</sup> Suppose  $P_y$  suffers a decrease of  $\Delta P_y$ . To maintain the same utility  $u$ , the loss  $-\Delta P_y \times \partial u / \partial P_y$  should be rebated by a commensurate gain in utility resulting from improvement in  $P_x$ :  $\Delta P_x \times \partial u / \partial P_x$ . Hence,

$$\frac{-\Delta P_y^u}{\Delta P_x^u} = \frac{\partial u / \partial P_y}{\partial u / \partial P_x}$$

more improvement is needed. This situation seems to be very prevalent. For example, when one is tracking a target in a plane, using a hand controller, horizontal accuracy cannot fully compensate for vertical inaccuracy; given a certain degree of overall inaccuracy, distance to the target is minimized when accuracy for both dimensions is equal. In general, the diminution of marginal utility is a conventional wisdom in economics and is indicated by psychological choice studies (e.g., Stevens, 1959).

### Resource Allocation

The graphical representation of infeasible aspirations is the existence of some indifference curves to the "northeast" of the POC. In this case, since the sum of the task demands  $D_x + D_y$  exceeds  $P^L$ , then the supply of the system to the tasks  $R_x + R_y$  will be equal to  $R^L$ . But how will the total capacity,  $R^L$ , split between the two tasks? We present here the normative solution; its adequacy as a descriptive model is yet an open question, but if utility is considered at all by the processing system, then this model is probably not fatally wrong.

The optimal mixture of  $R_x$  and  $R_y$  is the one that yields the joint performance associated with the highest utility. The best combination of performance levels is at the meeting point of the POC with the "northeasternmost" indifference curve. When the indifference curves are convex to the origin, that will be a tangent point in which the slopes of the POC and that indifference curve (namely, the objective and subjective substitution rates) are equal,<sup>5</sup> as illustrated by Point E in Panel C of Figure 2. This means that no extra utility can be gained by trading either more  $x$  for less  $y$ , or vice versa. Thus, the *resource allocation ratio*,  $R_y/R_x$ , is a function of the objective substitution rate and the subjective substitution rate. In other words, resource allocation depends on both objective relative demands of tasks and subjective task preferences.

Thus, a POC for a given pair of tasks and for a given subject may be regarded as the locus of all combinations ( $P_x, P_y$ ) that arise

from splitting  $R^L$  between the two tasks in all different allocation ratios (viz., under all possible task priorities).

### Task Difficulty

Since task difficulty is considered to be equivalent to resource efficiency, its effect on performance must interact with the effect of amount of resources. In other words, when some parameters of a task (or of a subject) change, so does the productivity of a unit of resources (viz., the average slope of the performance-resource function): The easier the task, the larger the average slope. When performance has no effective upper limit, decreased difficulty must also raise the marginal slope over all the regions of the function. Note, however, that when the functions approach a ceiling dictated by the nature of the performance measure, the marginal slope drops more rapidly the easier the task is.

The effect of difficulty on dual-task situations can be described by means of a family of POCs. When Task  $x$  is made more difficult, the POC has a smaller  $x$  intercept (see Figure 3). When Task  $y$  is made more difficult, the  $y$  intercept is smaller. Making both tasks more difficult should depress both intercepts.

We have just described how difficulty affects the set of feasible alternatives for joint performance. How will it affect the actual combination ( $P_x, P_y$ ) selected, given a certain pattern of task preferences? Since the optimal combination is the tangent point of the POC and the highest indifference curve, this effect is hard to predict without knowing the exact shape of the indifference curves

<sup>5</sup> To maximize utility, we have to determine just  $R_x$ , since  $R_y$  is given by  $R^L - R_x$ . Utility is maximized when

$$0 = \frac{\partial u}{\partial R_x} = \frac{\partial u}{\partial P_x} \frac{dP_x}{dR_x} + \frac{\partial u}{\partial P_y} \frac{dP_y}{dR_y} \frac{dR_y}{dR_x}.$$

Since  $dR_y/dR_x = -1$ , this can be rewritten as

$$\frac{dP_y/dR_y}{dP_x/dR_x} = \frac{\partial u/\partial P_x}{\partial u/\partial P_y}.$$

The left and the right wings have been already shown to be equal to the objective and the subjective substitution rates, respectively (see Footnote 2 and 4).

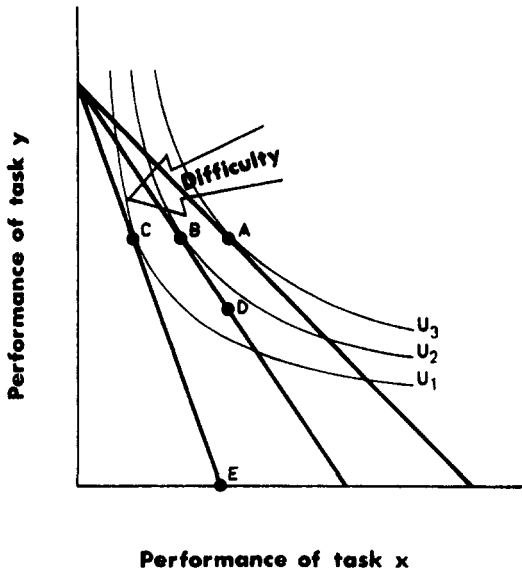


Figure 3. Illustration for the effect of task difficulty, given the indifference map presented in the figure. (A, B, and C are points of optimal resource allocation for easy, medium, and difficult Task  $x$ , respectively. D and E represent joint performance under medium and high difficulty, respectively, when performance of Task  $x$  is supposed to be protected.)

and the POC. Suffice it to say that to the extent that resource allocation depends on utility considerations, when the indifference curves are fairly parallel and convex to the origin and when the POC is fairly close to linear, the performance of the task whose difficulty is manipulated is likely to be much affected, whereas the performance of the other task will probably suffer very little or not at all (see the shift from Point A to Point B and then to Point C in Figure 3), and may even improve a little.

When one task is primary (in the sense that its performance is maintained at a fixed level) and the other task is secondary, varying the difficulty of either of them should typically affect only the performance of the secondary one (unless the primary task is made so difficult as to render its previous level of performance unreal). To illustrate, suppose that Task  $x$  in Figure 3 is the primary one. When it is made more difficult, joint performance shifts from A to D. A further increase in difficulty may result in an in-

ability to protect the required performance of the primary task even at the cost of a complete neglect of the secondary one (e.g., a shift from D to E). Suppose now that Task  $x$  is the secondary and that it is made more difficult. Joint performance will shift from A to B and then to C. Note that because of the interaction of the effects of resources and difficulty, the magnitude of the difficulty effect depends on the specific level of performance prescribed for the primary task. It is worth noting that the requirement that the performance of the primary task remain invariant is often not met (see Kerr, 1973; Rolfe, 1971).

### What is Hidden Behind a POC?

#### *Empirical POCs*

Performance operating characteristics have been defined as the bound of joint performance of two tasks with given demands when the system operates at full capacity. Experimenters may wish to obtain empirical POCs in their laboratories for at least two purposes. First, they may want to study the sensitivity of performance of a certain task to the amount of effort put into it by conjoining it with varying levels of demand applied by a concurrent task. Second, they may be interested in determining the amount of interference between two specific tasks and perhaps in comparing interference measures from several task pairs. Both objectives are often attempted by observed performance decrements from single- to dual-task performance in which the type or the difficulty of the concurrent task is varied. But since requirements in the different dual-task conditions are not always comparable, this technique often confounds processing potential with preference (or resource efficiency with allocation policy). As Sperling and Melchner (1978b) put it:

To compare two pairs of tasks, one cannot use just one condition of attention for each pair, as this would be comparing one point from each of two curves and not comparing two curves. (An analogous problem occurs in signal detection theory with ROC curves.)

Thus, it is desirable to plot a complete curve for any given task pair.

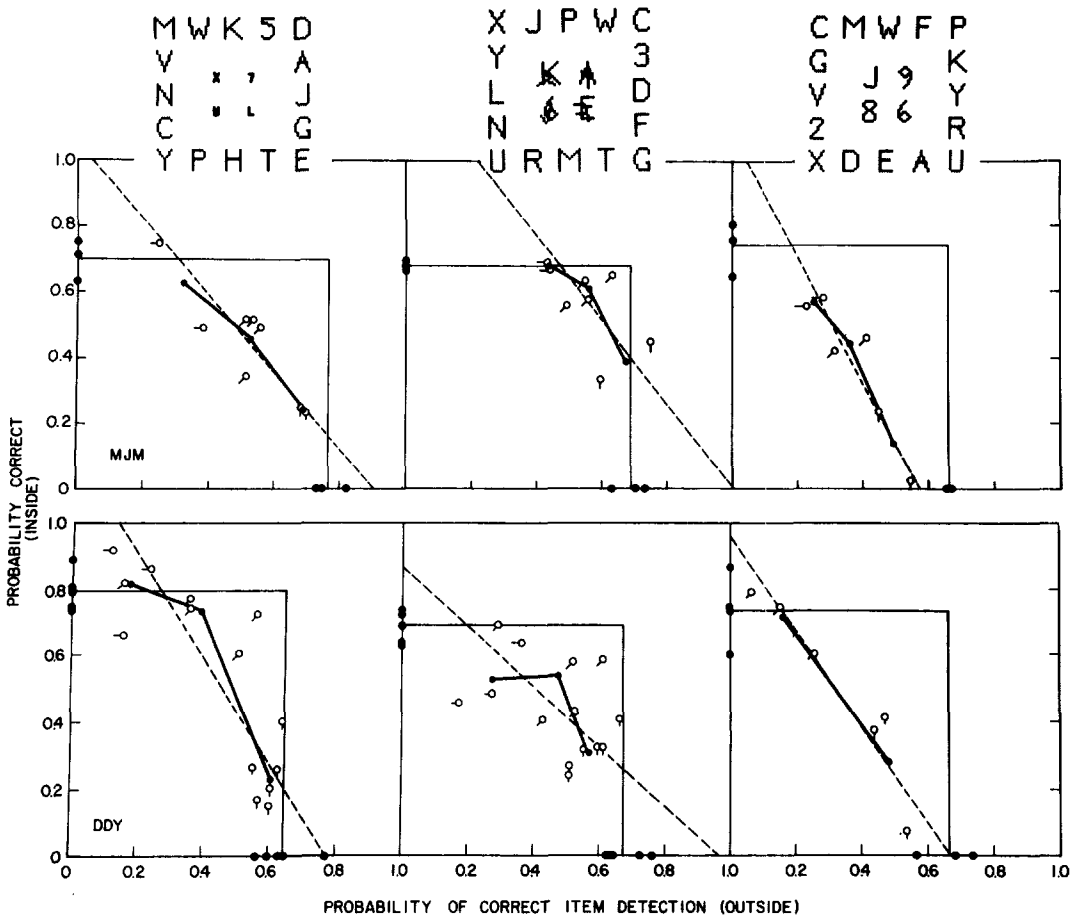


Figure 4. Data from divided attention experiments reported by Sperling and Melchner (1978a). (Each open circle represents data from one block of 30 to 60 trials [report of both targets]; each filled circle represents data from a control session [report of only the designated class of targets]. The direction of the "tail" on a data point represents the attention instruction: Down indicates "give 90% of your attention to the outer array"; left indicates "90% to inner array"; diagonal indicates "equal attention." The heavy lines connect points of average performance in each of the attention conditions. The vertical and horizontal lines are best fits to the control data; the diagonal lines are best fits to the multiple detection data [from Sperling & Melchner, 1978a, with permission; copyright 1978 by the American Association for the Advancement of Science].)

It follows from the theoretical definitions that the only admissible technique to obtain an empirical POC is to fix subject-task parameters for both tasks, to allow the subjects maximal control over quality of performance for both, and to induce them to change the relative emphases on the tasks by means of payoffs or instructions (Norman & Bobrow, 1976). The limiting case of uneven emphases should be the single-task performance levels of the two tasks. As already noted by Norman and Bobrow (1976), there

are very few instances in the literature of reporting POCs or results from which a POC can be recovered. Let us inspect the few that exist.

Sperling and Melchner (1978a, 1978b) used a paradigm of visual search for a numeral in a sequence of letter arrays. They had their subjects search for two targets each embedded in one or two different arrays that were presented simultaneously, one at the central part of the display and one surrounding it. (See stimuli in Figure 4.) Subjects



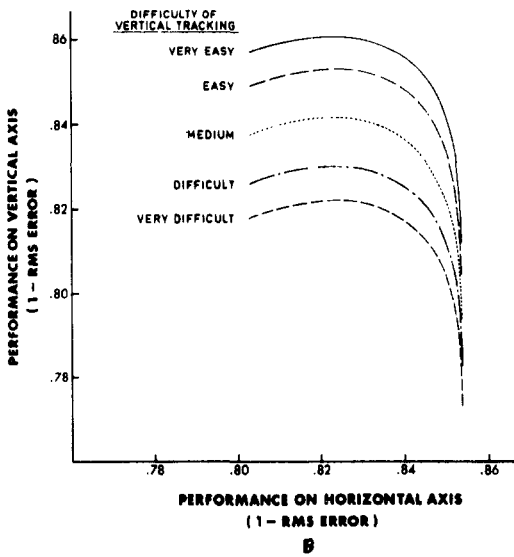


Figure 5. A family of POCs representing tracking accuracy (1 root mean square error) on each of the axes in dual-axis tracking as a function of task emphases. (Each POC corresponds to a different level of target vertical velocity and is obtained by jointly solving two second-order multiple regression equations for predicting performance on the two axes from the task emphases variable [from Gopher & Navon, Note 3].)

were asked to report the identity and location of the target once it was detected. They were instructed to divide their attention in varying proportions between the two arrays. In this way, Sperling and Melchner obtained the POC curves (which they called *attention operating characteristics*) shown in Figure 4. By a similar technique, Kinchla (Note 1) described the performance of subjects required to detect the occurrence of light at two different locations. Recently, Bartell and Kantowitz (Note 2) studied trade-off between tapping and digit naming in a similar way and plotted their data as POCs.

Gopher and Navon (Note 3) regarded two-dimensional pursuit tracking as time-sharing between horizontal and vertical tracking and measured tracking error in each of the dimensions. They manipulated the difficulty of each dimension independently by varying the velocity of the target movement, and they controlled relative emphases on the two dimensions by varying the ratio of tolerance

levels for error in each. Figure 5 illustrates the kind of results found in this study, presented as a family of POCs. The same method for varying task priorities was previously used by Wickens and Gopher (1977), although they did not plot their data as a POC.

