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LEVEL II

ON THE ECONOMY OF THE HUMAN PROCESSING SYSTEM: A MODEL OF MULTIPLE CAPACITY

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Preface

Optimization of task load and maximization of operator's spare capacity are major requirements in the design of many engineering systems. Human factors specialists confronted with these requirements most often find themselves poorly equipped and unable to provide well supported measures of load and capacity.

Unlike other human factors areas such as: display and control design, workplace design and environmental conditions, where the field worker can resort to handbooks, manuals and standards, there is very little concensus on concepts, methods and measures of task load. This rather frustrating state of events does not result from a neglect of research. Considerable effort has been devoted to the study of these problems in the last three decades. Direct measures of performance such as speed and accuracy, indirect secondary task techniques and complex time sharing situations were all thoroughly explored and experimented. Applications of information theory, signal detection models, control feedback theory and decision models were attempted by various investigators. The major drawback of these studies is that while useful and important specific information was obtained, general rules and across task comparison methods could not be defined.

The lack of tools and measures in the applied field only mirrors a similar situation within the domain of basic research. While several models of the human processing system have been proposed, each of them can only account for small parts of the experimental evidence.

In the present report we try to present a conceptual framework, a methodology and a model. We feel that the nomenclature we introduce is coherent and complete in that it covers many aspects of performance and factors which bear on it. We also believe that the proposed concepts and methods can be easily adopted by human factors specialists and readily presented in quantitative form.

ABSTRACT

An approach to human performance which is based on economic concepts is proposed. This approach hinges on the idea that the human processing system has a number of mechanisms each having its own capacity. Those capacities can at any moment be allocated among several processes. Since tasks may differ with respect to the types of mechanisms they call for and the demands they pose for the use of those mechanisms, it is argued that the hope to find single measures for system capacity and mental load may be groundless. Different pairs of time-shared tasks may conflict with each other to a variable degree, which is difficult to predict without knowing the overlap in their demand for various mechanisms. The amount and specific nature of trade-off between time-shared tasks can be displayed by means of performance operating characteristics. The effects of a number of properties of the system and of the tasks on the shape and interpretation of performance operating characteristics are discussed. The analysis in this paper also serves to elucidate the notion of resources brought forward by previous authors, to elaborate on the distinction between demand for and supply of resources, to discuss possible interactions between the effects of supply of resources and situation parameters on performance, and to conjecture about the way by which allocation policy depends on the value of outcomes of different allocations. Finally, relevant empirical evidence and implications for further research are discussed.

ON THE ECONOMY OF THE HUMAN PROCESSING SYSTEM: A MODEL OF MULTIPLE CAPACITY

In this paper we draw an analogy between a person performing one or more tasks and a manufacturer producing one or more products, and we try to push it the furthest it could be pushed. For this purpose microeconomics provides us with powerful tools which it would be a shame not to borrow and with useful terminology which it would be a waste not to adopt. By giving 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 (e.g. Broadbent, 1971; Garner, 1974; Gopher and North, Note 1; Kahneman, 1973; Kantowitz and Knight, 1974; Keele, 1973; Kerr, 1973; Moray, 1967; Norman and Bobrow, 1975, 1976; Posner and Boies, 1971; Schneider and Shiffrin, 1977; Shiffrin, 1976; Shiffrin and Schneider, 1977; Sperling and Melchner, in press; Treisman, 1969) can be placed and related to each other. This framework may serve to uncover some of the hidden assumptions in previous analyses, to see what happens when those assumptions are violated, to sharpen some concepts and to make some new distinctions. On this background some unique features of the human processing system protrude.

We first portray an ideal system which is the psychological analogue of the Homo Economicus, and then discuss possible points of departure of the real system from the ideal one. We start by re-formulating some old concepts and ideas in terms which are more convenient for our later discussion. Most of the reference to and confrontation with existing psychological literature is postponed until the final sections of the paper.

Some Basics

Resources

Let us first postulate the idea that the human system possesses a finite amount of processing facilities which we call by the name coined by Norman & Bobrow, 1975: resources (elsewhere referred to as effort, capacity, attention, etc. See, e.g., Kahneman, 1973; Moray, 1967; Shiffrin, 1976). Normally, performance of a task is positively related to the amount of resources available to it. Processing resources are analogous to the production factors input by, say, the farmer to grow some sort of crop: land, labor, water, fertilizers, etc.

The concept of resources can be used as a common denominator to bridge across the gap between two kinds of determinants of behavior, the environmental or mental parameters of the task on the one hand, and the commitment of the system to do it. Once we adopt the notion of resources, the first kind may be considered to determine the demand for resources applied by the task to the system and the second kind may be viewed as the factor associated with the supply of resources from the system to the task (cf. Kahneman, 1973, pp. 14-16). Considering the farming analogy, the demand corresponds to the inputs the farmer has to put in to grow a ton of corn, and the supply is the input he actually elects to invest.

The concept of resources becomes particularly necessary when we try to understand time-sharing performance. How else can we account for the fact that performance of a task can be affected not only by its own difficulty but also by the difficulty of another task with which it is time-shared? It appears as if both tasks apply demands to the same pool of resources and get supplies in proportions that are related to their relative demands. Again, think of the farmer who allocates his limited production factors between growing corn and rice according to what each requires.

Let us now be more specific about the functional relationships among the variables involved in performance.

Performance Functions

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, S-R compatibility, response complexity, amount of practice, etc. Norman and Bobrow (1975) seem to subsume all those parameters under the title data quality. As we feel that the connotation of this term is too limited, we prefer the name subject-task parameters. Subject-task parameters may characterize the task proper (e.g., response complecity), the environment (e.g., signal-to-noise ratio), or the permanent or transient 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 and Bobrow, 1975, between signal- and memory-data limits). Their common feature is that they are the constraints imposed by the task (or more precisely, by the encounter of a specific task and an individual subject) on the system. Within those constraints the system is free to mobilize its resources to perform the task in much the same way as the farmer decides how to invest his labor, water, and fertilizers for growing corn given the climate, soil fertility, and particular properties of the corn plant. For example, suppose one is to count the numbers of roosters and hens in a barnyard. He is constrained by, say, the level of illumination and his given skill to tell a rooster from a hen, but he has much freedom to choose how much of his perceptual and cognitive apparatus and his working memory space will be engaged in that counting.

Performance is determined by the amount of resources invested and how much can be done with them. Performances (P) is, thus, a function (f) of subject-task parameters (STP) which are imposed on the system and resources (R) which are controlled by it:

$$P = f(STP,R) . \quad (1)$$

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 (1). This theoretical quantity can be called the demand for resources. It is clear that demand (D) is a function (d) of subject-task parameters (STP) and level of intended performance (P^I):

$$D = d(STP,P^I). \quad (2)$$

That is, a task demands more processing resources the more difficult it is and the higher the criteria for successful performance are. For example, a tracking task 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; it is rather defined for a specific task and a specific level of performance.

Level of Intended Performance

There are two possible ways by which the level of intended performance is determined. In some tasks it is internally controlled. When the quality of performance is variable and has no tangible upper limit, the system will intend to a level of performance that maximizes the utility of performing the task (a point that is elaborated on later). If that utility grows indefinitely, which is the conventional assumption, then the system will intend to maximize the quality of performance, thus the demand will be infinite.

In other tasks the level of intended performance is externally controlled. One case is when performance is bounded by the nature of the task. Given the subject-task parameters, performance can improve only up to a certain level by investment of resources but not any more (cf. the notion of data-limit in Norman and Bobrow, 1975). That asymptotic level may serve then as the level of intended performance (because there is no sense in aspiring to more than the feasible), unless the utility of performance is maximized at a lower level. Another case of external control is when there exists a rigit standard for success, so that quality of performance has an all-or-none nature.[2] The external standard will be adopted by the system as its level of intended performance provided that the system benefits from performing the task at that level.

Supply

The system will supply resources to meet the demand to the extent that they are available. I.e., the supply (S) equals either the demand (D) or the limit on available resources (R^L), whichever is smaller:[3]

$$S = \min \begin{cases} D \\ R^L \end{cases} \tag{3}$$

Putting it in a different way, we can define the limit on performance P^L as the degree of performance obtained by using R^L resources with given subject-task parameters:

$$P^L = f(STP, R^L) \ . \tag{4}$$

P^L is the capacity of the system presented in terms of the specific task it is supposed to perform. An intended level of performance P^I is feasible if it is not greater than P^L.

Joint Performance

The analysis becomes more complicated and interesting when two or more tasks that use the same resources are performed simultaneously. In that case the variable of interest is the combination of levels of performance of those tasks. Let us consider the simple yet general enough case of two tasks, x and y, and denote their joint performance by (P_x, P_y).

It immediately follows from (1) and (2) that their joint performance is a junction (h) of their parameters (STP_x and STP_y) and resources alloted to each of them (R_x and R_y):

$$(P_x,P_y) = h(STP_x,STP_y,R_x,R_y) \quad , \qquad (5)$$

so that the combination of their demands for resources which may be denoted by (D_x,D_y) is a function (g) of their parameters (STP_x and (STP_y) and the intended joint performance denoted by $(P_x,P_y)^I$:

$$(D_x,D_y) = g\ [STP_x,STP_y,(P_x,P_y)^I]. \qquad (6)$$

Here the level on intended performance is defined over the combination rather than over the single tasks, because in order to select a combination, the system should consider the worth of combinations. That may not be directly derived from the worth of single-task performance of the two tasks, and we discuss later the cases in which it is not.

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. The system can achieve every combination (P_x,P_y) that can be given by (5) subject to the constraint that

$$R_x + R_y < R^L \quad , \qquad (7)$$

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, namely when

$$R_x + R_y = R^L \quad , \tag{8}$$

can be represented as a curve of the type called by economists production possibility frontiers in problems of production or consumption possibility budget lines in problems of consumption. We will follows Norman & Bobrow (1975) and call them performance operating characteristics (see illustrations in Figure 1). Performance operating characteristics (or POCs in short) trace

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Insert Figure 1 about here

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the bound of joint performance. All the combinations which are either on them or enclosed between them and the two axes are feasible. 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.