Suppose researchers study dual-task performance in the way described here. What are the possible phenomena they may expect to observe? To what extent are they justified in interpreting an empirical curve plotting performance of a task as a function of the other one as a POC in the sense defined above? What other interpretations can be offered for the same data? It is important to discuss all of these issues not only for the benefit of those who intend to collect data by the technique described here but also for anybody who would consider interpreting data about dual-task performance within the framework discussed in this article.

#### *The Strict Central Capacity Interference Model*

The previous section served to introduce a conceptual framework. Within this framework, one can conceive of a class of models that can be called *central capacity interference* models. Such models have been described, for example, by Broadbent (1971), Kahneman (1973), Moray (1967), Keele (1973), Norman and Bobrow (1975), and Posner and Boies (1971). For the following discussion we use as an anchor point an idealized prototype of them that may be considered as the psychological analogue of the Homo Economicus and that we call the *strict central capacity interference* model. The following six assumptions underlie it (for two of them we present the conditions that have to be met for those assumptions to hold): (a) sensitivity of performance to amount of resources; (b) additivity of demands (no extra cost for concurrence, no symbiosis between tasks); (c) independence of tasks; (d) fixed capacity; (e) controllability of resources; and (f) complementarity of supplies (continuity of performance, substitutability of outputs, compatibility of tasks, manageabil-

ity of resources, scarcity of resources, and efficiency of resource budgeting).

In succeeding sections, we discuss each of these assumptions and the effects that violation of each of them might have on behavior in dual-task situations or on its interpretation.

### *Sensitivity of Performance to Amount of Resources*

The slope of the performance-resource function at any given point (*viz.*, its first derivative), represents the sensitivity of performance to amount of resources (*viz.*, the marginal efficiency of resources). If marginal efficiency of resources is constant, then resources removed from one task will yield a fixed rate of improvement when directed to the other one, so we could expect a linear POC like Curve 1 in Figure 1. However, marginal efficiency may not be constant. As Norman and Bobrow (1975) argued, there is reason to suppose that as the amount of resources increases, efficiency typically decreases until it drops to zero. Processes at the region of complete inefficiency (*viz.*, when changes in resources do not affect performance), are called *data-limited processes* by Norman and Bobrow; when efficiency is non-zero, they call the task *resource-limited*. The existence of a rigid performance asymptote indicates that the negative acceleration of a performance-resource function would not be eliminated by scaling the performance measure in a different way.

When there is a decrease of sensitivity of performance of the two tasks to the resources they both depend on, the POC will be concave to the origin (as, say, Curves 2, 3, and 4 in Figure 1) or even perpendicular to the axes at the edges as in Curve 5 in Figure 1 (Norman & Bobrow, 1975): We lose very little on one task when adding a moderate level of the other one on top of it; but since improvement in performance of the second one costs more and more in terms of resources and since performance of the first one becomes more and more sensitive to re-

sources *withheld* from it, the objective substitution rate will continuously change.

Since this rate equals the ratio of marginal efficiencies, the curvature of the POC will be larger than the curvature of either of the performance-resource functions. So, a performance-resource function for a task generally cannot be recovered from a POC unless the performance-resource function of the other one is known. For example, the horizontal part of Curve 5 in Figure 1 can be interpreted as an indication that the sensitivity of Task *y* is minimal or that the sensitivity of Task *x* is maximal or both. Does this mean that a performance-resource function is a theoretical construct that must remain unspecified forever? If it were, then the value of this construct would be explanatory rather than predictive, much like the value of concepts such as subjective utility. However, there might be a way to uncover the hidden performance-resource functions.

Note that if we knew the performance function of one of the concurrent tasks, we could derive the function of the other one. So, how do we bootstrap the chain of derivation and obtain the first one? In principle, once a reliable, perfectly linear POC is observed, either of the tasks associated with it can be regarded under certain assumptions as having a linear performance-resource function and can be used as a vehicle for deriving performance-resource functions for any other task, thereby to predict interference between any two tasks. This procedure, which is described and discussed more formally in the Appendix, could be extremely valuable if it worked. However, it is predicated on the assumption that performance trade-off reflected in a POC is always due to central capacity interference. This article discusses some arguments that give rise to doubts about this view.

A concave POC may thus be attributed to decreasing marginal efficiency of resources for at least one of the tasks. However, such an interpretation does little more than restate the phenomenon. Why does the marginal efficiency decrease? We elaborate on this issue later.

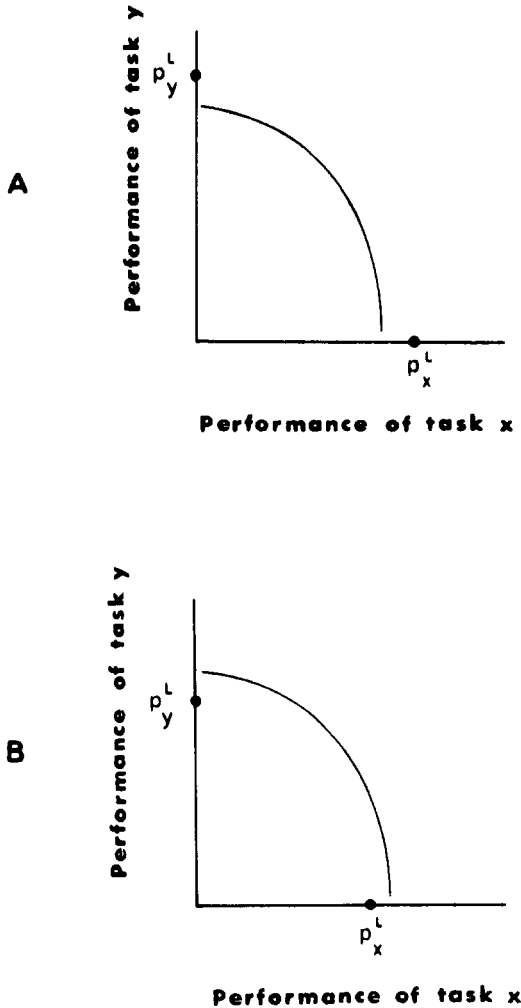


Figure 6. Panel A: A discontinuous POC exhibiting the existence of a concurrence cost. Panel B: A discontinuous POC exhibiting the existence of a concurrence benefit. (In both cases,  $p_x^L$  and  $p_y^L$  belong to the POC. The origin corresponds to the worst performance levels of both tasks (e.g., chance level accuracy).)

### Additivity of Demands

If tasks compete for the use of resources they both need and if such a competition is the only source of task interference, then the demand for resources applied by the two conjoined tasks with given intended performance levels,  $D_{xy}$ , must equal the sum of the demands of the tasks when performed separately,  $D_x + D_y$ . Kahneman (1973) suggested that some task pairs interfere with

each other structurally; namely, their joint demand  $D_{xy}$  is greater than  $D_x + D_y$ . It can be easily shown that in this case the POC will be discontinuous at the points of intersection with the two axes (or at least one of them) in the way shown in Panel A of Figure 6: Maximal performance in single-task situations ( $p_x^L$  and  $p_y^L$ ) is higher than what can be extrapolated about performance of the same task conjoined with the worst level of performance of the other task, because the mere act of adding a second task will withhold from the first one more resources than required by the new one. We label such an overcharge by the term *concurrency cost*. Indications about the existence of discontinuity effects like these were found by Gopher and North (Note 4), Kantowitz and Knight (1974), Sperling and Melchner (1978a), Wickens and Gopher (1977), and others.

$D_{xy}$  may conceivably be smaller than  $D_x + D_y$ . To be consistent, we call this relation *concurrency benefit*. The extreme case of concurrency benefit occurs when the POC is again discontinuous at the intersections with the axes (or at least one of them), but this time in a different and apparently paradoxical manner: A task can be performed better when conjoined with a moderate level of another one than when performed in isolation (see Figure 6, Panel B).

*No extra cost for concurrence.* One possible cause for concurrence cost is *partial incompatibility* of the tasks, which means that their outputs, or throughputs, or preconditions conflict in some sense. Consider, for example, the conflicting activations or response tendencies created by the word and the color in a Stroop task (Stroop, 1935). Another example is the interference between activities having incompatible rhythms (like singing a waltz while dancing a tango). In those cases, the performance of one task involves main or side effects that make the other task more difficult (and, probably, vice versa). This way, each of the tasks requires more resources when conjoined with the other one. A more severe case is one in which there is some structural constraint that hampers any coordination between the two tasks

so that involvement in one of the tasks precludes any degree of success in the other one. In that case of *total* incompatibility, there is no concurrence cost simply because there can be no concurrence. To illustrate, simultaneous inverse operations of two switches that are 40 cm apart are totally incompatible when attempted with the same hand but are just partly incompatible when done by different hands.

Another source for concurrence cost is that the process of organizing, coordinating, scheduling, and allocating resources may require resources in itself (see Lindsay, Taylor, & Forbes, 1968; Moray, 1967). Thus, the price we pay for trying to do much at once is a drop in total capacity available for what we are really interested in.

Finally, note that the existence of concurrence cost and capacity interference are not mutually exclusive. Processes may compete for resources and may, in addition, require or create conditions that are harmful for each other. Because of the possibility of a concurrence cost, one should be cautious in interpreting performance decrements from single- to dual-task situations as representing capacity interference (for a similar conclusion, see Kantowitz & Knight, 1976b.) Sampling several points on a POC by manipulating task emphasis should give one a better idea of the locus of task interference.

*No symbiosis between tasks.* Although the possibility that a task benefits to some extent from being conjoined with the other one appears at the first glance to be implausible, actually it is not. For example, Nickerson (1970) reported that the occurrence of an auditory stimulus preceding or following a visual one by a variable interval had a facilitative effect on reaction time to the visual stimulus. Bernstein (1970) listed several similar results. Some other examples are mentioned below.

The mutual advantage may be due to symbiotic relations, namely that the output or side effects of one process make processing of the other one easier. For example, since some stimuli tend to appear together, the process of recognizing any one of them may be facilitated by information gained by on-

going processing of the others, as indicated by context effects (Tulving, Mandler, & Bauml, 1964), forward and simultaneous priming effects (Kadesh, Riese, & Anisfeld, 1976; Meyer & Schvaneveldt, 1976), the word superiority effect (J. Johnston & McClelland, 1974; Reicher, 1969; Wheeler, 1970), and configural superiority effects (Pomerantz, Sager, & Stoeve, 1977; Weisstein & Harris, 1974). A correlation between identities of two simultaneous nonverbal signals may increase the discriminability of both (Long, 1977). Motor tasks may make use of feedback information provided by concurrent perceptual activity. Recall of the words of a song may sometimes be aided by singing its tune. Foot tapping while playing a musical instrument seems helpful (at least for novice players).

Concurrence benefits may also arise from some redundancy in components of the tasks. If the two tasks depend in part on the output of the same intermediary process, then the latter has to be executed just once when both tasks are done at the same time. For example, to estimate the distance of two remote targets, one could use the same distance cues and compute their impact just once.

So, in all those situations part of the detrimental effect of the load imposed on the system by time-shared tasks is rebated by the merits of cooperation. In the following section, we discuss situations for which the load may not be detrimental in the first place.

### *Independence of Tasks*

Time-sharing situations are considered as dual tasks because it is assumed that the tasks preserve their separate identities while being conjoined. However, sometimes joint processing is not a temporal concatenation of two tasks but is rather done by a categorically different strategy that operates on the integral whole. In that case,  $D_{xy}$  might not be determined at all by  $D_x$  and  $D_y$ . One example from perception is the processing of stimuli varying on two dimensions that are called *integral dimensions* by Garner (1976), such as the location of points in

the plane. One explanation for word superiority and configural superiority effects ascribes them to holistic processing. There are some indications that sufficient practice with a dual-task situation may serve to unify several tasks into one entity (LaBerge, 1973; Seibel, 1963).

We have thus far tried to explain costs and benefits of concurrence in terms of demands. We now discuss the possibility that the source of benefit resides in the supply.

### *Fixed Capacity*

A POC is defined as the limit on joint performance that can be achieved by varying allocation of resources out of a given limited pool. However, as Kahneman (1973) and Welford (1968) suggested, capacity might be elastic to some extent. People's level of arousal fluctuates. Increasing load may induce a rise in arousal (see Kahneman, 1973, pp. 17-24) so that the system can mobilize resources that have not been available with a lower load. If capacity stretches to accommodate a heavier load, then in a dual-task situation we may find ourselves in the happy state of having to slice a larger cake: The system can offer to time-shared tasks more than it can supply to any one of them in isolation. In this case, one would be able to do a little of Task  $y$  without any harm to the maximal performance of Task  $x$ , and vice versa (see Curve 5 of Figure 1). It is conceivable, although less probable, that imposition of a second task would act through increase in arousal to *improve* performance of the first task beyond its apparent single-task limit, as is illustrated in Panel B of Figure 6.

A word of caution should be said about the notion of elastic capacity. Even though capacity can conceivably grow, it probably cannot grow indefinitely. Capacity is, presumably, the stable level of what the system can supply in circumstances of heavy load, not the occasional peaks that cannot be accounted for by any systematic factor.

### *Controllability of Resources*

The notions of selective and divided attention and resource allocation are based on

the implicit assumption that resources are at the disposal of the system to be allocated at will (not necessarily consciously). That is to say, the system can select any combination of performance levels that does not overtax its capacity. There are many demonstrations of voluntary control of attention in certain time-sharing situations (Gopher & North, 1974; Kahneman, 1970; Sperling & Melchner, 1978b; Wickens & Gopher, 1977; Gopher & Navon, Note 3). However, as noted by Kahneman (1973, p. 100), Schneider and Shiffrin (1977, p. 2), and others, the system is not always perfectly free to decide what and how much to emphasize. In some situations the environment enforces a certain emphasis. There are many examples in the literature for aspects of the environment one cannot help processing and for activities one cannot avoid, for example, the orienting response (Pavlov, 1927); the Stroop effect, (Stroop, 1935); failures of focused attention in dichotic listening (Moray & O'Brien, 1967; Treisman & Riley, 1969), in visual search (Shiffrin & Schneider, 1977), or in visual discrimination (Eriksen & Hoffman, 1973); processing of irrelevant dimensions in speeded classification tasks (Garner, 1974); and failures to ignore the overall structure of patterns (Navon, 1977). When a certain level of a process is mandatory, then it attracts the amount of resources it demands and leaves the residual for the control of the system. The feasible possibilities of joint performance in such a situation are described by an incomplete POC of the type illustrated by the solid line labeled 7 in Figure 1. The performance of  $y$  cannot be improved beyond  $P_y^o$  not because Task  $y$  cannot utilize more of the resources spared by worsening performance of  $x$  but because the performance of  $x$  cannot be worsened below  $P_x^o$ .

Because humans may not completely master their resources, we should distinguish between performance in a single-task situation and performance in a *dual-task focused-attention* situation. This is especially important in perceptual tasks: A stimulus is best ignored when it is absent. If its mere presence withholds some resources from the to-be-attended stimulus, then estimating the bound-

dary condition of joint performance either by means of telling a subject to process just one of two present stimuli or by presenting him or her with just one may yield different results. When the first method is selected (as done, e.g., by Sperling & Melchner, 1978b), the apparent limit on processing of the to-be-attended stimulus may be short of the maximal level because of "invisible" processing of the competing to-be-ignored stimulus. Results of a visual discrimination experiment reported by Eriksen and Hoffman (1973) suggest both that processing of irrelevant stimuli may take place (their identities were found to affect latency to identify the target) and that it may result in impairment of processing of the relevant ones (the appearance of *any* nontarget stimulus turned out to slow identification of the target). A performance decrement of this type is the involuntary cost of concurrence. It should be remembered, nonetheless, that such decrement may be due not only to mandatory processing but also to degradation in input quality; for example, by lateral masking (Estes, 1972; Townsend, Taylor, & Brown, 1971).

### *Complementarity of Supplies*

In their analysis of POCs, Norman and Bobrow (1975) assumed complete complementarity between processes, which means that  $R_x + R_y = R^L$ . That is to say, the system will supply to the two tasks whatever it can at the moment. If it does not, the observed joint performance does not lie on the POC, which is defined as the outcome of full capacity operation. One could conjecture that the system cannot rest idle or partly idle: All resources have to be spent somehow (Kahneman, 1973, p. 130). Even if that were true, not all the resources have to be directed to the tasks studied, so the supply to them does not exhaust the whole pool.

There are a number of reasons for lack of complementarity. Four of them are discussed in the following sections.

*Continuity of performance.* Norman and Bobrow (1975) presented "the principle of graceful degradation" and "the principle of

continually available output," which state that quality of performance is a matter of degree and that it is often smoothly related to the amount of resources invested.

However, there may be some tasks that can be performed in one of several discrete levels. Some other tasks may not improve unless a threshold amount of additional resources are available (as illustrated by Norman & Bobrow, 1975, Figure 1). In either case, the POC will look like a step function (see Curve 8 in Figure 1), because so are the performance-resource functions. Hence, not all available resources can always be utilized.

*Substitutability of outputs.* The performer shifts positions on a given POC when there is some utility trade-off between the output of the two tasks that is varied over situations (e.g., by changing task emphases). However, consider the situation illustrated in Panel B of Figure 2. There is just one map of indifference curves, and there is no trade-off at all because the output of both tasks must be coordinated to yield the desired effect; an improvement in performance of either one of the tasks is ineffective unless matched by a commensurate improvement in performance of the other one; a degradation in performance of either of the tasks cannot be compensated for whatsoever by any improvement in performance of the other one. One example is the performance of the two hands in piano playing. Another example is listening to the two channels of a stereo recording. A good analogy from choice behavior is the utility associated with complementary commodities such as a right shoe and a left shoe. In this case an empirical POC may be square because forcing subjects to degrade their performance of one task should not induce them to use the released resources to improve performance of the other one.

*Compatibility of tasks.* We have presented the idea that partial incompatibility of tasks makes simultaneous performance more difficult than predicted by consideration of the separate demands. In this case, joint performance will be relatively poor, but all available resources will probably be engaged

in either of the activities so that some trade-off between the tasks will exist. However, when the tasks are totally incompatible, they can be performed only in sequence (or in alternation if they take a long time). If one task does not exhaust the capacity, the excess resources will remain unused.

Note that according to the single-channel hypothesis (Welford, 1952), all tasks are totally incompatible in this sense. Some theorists (e.g., Kerr, 1973; Posner & Boies, 1971) exclude from this category only tasks or operations that do not require any capacity whatsoever.

*Manageability of resources.* Another possible sort of interference is one that impairs the flow of resources between tasks. The system may be able to perform both tasks simultaneously at a certain level, but it is not flexible enough to be able to divert resources from one process to the other one. If some resources are released, the system will not capitalize on them, not because they are useless or because it does not want to, but because it does not know how. So the free resources will remain unused. The empirical POC, which is square (see Curve 1 in Panel B of Figure 12), is an underestimate of the potential of the system had all resources been engaged, as is indicated by the large concurrence cost. The system does not have full control of its resources, but this time not because it is preprogrammed to prefer one process in spite of any antagonistic deliberate intentions, as is the case with mandatory processes. It is tuned, rather, to a certain mode of sharing the common resources; it can degrade the performance of any of the tasks yet with no benefit for the other one. There is an upper bound on the amount of resources directed to the processes, whereas in the case of mandatory processes, the bound is lower.

*Scarcity of resources.* For complementarity to hold,  $D_{xy}$  must not be smaller than  $R^L$ ; that is, the demand for resources applied by the two tasks together must not be met (or just barely met) by the capacity of the system. In Kahneman's (1973) words, "supply is an increasingly insufficient response to demand" (p. 200). That is why

every bit of resources is assumed to be used by one process or another. That is how we justify the interpretation of an empirical POC as the bound of joint performance.

Complementarity may not hold when resources are not scarce (i.e., when the joint demand is well within the capacity of the system). But why should the system be satisfied with less than it can do in the first place?

One case is that in which the performance of both tasks is insensitive to the amount of resources (is data limited), in which case they will be required only as long as they are effective; that level may be within the reach of the system. In that case, the square POC does not reflect the limit on resources but rather the limit on their effect on performance.

Another possibility is that the level of intended performance is imposed on the system by external standards of success so that quality of performance has an all-or-none nature.<sup>6</sup> May the system aspire for less than it is able to do even when more resources yield better output and better output is more profitable?

We have been assuming that the system tries to maximize the utility of performing the task. The utility of performance is determined by the value of the consequences and the cost for the system. It is possible that in some cases resources cost nothing because they are always available. If so, then only the quality of performance will be considered, and to maximize it, all the resources

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<sup>6</sup> By this we do not mean that all aspects of the output of the system have an all-or-none nature in themselves. Norman and Bobrow pointed out that performance generally degrades "gracefully" when the system becomes overloaded (1975) and that although some aspect of performance reaches its top or bottom, other aspects may still vary (1976). Nevertheless, despite the continuity of the output, the external success criteria may be dichotomous; namely, the performer may either succeed or fail. Furthermore, when quality of performance is strictly confined to one aspect (say, accuracy), variability in the other aspects (say, speed) is irrelevant from the point of view of the performer. He may aim just for the critical level defined over the relevant aspects of performance.

will be mobilized. However, recalling that resources are just another name for "mental effort" (Kahneman, 1973), it is not unreasonable to assume that mental activities may involve some cost.<sup>7</sup>

Suppose the cost of a unit of resources is constant (or increasing). We have already argued that resources often yield diminishing returns in terms of performance. From choice studies (e.g., Stevens, 1959), we may infer that the function associating value with the performance measure is probably negatively accelerated, too. So it is not unreasonable to conclude that the value added by a unit of resources decreases as more resources are added but that the cost is constant. Suppose utility is the difference between the value and the cost.<sup>8</sup> Then, as can be seen in Figure 7, utility is maximized at the point  $R^0$  where the cost of the last unit of resources invested equals the gain from investing it. If the optimal amount of resources is smaller than the amount available,  $R^L$  (in other words, the highest indifference curve intersects the POC), then the system will operate below full capacity. To discover the full capacity of the system, experimenters should raise the value attributed to good performance by means of payoffs, instructions, and so on.

Another possibility is that the system does not aim at maximizing utility but rather at reaching a certain satisfactory level (cf. the notion of "satisficing"; Newell & Simon, 1972). The consequence is the same: intending to a level of performance that is modest with respect to the potential. The empirical POC, whichever shape it may have, is determined by what the system wants and not so much by what it is capable of doing.

One could contend that there is no sense in assuming fixed capacity if the system hesitates to use all of it. If that is the case, it seems sensible to state that the system allocates not its capacity but whatever amount of resources it finds apt at the moment to invest, in much the same way that a housewife does not spend all her assets on various commodities, but rather her allowance for the week's food. We suspect, however, that the top of joint performance is not

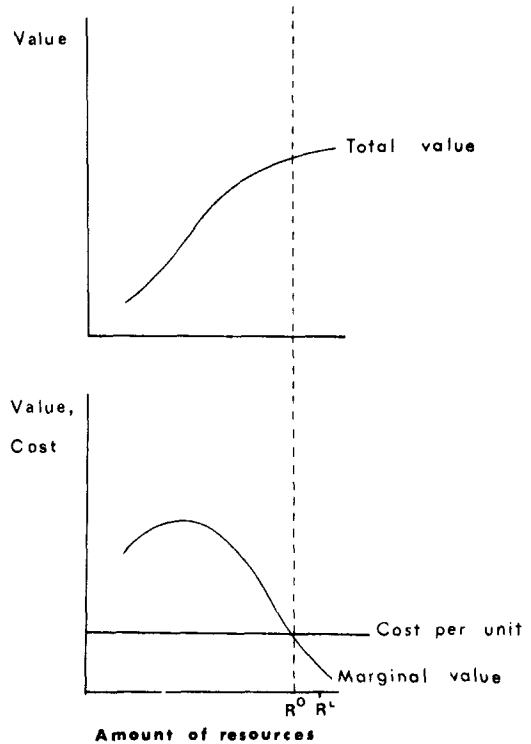


Figure 7. Hypothetical functions associating total value, marginal value, and marginal cost with amount of resources.

so far from what is manifested in carefully devised experimental situations, so the term *capacity* is still useful.

*Efficiency of resource budgeting.* When the system does not use its resources judiciously, complementarity holds only technically: The POC describes operation at full *capacity* but not at full *capability*. The system may not be fully efficient because it is not aware of the effectiveness of resources.

<sup>7</sup> Note that our present use of the term *cost* is different than the sense used previously in this article and by some other authors (e.g., Posner & Snyder, 1975a, 1975b). We now refer by this term not to the loss incurred by the inability to realize benefits of alternative activities but rather to the real loss (discomfort or "mental energy" consumption or the like).

<sup>8</sup> Although convenient, it is not necessary to assume an additive function. Coombs and Avrunin (1977) defined a class of composition rules (called *proper preference functions*) that would yield the effect described below.



For example, it may invest more resources than the minimum required to reach a performance asymptote because it has never realized the Sisyphean nature of its operation. In this case, some engaged yet unproductive units of resources could have produced more if directed to another activity.

### *Testing Central Capacity Interference*

We have argued that performance decrements from single- to dual-task situations are poor evidence for capacity interference because they may result from other kinds of interference. A more convincing argument is the existence of performance trade-offs in time-sharing situations: If performance of a task can improve only at the expense of the performance of the other one, it seems plausible that both tasks use the same resources. As noted above, very few researchers have manipulated task emphases in a way that would enable them to observe such performance trade-offs. A more frequent approach is to examine the effect of the difficulty of one task on the performance of the other. The rationale is that the more difficult a task, the more it consumes resources that under the capacity interference hypothesis could otherwise have been invested in the performance of the concurrent task (Kahneman, 1973; Keele, 1973; Kerr, 1973). However, when applying this method, one should beware of several pitfalls.

First, this rationale is valid only as long as the difficulty manipulation of one task does not inadvertently affect the difficulty of the other one as well. For example, suppose that a subject were required to identify a stimulus presented at a fixed location while tracking a randomly moving target to another location (see, e.g., Gopher & North, 1974). The more difficult the tracking is, the higher the mean distance between the target and the stimulus to be identified; thus, if the subject fixates on the target, the stimulus will be seen more peripherally.

Second, failures to find performance decrements (see, e.g., Briggs, Peters, & Fisher, 1972; Kantowitz & Knight, 1974, 1976b; Wattenbarger & Pachella, 1972) should not

be held against the capacity interference notion unless it can be shown that the failures are not due to allocation policy. As argued earlier and as illustrated in Figure 3, if resource allocation is determined just by the preferences of the performer, the difficulty manipulation is likely to affect only the performance of the task manipulated. One remedy would be to ensure that the performance of the manipulated task is maintained at the same level. Designating it as the primary one may not be sufficient, since actual performance may nevertheless turn out to vary with difficulty (as is the case, e.g., in experiments reported by Griffith & Johnston, 1977, and Martin, 1977; see also reviews by Kerr, 1973, and Rolfe, 1971). A statistical solution is to analyze the effect of difficulty on secondary task performance by means of analysis of covariance in which the covariate is the corresponding primary task performance. But, since the source of this problem is the use of just one condition of resource allocation for each level of difficulty, the problem can be best eliminated by manipulating task emphases in addition to difficulty so that a family of POCs can be estimated (as was done by Gopher & Navon, Note 3).

We now turn to examine in detail one experimental example that demonstrates how hard it is to interpret results of experiments in which only difficulty is manipulated, how they can nevertheless be reconciled with the central capacity interference notion, and how much speculation could be done away with by designing in advance experiments to obtain families of POCs.

Kantowitz and Knight (1974) combined a self-paced digit-naming task with a continuous experimenter-paced tapping task. They manipulated the complexity of the digit task by requiring the subject to apply different transformations differing in complexity on digits presented visually. Difficulty of tapping was manipulated by changing the width of targets and the distances between them. Their data are plotted in Figure 8 as points on a joint performance plane after tapping performance scores have been converted to percentages of transmitted information (actual transmitted information out of maximal

transmitted information if tapping is perfect; see Footnote 2.)<sup>9</sup> These data, and in particular the failure of the complexity of the digit task to affect the performance of the hard tapping in spite of the improvement in tapping when it was performed in isolation, were argued by Kantowitz and Knight (1976a) to be problematic for the central capacity interference notion. They suggested that such findings could arise from violation of either of the assumptions that we call complementarity of supplies and fixed capacity.