POCs may have various shapes. Later in this paper we discuss some determinants of the shape of the POC. The slope of a POC at a given point represents the objective substitution ratio, namely how much improvement in one task can be gained by sacrificing one unit of the other task. It is straightforward to posit that this ratio reflects the ratio between the marginal contributions of a unit of resources to the two tasks: A unit of resources moved from task x to task y leads to a decrease in performance of x by the marginal contribution to y. One may also interpret this ratio as the relative difficulty of the tasks. Increasing the difficulty

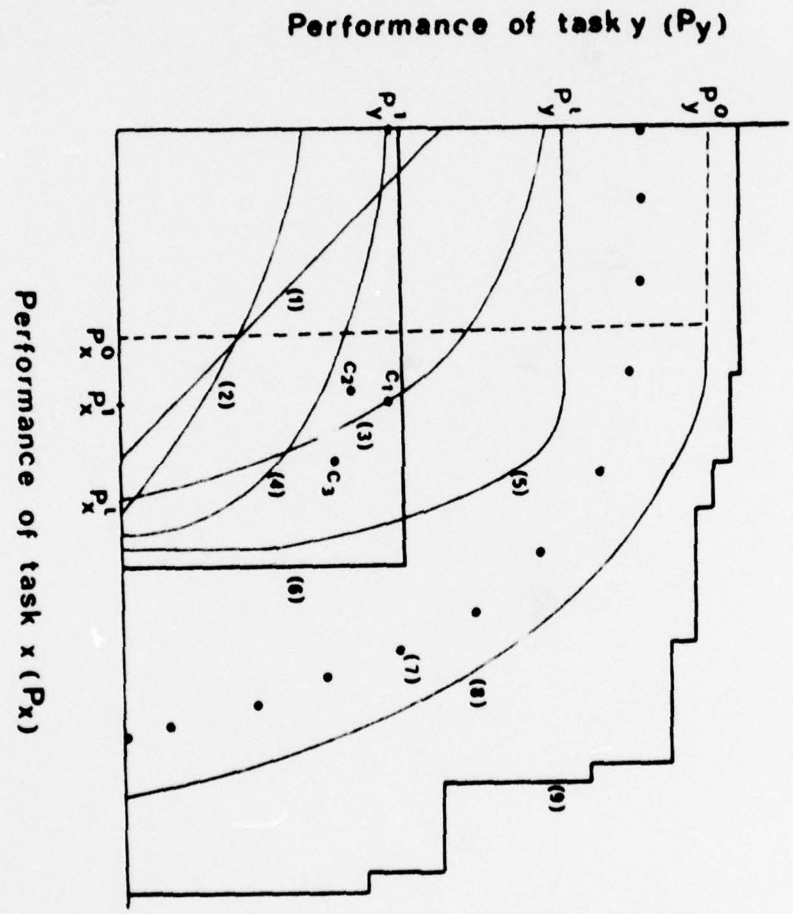

Fig. 1: Illustrations for various types of performance operating characteristics.

of task x should drive the POC leftwards. Making task y more difficult shifts the POC downwards. An increase in the difficulty of both tasks is reflected in a POC which is closer to the origin in both dimensions.

The POC comprises of a set of alternative combinations only one of which is realized in a particular situation. By choosing a certain combination, say C_1 in Figure 1, the system benefits from the outcomes of performing the tasks at the corresponding levels (namely, P_x^1 and P_y^1 if C_1 is chosen), but at the same time it gives up part of what could have been gained had it been involved in one task exclusively (namely, $P_x^L - P_x^1$ and $P_y^L - P_y^1$) or in the two tasks in different proportions. Thus, every benefit is typically associated with some concomitant sacrifice,a sacrifice that is sometimes called by economists <u>opportunity cost</u>. So, 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 the analysis of the situation is similar to the analysis of single-task performance. More specifically, when both tasks use the same kind of resources, 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? In order to analyze this case let us assume that utility is a monotonically nondecreasing function of performance, at least up to the intended level.

Remember that when performance has no tangible upper limit, and utility is nondecreasing in it, then the demand will be infinite.

Let us consider again our economic analogy. When a consumer selects among different bundles of commodities or when a farmer who owns a self-sufficient farm elects to produce a particular combination of products, their decisions probably reflect their preferences. Those preferences can be displayed 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). In the domain of human performance, the performer must have preferences among different mixtures of outputs of the tasks he performs which can be represented by means of indifference curves. Figure 2 presents three types of patterns of preferences.

Insert Figure 2 about here

The first one, depicted in Figure 2A, is a case of perfect trade-off: One can exchange a unit of P_x for a constant number of units of P_y that is equivalent to a unit of P_x in terms of utility. This rate of exchange (namely the slope of the curve) may be called subjective substitution ratio. As illustrated by the difference between the two sets of curves in Figure 2A, it may vary for different subjects and tasks. Cases of perfect trade-off are characterized as aforesaid by constant ratios within given situations. Task pairs which meet this condition consist of tasks that can completely

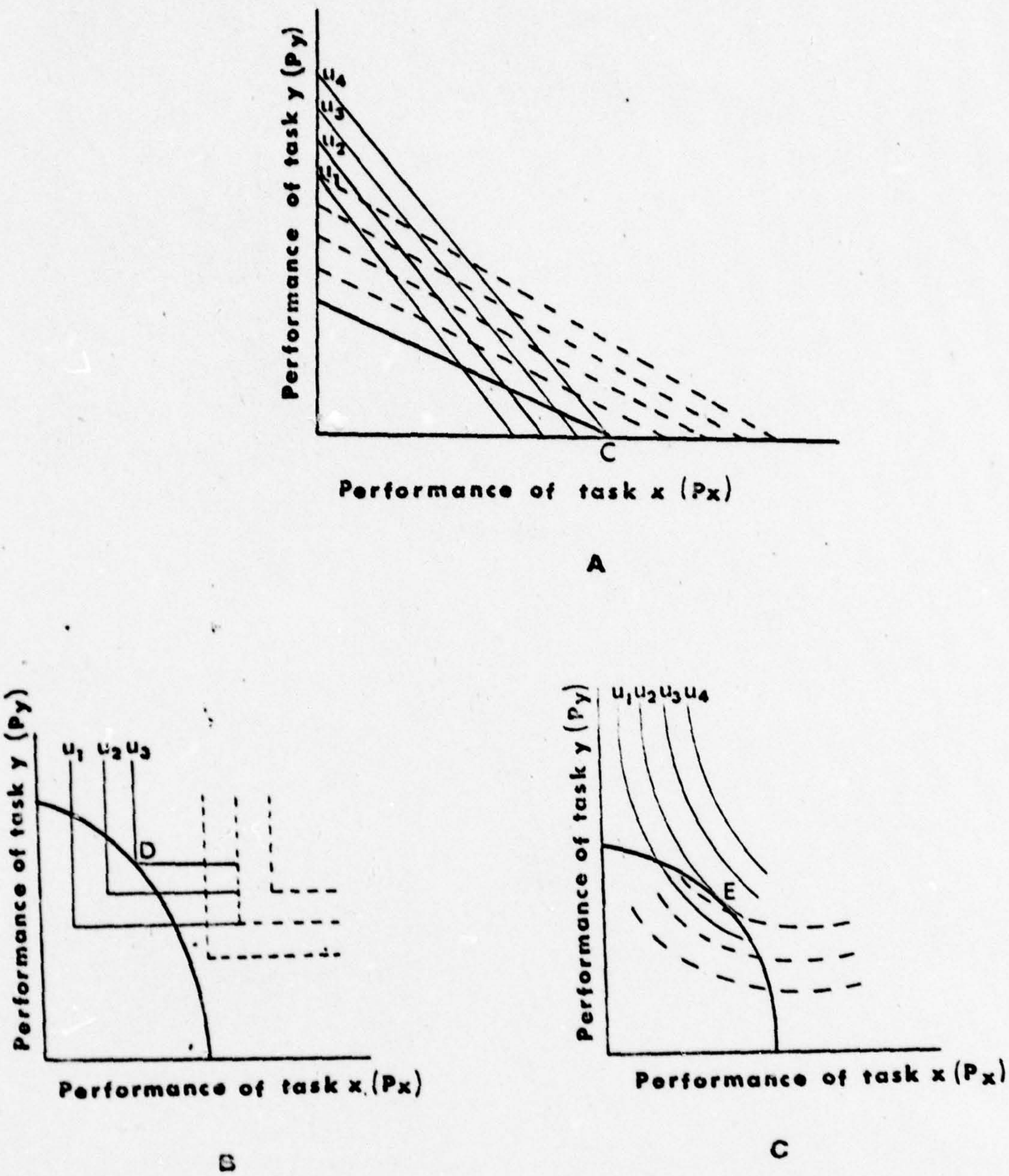

Fig. 2: Illustrations for three types of indifference curves. Panel A describes perfect trade-off. Panel B describes perfect cooperation. Panel C describes partial compensation. Each of the two sets of curves in each panel, the solid curves and the dashed ones, correspond to a different situation or subject. The bold curve is a performance operating characteristic.

substitute for each other. For example, in binaural presentation of sounds, one would benefit the same from listening to either ear exclusively or to both in various proportions.

The second type of indifference curves, presented in Figure 2B, reflects cooperation between tasks. 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 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. This case is analogous to the utility associated with complementary commodities such as a right shoe and a left shoe.

The last type of indifference curves, illustrated in Figure 2C describes two partly compensatory tasks. This is the intermediary case between the first two, and it exists whenever degradation of P_x can be compensated by some improvement in P_y (or vice versa) yet the subjective substitution ratio 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 more improvement is needed. This situation is probably the most frequent one.

For example, when tracking a target in the 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.

There may be some other shapes of indifference curves in realistic situations, and many more can probably be produced in experimental situations if the experimenter is ingenious enough in manipulating demand characteristices and pay-off conditions. One example is a situation in which one task is primary and the other one is secondary. The interested reader is invited to figure out the shape of the indifference curves in that case.

Resource Allocation

The graphical representation of infeasible aspirations is the existence of some indifference curves to the "north-east" 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, $S_x + S_y$, will be equal to R^L (by (3)). But how will the total capacity, R^L, split between the two tasks? The optimal mixture of S_x and S_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 "north-easternmost" indifference curve. When the indifference curves are convex, that will be a tangency point where the slopes of the POC and the indifference curve (namely, the objective and subjective substitution ratios) are equal (see point E in Figure 2C). That means that no extra utility can be gained by trading either more x for less y or vice versa. When both the indifference curves and the POC are linear, the optimal point will be the intersection of the POC with the highest indifference curve, which must fall on one of the ends of the POC (see point C in Figure 2A), unless the slopes of the POC and the indifference curve are equal. Since the normal situation is presumably of the type depicted in Figure 2C, it follows that in general the resource allocation ratio (S_y/S_x) is a function (sr) of the objective substitution ratio $(\Delta P_y/\Delta P_x)$[4] and the subjective substitution ratio $(\Delta U_y/\Delta U_x)$:

$$S_y/S_x = sr(\Delta P_y/\Delta P_x, \Delta U_y/\Delta U_x) .$$

In other words, resource allocation depends on both objective relative demands of tasks and subjective task preferences.

Multiple Resources

Up to this point we might have appeared to view resources as a sort of general undifferentiated entity very much analogous to a common currency in a monetary system or to energy in a physical system or to the general intelligence factor G in theories of human intelligence: Tasks interfere to the extent that they depend on resources from that general pool. However, as suggested or implied by previous authors (e.g., Allport, Antonis and Reynolds, 1972; Kantowitz & Knight, 1974, 1976; Kerr, 1973; Norman and Bobrow, 1975; Wickens, Note 2), there may be various types of resources as there are various factors that may be input to production. Resources are probably not 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 at a unit of time). Different tasks may require those different types of resources in various compositions. Thus, we can modify the performance function in (1) so that it depends on the amounts of several specific resources, say R^1, R^2, and R^3:

$$P = f(STP, R^1, R^2, R^3). \qquad (10)$$

<u>Fixity of Proportions</u>

A distinction should be made here between two kinds of performance functions, a <u>fixed-proportions</u> function and a <u>variable-proportions</u> function. The first one reflects very rigid requirements for specific resources. An example is a process that can use exactly two units of STM capacity with one unit of VIS capacity; any increase in one of them without a concomitant increase in the other one would not improve performance at all. 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 resources, 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 functions are illustrated in Figure 3 by means of iso-performance contours as a function of two types of resources. In the fixed-proportions case

(Figure 3A), the ratio of 2 units of R^1 to one unit of R^2 is mandatory. In the variable-proportions case (e.g., Figure 3B) resources can be input in various mixtures.