The hypothetical POCs that we plotted in Figure 8 show how these apparently perplexing data can be accommodated by central capacity interference models. Performance of the easy tapping task is not affected by the digit task complexity because subjects always select to perform tapping perfectly. However, the insensitivity of the performance of the hard tapping task to the digit task complexity may be attributed to allocation policy rather than to any limits on resources or performance scale. As argued above, it is very likely that to maximize utility, the subject may have had to change only the performance of the digit task.

Granted, the curves in Figure 8 are hypothetical, and their function is not to support one interpretation of the data reported by Kantowitz and Knight (1976a) over alternative ones but rather to demonstrate that those data are not sufficient to rule out the central capacity notion.<sup>10</sup> One cannot be sure what the real picture is unless enough data are collected to reveal it. This can be done by manipulating task emphases *and* task difficulty in a way that would enable plotting a family of POCs. While revising this article for publication, we learned that Bartell and Kantowitz (Note 2) had recently obtained such families of POCs for two variants of tapping and digit naming. Their results for paced tapping and unpaced digit naming (the tasks used in the situation described by Kantowitz & Knight, 1976a), are quite compatible with the picture we hypothesize in Figure 8.

Another source of evidence about capacity interference is interaction between task difficulties. Kantowitz and Knight (1976b) de-

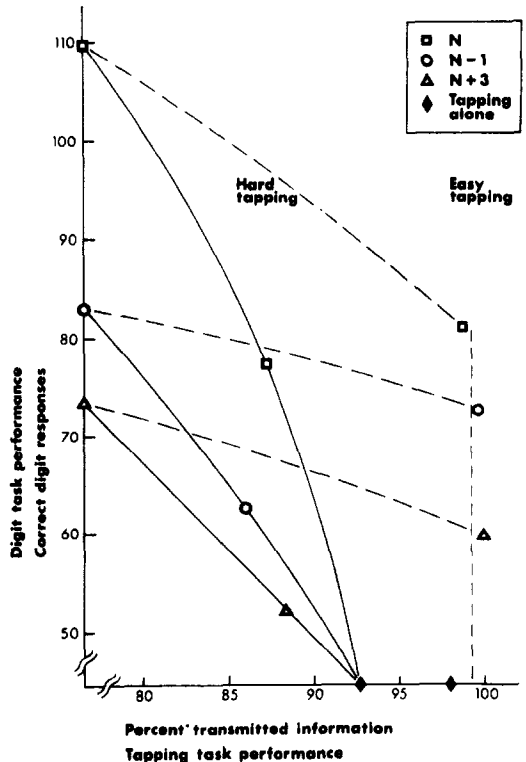


Figure 8. Data from a time-sharing experiment involving digit naming and paced tapping tasks (Kantowitz & Knight, 1974), plotted as points on a joint performance plane. (The curves are hypothetical POCs that account for the data, the solid ones for the hard tapping task and the dashed ones for the easy tapping task.)

rived from the central capacity interference model the prediction that whereas the performance of a difficult primary task will be impaired by conjoining it with a secondary one (or making the secondary one more difficult), the performance of an easy primary task will show little, if any, decrement as a result of such manipulations because "the demands imposed by primary and secondary tasks together do not exceed available chan-

<sup>9</sup> Data from one version of the digit task are not included in the figure because they appear to indicate an interaction that was found nonsignificant.

<sup>10</sup> Also, the curvature of the curves should not be taken too seriously because the origin was determined arbitrarily. Placing the axes at the worst performance levels may change the curvature yet would not change the point made here.

nel capacity" (p. 344). They interpreted failures to find such an interaction in some studies, including their own, as an embarrassment for strict models of single capacity. However, as Lane (1977) pointed out, the existence of interaction of the sort Kantowitz and Knight (1976b) considered as a necessary prediction from central capacity depends on the shapes of the performance-resource functions corresponding to different levels of task difficulty and the particular choice of difficulty levels of each task.<sup>11</sup> In fact, when none of the functions approach a natural bound on performance (as accuracy of 100%), the effect of difficulty on quality or speed of performance is enhanced the larger the amount of available resources. Thus, in this case we should expect the opposite of the above prediction; that is, that difficulty of a task will cause greater impairments in performance the easier the concurrent task is. Recently, Bartell and Kantowitz (Note 2) also predicted and partly confirmed the latter prediction.

In sum, testing central capacity interference is quite complex. Much evidence that apparently is incompatible with capacity models may be reconciled with them. However, some other arguments can be raised against the notion of central capacity as a general explanation for task interference. We discuss these arguments next.

## Multiple Resources

### *Introduction With Some Evidence*

Up to this point, resources have been construed as a sort of general undifferentiated entity analogous to a common currency in a monetary system or to energy in a physical system or to the general intelligence factor in theories of human intelligence: Tasks interfere to the extent that they depend on resources from that general pool. We now turn to advance another view of resources brought out by Norman and Bobrow (1975) that there may be various types of resources as there are various factors that may be put into production.

Kahneman (1973) makes a distinction between two types of attention models, structural models and capacity models, "which respectively emphasize the structural limitations of the mental system and its capacity limitations" (p. 11). By the term *structural limitation*, Kahneman includes all the factors that we claim to produce extra cost for concurrence as well as the inability of some processing apparatuses to serve both tasks simultaneously although they are needed by both. Neither type of model in itself is able to account for all known phenomena of interference.

The central capacity notion cannot withstand the finding that when the performance of a certain task is disrupted more than the performance of another one by pairing either of them with a third one, it is nevertheless disrupted *less* by a fourth one. For example, Brooks (1968) demonstrated how the same task was performed more slowly when both its processing and overt responding seemed to call for the same processing system (or modality) than when they used different systems: Vocal responses were found to interfere more than spatial responses with recall of a sentence but less than spatial responses with recall of a line diagram. Baddeley, Grant, Wight, and Thomson (1975) reported that performance in a pursuit rotor task deteriorated when paired with Brooks's visual recall task but not when paired with his verbal recall task. The possibility that Brooks's visual task is simply more difficult than his verbal task seems implausible in view of Brooks's own data.

A similar result is the finding that auditory presentation of a word to be remembered impairs shadowing of a message played to

<sup>11</sup> Recently Kantowitz and Knight (1978) defended their argument by contending that a difficult task, by definition, actually consumes more resources than an easier one. We think, however, that this is true only if difficulty is identified with demand. When subjects are supposed to perform as well as they can and, in addition, use all available resources to perform the task, then a difficult level of a task is one that is performed worse than an easier level with the *same* amount of resources; in other words, it is less efficient in resource usage.

the other ear more than visual presentation of a word does (Mowbray, 1964). Allport, Antonis, and Reynolds (1972) replicated this finding and extended it by showing that interference with shadowing could be almost eliminated by using nonverbal concurrent tasks such as picture encoding or playing piano music from a score. Treisman and Davies (1973) provided more complete and convincing evidence. They reported that monitoring tasks interfered much more with each other when stimuli were presented in the same sense modality, visual or auditory, than when they were presented in different modalities. Another example in this vein is provided by North (Note 5). North asked subjects to perform the four tasks listed at the leftmost column of Table 1 in all dual-task combinations (including the combination of a task with another identical one). Mean levels of performance of two of those tasks when paired with each of the four concurrent ones are presented in Table 1. As can be seen in the table, the order of interference effects exerted by the various tasks on tracking performance is almost the reverse of the order of their effects on immediate identification performance. Similar results have been obtained by Sverko (Note 6) with another set of tasks.

Hence, there seem to exist various components that different processes share to variable degrees. This conclusion appears to warrant the idea that a major source of conflict between tasks is structural (see Allport et al., 1972). However, a strict structural model seems inadequate once we realize that processes that use the same mechanisms sometimes interfere with each other but seldom block each other completely. For example, when input and response are in the same modality, as in Brooks's experiments, performance is impaired but is still feasible. The same is true when stimuli to be monitored are presented concurrently to the same modality, as in the study of Treisman and Davies (1973). Thus, the same type of argument that made previous authors abandon the view of the processing system as a single channel and conceive of it as a single pool of distributable resources may lead us to

Table 1

*Performance of Tracking and Immediate Digit Identification as a Function of Type of Concurrent Task*

Concurrent task	Criterion task	
	Tracking	Immediate digit identification
Tracking	29.9	.93
Immediate digit identification	24.3	1.50
Digit classification	20.8	1.87
Delayed digit identification	23.1	2.44

*Note.* Data are adapted from North (Note 5). Tracking performance is measured in root mean square error; immediate digit identification is measured in average time between correct responses.

reject the idea of multiple channels or mechanisms in favor of a notion of multiple resources (see Table 2): Not only can the processing system as a whole be involved in several activities in variable proportions but a *specific* mechanism or modality is not necessarily dominated by one process exclusively but instead can accommodate more than one process at the expense of quality or speed of performance. In other words, resources may not be homogeneous because the human system is probably not a single-channel mechanism but rather a complicated system with many units, channels, and facilities. Each may have its own capacity (which is, roughly, the limit on the amount of information that can be stored, transmitted, or processed by the channel at a unit of time). Each specific capacity can be shared by several concurrent processes; thus it constitutes a distributable resource. Different tasks may require those different types of resources in various compositions.

Inspect, for example, North's results presented in Table 1. Tracking performance is most impaired by a competing tracking task, but it is roughly equally disrupted by the other three tasks (as indicated by nonsignificant differences between them). On the other hand, the immediate digit identification task is differentially sensitive to the three digit tasks. This result can be explained if we assume that the digit tasks, which are similar

Table 2

*Evolution of the Notion of Multiple Capacity from Previous Views of the Human-Processing System*

No. of processing facilities	No. of processes that can use a processing facility at a time	
	One	More than one
Single	Single channel (Welford, 1952)	Single capacity (Kahneman, 1973)
Multiple	Multiple channels (Allport et al., 1972)	Multiple capacity

*Note.* The dashed arrows designate two orthogonal expansions of the single channel hypothesis that led to the two different explanations of the source of task interference which Kahneman (1973) calls capacity models and structural models. The solid arrows signify the merge of these seemingly opposed classes of models to the idea of multiple capacity.

in physical structure, temporal organization, and nature of input, demand different amounts of a certain type of resource that is not used at all by the tracking task and demand the same amount of another type of resource that is required for tracking. Note that this explanation resorts both to the existence of specific demands and to their quantitative nature. Both are combined in the notion of multiple resources.

This approach to time-sharing is, on one hand, structural in the sense that it identifies the limit on performance with the availability of any one of several processing mechanisms and ascribes task interference to the overlap in engaged mechanisms. But it is also a capacity approach, because rather than assuming that any mechanism can be accessed by just one process at a time, it posits that a mechanism has capacity that can be shared by several processes. This marriage between the two types of model is parsimonious in that it does not partition the universe of task pairs into those that are structurally incompatible and those that interfere just because limited attention of the central processor has to split between them. Task pairs of the former sort are considered in this view to simply have more types of required resources in common than task pairs of the latter sort have in common. Thus, they do not have to exhibit concurrence cost of

the sort illustrated in Panel A of Figure 6. This prediction is in contrast with one that may be derived from the hypothesis advanced by Kahneman (1973, p. 200), that concurrent requirements made by the two tasks to the same mechanism will result in a heavier load on the central pool. Since this approach deals with most interference phenomena regarded by Kahneman as cases of structural interference in terms of capacity, it eliminates a source of discomfort that might be felt toward the concept of structural interference that "precludes by definition any capacity explanation of a wide variety of interesting non-trivial findings" (Kantowitz, in press).

On the other hand, all of us may be disconcerted by the prospect of devaluation of the precious time-honored concept of attention; although most people are probably willing to admit multiple structures, the disintegration of the solid construct of attention and the proliferation of resources might seem strange, if not threatening. At this point, it may be conducive to suggest that the conventionally taken-for-granted bond between the concepts of attention and resources (or capacity) might be undone. The notion of unitary attention was a natural conceptualization of a pervasive introspection at the time when attention was almost synonymous with the focus of awareness. It permeated

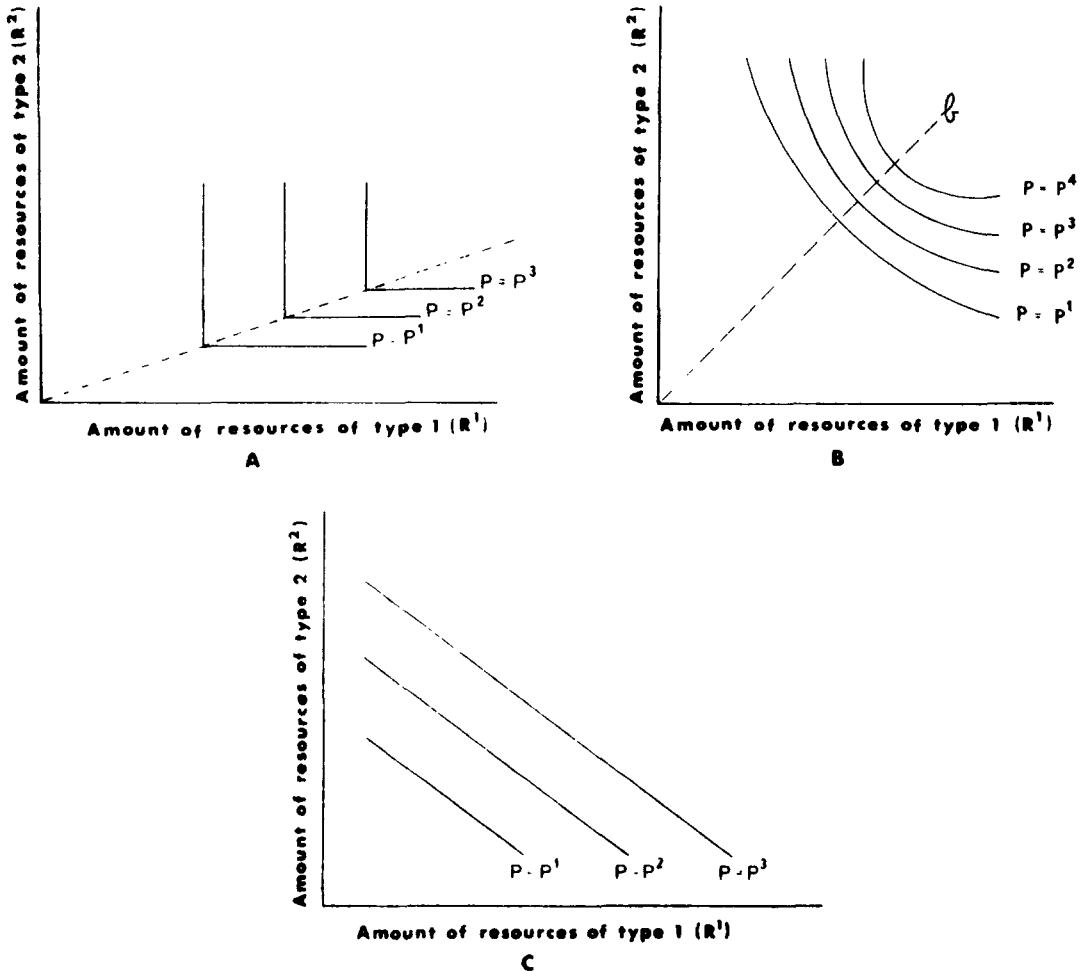


Figure 9. Isoperformance contours as a function of two types of resource,  $R^1$  and  $R^2$ . (Each contour connects all resource combinations that yield the same level of performance, e.g.,  $P^2$ . Panel A presents a fixed-proportions performance function. Panel B and C present variable-proportions performance functions.)

our thought under the disguise of capacity even after we relinquished equating processing with thinking or consciousness, perhaps because it was compatible with the view of the organism as an information channel. Is it still compatible with the widely accepted view of the mind as a complicated processing system? Of course, we could identify attention with some single construct within that system (e.g., with the availability of the central processor). But once it is realized that attention is not the sole internal input to

performance, it loses a good deal of its explanatory power. We could entertain both our firm and phenomenally valid belief that we cannot attend to more than one thing at a time and our growing conviction that performance limitations are often unrelated with this basic fact, if we divorced the notions of attention and resources. Attention is a phenomenal experience whose best definition is probably the one given by James: "Every one knows what attention is" (1890, p. 403); as such, its uniqueness is a given. Resources

are the hypothetical provisions for processing; as such, their uniqueness is an empirical issue.