Insert Figure 3 about here

Demand Compositions

To obtain a desired level of performance the system may use certain combinations of the specific resources so that there is a relation (d) mapping subject-task parameters and intended performance levels onto compositions of specific demands:

$$(D^1, D^2, D^3) = d(STP, P^I) . \tag{11}$$

Note that if proportions are not fixed, d is not a one-valued function, i.e., there may be many compositions of specific resources that give rise to P^I given the subject-task parameters. Nevertheless, one or more compositions may be optimal in the sense that they minimize the overall amount of resources required to bring about P^I (or the cost associated with them). On the other hand, for each type of resources i there may be some threshold amount ($\bar{D}^i$) required in order to produce P^I. That amount cannot be substituted by any other type of resources.

Some types of resources are not relevant at all for certain tasks, in other words, the task demand for them is zero. Thus, for any task x, all

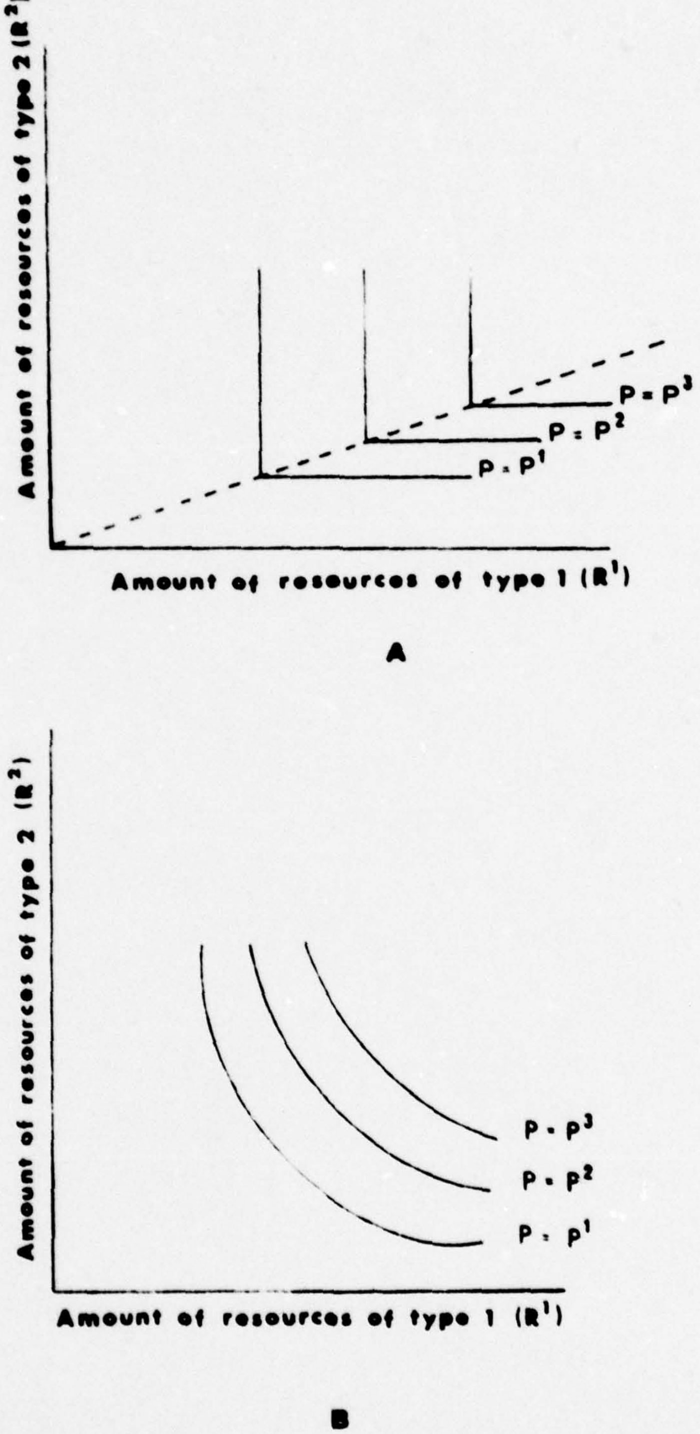

Fig. 3: Iso-performance contours as a function of two tupes of resources, R^1 and R^2. Each contour connects all resource-combinations that yield the same level of performance function. Panel B presents a variable-propertions performance function.

the resources can be classified into two classes, the set of resources which 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 which is not used at all by other tasks. Several relationships between resource compositions of two tasks are illustrated in Table 1. As can be seen from Table 1, the

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Insert Table 1 about here

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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 left of the double line in Table 1); $X - Y$, which is the set of resources that can be used by task x but not by task y (e.g., R^4 in case I in Table 1); $Y - X$, which is the set of resources that can be used by task y but not by task x (e.g., R^3 in case I in Table 1); 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 1). We are mainly interested in the demand for and supply of resources of the set $X \cap Y$, so let us use special notation, D^* and S^*, to denote them respectively. 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

6. Note that our use of the term "cost". is different than the use made by Posner and his associates (see, e.g., Posner & Snyder, 1975, 1975a). They consider the cost of a process to be the loss incurred by investing resources in it of what could have been gained had those resources been devoted to an alternative task (roughly what we earlier called: opportunity cost). We refer by this term not to the inability to realize benefits of alternative activities but rather to the real cost (say "mental energy" consumption).

7. It is not necessary, although convenient, to assume an additive function. Coombs & Avrunin (1977) define a class of composition rules (called proper preference functions) that would yield the effect described below.

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. In such cases, D^*_x stands for the threshold amount $\bar{D}_x^{X \cap Y}$ (namely for the minimal amount of common resources required for performing task x at the intended level). Similarly, D^*_y stands in this case for $\bar{D}_y^{X \cap Y}$.

What is Hidden Behind a POC?

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 try to obtain empirical POCs in their laboratories. It follows from the previous discussion that the only admissible technique to obtain an empirical POC is to vary task preferences by means of pay-offs or instructions (cf. Norman & Bobrow, 1976). Now we focus on the conditions that have to be met in order that (a) an empirical curve can be interpreted as a POC as defined here, (b) a POC is a smooth continuous curve which intersects both axes (e.g., curves 1,2,3, and 4 in Figure 1). We also discuss the effects that violation of a particular condition or variation of some other variables may have on the shape or on the interpretation of the POC. First, we list all the relevant variables and conditions. For three of them we also present the conditions or variables on which they in turn depend.

1 Similarity of demand compositions
- 1a Existence of common resources
- 1b Similarity of compositions of common resources

<u>2</u> Variable-proportions performance function

<u>3</u> Sensitivity of performance to amount of resources

<u>4</u> Additivity of demands

<u>4a</u> No extra cost for concurrence

<u>4b</u> No symbiosis between tasks

<u>5</u> Fixed capacity

<u>6</u> Controllability of resources

<u>7</u> Distributability of resources

<u>8</u> Complementary of supplies

<u>8a</u> Continuity of performance

<u>8b</u> Compatibility of tasks

<u>8c</u> Scarcity of resources

<u>8d</u> Efficiency of resource usage

<u>9</u> Constancy of demands

We now turn to examine in more detail the importance of each of these points.

<u>Similarity of Demand Compositions</u>

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.

<u>Existence of common resources</u>. If the types of resources the tasks demand are completely disjoint, namely $X \cap Y = \emptyset$ (e.g., case VI in Table 1), 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 the performance of the other one, so that 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 resources both tasks use are the same (e.g., cases II, III, and V in Table 1), then every unit of resources used by one of the tasks could have been used alternatively to improve the performance of the other one; and every unit spared by degrading the performance of one can be invested in improving 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 IV in Table 1), 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 aside of the types common to both, then the resources which are 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 because of two reasons; one, some released resources are irrelevant; two, even the relevant ones are not sufficient. To illustrate, suppose one performs simultaneously the tasks x and y of case IV in Table 1 about equally well (at point C_1 in Figure 2). Decreasing performance of x by one unit saves 5 units of R^3 which is useless for task y, but just one unit of the relevant R^2. To improve performance of y by one unit the system should be able to recruit extra 5 units of R^2. Else, if those are not available, either not all the disengaged amount of R^1 is exploited (say, just 0.6 of R^1 with 3 of R^2), or the system operates in suboptimal proportions (say, one unit of R^1 with 3 of R^2). Either way y is improved by less than one unit. A similar thing would happen if one attempted to change task emphases to the opposite direction, namely to improve performance of x at the expense of performance of y. Therefore, the POC in this case is more concave (as in, say, curves 3 and 4 in Figure 1) than in cases with larger share of common resources within the demand compositions, such as case V.

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 was just one input that could affect the performance of both tasks (say, R^1 in case V in Table 1), then resources removed from one task would 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 III in Table 1). However, consider a situation in which the tasks require different combinations of the same types of resources (e.g., case II in Table 1). 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.

An economic example may illustrate the point best. Suppose the most efficient way of picking eggplants requires 5 laborers per one tractor, whereas harvesting potatoes is fully automatized and requires only one laborer per a tractor. Suppose that exactly one tractor and 5 laborers are now employed in picking eggplants, and 2 tractors and 2 laborers harvest potatoes. If we transform one tractor and one laborer from potatoe harvesting to eggplant picking, potatoe yield will be cut in half but eggplant yield will not be doubled, because now there are just 6 laborers picking eggplants with 2 tractors. If we give up potatoes completely, one more tractor and one more laborer will be available for picking eggplants, but their marginal contribution will even be smaller, because now the ratio of laborers per tractor (7:3) is even farther from the optimal one. Hence, the objective substitution ratio changes as resources allocation is changed so that to obtain more of one product 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 very unprobable 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.

<u>Variable-proportions Performance Function</u>

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 Figure 3A), then performance could be improved only if <u>all</u> relevant types of resources were proportionally more available. For example, suppose one unit of R^1 and 5 units of R^3 are available for task x in case IV of Table 1, so that the task can be performed at level P^1. To improve performance the system needs supplements of both R^1 and R^3 — 5 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 performance of x unless there is an excess amount of R^3 that has been idel 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, in order 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 Figure 3B). 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, namely on how much improvement in performance is yielded by adding a unit of resources.

Sensitivity of Performance to Amount of Resources

As stated in (10), performance is a function of multiple variables. One can depict its dependency on each of those variables by plotting performance as a function of a certain variable, say R^1, holding all other ones constant. The slope of that function (namely the partial derivative) represents the sensitivity of performance to the amount of R^1. That sensitivity may not be constant. As Norman & Bobrow (1975) argue in their discussion of performance-resource functions, as the amount of resources increases the sensitivity typically decreases until it drops to zero. Processes at the region of insensitivity (namely when changes in resources do not affect performance) are called by Norman & Bobrow "data-limited processes"; when sensitivity is nonzero (namely when increases in the amount of resources results in improved performance) the task is called by Norman & Bobrow "resource-limited". Norman & Bobrow suggest to interpret a flat part of a POC perpendicular to one of the axes as an indication that the task associated with that axis is data-limited. For example, the horizontal segment of the POC in Figure 4A is attributed to the fact that the performance of task y cannot be improved beyond P_y^o no matter how much additional resources are directed to it.

It should be born in mind that the observed inability of task y to improve in a dual-task situation does not imply that resources have done their utmost for the processing of y. It may just mean that task y cannot capitalize on the particular kind of resources that are spared by worsening performance of task x. It may still be sensitive to resources of some other types which are not shared by x (namely of the set Y - X), thus are not released when performance of x deteriorates.

Insert Figure 4 about here

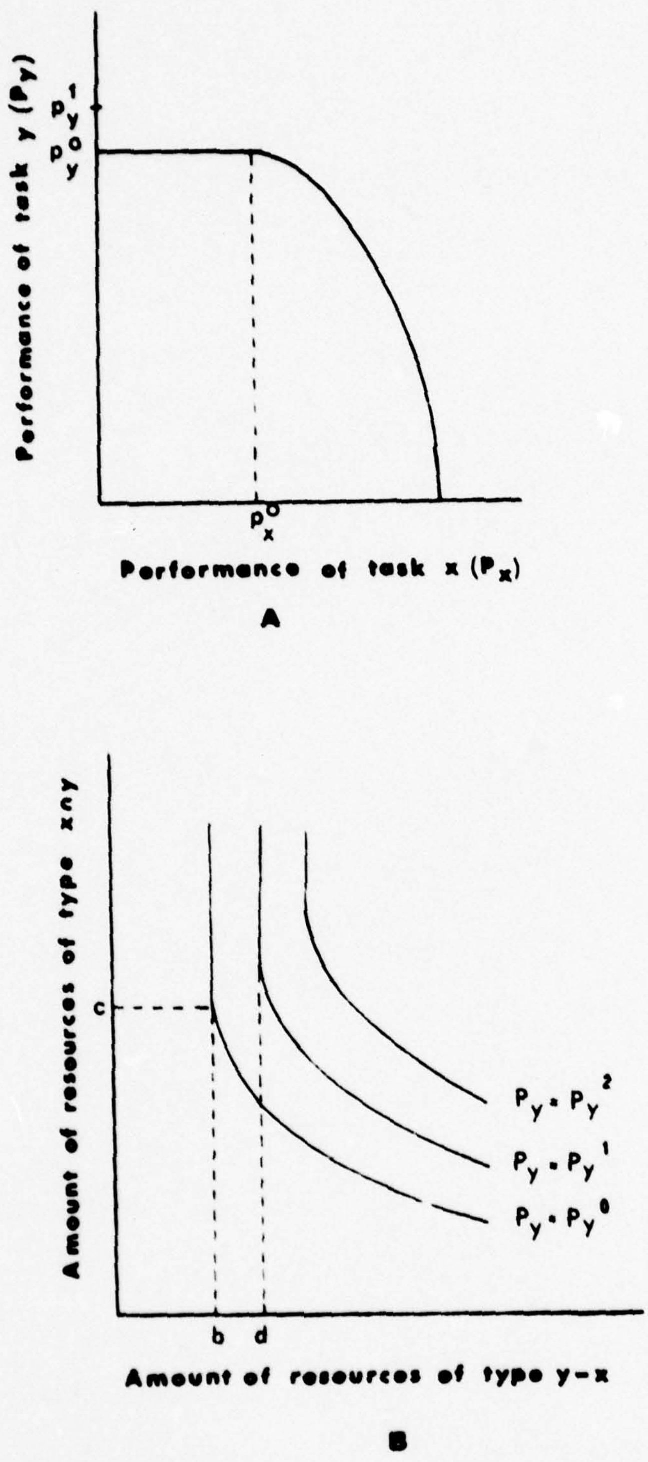

Fig. 4: Panel A presents a POC with a flat region. Panel B illustrates the sort of trade-off between $X \cap Y$ and $Y - X$ resources which may be the cause of limit on the performance of task y. See text for explanation.

Those other types of resources may be in shortage because in general the task can use of them more 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 just means in that case that doing task x at a level not higher than P_x^o cost 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 which 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 iso-performance contours in Figure 4B. 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^o, which will be the upper bound of the POC (see Figure 4A). 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?

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). I.e., adding more and more resources of just one type typically removes the task away of the ideal proportions of specific resources. If all the resources were increased, economists would probably argue, the output would increase proportionally (a case of "constant returns to scale" in economic terminology).

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. For instance, investing more resources 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).

However, that asymptote may be conditional on the given quality of sensory input (or more generally, on the given level of any subject-task parameter). If the production relationship between resources and input quality is like that described in Figure 4B (with resources in the ordinate and input quality in the abscissa), then different levels of input quality may be associated with different patterns of demand for resources. For example, when input quality is better, less 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 input quality takes part in determining not just performance per se but also whether and how it is affected by resources. How exactly these two factors interact is what we hope to reveal in a study we are pursuing now.

Additivity of Demands

If tasks do 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 common resources applied by the two conjoined tasks (D^*_{xy}) must equal the sum of the demands of the tasks when performed separately:

$$D^*_{xy} = D^*_x + D^*_y \quad . \tag{12}$$

When D^*_{xy} is greater than $D^*_x + D^*_y$ 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 Figure 5A; maximal performance in single-task situations (P^L_x and P^L_y) is much higher than performance of the same task conjoined with any level of performance of the other task, because the mere act of adding a second task will take away from the first one more resources than required

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Insert Figure 5 about here

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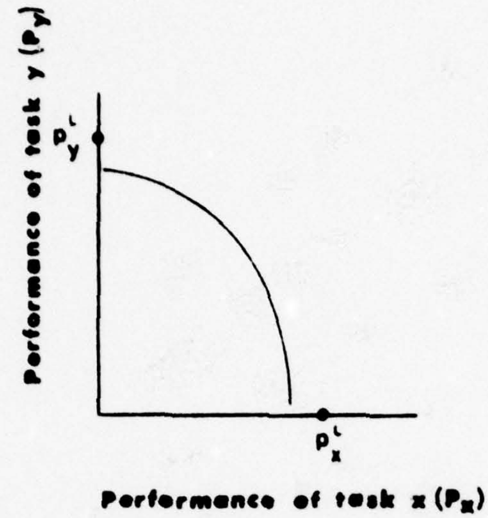
by the new one. We borrow from Kahneman (1973) the term structural interference to label this phenomenon, although we apply this name to a much narrower class of interference phenomena than he does. Indications about the existence of interference effects like these were found by Gopher & North, 26-A



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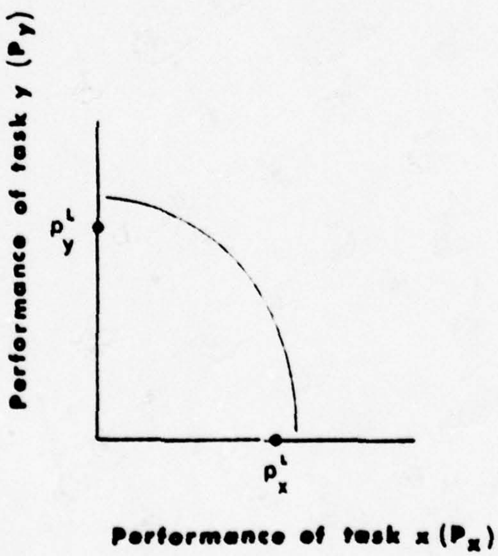

B

Fig. 5: Panel A presents a discontinuous POC exhibiting structural interference. Panel B presents a discontinuous POC exhibiting structural facilitation. In both cases P_x^L and P_y^L belong to the POC.

(Note 1), Sperling & Melchner (in press), Wickens & Gopher (in press), and others.

When D^*_{xy} is smaller than $D^*_x + D^*_y$, the POC will again be 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 5B). To be consistent we call this <u>structural facilitation</u>.

<u>No extra cost for concurrence</u> : One possible cause for structural interference is partial incompatibility of the tasks, i.e., the two tasks use the same resources but in different ways so that 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. Note that incompatibility is explained here not in terms of competition for a certain processing apparatus (see Kahneman, 1973), because D^*_x and D^*_y by definition include the demands for the capacity of all apparatuses, but rather in terms of opposed outputs or throughputs (for example, the conflicting activations or response tendencies created by the word and by the type color in a Stroop task; Stroop, 1935).

Another explanation for structural interference 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 one pays for trying to do much at once is a drop in total capacity available for what he is really interested in.

Finally, note that structural interference and capacity interference are not mutually exclusive. Processes may compete for the same resources and in addition require or create conditions which are harmful for each other.

A good review of findings that may be interpreted as structural interference as defined here is given in Kahneman (1973).

No symbiosis between tasks: Facilitation means that each task benefits from being conjoined with the other one. The mutual advantage may be due to symbiotic relationships, 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 aided by information gained by on-going processing of the others, as indicated by context effects (e.g., Meyer & Schvaneveldt, 1976; Tulving, Mandler & Baumal, 1964) and the word superiority effect (e.g., Johnston & McClelland, 1974; Reicher, 1969; Wheeler, 1970). Motor tasks may make use of feed-back information provided by concurrent perceptual tasks.

Facilitation 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.

Another possible account for facilitation is that sometimes joint processing is not temporal concatanation of two tasks but is rather done by a categorically different strategy which operates on the integral whole. One example from perception is the processing of stimuly varying on two dimensions which are called by Garner (1976) "integral dimensions", such as the location of points in the plane. In that case D^*_{xy} might have no connection with D^*_x and D^*_y.

So, in some situations part of the detrimental effect of the load imposed on the system by time-shared tasks is rebated by the merits of co-operation. An ordinary POC can be obtained only for strictly competitive tasks.

We have thus far tried to explain interference and facilitation in terms of demands. We now turn to discuss the possibility that the source of facilitation 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 (see Norman and Bobrow, 1975). However, as Kahneman (1973) and Welford (1968) suggest, capacity might be elastic to some extent. As we all know, 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 in curve 5 of Figure 1). It is less probable that imposition of a second task would act via increase in arousal to improve performance of the first task beyond its apparent single-task limit, as is illustrated in Figure 5B.

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 the stable level of what the system can supply in circumstances of heavy load, and not the occasional peaks which cannot be accounted for by any systematic factor.

While ackowledging the possibility of elastic capacity, we should add our reservations about its plausibility. Most empirical observations which may suggest that capacity grows with the increase of load can be accounted for within the view advanced in this paper in another way: A new task added on top of an old one is often able to capitalize on formerly unused resources due to the dissimilarities in the resource compositions of the two tasks. Thus, we can maintain the parsimonious assumption that capacity is fixed or at least independent of task load. The high arousal which typically accompanies heavy load may now be interpreted as reflecting the state of stress associated with increasing demand rather than as an increase in processing potential.

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 conscious). I.e., the system can select any combination of performance levels which does not overtax its capacity. There are many demonstrations of voluntary control of attention in certain time-sharing situations (e.g., in Gopher, Navon & Chillag, Note 3, Gopher and North, 1974; Kahneman, 1970, Sperling and Melchner, in press; Wickens & Gopher, in press). However, as noted by Kahneman (1973, p.100), by Schneider & Shiffrin (1977, p.2) and by others, not always the system is 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 which one cannot help processing and for activities one cannot avoid; e.g., 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), and in visual discrimination (Eriksen & Hoffman, 1973), processing of irrelevant dimensions in speeded classification tasks (Garner, 1974), inevitability of perceiving 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 for the control of the system the residual. The feasible possibilities of joint performance in such a situation are described by an incomplete POC of the type illustrated by the solid line labelled 8 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 <u>cannot</u> be worsened below P_x^o.