Before discussing the implications of the multiple resource notion in more detail, we now introduce some nomenclature that we use later.

### *Multiple Resources Performance Functions*

If several specific resources exist, then performance depends on the amounts of each of them. Thus, performance functions can be redefined as functions of two sets of variables, various subject-task parameters, and various types of resources.

A distinction should be made here between two kinds of performance functions, a fixed-proportions function and a variable-proportions function. The first one reflects rigid requirements for specific resources. An example is a process that can use exactly two units of short-term memory (STM) capacity with one unit of visual information storage (VIS) capacity; any increase in one without a concomitant increase in the other would not improve performance. Variable-proportions functions reflect more flexible use of specific resources. They arise when there is more than one way to do a task. There may be one optimal composition of resources, but deviations are tolerated, and performance usually benefits to some extent from increases of one type of resource, even when not accompanied by commensurate increases of other types. For instance, the process makes some use of a third unit of STM, although only one unit of VIS is available. The two types of performance function are illustrated in Figure 9 by means of isoperformance contours as a function of two types of resources. In the fixed-proportions case (Panel A, Figure 9), the ratio of three units of  $R^1$  to one unit of  $R^2$  is mandatory. In the variable-proportions case (Panels B and C of Figure 9), resources can be input in various mixtures. The extreme case of variable proportions illustrated in Panel C of Figure 9 occurs when the use of the two types of resource is perfectly substitutive.

To obtain a unit of performance, the system may use a certain combination of the specific resources; this may be called a *demand composition*.<sup>12</sup> When proportions are fixed, the subject-task parameters determine a unique composition. If proportions are not fixed, there may be many compositions of specific resources given the subject-task parameters. Nevertheless, when substitution is not perfect, one or more compositions may be optimal in the sense that they maximize the slope of the performance function; for example, in Panel B of Figure 9, performance improves faster when  $R_1$  and  $R_2$  are input in a ratio of 1:1 (along dashed line b). In that case, the demands for specific resources will be inversely related to the marginal contributions of each to performance,  $\partial P / \partial R^i$  along the steepest gradient (from considerations similar to those used for the proof in Footnote 4).

Some resource types are irrelevant for certain tasks; in other words, the task demand for them is zero. Thus, for any task  $x$ , all the resources can be classified into two classes, the set of resources that can be used by Task  $x$  ( $X$ ) and the set of irrelevant resources ( $\bar{X}$ ).

Different tasks may have different optimal compositions of specific resources. Some tasks may even use resources of a type that is not used at all by other tasks. Several relations between resource compositions of two tasks are illustrated in Table 3. As can be seen from Table 3, the demands for specific resources of any two tasks may overlap to variable degrees.

For any two tasks,  $x$  and  $y$ , the whole arsenal of resources  $R^L$  can be viewed as composed of four sets:  $X \cap Y$ , which is the set of resources usable by both tasks (to the

<sup>12</sup> Note that here, unlike previously, the term *demand* is used in a per unit sense. It is not the amount of each type of resource required to obtain a certain performance level but rather the average amount of resources per unit of performance. It is possible to distinguish between marginal and average demand, but we do not pursue this distinction here. To simplify analysis, we assume that all marginal demand compositions preserve the same *proportions* of specific resources.

Table 3  
*Illustrations for Six Types of Relationships  
 Between Optimal Resource Compositions of  
 Two Tasks*

Case	Task	Resource type			
		R <sup>1</sup>	R <sup>2</sup>	R <sup>3</sup>	R <sup>4</sup>
1	x	1	2	0	5
	y	2	1	5	0
2	x	1	2	0	0
	y	2	1	0	0
3	x	2	1	0	0
	y	2	1	0	0
4	x	1	0	5	0
	y	1	5	0	0
5	x	1	0	0	0
	y	1	0	0	0
6	x	1	0	0	0
	y	0	1	0	0

*Note.* Each entry shows the number of units of the column type of resource required per a unit performance of the row task under optimal proportions. A zero means that the column type of resource is completely irrelevant for the row task, namely it can never be employed for its performance. A double line separates resources that are not used by either of the tasks from the other resources. A triple line separates resources that are not used by either of the tasks from the other resources.

left of the double lines in Table 3);  $X \cap Y$ , which is the set of resources that can be used by Task  $x$  but not by Task  $y$  (e.g.,  $R^4$  in Case 1 in Table 3);  $Y \cap X$ , which is the set of resources that can be used by Task  $y$  but not by Task  $x$  (e.g.,  $R^3$  in Case 1 in Table 3); and  $\bar{X} \cap \bar{Y}$ , which is the set of resources irrelevant for both tasks (to the right of the triple line in Table 3).

In case proportions are not fixed, the performer would do well to minimize the overlap. For example, a reader uses sensory information extracted from the page and conceptual information retrieved from memory. Adding a memory task on top of the reading task may induce a change in strategy: Frequency of eye fixations may be increased so that greater intake of sensory information compensates for the smaller use of memory processes which are now a scarcer resource.

However, flexibility in resource use may be limited. For each type of resource there may be some threshold amount required to produce a unit of performance of a given task; that amounts cannot be substituted for by any other type of resource. In such cases, the demand of a task for common resources is the minimal amount of those resources required for performing that task.

### *Nature of Tasks*

It was suggested above that a change in the difficulty of one of the tasks or both should result in a shift of the POC with respect to the axes with no transmutation of its shape. This is, of course, predicated on the assumption that the change in difficulty is a quantitative modulation in one of the parameters of the task, which does not modify its nature qualitatively. But what is this "nature of a task" that is supposed to be preserved over different levels of difficulty? It is not easy to define it within the framework of central capacity models; it becomes easier once we adopt the notion of multiple capacity. Nature of a task may be defined, then, as the *relative* weights of the various resources in the demand composition. The manipulation of difficulty is thus said to change the task qualitatively if it modifies the relative weights; the nature of the task can be considered the same only if the demands for all the resources vary proportionally. It may be that very few difficult manipulations meet the latter requirement. A certain subject-task parameter may affect differentially the load on different processing facilities. Also, different parameters may differ with respect to the loads they impose on those facilities (Sternberg, 1969).

### *What Else is Hidden Behind a POC?*

The idea of multiple capacity provides some new insights into what to anticipate about dual-task performance and how to interpret empirical findings about it. It also sheds new light on some issues discussed above within the framework of central capacity. The following discussion is organized



according to points that have to be considered while interpreting POCs in terms of multiple resources.

### *Similarity of Demand Compositions*

Tasks interfere with each other to the extent that their demand compositions are similar so that they have to compete for resources. We distinguish between two aspects of that resemblance.

*Existence of common resources.* If the types of resource the tasks demand are completely disjoint, namely,  $X \cap Y = \emptyset$  (e.g., Case 6 in Table 3), then the tasks should be capable of being performed in parallel. In that case, resources released by degrading performance of one task are irrelevant for the performance of the other one, so their performance is completely independent. Such a situation is represented by a square POC (Curve 6 in Figure 1).

On the other hand, if the types of resource that both tasks use are the same (e.g., Cases 2, 3, and 5 in Table 3), then every unit of resources used by one of the tasks could have been used alternatively to improve the performance of the other one. Hence, the trade-off between performance of the two tasks is relatively large (as in, say, Curves 1 or 2 in Figure 1).

When a task demands in conjunction with the common resources some other resources that cannot be used by the other one (e.g., Case 4 in Table 3), part of the resources released by deterioration in its performance cannot be capitalized on very well by the alternative task. If, in addition, the alternative task also demands other resources that are not common to both tasks, then the resources spared by degrading performance of the first one can be used by the second one just to the extent that other resources are also available. Thus, in this case, trade-off is limited for two reasons: (a) Some released resources are irrelevant and (b) even the relevant ones are not sufficient. To illustrate, suppose one performs simultaneously Tasks  $x$  and  $y$  of Case 4 in Table 3 about equally well (at point  $C_1$  in Curve 3 of Figure 1). Decreasing performance of  $x$  by one unit

saves five units of  $R^3$ , which is useless for Task  $y$ , but just one unit of the relevant  $R^1$ . To improve performance of  $y$  by one unit, the system should be able to recruit an extra five units of  $R^2$ . Otherwise, if five units are not available, either not all the disengaged amount of  $R^1$  is exploited (say, just .6 of  $R^1$  with three of  $R^2$ ) or the system operates in suboptimal proportions (say, one unit of  $R^1$  with three of  $R^2$ ). Either way,  $y$  is improved by less than one unit. A similar thing would happen if one attempted to change task emphasis to the opposite direction, that is, to improve performance of  $x$  at the expense of performance of  $y$ . Therefore, the POC in this case is more concave to the origin (as in, say, Curves 3 and 4 in Figure 1) than in cases with a larger share of common resources within the demand compositions, such as Case 5.

Note, however, that if the disjoint resources (in this case,  $R^2$  and  $R^3$ ) are not scarce, trade-off could be perfect.

*Similarity of compositions of common resources.* Even when both tasks use resources of the same type, the amount of trade-off depends on the resemblance between the ways in which each task combines the ingredients. If there were just one input that could affect the performance of both tasks (say,  $R^1$  in Case 5 in Table 3) and if performance of both were linearly related to amount of  $R^1$ , then resources removed from one task could yield a constant rate of improvement when directed to the other one. This perfect trade-off is described by a linear POC (Curve 1 in Figure 1). The same would still be true if there were two sorts of input taking similar parts in both  $x$  and  $y$  (e.g., Case 3 in Table 3). However, consider a situation in which the tasks require different combinations of the same types of resources (e.g., Case 2 in Table 3). If proportions are not fixed, then all resources released by Task  $x$  can be used somehow by Task  $y$ , but the mixture of resources available for  $y$  will become less and less optimal as the performance of  $x$  deteriorates. If the performance function of  $y$  is sub-additive (as illustrated, for example, by the isoperformance contours in Panel B of Figure

9), that will result in a diminishing improvement in performance of  $y$ .

To illustrate the point, suppose that the most efficient way of reading this article requires one unit of Long-Term Memory (LTM) search per two units of STM whereas retrieving previously stored pertinent information about attention and performance requires two units of LTM search per one STM unit. Suppose that exactly one STM unit and two units of LTM search are now engaged in retrieving and that the amounts of these resources expended in reading are four and two, respectively. If we transform two STM units and one LTM search unit from reading to retrieving, reading performance will be cut in half, but retrieval output will not be doubled, because now there are just three LTM search units engaged in retrieving, with three STM units. If we give up reading completely, more units of each resource will be available for retrieving, but their marginal contribution will be even smaller, because now the ratio of LTM search units per STM units (4:5) is even farther from the optimum. Hence, the objective substitution rate changes as resource allocation is changed so that to obtain more of one output we have to give up more and more of the other one. The POC in this case is concave (e.g., Curves 3 or 4 in Figure 1).

On intuitive grounds it seems improbable that two different tasks have exactly the same demand compositions. Each presumably requires some resources that are useless for the other one, and the two tasks probably use the common resources in different proportions. So there are at least two reasons why a linear POC must be rare.

### *Fixity of Proportions*

Suppose  $X - Y \neq \emptyset$  and  $Y - X \neq \emptyset$ ; in other words, some types of resources are required by Task  $x$  but not by Task  $y$ , and vice versa. If resources were used in absolutely fixed proportions (see Panel A of Figure 9), then performance could be improved only if *all* relevant types of resource were proportionally more available. Suppose, for example, one unit of  $R^1$  and five units of

$R^3$  are available for Task  $x$  in case 4 of Table 3, so that the task can be performed at the level  $P^1$ . To improve performance, the system needs supplements of both  $R^1$  and  $R^3$ —five parts of  $R^3$  per one part of  $R^1$ . Increasing just one of them is useless. In this case, the amount of  $R^1$  that is released by degrading performance of Task  $y$  cannot improve very much the performance of  $x$  unless there is an excess amount of  $R^3$  that has been idle before. If  $R^3$  is also scarce, then fixity of proportions will result in no trade-off between the two tasks: The POC will be square (Curve 6 in Figure 1).

So, for some trade-off to exist in case the types of resources used by the tasks are partly disjoint, the performance functions should be of the variable-proportions type (see Panel B of Figure 9). More specifically, common resources should be able to substitute for other ones so that any transfer of common resources from one task to another may improve performance of the latter to some degree.

But to what degree? This is a different question, the answer to which depends on the sensitivity of performance to the amount of common resources.

### *Central Capacity Assumptions Revisited*

*Sensitivity of performance to amount of resources revisited.* It was noted that the marginal efficiency of resources may decrease and may even drop to zero. If performance depends on several resources, this may be true for the marginal efficiency of any of them (namely, the partial derivative of performance with respect to the amount of that resource).

It should be borne in mind that an observed failure of a task to improve in a dual-task situation does not necessarily imply that resources have done their utmost for its processing. It may simply mean that that task cannot capitalize on the particular kinds of resources that are spared by worsening performance of the other task. It may still be sensitive to resources of some other type that are not shared by the other task and thus are not released when performance of

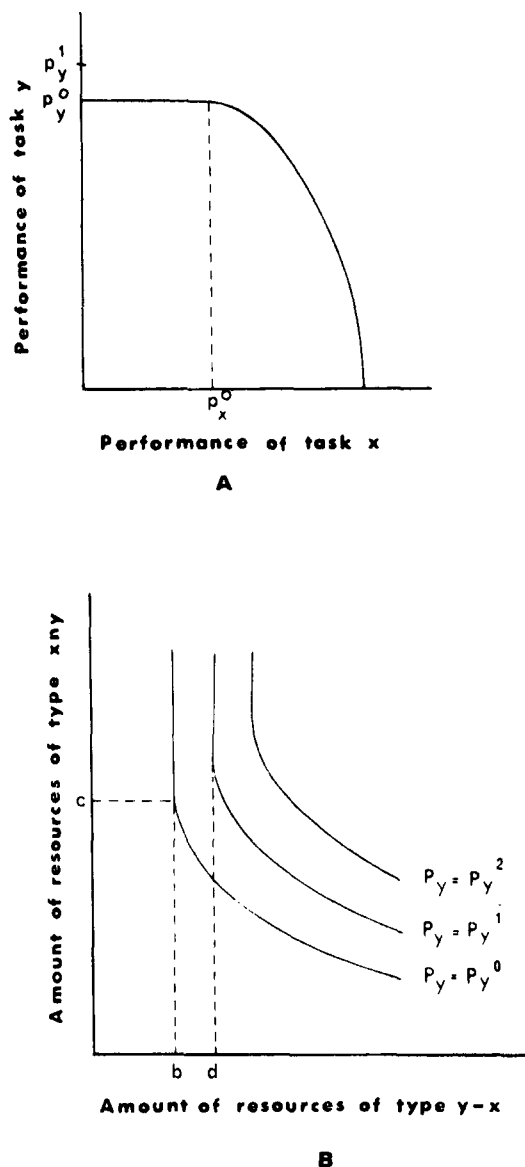


Figure 10. Panel A: A POC with a flat region. Panel B: The sort of trade-off between  $X \cap Y$  and  $Y - X$  resources that may be the cause of limit on the performance of Task y.

the latter deteriorates. Performance of Task y in Panel A of Figure 10, for example, cannot improve beyond  $P_y^0$  because it is insensitive to resources of the set  $X \cap Y$  yet not necessarily to resources of the set  $Y - X$ .

The  $Y - X$  resources may be in shortage because in general the task can use more of

them than the system can ever supply. If this is true, then the task is sensitive to those specific resources even in a single-task situation; the flat region of the POC in Panel A of Figure 10 simply means in that case that doing Task x at a level not higher than  $P_y^0$  costs nothing in terms of the performance of y.

Alternatively, the system may be temporarily short of  $Y - X$  resources because concurrently with Tasks x and y, it performs some third process that uses them as well. A good example for the kind of additional processing that may be unavoidable in dual-task situations is that of coordinating the tasks and monitoring the resource allocation. But there may be some other additional processes that curtail the amount of  $Y - X$  resources available for Task y, such as all the routine mental and perceptual activities. In these cases the sensitivity of the task to the common resources  $X \cap Y$  may depend on the amount of  $Y - X$  available. This is illustrated by the isoperformance contours in Panel B of Figure 10. When the amount of  $Y - X$  is b, Task y cannot use more than the amount c of  $X \cap Y$  resources; hence the effective limit on performance of y is  $P_y^0$ , which will be the upper bound of the POC (see Figure 10, Panel A). Nevertheless, the task could have used more than c of  $X \cap Y$  if it had a larger allotment of  $Y - X$  (say, d). In that case, the POC would have been flattened at a higher point (say,  $P_y^1$ ).

Why should the performance-resource functions be negatively accelerated (or reach an asymptote) in the first place? To phrase the question in economic terminology, why should the returns from resources diminish? This question was posed earlier; now we are ready to attempt an answer.

The prevalent explanation in economics is that diminishing returns from varying one sort of input occur when other sorts of input are held constant so that "the varying inputs have less and less of the fixed inputs to work with" (Samuelson, 1967, p. 26). Adding more and more resources of just one type typically moves the task away from the ideal proportions of specific resources. If all the resources were increased, economists argue,

the output would probably increase proportionally, a case of "constant returns to scale."

However, in the domain of human processing, even the sensitivity to the *overall* amount of resources may progressively diminish because subject-task parameters may be viewed as inputs to performance functions just as resources are. Investing more resources, for instance, can compensate less and less for poor quality of sensory input. Performance will reach an asymptote when "the stimuli themselves simply will not support any better performance" (Norman & Bobrow, 1976, p. 508).

However, the asymptote may be conditional on the given quality of sensory input (or more generally, on the given level of any subject-task parameter). If, for instance, the production relation between resources and sensory quality is like that described in Panel B of Figure 10 (with resources in the ordinate and sensory quality in the abscissa), then different levels of sensory quality may be associated with different patterns of demand for resources. When sensory quality is better, for example, fewer resources may be required to perform at an acceptable level, but perhaps more of them can be utilized and more can be done with what is utilized. So sensory quality takes part in determining not just performance per se but also whether and how performance is affected by resources.

If performance asymptotes are, nevertheless, the same regardless of the levels of subject-task parameters, the source of the limit must be in the insensitivity of the performance scale itself (e.g., error rates cannot drop below zero) rather than in any constraints imposed by the parameters (Kantowitz & Knight, 1976a; Norman & Bobrow, 1976). So, we can distinguish between two kinds of limits on performance by their sources, a *data limit* and a *scale limit*. Data limits may vary with task difficulty, but there is just one scale limit.

*Additivity of demands revisited.* Concurrency cost was defined as the additional demand imposed on the system by a combination of two tasks above and beyond their own requirements. If there were just a single

pool of resources, that extra demand would be reflected in a performance decrement of the sort illustrated in Panel B of Figure 6. However, in case there are several resources, concurrence cost may be charged to a pool of resources that are irrelevant for one or both of the tasks. In the former case, single-to dual-task performance discontinuity may be observed just for one task. In the latter case, concurrence cost will not be visible in performance data at all. This may occur, for instance, when both tasks use mainly peripheral mechanisms while the cost of concurrence is due to more central coordination. That invisible concurrence cost could be revealed, presumably, if a third task that requires central processing were added. Some indication for an effect like this is provided by data reported by Wempe and Baty (Note 7): Their subjects performed a tracking task with or without a secondary auditory choice reaction time task. Tracking performance on either axis in the dual-axis condition was not inferior to the corresponding single-axis performance level. However, whereas auditory task performance showed no decrement when paired with single-axis tracking, such a decrement was observed when the primary task was dual-axis tracking. It thus appears that although vertical and horizontal tracking hardly ever interfere with each other (see also Gopher & Navon, Note 3), their coordination probably taxes some mechanisms that are relevant for performance of the auditory task.

*Fixed capacity revisited.* Most empirical observations suggesting that capacity grows with the increase of load can be accounted for within the view advanced in this article in another way: A new task added on top of an old one is often able to capitalize on formerly unused resources as a consequence of the dissimilarities in the resource compositions of the two tasks. Thus, we can maintain the parsimonious assumption that each capacity is fixed or at least independent of task load. The high arousal that typically accompanies a heavy load may now be interpreted as reflecting the state of stress associated with increasing demand, rather than as an increase in processing potential.

### *Constancy of Demands*

One basic assumption that we and other authors have made so far is that the trade-off in performance of the two tasks described by a POC results from competition for resources. Is that necessarily true?

The answer depends on what we mean by the terms resources and subject-task parameters. How would you classify, for instance, the quality of the retinal image of a visual stimulus? Suppose you consider it to be a kind of a subject-task parameter rather than a resource. We tentatively postulate the understanding of the terms exhibited by this classification and discuss its implications.

As stated above, performance is affected not only by amount of resources but also by various subject-task parameters. In the same way that the sensitivity of performance to amount of resources may vary, so may its sensitivity to any of the subject-task parameters. Suppose the situation we study is within the region in which performance is sensitive to both resources and subject-task parameters. This means that performance can improve either because the task gets more supply of resources or because it demands less. Hence, there are two ways in which a task can benefit at the cost of the other one with which it is time shared: It can draw more resources from the limited pool of common resources or it can attempt to lower its demand at the expense of the demand of the other task. In the latter case, the tasks do not compete for resources but rather for the quality of the data they operate on.

But how is this possible? Should we not assume that subject-task parameters are constant for a given experimental situation and a given subject? If we accept the interpretation of subject-task parameters postulated at the beginning of this section, this assumption may not hold.

Imagine yourself in a big rally held on a large lawn. Speeches are being relayed by loudspeakers that are positioned at the back of the lawn. There is no chance to hear the speakers without the electronic amplification because of the noise and the distance of the

audience from the podium. Now, the conjunction of the task of listening to the speeches and watching the gestures and facial expressions of the speakers certainly does not overtax the human processing system (especially given the high redundancy in rally rhetoric). However, if the lawn is very large and the auditory signal-to-noise ratio is low, one may find oneself facing the dilemma whether to get closer to the podium to see better or to the loudspeakers to hear better. The set of solutions to that dilemma can be plotted as a POC. However, that POC does not reflect all possible resource allocations, given system capacity and subject-task parameters as POCs are presumed to do, but rather presents all different outcomes of competition for input quality. A person may not change the division of his or her attention between watching and listening but still may move along the POC because of change in the relative difficulty of the two activities. Lack of trade-off (as exhibited by flat parts of the POC) may be attributed to insensitivity of performance to the range of input qualities associated with the situation (e.g., when the lawn is not larger than a living room).

The property that improvement in the quality of input to one of the processes comes only at the expense of input quality to the other one is not unique to the particular example given above. It may characterize many more typical dual-task situations. Consider, for example, the following hypothetical experiment. A subject is asked to identify a letter flashed briefly at one of two possible locations and then is asked to do the same after being told at which of the two locations the flash will appear. Probably nobody would be too surprised to find that with some letters, exposure durations, and separations of the two locations, the subject's performance is better in the second condition. One might be tempted to ascribe the poorer performance under spatial uncertainty to the need to split attention. When it is certain that the subject fixates all the time at the same point, this explanation seems to be the only plausible one (Eriksen & Hoffman, 1974; Posner, Nissen, & Ogden, Note 8). However, when

subjects can move their eyes around the field, the stimulus is less likely to fall on the fovea under the spatial uncertainty condition. Hence, in this condition the two locations compete for resolution of their retinal images rather than for attention.

The ability of the system to manipulate by itself the relative input quality for a number of competing visual processes by initiating eye movements is a good demonstration of the flexibility that generally characterizes the approach of the human system to many multistage processes: By varying its processing (or resource allocation) in early stages, the system may be able to determine to some extent the quality of the throughput to later stages. For example, it may sample more information or less from different segments of the sensory environment (viz., visual field, sound waveform, etc.), thereby affecting the quality of the data the interpretive processes operate on. Another example comes from processes that use some information retrieved from memory (and which process does not?): The quality of a retrieved code depends not just on the completeness and availability of the corresponding representation but also on the effort expended during search and retrieval. Hence, the system may be able to control to some degree the demand of late stages by way of the supply policy in earlier ones.

So, even in a highly standardized and experimentally controlled situation, the demand of the individual processes subsumed in it may be under the control of the system, at least partly. But this creates a severe problem of interpretation. When the performance of a task deteriorates, is it because the task now gets fewer resources or because it now requires more? At the present state of the art, answering this question seems as impracticable as would be a solution to the problem of whether one person is hungrier than another because he or she gets less food or because he or she needs more, had we not possessed independent measures for need and supply of food.

One way out of this impasse seems to be to admit that as yet we do not have the acid test for separating supply and demand and

to abandon the interpretation of the concepts of resources and subject-task parameters that was postulated for the discussion in this section. The alternative to that interpretation is to characterize a situation by its immutable constraints and to observe how the system manages the various processes to be performed within the latitude set by those constraints. The degree of freedom the system has may be likened to a pool of resources. But this definition of resources is much more inclusive than those made by other authors. Resources may include even such things as visual resolution, number of extracted features, and quality of retrieved codes, provided that these can be manipulated by the system within the constraints of the situation. In other words, this interpretation of the subject-task parameters/resources confrontation regards it as a distinction between what is imposed on the system on one hand and what the system does with it on the other hand. Subject-task parameters may be given in a particular situation, yet their effect on the system depends on how it elects to cope with them. Since resources are regarded as degrees of freedom, any change in joint performance reflects, by definition, a change in resource allocation. However, the concept of resource allocation, as it is defined here, is much broader than the concepts of divided attention or shared capacity.