Because of the possibility that humans do not completely master their resources, we should distinguish between performance in a <u>single-task</u> 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 takes some resources away from the to-be-attended stimulus, then estimating the boundary condition of joint performance by means of telling a subject to process just one of two present stimuly or by presenting him just with that one may yield different results. When the first method is selected (as done, e.g., by Sperling & Melchner, in press), 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 & 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 non-target stimulus turned out to slow identification of the target). A performance decrement of this type is the cost of concurrence, thus may be considered as a sort of structural interference. It should be remembered, nonetheless, that such decrement may be due not only to mandatory processing but also to degradation in input quality, e.g., via lateral masking (Estes, 1972; Townsend, Taylor & Brown, 1971).

Distributability of Resources

The idea that resources can be allocated in many different ways relies on the assumption that resources are a continuous quantity (or a large number of homogeneous units) that can be divided in any portions. Otherwise, if they come in big chunks there are just few ways that they can be allotted to tasks. In that case, the POC will be a set of discrete points (see curve 7 in Figure 1). Interpolated points are not real, because resources are transferred between tasks in big chunks.

Complementarity of Supplies

In their analysis of POCs, Norman & Bobrow (1975) assume complete complementarity between processes which, translated to the terminology we use, probably means

$$S_x^* + X_y^* = X \cap Y \; . \tag{13}$$

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. Even if that is 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 & Bobrow (1975) present two principles, "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 (assuming that resources are distributable).

However, there may be some tasks which can be performed in one of several discrete levels. Some other tasks may not improve unless a treshhold amount of additional resources are available (as illustrated by Norman and Bobrow themselves in their Figure 1). In either case the POC will look like a step function (see curve 9 in Figure 1), because so are the performance-resource functions. Hence, not all available resources can always be utilized.

Compatibility of tasks: We have presented the idea that partial incompatibility of tasks makes simultaneous performance more difficult than predicted by considering 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. A more severe case is when 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 the tasks can only be performed in sequence (or in alternation if they take a long time). If one task does not exhaust the capacity, the excess resources will remain disused.

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 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 neither because they are useless nor because it does not want to, but because it does not know how. So the free resources will remain disused. The empirical POC which is square (see curve 1 in Figure 6A) is an underestimate of the potential

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Insert Figure 6 about here

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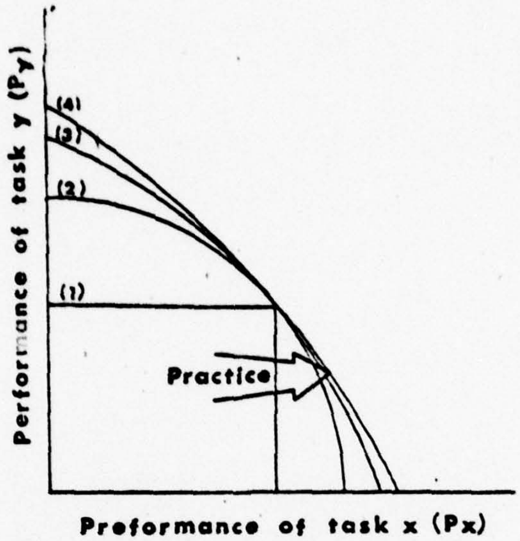
of the system had all resources been engaged. The system does not have full control on its resources, but this time not because it is pre-programmed to prefer one process in spite of any antagonistic deliberate intentions as is the case with mandatory processes; it is rather tuned to a certain mode of 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.

Practice with joint performance may make the two tasks more coordinable in the sense that the system learns how to utilize its resources more efficiently in all degrees of task emphases. As one gets more practiced, his POC becomes less bowed-out (see Figure 6A). An alternative 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 Figure 6B). Practice may also reduce the cost of organization in cases of partial incompatibility, so that more resources are left over for the tasks temselves and the POC gets higher. Of course, practice may have all three effects.

Note that knowledge about the source of task interference is important



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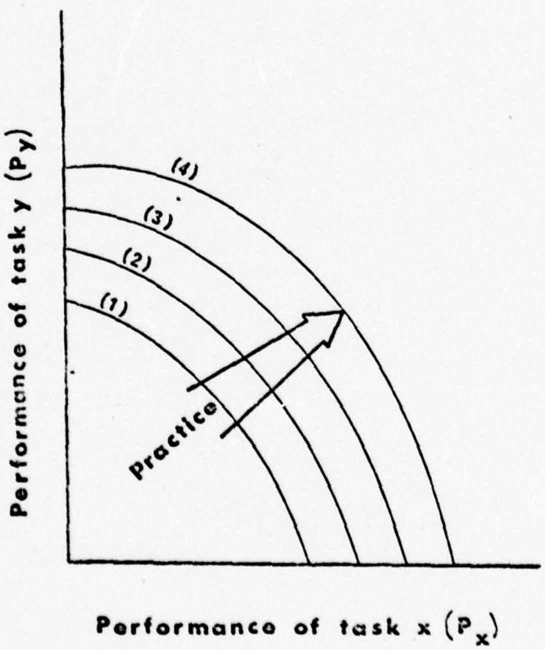

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Fig. 6: Illustrations for two possible effects of practice. Panel A presents improvement in the ability to allocate resources between the time-shared tasks. Panel B presents improvement in performing each individual task.

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 do. 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 is to eliminate or reduce the conflict by training the two tasks simultaneously. An interaction between different tasks and different schedules of training which is consistent with this analysis is reported by Gopher & North (in press).

Scarcity of common resources: One of the assumptions underlying analysis of POCs is that

$$D_x^* + D_y^* \geq X \cap Y \qquad (14)$$

i.e., the demand for common resources applied by the two tasks together is not met (or just barely met) by the capacity of the system. In Kahneman's words: "... supply is an increasingly insufficient response to demand" (Kahneman, 1973, 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. The general rule of joint supply may be:

$$S_x^* + S_y^* = \min \begin{cases} X \quad Y \\ D_x^* + D_y^{*\,5} \end{cases} . \qquad (15)$$

I.e., the system will offer not more than is required. But, why should it be satisfied with less than it can do in the first place? Why should the level of intended performance be modest with respect to the potential? In other words, in what circumstances will resources not be scarce?

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

Another case is when although both tasks make use of a common resource, they do not compete for it because it can be used by both tasks concurrently. Resources may be scarce if they are either consumable (such as processing energy whatever it is) or occupiable (such as memory space). However, there are durable and perfectly accessible resources, such as information (when there is no competition for communication channels). When the two tasks share such resources which are free for every process at any time, either of the tasks can be performed with no effect on the other one, as it is when they do not share any resource whatsoever. In this case a lack of trade-off results not because the tasks do not share resources, but rather because what they do share is not consumable or occupiable.

A third possibility is that the level of intended performance is externally controlled, namely imposed on the system by the nature of the task or the external standards of success. 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 when the level of intended performance is internally controlled, it will 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 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 will be mobilized. However, remembering that resources are just another name for "mental effort" (Kahneman, 1973), it is not unreasonable to assume that mental activities may involve some cost.[6]

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 quite safe to conclude that the value added by a unit of resources decreases as more resources are added while the cost is constant. Suppose utility is the difference between the value and the cost. Then, as can be seen in Figure 7, utility is maximized at the point R^{O} 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 its full capacity experimenters

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Insert Figure 7 about here

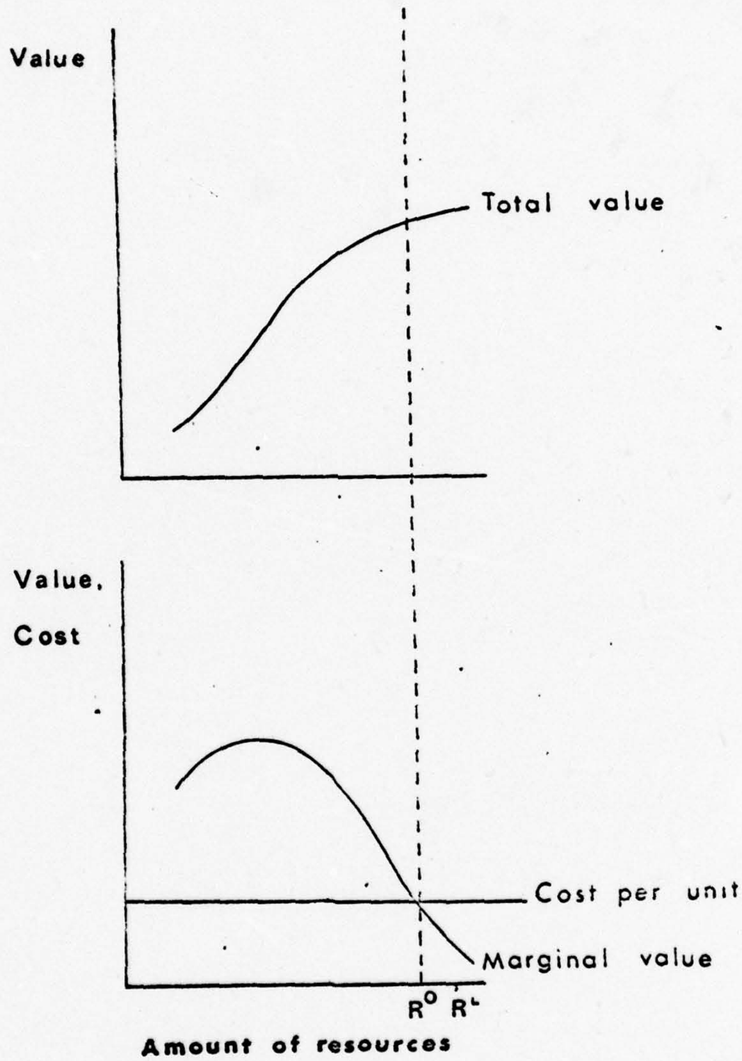

Fig. 7: Hypothetical functions associating total value, marginal value and marginal cost with the amount of resources.

should raise the value attributed to good performance by means of pay-offs, instructions, etc.

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 worse than the best that could be achieved. The empirical POC, whichever shape is may have, is determined by what the performer wants and not so much by what he is able to.

One could contend that there is no sense in assuming fixed capacity if the system hesitates whether to use all of it. 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 spends on various commodities in the market not all her assets but rather her allowance for the week food consumption. We suspect, however, that the top of joint performance is not so far from what is manifested in carefully devised experimental situations, so that the term of capacity is still useful.

Efficiency of resource usage: When the system does not utilize its resources judiciously, complementarity holds only technically: The POC describes operation at full capacity but not of full capability. The system may not be fully efficient because it is not aware of the effectiveness of the various resources. For example, it may invest more resources than the minimal amount 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.

Constancy of Demands

One basic assumption we, as well as 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". For instance, how would you classify 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 will tentatively postulate the understanding of the terms exhibited by this classification and discuss its implications.