Another approach is to distinguish between two kinds of control the system may have: the control on the use of its processing devices and the control on the properties of the input flowing to them. The first kind of control, *processing resources*, corresponds to our intuitive notion of attention. The latter, *input resources*, represents the flexibility the performer has for what is to be operated on. Both kinds of resources are limited. Processing resources are limited by the capacities of the various processing devices, and input resources are limited by the subject-task parameters. This approach seems to be more in accord with our usual image of the human processing system, but it admits concepts that are at present difficult to operationalize. So, we offer these two approaches with no

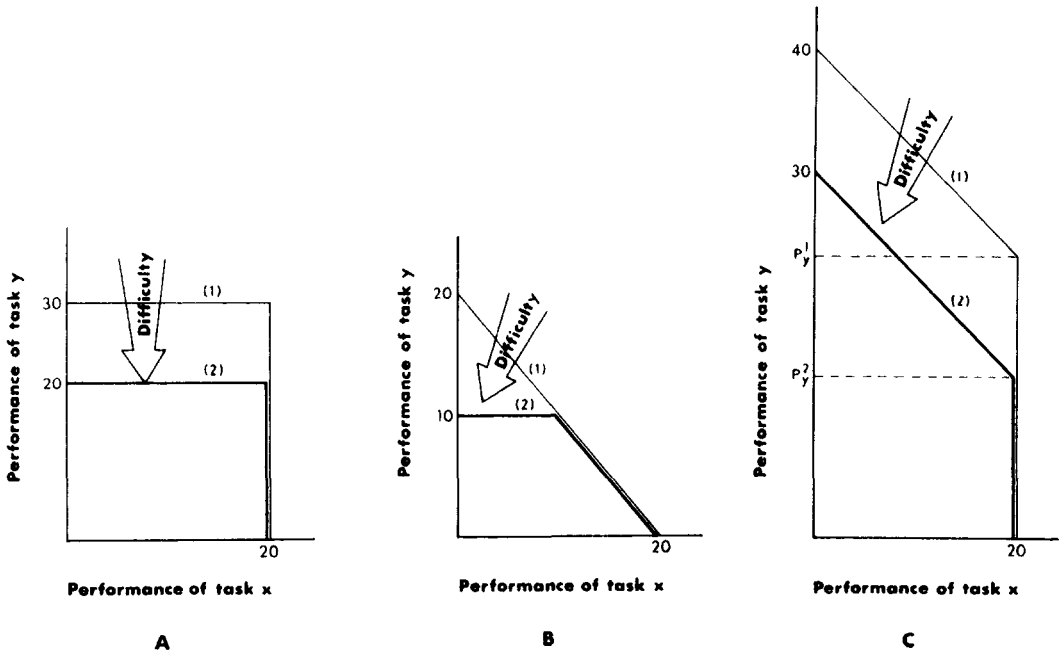


Figure 11. Illustrations for three possible effects of manipulating a parameter that taps resources relevant only for the performance of  $y$ . (Panel A: The case of complete absence of common resources. Panel B: The case of existence of both common and disjoint resources used in fixed proportions. Panel C: The case of common and disjoint resources used substitutively.)

commitment to either of them. Different readers may foster one or the other.

### Effects of Difficulty Manipulations Revisited

Suppose the performance of a task is observed to be related to the manipulation of a certain parameter. It may mean that the manipulation affects the demand for some (or all) resource types required by that task. If that task,  $y$ , is conjoined with another one that does not use those resource types, the manipulation will be ineffective for the performance of the latter task. Note that this can happen in two cases: (a) When  $X \cap Y = \emptyset$ , (i.e., the tasks do not overlap at all in their demand for resources) and (b) when  $X \cap Y \neq \emptyset$  but the difficulty manipulation of Task  $y$  has a differential effect on the demands (i.e., changes the nature of the task) so that it taps only resources from Set  $Y - X$ .

The effect of the difficulty manipulation in the first case is illustrated in Panel A of Figure 11: There is no performance trade-off

at all, so manipulating the difficulty of a task affects only the maximal level of performance of that task.

In the second case, however, there is a partial trade-off, but since the manipulation has no bearing on the demand for common resources, it affects neither the performance of the competing task nor the amount of the trade-off. The specific effect depends on the manner in which the various resources are combined.

First, let us examine what happens when the performance functions are of the fixed-proportions type (see Figure 9, Panel A). When the difficulty manipulation makes a resource of the set  $Y - X$  (or  $X - Y$ ) scarce relative to a common resource, it also restricts the amount of the common resource that can be used by the manipulated task so that the residual is made available to the other task. A simple example may illustrate this point best. Suppose the system possesses 20 units of  $R^1$  and 20 units of  $R^2$  and that the demand for resources for a unit increase of both tasks is constant over all levels of

performance: Task  $x$  demands one unit of  $R^1$ ; Task  $y$  demands one unit of  $R^1$  *and* one unit of  $R^2$ . The corresponding POC is Curve 1 in Panel B of Figure 11. Now suppose that a parameter of Task  $y$  is manipulated to increase its demand for  $R^2$  to two units. This change sets a new limit to the performance of  $y$ , which is 10, but since to achieve that level the performer needs no more than 10 units of  $R^1$ , the rest can be directed to Task  $x$ . The resulting POC is Curve 2 in Panel B of Figure 11.

When the proportions of input resources are not fixed, the performer can reduce interference between concurrent tasks by operating less with the common resources and more with the disjoint ones. The extreme case of variable proportions occurs when the use of different types of resources is perfectly substitutive; namely, either of several resources can be used by itself (see Panel C of Figure 9). Take the example in the preceding paragraph and just change the italicized *and* to *or*, and you obtain the effect demonstrated in Panel C of Figure 11: A reduction in the efficiency of the disjoint resource  $R^2$  decreases the level of performance of  $y$  that can be attained with no cost to the performance of  $x$  (see the decrease from  $P_y^1$  to  $P_y^2$  in Panel C of Figure 11). An empirical example for an effect of this sort is the result of Gopher and Navon (Note 3) presented in Figure 5: The vertical distance between any two curves is uniform over the entire domain. If the use of resources is just partly substitutive, as illustrated in Panel B of Figure 9, then to maintain the performance of  $y$  at the same level, a larger amount of  $R^1$  has to be invested in it; thus Task  $x$  suffers. It is hard to predict whether it will suffer more or less with higher performance of  $y$ . If the isoperformance contours are progressively more concave (as in Panel B of Figure 5), it will suffer less; if they are equally concave, it will suffer the same, so the family of POCs will look as in Panel C of Figure 4; if they are progressively less concave, Task  $x$  will suffer more the higher the performance of Task  $y$ . In this case, a manipulation that taps a disjoint resource will produce a fanlike family of bowed-out POCs

that is practically indistinguishable from the effect of manipulating the demand for a common resource.

This analysis should call our attention to an important point: The overlap in demand composition of concurrent tasks may be partial; that is, they may use some common resources, and at the same time each task may resort to some resources not required by the other one. Hence, a failure of a manipulation of the difficulty of one task to affect the performance of the other one (when the performance of the first one is held constant) proves only that resource overlap is not total—not that overlap does not exist. On the other hand, even when joint performance exhibits a considerable trade-off due to shifts in resource allocation, the tasks may still depend on some different mechanisms that can be detected by manipulating various subject-task parameters and observing effects like the ones in Panels B and C of Figure 11. The lesson is that there is one more good reason for researchers to do what we have already recommended: to manipulate subject-task parameters as well as task preferences and present their effects by families of POCs. Different parameters may yield different pictures depending on the resources they tap. The mere fact that the pictures are different suggests that the tasks do not compete for only one resource.

### *Practice With Dual-Task Performance*

One view of the role of practice is that it serves to reduce the demands of the tasks so that resources yield better output; thus the POC gets higher (see Panel A of Figure 12). An alternative view is that with no practice with a specific dual-task situation, there is a problem of manageability of resources. Practice may make the two tasks more coordinateable in the sense that the system learns how to utilize its resources more efficiently in all degrees of task emphases. With more practice, the POC becomes less bowed-out (see Panel B of Figure 12). Practice may also reduce the cost of organization in cases of partial incompatibility so that more resources are left over for the tasks themselves and



the POC gets higher (see Panel C of Figure 12). Alternatively, the effect of practice may be to unify the two tasks into one categori-

cally different entity. If one accepts the notion of multiple resources, that may mean that a strategy is being developed that mini-

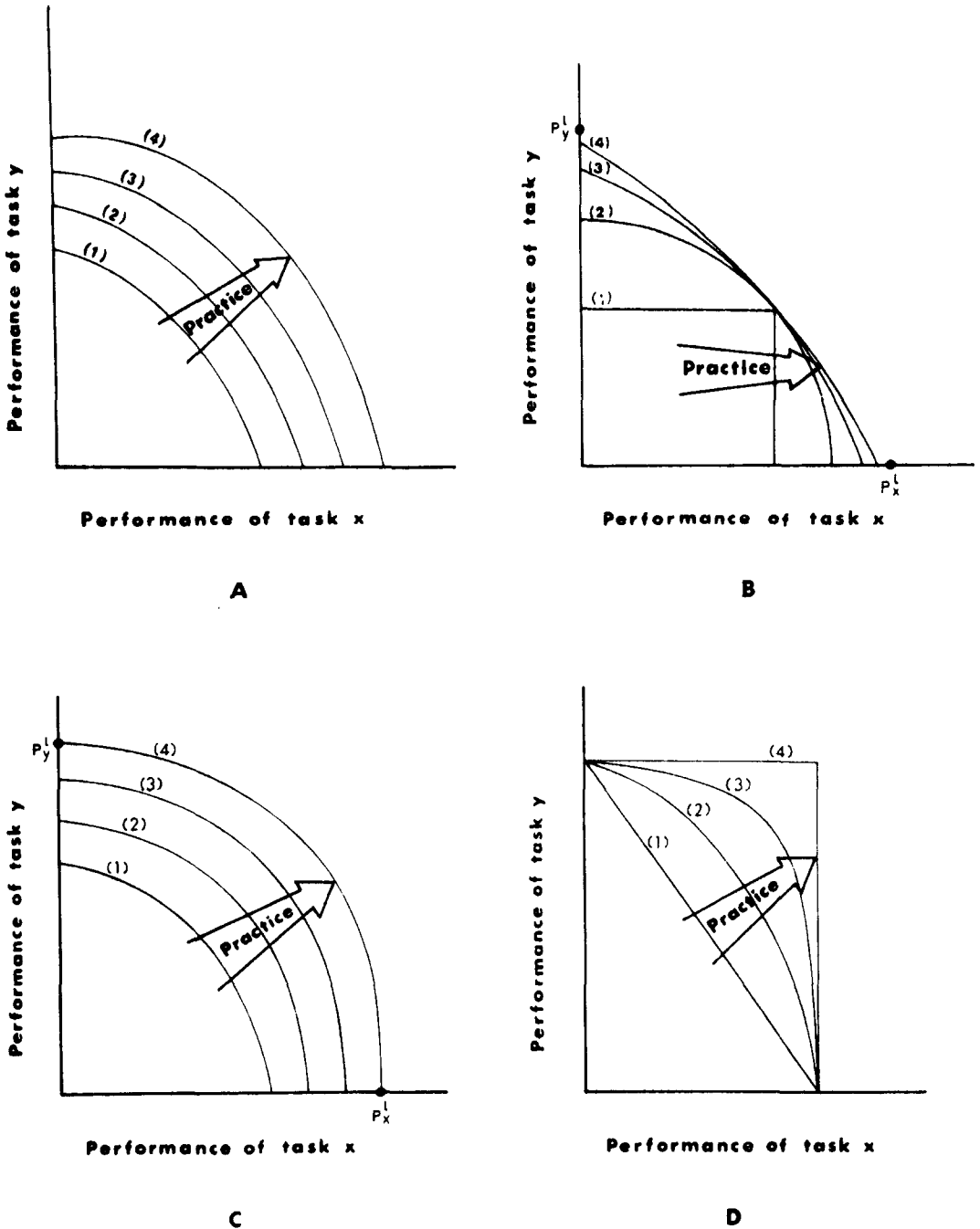


Figure 12. Illustrations for four possible effects of practice. (Panel A: Improvement in performing each individual task. Panel B: Improvement in the ability to allocate resources between the tasks. Panel C: Diminishing concurrence cost. Panel D: Reduction of overlap in demand compositions.)

mizes the overlap in the kinds of resources required by the two tasks. In that case the effect of practice will be as illustrated in Panel D of Figure 12.

Note that knowledge about the source of task interference is important for planning the appropriate schedule of training. If poor time-sharing is believed to stem from capacity overload, then each of the activities can be trained separately; as the separate demands decrease, so will joint demand. However, if the low quality of joint performance is thought to be due to a conflict between the conjoined tasks, the only way for improvement to occur is to eliminate or reduce the conflict by training the two tasks simultaneously. An interaction between different tasks and different schedules of training that is consistent with this analysis is reported by Gopher and North (1977).

#### *Analysis of Dual Task Performance: A Short Summary*

Performance operating characteristics are a useful technique for displaying and analyzing behavior in dual-task situations. However, they should be interpreted with caution. What they represent and what could give rise to the particular shape they take depend on what can be assumed about all the points discussed in the second and fourth sections of this article.

A POC can be held to reflect competition for processing resources only if demands are believed to be constant. An empirical POC can give us an idea of the capacity of the system only subject to the assumption of fixed capacity and complementarity of supplies. The amount of trade-off depends on the similarity of demand compositions, the sensitivity of performance to amount of resources, the complementarity of supplies, and whether or not the performance function is of the variable-proportions type. Incomplete POCs may arise in case resources are not controllable. Nonadditivity of demands may result in either superiority or inferiority of dual-task situations over corresponding single-task ones. Difficulty manipulations that tap common resources typically produce a fan-

like family of POCs, whereas if they tap a disjoint resource, they may produce either of the effects depicted in Figure 11.

### General Discussion

#### *Multiple Resources Versus Other Approaches*

We propose here a conceptual framework and use it for inspecting various interpretations of phenomena of dual-task performance. Within this framework we put forward and advance a theoretical possibility that hitherto has been overlooked or neglected—the idea of multiple resources. For two reasons, we suggest that in every attempt to interpret findings about human performance, this alternative should be considered seriously. First, it accounts for findings that indicate structure-specific interference that neither central capacity models nor structural models could adequately explain, as we argued earlier. Second, many experimental findings would embarrass the *strict* model of central capacity interference: limited performance trade-off as exemplified by the results of Gopher and Navon (Note 3; presented in Figure 5); absence of performance decrement due to addition of a second task as demonstrated by the results of Sperling and Melchner (1978; presented in Figure 4), by Martin (1977), or by Roediger, Knight, and Kantowitz (1977); insensitivity of probe performance to the load of primary task processing as shown by Comstock (1973), W. Johnston, Griffith, and Wagstaff (1972), and Posner and Klein (1973); and additivity of effects of difficulty and task emphases as found by Gopher and Navon (Note 3). These findings are nevertheless not sufficient to reject the *whole* class of central capacity models, because they can be explained by relaxing one or more of the assumptions underlying its strict version. However, one needs a *number* of explanations (such as elastic capacity, data limitation, structural interference, and automaticity) to adhere to the central capacity notion and still be able to account for those findings. In contrast, the multiple resources approach offers a unified, although complex, explanation for all of them. Thus, the most parsimonious view of

the field seems to have proved inadequate; the remaining alternatives are either to augment, patch, and hedge that view to the point that it barely resembles its original form, or to substitute it altogether with a broader, and necessarily more complex, view.