As stated in (1) performance may be 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. It is reasonable that in parallel with the diminishing returns exhibited by performance-resource functions, a similar trend migh characterize the dependency of performance on any of the subject-task parameters. For example, the detection of a pure tone withing a background of noise is affected by the signal-to-noise ratio when it is relativel small; but once the signal-to-noise ratio is large enough, attenuation of the noise or increase in the level of the signal have little affect on performance.

Suppose the situation we study is within the region where 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 it is time-shared with; it can, of course, draw more resources from the limited pool of common resources. But it can also attempt to lower its demand at the expense of the demand of the other task. In this 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? The answer is that 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 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 pulpit. Now, the conjunction of the task of listening to the speeches and watching the gestures and mimicry of the speakers certainly do not overtax the human processing system (especially given the high redundancy in rally speeches). However, if the lawn is really large and the auditory signal-to-noise ratio is low, one may find himself facing the dilemma whether to get closer to the pulpit 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 demands as usually POCs are believed to do, but rather presents all different outcomes of competition for input quality. One may not change the division of his attention between watching and listening still 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 a lot of more typical dual-task situations in which there is some structural interference. 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 he is asked to do the same thing after being told at which of the two locations the flash will appear. Nobody would probably 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 ensured that the subject fixates all the time at the same point, this explanation seems to be the only plausible one (Posner, Nissen and Ogden, Note 4). However, when the subject can move his 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 for the flexibility which 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. vizual 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 via 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 at the control of the system, at least partly. But this creates a severe problem of interpretation. When the performance of a task deteriorated, is it because it now <u>gets less</u> resources or because it now <u>requires more</u>? At the present state of the art, answering this question seems as impracticable as would be a solution to the problem of whether a person is hungrier than another one because he gets less food or because he needs more, had we not possessed independent measures for need and supply of food.

One way out of this impasse seems to admit that as yet we do not have the acid test for separating between supply and demand, and to abandon that interpretation of the concepts of resources and subject-task parameters which was postulated for the discussion in this section. The alternative for 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 degrees 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 previous authors. Resources may include even such things as visual resolution, number of extracted features, quality of retrieved codes, etc., provided that those can be manipulated by the system within the constraints of the situation.

In sum, this interpretation of the subject-task parameters — resources confrontation regards it as a distinction between what is imposed on the system on the 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 in dual-task situations 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 on the one hand and the control on the properties of the input flowing to them on the other hand. The first kind (which may be called processing resources) corresponds to our intuitive notion of what attention is. The latter (which may be called input resources), represents the flexibility the performer has with regard to what is to be operated on. Both kinds of resources are limited: Processing resources are limited by the capacities of the various processing devices. 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 presently very difficult to operationalize. So, we offer these two approaches with no commitment to either of them. Different readers may foster one or the other according to their intellectual taste or scientific doctrines.

POC Analysis: A Summary and some Demonstrations

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 depends on what can be assumed about the nine points discussed above.

A POC can be held to reflect competition for resources (or what has been traditionally considered as resources) only if demands are believed to be constant. An empirical POC can give us an idea of the capacity of the system only if we assume 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, complementary 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 and/or not distributable. Finally, nonadditivity of demands may result in either superiority or inferiority of dual-task situations over corresponding single-task ones.

We propose here a framework withing which empirical data can be collected and interpreted. We would like to have been able to demonstrate its potential by applying it on existing data. However, as already noted by Norman & Bobrow (1976), there are very few instances in the literature of reporting POCs or results from which a POC can be recovered. The problem is that experimenters usually do not manipulate allocation of resources via varying task preferences as should be done to obtain a POC. The most relevant studies that we know of are those of Gopher & North (Note 1), Gopher, Navon and Chillag (Note 3), and Sperling & Melchner (in press). Let us now use data from two of these studies to demonstrate POC analysis.

Sperling and Melchner (in press) 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 of two different arrays that were presented simultaneously, one at the central part of the display and one surrounding it (see stimuli in Figure 8). Subjects were asked to report the identity and location of the target once it was detected.

Insert Figure 8 about here

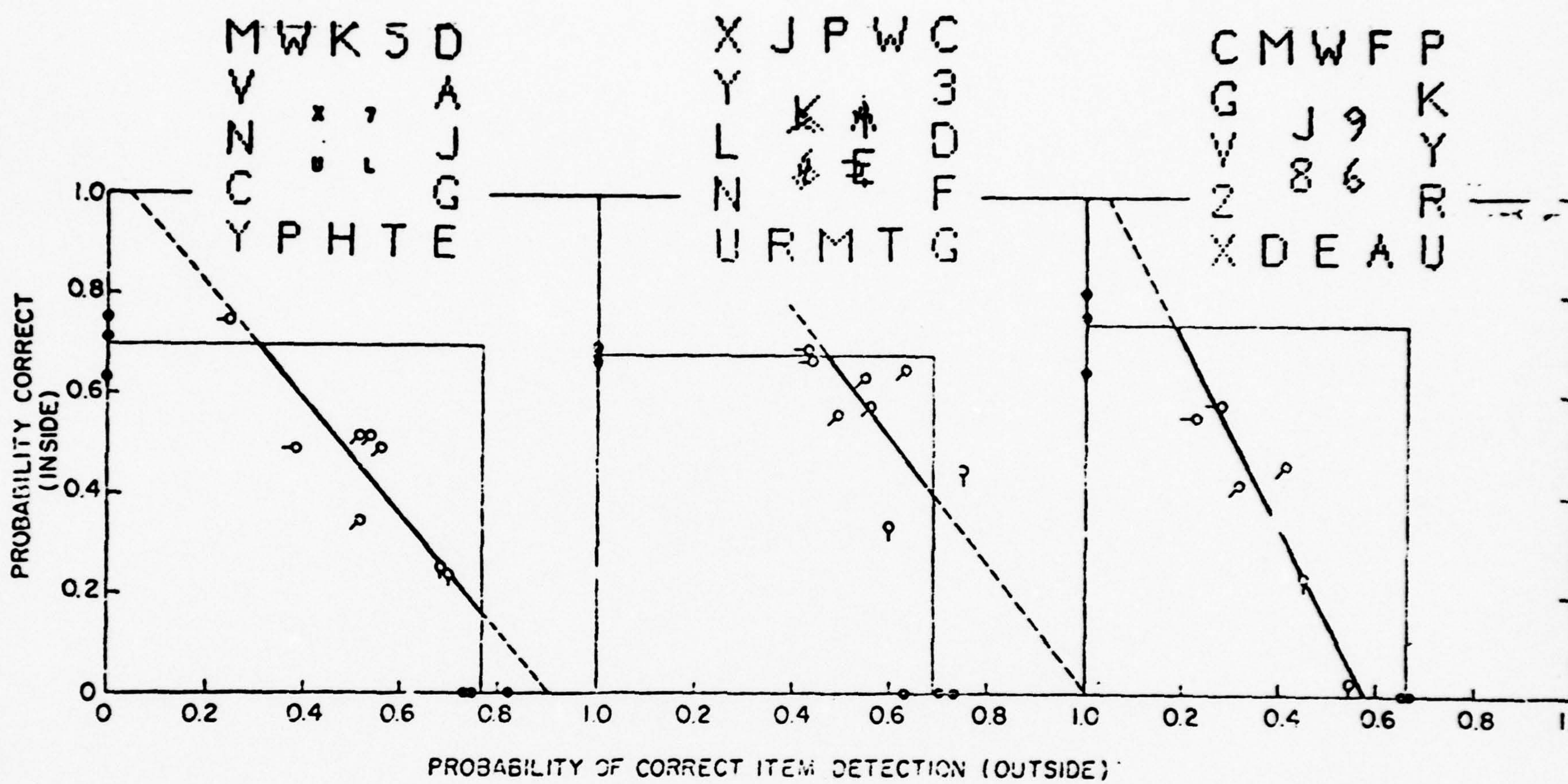

Fig. 8: Data from divided attention experiments reported in Sperling and Melchner (in press). Each open circle represents data from one block of 30 to 60 trials (report of both targets); each filled circle represents data from a control session (report of only the designated class of targets). The direction of the "tail" on a data point represents the attention instruction: down indicates "give 90 percent of your attention to the outer array", left indicates "90 percent to inner array", diagonal indicates "equal attention". The vertical and horizontal lines are best-fits to the multiple detection data (from Sperling & Melchner, in press).

They were instructed to divide their attention in varying proportions between the two arrays. In this way Sperling & Melchner obtained the POC curves (which they call Attention Operating Characteristics) in Figure 8. Although Sperling & Melchner elected to fit their data from three conditions of divided attention by a straight diagonal line, it is fairly evident that if one added the data from the focused attention conditions lying on the axes, the resulting POCs would look concave to variable degrees.

What can be learnt from these results in the light of our discussion of POC analysis? First, the two tasks use some common resources. Second, those resources are distributable. Third, they are also controllable, at least in a gross manner, which is evident by the ability of subjects to follow instructions to divide their attention in variable proportions. Four, the decrement in performance of one task accompanying an improvement of the other one is consistent with the assumption of complementarity of supplies, namely that the experimental manipulation have managed to force subjects to scrape the ceiling of their capacity.

Given these conclusions we can now turn to discuss the effect of the nature of the paired tasks. As can be seen in Figure 8, the search task in the outer array was always the same, searching for a target numeral on the background of large letters; however, in different conditions it was paired with different types of inner array composed of either small characters or visually degraded large characters or large characters for which the task was reversed (searching for a letter on the background of numerals). The trade-off relationships of the search task in the outer array with the different tasks in the inner array turned out to differ. For example, normal characters, large or small, interfered with it more than degraded characters did. Is it because searching normal characters is simply more demanding than searching degraded characters? Probably not, since their levels of single-task performance were about equal. Thus, the source of the difference probably resides in the nature of the tasks. The dissimilarity in POCs may have resulted from the difference in amount of overlap of demand compositions in the two conditions: Searching degraded characters presumably requires cognitive efforts to extract a familiar pattern out of the noise within which it is embedded,which may be different from recognition processes needed for searching normal characters, large or small. Thus allocating 90 percent of the common resources to the outer array leaves to the inner array a small share of what it demands in case all it demands is common (as presumably is the case with the normal characters) but a larger share in case it depends also on resources not used by the "outside" task (as presumably is the case with the degraded characters). That explains, for example, why 10 percent attention are sufficient to set the probability of identifying the target at .40 when paid to degraded characters but only at .25 when paid to small ones.

Another interesting issue that will be just briefly mentioned is whether attention is distributed in space or sways between tasks over time. It is possible that the task of searching small characters is completely incompatible with searching large ones in that both tasks not only demand the same mechanism but also cannot use it at the same time. Hence, because both tasks cannot be performed in parallel, they are alternated. Sperling and Melchner found a negative correlation across trials between identification of the two targets when displayed simultaneously, a finding which lends support to this hypothesis.

Data from the third condition (reversed tasks) appear to exhibit structural interference, at least in one direction, on top of the capacity interference discussed previously. Paying 10 percent of the attention to the inner array seems to help performance at the center very little but disrupts considerably performance at the outer array as compared with the case in which the latter is focused at exclusively. This is not surprising in view of the fact that the two tasks in this condition are diametrically opposed: A stimulus which is supposed to trigger identification in one task should inhibit it in the other one.

So far for the results of Sperling & Melchner. Let us inspect now POCs from another source.

It follows from our theoretical discussion 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. Experimental manipulations that appear to meet this requirement were done by Gopher, Navon & Chillag (Note 3). They 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 frequency of the target movement, and controlled relative emphases on the two dimensions by varying the ratio of tolerance levels for error in each.

As expected, they found that POCs of different difficulty levels were similar in shape but not in their location. Surprisingly, performance was not monotonous in difficulty in all cases. This phenomenon appears embarrassing for the fixed capacity hypothesis, but it may also be due to factors like motivation, boredom, etc.

A conspicuous property of the POCs presented by Gopher, Navon and Chillag is their strong curvature. It is impossible to discuss here in detail conceivable causes for the limited trade-off reflected by those POCs, because this would necessitate much more knowledge about the procedure and design of the experiment. Suffice it to mention the two most plausible explanations. One, the most stringent tolerance level set by the experimenters was not possible regardless of how large the amount of resources invested (namely, it was beyond what Norman & Bobrow, 1975, call "data-limit"). In other words the tasks do not manifest large interference because performance is relatively insensitive to amount of resources. Alternatively, perhaps despite the apparent similarity of the two tasks their demand compositions were fairly disjoint. Thus, although performance may on the whole be sensitive to amount of resources, it does not depend very much on the <u>specific</u> kinds of resources taken or released by the competing task. This conclusion does not seem so provocative on second thought if we remember that one uses different muscles and efferent pathways to move the hand controller vertically and horizontally. However, if these two tasks are not similar enough to call for exactly the same resources, then it may be a formidable problem to find two tasks which are that similar and yield perfect trade-off.

Finally, it is instructive to inspect an empirical curve which with respect to the concept of a POC constitutes what Winston (1973) calls "a near miss". In other words, it is actually not a POC although it resembles it. Kalsbeek & Sykes (1967) paired a primary task of responding to lights appearing in succession with a secondary task of responding to tones. They varied the rate of light presentation and plotted secondary task performance as a function relating performance of one task to the difficulty of a competing one. However, since the actual rates used by Kalsbeek & Sykes for each subject were percentages of the maximal rate that could be handled by him or her with no errors in a single-task situation, they labelled the axis representing those levels of difficulty as "performance on the primary task". Since the other axis is rightfully labelled as "performance on the secondary task", the curve obtained might look like a POC. However, it is not a real POC, because actual primary task performance in the dual-task situation may not correspond to the percentages of maximal rate handled in a single-task situation. Moreover, subjects may have worked below full capacity when the primary task was easy. That this was indeed the case is indicated by the fact that total performance on both tasks improved as primary task was made more difficult.

The lesson is that to get a POC one should fix subject-task parameters for both tasks, allow the subjects maximal control over quality of performance for both, and induce them to change the relative emphases on the tasks.

Discussion

We propose a conceptual framework, a methodology and a model. We feel that the nomenclature we introduce is coherent and complete in that it covers many aspects of performance and factors which bear on it. But it is difficult to argue for a set of concepts and it is even more difficult to convert people to a new one. Conceptual frameworks can be judged only in retrospect as to how fruitful they have proved to be and how much they have helped people to communicate and to organize their thinking. We have already discussed and demonstrated the proposed procedures for analyzing empirical data. So let us concentrate now on the substance of the theoretical suggestions we make.

We consider the advancement of the idea of multiple resources to be one of the main messages of this paper. Let us take another look at it on the background of previous approaches.

Kahneman 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" (1973, p.11). The model we delineate is on the one hand structural in the sense that it identifies the limit on performance with the availability of various processing mechanisms, and ascribes task interference to the overlap in engaged mechanisms. But it is also a capacity model, 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 models seems to be successful, because neither one in itself is able to account for all known phenomena of interference.

Empirical Evidence

Various arguments can be raised against the single central capacity notion. Kantowitz & Knight (1976) derive from it the prediction that while 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 very little, if any, decrement as a result of such manipulations, because "the demands imposed by primary and secondary tasks together do not exceed available channel capacity..." (Kantowitz & Knight, 1976, p. 344). They interpret failures to find such an interaction in some studies, including their own, as an embarrassment for strict models of single capacity. However, unfortunate for our view of the human processing system which is similar in this respect to that proposed by Kantowitz & Knight, we regard their evidence as insufficient. First, an observed additivity of the effects of difficulty levels of the two tasks may be due to a failure of the experimental situation to satisfy the condition Knatowitz & Knight themselves set for the prediction to bear out (see above quotation). Second, as Lane (Note 5) points out, the existence of interaction of the sort Kantowitz and Knight consider as a necessary condition for central capacity depends on the shape of the function relating performance to task difficulty and available resources and the particular choice of difficulty levels of each task.

It seems much more difficult, however, to reconcile models of central capacity with another sort of findings reported by Kantowitz and his associates. They have located some pairs of tasks for which although the performance of one of them may deteriorate when conjoined with an easy level of the other one, it does not deteriorate further when the other one is made more difficult (Kantowitz & Knight, 1976; Roediger, Knight & Kantowitz, 1977). A physiological observation of great relevance is the finding of Wickens, Israel & Donchin (1977) that the amplitude of the P-300 component of the evoked potential corresponding to a task of counting auditory tones dropped equally with the addition of either single-axis tracking or more difficult dual-axis tracking. If the difficulty of a task affects single-task performance but fails to affect the performance of another task it is time-shared with (given that its own performance is maintained at a constant level), then the two tasks cannot depend on the same capacity.

The central capacity notion cannot withstand the finding that sometimes while 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 (1967) 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 & Thomson (1975) reported that performance in a pursuit rotor task deteriorated when paired with Brooks' visual recall task but not when paired with his verbal recall task. Unfortunately, they did not use a control that would rule out the possibility that Brooks' visual task is simply more difficult than his verbal task, although it seems implausible in view of Brooks' own data. A similar result that can also be criticized in a similar way is the finding that auditory presentation of a word to be remembered impairs shadowing of a message played to 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 non-verbal concurrent tasks such as picture encoding or playing piano music from a score. Treisman & 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 6) in his doctoral dissertation. North asked subjects to perform the four tasks listed at the left-most column of Table 2 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

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Insert Table 2 about here

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presented in Table 2. 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 cancelling performance. Similar results have been obtained by Sverko (Note 7) with another set of tasks.

Table 1

Illustrations for six types of relationships between optimal resource compositions of two tasks. Each entry shows the relative number of units of the column type of resource required to perform the row task. A zero means that the column type of resource is completely irrelevant for the row task, even when composition of resources is suboptimal. A double line separates resources used by both tasks from the rest. A triple line separates resources that are not used by either of the tasks from the rest.

Resource Type

Case	Task	R^1	R^2	R^3	R^4
I	x	1	2	0	5
	y	2	1	5	0
II	x	1	2	0	0
	y	2	1	0	0
III	x	2	1	0	0
	y	2	1	0	0
IV	x	1	0	5	0
	y	1	5	0	0
V	x	1	0	0	0
	y	1	0	0	0
VI	x	1	0	0	0
	y	0	1	0	0

Hence, there seem to exist various components which different processes share to variable degrees. This conclusion appears to warrant the idea that a major source of conflict between tasks is structural, a claim that was advocated by Allport, Antonis & Reynolds (1972). However, a strict structural model seems inadequate once we realize that processes which use the same mechanisms sometimes interfere with each other but they seldom block each other completely. For example, when input and response are in the same modality, as in Brooks' 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 & Davies (1973). Thus, the same type of argument that made previous authors abandon the view of the central processor as a single channel and conceive of it as a single pool of resources leads us to reject the idea of multiple channels or mechanisms in favor of the notion of multiple resources (see Table 3): Not only the processing system as a whole can be involved in several activities in variable proportions; also a specific mechanism or modality is not necessarily dominated by one process exclusively but can rather accommodate more than one process at the expense of quality or speed of performance.

Insert Table 3 about here

North's results presented in Table 2 provide additional support for this idea. Tracking performance is most impaired by a competing tracking

Table 2

Performance of tracking and immediate digit cancelling as a function of the type of the concurrent task (adapted from North, Note 4).

	Criterion Task	
Concurrent Task	Tracking[1]	Immediate Digit Cancelling[2]
Tracking	29.9	.93
Immediate Digit Cancelling	24.3	1.50
Digit Classification	20.8	1.87
Delayed Digit Cancelling	23.1	2.44

1. Performance measured in root mean square error.

2. Performance measured in average time between correct responses.

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 concelling task was differentially sensitive to the three digit tasks. This result can be explained if we assume that the digit tasks, which are similar in physical structure, temporal organization and nature of input, demand different amounts of a certain type of resource which is not used at all by the tracking task, but they demand the same amount of another type of resource which 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.

And finally, recall the POCs plotted by Sperling & Melchner (in press) which suggest that although different structures may be competed for by different task pairs, those structures can be shared in various proportions depending on instructions.

The notion of multiple resources is parsimonious in that it does not partition the universe of task pairs into those which are structurally incompatible and those which interfere just because the limited attention of the central processor has to split between them. Task pairs of the former sort are considered in our view to just have more types of required resources in common than task pairs of the latter sort have in common. Thus, they do not exhibit structural interference of the sort illustrated in Figure 5A. This is in contrast with a prediction which 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 heavier load on the central pool. Which of the two predictions will be born out is yet to be shown.

Serial vs. Parallel Processing

While our approach can account for findings which have served to support serial stage models of information processing (e.g., Sternberg, 1969), or hybrid parallel-serial models (Kantowitz & Knight, 1974, 1976), it by no means requires that we assume seriality 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 thus tend to coincide in time (cf. Kantowitz & Knight, 1974), but rather because their demands for capacities of specific mechanisms (operating in parallel or in sequence) are similar.

Note that we have deliberately neglected in this paper the temporal dimension of processing. Time-shared tasks can theoretically 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 usage of any specific processing unit or storage device may be shared between tasks and that may mean either that it accommodates the tasks at the same time or that it serves each of them at a different time. So theoretically it may happen that unit a is engaged simultaneously by tasks x and y, while unit b is used first by task x and then by task y, whereas unit c is used first by task y and only then by task x. Thus, resource allocation may not be just a problem of efficient budgeting but rather an intricate problem of scheduling and coordination further complicated by constraints which are due to dependence of some units on the output of other ones. The static economic metaphor may, thus, have to be replaced by a more dynamic one that involves continual change in the use processes make of various processing facilities. But we feel that this objective falls beyond the scope of this paper.

Automatic Processes

Some psychological processes appear at a first glance to defy the law of scarcity which seems to prevail in economic systems, namely, they do not seem to interfere with each other (see, e.g., Posner & Boies, 1971; Posner & Klein, 1973; Schneider & Shiffrin, 1977; Shiffrin & Gardner, 1972). This led several scholars (e.g., Keele, 1973; Posner & Snyder, 1975; Shiffrin, 1975; Shiffrin & Schneider, 1977) to assume that part of human information processing, especially some tasks involved with perception and access to long-term memory, is automatic. Neisser (1967) also argues that some early perceptual processes are executed "preattentively", 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 the sections "Controllability of Resources" and "Compatibility of tasks". A stronger claim about automatic processes is that they do not require attention (or more generally, any limited processing power) at all. The latter is a possibility which one ought to consider seriously, and if it is true then the domain of processes with which this paper deals, namely processes which do demand resources, is just a subset of all processes.