Which empirical evidence would tip the scale in favor of one of the alternative interpretations? As a rule, the multiple resources hypothesis cannot be tested with just one pair of tasks; it requires that several task pairs exhibit disparate behavior.

For example, the elastic capacity explanation for lack of interference between two tasks will be ruled out if it is demonstrated that either of them is interfered with by a third task.

An attempt to attribute a plateau of a POC to a scale limit will collapse if it can be shown that the apparent limit is surmounted with an easier version of the same task.

If a plateau exhibited by the performance of a certain task when paired with a second one vanishes when that task is paired instead with a third one that is known to be at least as difficult as the second one, then such a plateau cannot be held as a manifestation of local insensitivity of performance to resources in general, but rather to a particular type of resource.

Interference between tasks should not be ascribed to a certain structural conflict (say, incompatibility of operation of the two hands) if it does not exist for other task pairs that are a priori expected to suffer the same kind of conflict.

Similarly, it is unlikely that two given tasks do not interfere because they are processed as one integral task, if either of them does manifest mutual interference with a third task that intuitively does not seem less prone to unitization than the second one.

Generally, if the magnitude of interference of each of a set of tasks with a certain Task  $x$  fails to correlate with the amount of their interference with another Task  $y$ , then the source of interference cannot be central but must rather be due to the degree of overlap of mechanisms required by the tasks being paired. If, in addition, subjects exhibit sensi-

tivity to task emphasis instructions as revealed by considerable performance trade-offs, then the use of those mechanisms must be distributable. In conjunction, such results suggest that multiple resources are involved in processing those tasks.

Effects of difficulty manipulations like the ones illustrated in Figure 11 would indicate that those manipulations do not affect the efficiency of resources in a unique pool, so perhaps difficulty in general should not be construed in that simple manner. Another piece of evidence in this vein would be diversity in configurations of POCs produced by different difficulty manipulations.

A series of findings like these would converge to warrant the conclusion that central capacity models are insufficient for explaining a wide range of performance trade-off phenomena.

The claim about the existence of multiple resources would gain much support if a large body of interference data could be related to some analysis of tasks by components, modalities, or mechanisms. It would be ideal if we could predict the data by an a priori theory of task demand compositions. However, since there is no reason to believe that in the domain of human performance we can do much better than has been done in other fields of psychology, a more tangible objective is to try to account for the data by a post hoc model. To do this, we can pair each of a number of tasks with each other. If the range of tasks used is diverse enough, every type of resource will presumably be competed for by at least two tasks. Interference data from all the task combinations may be sufficient then for recovering, by means of post hoc statistical techniques such as multidimensional scaling, a resource space.

Once we gain a better idea of the resource space and of where various tasks are located in it by means of such heuristic techniques, we may proceed to unfold the precise forms of various performance functions. It may be possible to find, for every type of resource, a family of tasks that compete with each other just for it; and then to apply the procedure described in the Appendix to compute the partial derivatives of the performance of

various tasks with respect to that specific resource. Once this is done, we may be able to predict performance trade-off between tasks. As in every attempt at multidimensional scaling or factor analysis, the hope is that a few dimensions or factors will be sufficient to account for most of the variance and that they will mesh with our previous knowledge about structure of tasks. However, if the number of resources identified in that way proves to be very large, we may then have to judge the notion of multiple resources as not useful, albeit not necessarily invalid. But even then, it will be advisable to keep it at the back of our minds as a last-resort explanation.

What would convince us to abandon the notion of multiple resources? Technically speaking, like any other theory or metatheory that states the existence of entities whose number and nature are unspecified (e.g., distinctive features, processing stages, facets of intelligence), the notion of multiple resources is not logically falsifiable (let alone the fact that its major competitor can be regarded as one of its particular cases). In practice, the way to reject the notion of multiple resources, like any other elaboration in conceptualization, is to repeatedly demonstrate that simpler approaches suffice to capture empirical phenomena like the ones tested by means of the procedures mentioned in this section. In any event, we suggest that the notion of single capacity will no longer enjoy the distinguished status of the only conceivable energetic explanation to variability in performance and task interference; rather, it will have to survive confrontation with multidimensional models of resources, just as the notion of unidimensional intelligence was ordained to a similar struggle once the idea of facets of intelligence was brought forth.

### *Serial Versus Parallel Processing*

Although our approach can account for findings that have served to support serial stage models of information processing (e.g., Sternberg, 1969) or hybrid parallel-serial models (Kantowitz & Knight, 1974, 1976b), it by no means requires that we assume seri-

ality of processing: Different processing mechanisms may operate in parallel as well as in sequence. Thus, similar tasks may interfere not because their demands for central capacity are made during the same processing stages and thus tend to coincide in time (cf. Kantowitz & Knight, 1974; Kerr, 1973; Posner & Boies, 1971) but rather because their demands for capacities of specific mechanisms (operating in parallel or in sequence) are similar.

We have deliberately neglected in this article the temporal dimension of processing. Time-shared tasks can in principle be performed in parallel, in sequence, or intermittently, and it is quite difficult to diagnose experimentally which mode of time-sharing is actually taking place in a given situation (see Townsend, 1974). These modes seem to exhaust the possibilities if we consider the only allocatable entity to be the processing system in toto or the central processor or some other unique agency. However, once the notion of multiplicity of resources is adopted, it must be realized that there are many more conceivable modes of time-sharing. The use of any specific processing unit or storage device may be shared between tasks, either accommodating the tasks at the same time or serving each of them at a different time. So, theoretically, it may happen that Unit *a* is engaged simultaneously by Tasks *x* and *y* whereas Unit *b* is used first by Task *x* and then by Task *y*, and Unit *c* is used first by Task *y* and only then by Task *x*. Thus, resource allocation may be not just a problem of efficient budgeting but rather an intricate problem of scheduling and coordination further complicated by constraints that are due to dependence of some units on the output of others. The static economic metaphor may, thus, have to be replaced by a more dynamic one that involves continual change in the use that processes make of various processing facilities. But this objective falls beyond the scope of this article.

### *Automatic Processes*

Some psychological processes appear at first glance to defy the law of scarcity that

seems to prevail in economic systems; namely, they do not seem to interfere with each other (Posner & Boies, 1971; Posner & Klein, 1973; Schneider & Shiffrin, 1977; Shiffrin & Gardner, 1972). This observation led several researchers (Keele, 1973; Posner & Boies, 1971; Posner & Snyder, 1975a; Shiffrin, 1975; Shiffrin & Schneider, 1977) to assume that parts of human information processing, especially some processes involved with encoding and access to long-term memory, are automatic. Neisser (1967) also argued that some early perceptual processes are executed "pre-attentively"—in other words, they seem to be automatic.

The weakest sense of automaticity involves the amount of knowledge the system has on its own operation. If we identify attention with conscious awareness, then all unconscious processing is by definition non-attended. Another conceivable sense of automaticity is a rigid predetermined allocation of resources triggered by some particular internal or external input events. This possibility is discussed in previous sections. A stronger claim about automatic processes is that they do not require any limited processing power at all.

An alternative view is that processes that appear to be free (i.e., to demand no resources) are merely cheap. In other words, when a task requires a very small amount of resources to be executed at a desirable level, it may be performed without an observable disruptive effect on any other task it is time shared with. In that case, a failure to find capacity interference or load effects may be due to inadequacy of experimental manipulation or sensitivity of measurement. That this might be the case is indicated by findings of Becker (1976).

Another possible explanation for lack of interference interpreted to indicate automaticity is that processes that do not mutually interfere do require resources, yet different types of them; namely, they call for devices or channels that are completely independent (or for parts of the same channel that are completely parallel, if you wish). Some processes use "conscious resources" to which we usually refer when talking about attention.

Some others (or the same ones after intensive practice; see LaBerge, 1973, or Neisser, 1976) may not use "conscious resources," so they appear not to compete with processes of the first type. However, that does not mean that they do not use any resources at all; they may be proved to compete with other processes using the same kinds of resources.

An absence of load effect may also be observed when resources are not scarce. Suppose the joint demand of the tasks is smaller than available capacity. Then the "load" acts just to activate resources that have been idle before. Possible reasons for their being idle were enumerated in the second section under the heading "Scarcity of Resources."

### *Implications for Research*

The idea of multiple resources has some important implications for research in attention and performance.

Psychologists who consider capacity as a unitary pool may attempt to develop measures for both capacity and the load imposed on it by certain tasks or task combinations (e.g., Kahneman, Beatty, & Pollack, 1967; Kalsbeek & Ettema, 1963; Michon, 1966; Wierwille & Williges, Note 9). However, as capacity may be a vector rather than a single quantity, it may also be meaningless to talk of mental load as a single quantity. When proportions are fixed, task load is a vector. When they are not, it is a set of alternative vectors one of which is to be selected, considering available capacity and the load imposed by concurrent activities, so that joint load in the bottlenecks will be minimized. In either case, perhaps one should ponder whether it is fruitful to search for a single objective measure or a single behavioral or physiological correlate for mental load.

For the same reason, attempts to identify a single task that will serve as a standard secondary task for all the tasks whose demands are to be compared (see Kelly & Wargo, 1966; Michon, 1966) seem even less warranted.

In the domain of individual differences, we are now in a position to doubt the meaningfulness and potential success of attempts to characterize people by their "time-sharing ability" (Parker, Note 10). Indeed, Sverko (Note 6) failed to isolate a unique time-sharing-ability factor by factor-analyzing subjects' performance in various dual-task situations. This failure is not surprising if there is no unique pool of resources to be allocated but instead several of them. People may differ in their specific capacity as well as in their specific abilities to time-share each of them.

Interpreting effects of any manipulation of a subject-task parameter on dual-task performance is risky unless further information about allocation policy is available. To get a complete picture of how two specific tasks are time-shared, one should manipulate various subject-task parameters as well as task preferences and present their effects in terms of a family of POCs. Every such POC should contain as its boundary conditions measurements in the corresponding single-task situations (and also in a dual-task focused-attention situation if it is feasible). This procedure will help to clarify the source of task interference, and will at least distinguish between performance trade-off and concurrence cost. In interpreting results of such studies, one should bear in mind the points discussed in this article and summarized at the end of the fourth section. To clarify the picture even more, one might consider using the procedures described at the beginning of this section.

We do not advocate any interpretation in particular, although we have, of course, our own biases. Our purpose has been to point out the many theoretical possibilities that exist and to emphasize that caution is needed in interpreting empirical data of dual-task performance. Because of the complexity of issues, it is important to have a coherent conceptual framework that will help people communicate and organize their thinking.

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## Appendix

### In Search of Performance-Resource Functions

We have pointed out that since a POC is determined by two performance-resource functions, it generally does not provide sufficient information for recovering either of them. Here we discuss a way to circumvent this difficulty.

First, we have to assume that all observed task interference results from competition for resources from a single pool or at least that one can isolate interference that is due to that competition. Suppose now that one finds a pair of tasks,  $x$  and  $y$ , that exhibits a perfectly linear performance trade-off. A linear POC entails that for every amount of resources invested in  $x$ ,  $R_x$ , the ratio  $(dP_y/dR_y)/(dP_x/dR_x)$  is a negative constant,  $-k$  (see Footnote 2). In other words, let  $P_y = g(R)$  and  $P_x = f(R)$ ; then for every  $R$ ,  $g'(R^L - R) = -k \times f'(R)$ , hence  $g(R^L - R) = C + 1/k \times f(R)$ .

By definition of the concept of resources, we can let  $g(o) = 0$  and  $f(o) = 0$ , thus  $C = -1/k \times f(R^L)$ . It is also natural to assume that both  $f$  and  $g$  are nondecreasing in  $R$ . Their specific relations may fall in the following categories:

1. Both  $f$  and  $g$  are linear.
2. One of the functions,  $f$  and  $g$ , is negatively accelerated, and the other one is positively accelerated.
- 3a. The acceleration of both functions switches from positive to negative (or vice versa). The direction of sign change (namely, the sign of the third derivative) is the same in both functions, but the inflection point of one of them is at  $R_o$  [ $R_o \neq (R^L/2)$ ] while the inflection point of the other one is at  $R^L - R_o$ .
- 3b. The same as in 3a, only the inflection point of both is at  $R^L/2$ .

Let us restrict ourselves to these cases, since it is hard to see a reason for a performance-resource function to have more than one inflection point and since the more tractable cases will suffice to make our point. Let us consider now the plausibility of each of these cases.

It does not seem very reasonable that returns from resource investment diminish for one task yet increase for the other one as Case 2 requires. Case 3a appears to be actuarially unlikely; it must be a rare event that two different S-shaped functions have their inflection points spaced so symmetrically. Furthermore, under each of the Cases 2 and 3a, the two tasks should interfere differently with a third task. If one nevertheless finds a task that exhibits the same trade-off relation with each of the former two, then these cases will be ruled out.

It is a matter of speculation to judge which of Cases 1 or 3b is more plausible in a particular situation. However, we suggest that for the time being the distinction between these two cases is practically unimportant. As long as we do not know what the true scale of resources is, we can define it to be the domain of a linear function whose range is the performance of a task that ex-

hibits a linear trade-off with another one; that is, we can ascribe every unit of performance improvement to a unit increase in resource investment. If the true measure of resources ever emerges, and the dependence of performance of that task on resources proves then to be captured by a third-order polynomial equation rather than by a linear one, then all performance-resource functions derived under the linearity assumption in the way described below will be distorted in the same systematic fashion. Meanwhile, we would do well to follow Cohen's (1965) advice: "Until true measures exist, our conclusions must relate to the numbers our available measures yield" (p. 113).

So, we can use either  $x$  or  $y$  as standard tasks whose performance-resource functions are assumed or defined to be linear. To obtain the performance-resource function of any other Task  $z$ , we should pair it with one of the standard tasks, say  $x$ , and obtain a POC that can be conceived of as a function  $T$  relating  $P_z$  to  $P_x$ . Let  $h$  denote the performance-resource function associated with Task  $z$ . Hence,  $h(R_z) = T(P_x) = T[f(R^L - R_z)]$ . Since  $f$  is assumed to be linear,  $f(R^L - R_z) = a - b \times R_z$ , where  $a$  and  $b$  are some unknown constants. Hence,  $T(P_x^L - P_x)$  determines  $h(R_z)$  up to a linear transformation. In other words,  $h(R_z)$  is equivalent to the outcome of rotating the POC about the vertical line intersecting the abscissa at  $P_x^L/2$ .

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