An alternative view is that those processes which appear to be free (i.e.,demand no resources) are in fact just cheap. In other words, when a task requires a very small amount of resources in order 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 and/or sensitivity of measurement. That this might be the case is indicated by recent findings of Becker (in press).

Another possible explanation for lack of interference interpreted to indicate automaticity, is that processes which do not interfere do require resources yet different types of them; namely they call for devices or channels, which are completely independent (or for parts of the same channel which 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 kind 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 are enumerated above in the section "Scarcity of resources".

Implications for Research

The idea of multiple resources have 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. 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 very fruitful to search for a single objective measure and/or a single behavioral or physiological correlate for mental load.

Out of 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 8). And indeed, lately Sverko (Note 7) 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 rather several of them. People may differ in their specific capacities as well as in their specific abilities to time-share each of them.

If we accept the approach of multiple resources, a more meaningful objective emerges: to find out what types of resources exist and to map out demand compositions of different tasks by pairing each of them with each of the other ones. If the range of tasks used is diverse enough, every type of resources 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 multidimensional scaling a resource space as well as the demand vectors associated with each of the tasks. This is an extensive project which we have ventured to undertake and will hopefully be completed in several years.

Our general recommendation for studies of time-sharing performance follows a comment made by Sperling & Melchner (in press):

> "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.)"

We agree and add the following: Out of the same reason one cannot study the effect of difficulty of tasks by just one condition of attention. 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 set 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). We believe that this will help to clarify the sources of task interference, and will serve to base much work in the field on common terms.

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FOOTNOTES

2. By this we do not mean that all the aspects of the output of the system have an all-or-none nature in themselves. Norman & Bobrow point out that generally performance degrades "gracefully" when the system becomes overloaded (1975), and that while 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 aspect(s) of performance.

3. Note that by (2) and the definition of the level of intended performance, when there exists an asymptotic level of performance, the demand for resources cannot exceed the amount required to reach that level.

4. Note that $\Delta P_y/\Delta P_x$ is in turn a function of the performance functions of both tasks, because it is obtained by dividing the derivative of performance of y with respect to resources ($\Delta P_y/\Delta R$) by the corresponding derivative of x performance ($\Delta P_x/\Delta R$), subject to the condition that $R_x + R_y = R^L$.

5. For reasons of simplicity of notation, we neglect here the possibility that demands are not additive. It is simple to generalize the principle of complementarity for cases of nonadditive demands as well.

6. Note that our use of the term "cost" is different than the use made by Posner and his associates (see, e.g., Posner & Snyder, 1975, 1975a). They consider the cost of a process to be the loss incurred by investing resources in it of what could have been gained had those resources been devoted to an alternative task (roughly what we earlier called: opportunity cost). We refer by this term not to the inability to realize benefits of alternative activities but rather to the real cost (say "mental energy" consumption).

7. It is not necessary, although convenient, to assume an additive function. Coombs & Avrunin (1977) define a class of composition rules (called proper preference functions) that would yield the effect described below.

Appendix A

A perfect trade-off between performance of two tasks is represented by a linear POC (as in Figure 9A). There are two principal ways by which trade-off

Insert Figure 9 about here

may be limited. One, trade-off may be confined to a certain region of joint performance and not exist in others (as in Figures 9B and 9D). Two, when trade-off exists it may be imperfect in the sense that the performer is rewarded less and less in terms of quality of performance of one task for degrading performance of the other one (as in Figure 9C and the middle part of the curve in Figure 9D). To characterize a POC in a precise way from these two aspects we propose the following measures:

Width of trade-off (WTO) reflects the relative span of the region of joint performance in which some trade-off exists out of the total range of joint performance. Let α denote the angle (in degrees) enclosed between the two rays extending from the origin to the two extreme points of the segment of a POC with a positive finite slope. Then WTO is defined as $\alpha/90$. It assumes the value 1 when some trade-off exists throughout the POC (e.g., Figures 9A and 9C). It assumes a value between 0 and 1 when the trade-off is confined only to a certain range (e.g. Figures 9B and 9D) and it assumes the value 0 when there is no trade-off at all, namely the POC is square.

Depth of trade-off (DTO) corresponds to the *amount* of trade-off when it exists which is reflected in the degree of curvature of the POC. Since this may vary for different parts of a POC, DTO need not be a single measure but rather may characterize a given part of a POC as well as the POC as a whole.

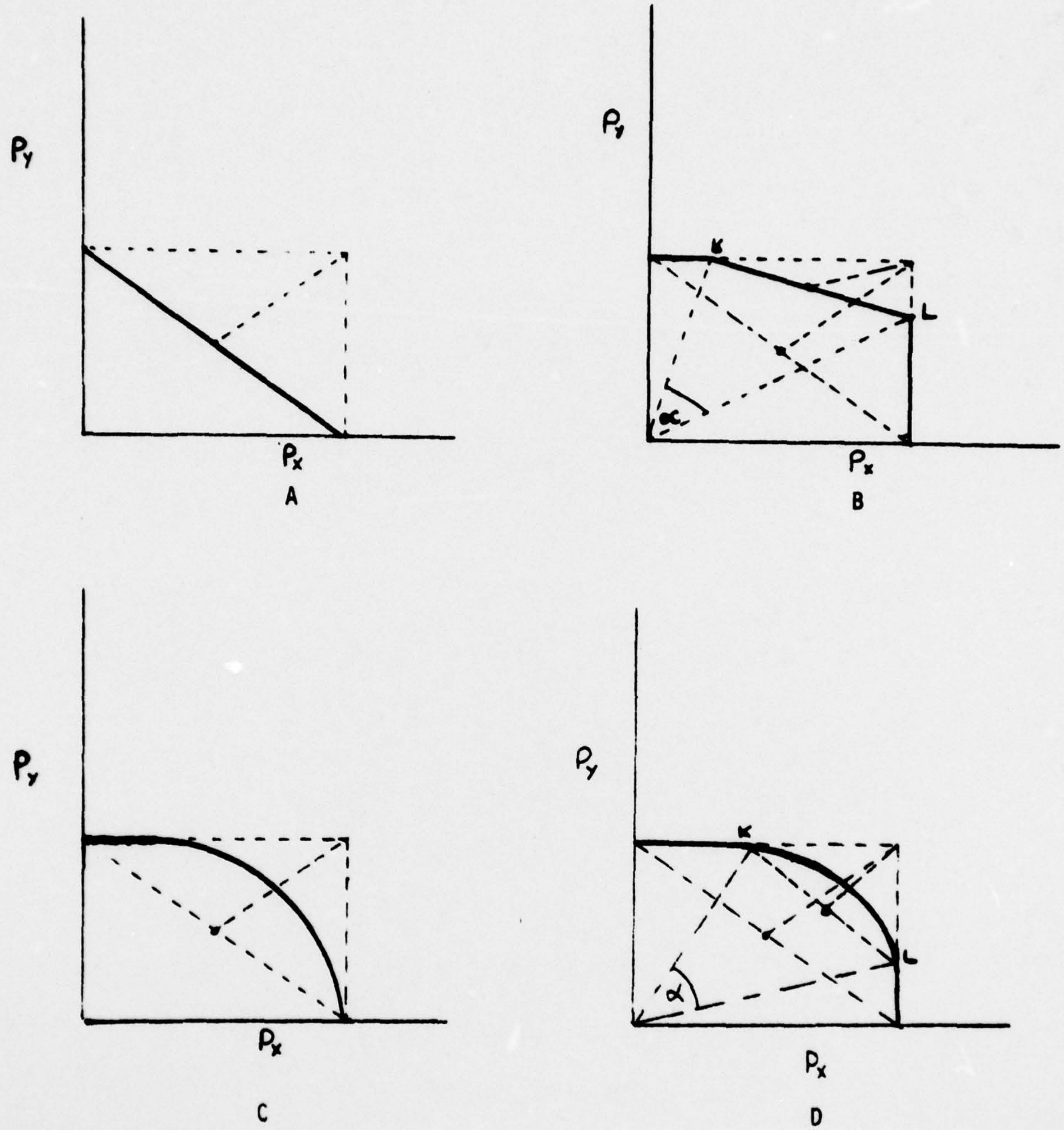

Fig. 9: Four hypothetical POC curves. Panel A presents perfect trad-off. Panel B presents a narrow but maximally deep trade-off. Panel C presents a shallowy but maximally wide trade-off. Panel D presents a narrow and shallow trade-off. See text for further explanations.

If we could obtain continuous smooth POCs. then the natural measure for curvature of a part of them would be the second derivative in case it is constant in that region, and in case it is not - the rate of change in slope (first derivative) between the two extreme points: However, since most of the time data about local slopes of a POC may be missing or not very reliable, we propose a simple geometrical procedure for estimating the depth of trade-off of a given part: Suppose the two extreme points of that part are given by the coordinates (x_1, y_2) and (x_2, y_1). Connect them by a straight line segment and find its midpoint (namely the points with coordinates (x_1+x_2) and $(y_1+y_2)/2.$) Now connect this midpoint to the point (x_2, y_2) by a straight line segment. This line segment will intersect the POC at a certain distance from the point (x_2, y_2). The ratio between this distance and the total length of the line segment defines the DTO for that part of the POC. When the part is linear, DTO equals 1 (see Figures 9A and 9B). When the part is square, DTO equals 0. When the part is curved to some degree, DTO assumes a value between 0 and 1 depending on the degree of curvature (see Figures 9C and 9D).

Note that if the curvature of the POC is not uniform over all its parts, DTO will assume different values in different regions. Moreover, in that case the value of DTO for a given part may be different from (typically greater than) the value of DTO computed for a longer part which subsumes the former one (or for the POC as a whole). In that case the two values should be interpreted as representing two different properties of the POC. For example, the DTO value of the part KL in Figure 9B is 1 which means that when trade-off exists it is perfect. However, the DTO value for the whole curve in Figure 9B is smaller than 1, which indicates that joint performance is better than an additive mixture of the two single-task performance levels.

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20. Abstract

An approach to human performance which is based on economic concepts is proposed. This approach hinges on the idea that the human processing system has a number of mechanisms each having its own capacity. Those capacities can at any moment be allocated among several processes. Since tasks may differ with respect to the types of mechanisms they call for and the demands they pose for the use of those mechanisms, it is argued that the hope to find single measures for system capacity and mental load may be groundless. Different pairs of time - shared tasks may conflict with each other to a variable degree, which is difficult to predict without knowing the overlap in their demand for various mechanisms. The amount and specific nature of trade-off between time-shared tasks can be displayed by means of performance operating characteristics. The effects of a number of properties of the system and of

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the tasks on the shape and interpretation of performance operating characteristics are discussed. The analysis in this paper also serves to elucidate the notion of resources brought forward by previous authors, to elaborate on the distinction between demand for and supply of resources, to discuss possible interactions between the effects of supply of resources and situation parameters on performance, and to conjecture about the way by which allocation policy depends on the value of outcomes of different allocations. Finally, relevant empirical evidence and implications for further research are discussed.