RESOURCE ALLOCATION IN CEREBRAL SPECIALIZATION

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In this paper, we develop a broad and cohesive theoretical framework from which to understand how cerebral specialization of function contributes to the adaptivity and flexibility of the human information processing system. In particular, we propose that the anatomical division of the brain can be mapped onto a division of processing resources so that the left and right hemispheres together comprise a system in which there are two pools of mutually inaccessible, finite, resources. Further, these two types of resources cannot be made

available in different amounts for a normal individual whose callosum is intact. Thus, the framework we propose is essentially a special case of a multiple-resources model of limited-capacity information processing (Navon & Gopher, 1979), in which we tie the existence and number of resource pools to the anatomical structure of the brain. Our theoretical structure allows us to account for a broad range of data from both the divided attention and cerebral specialization literatures, including experiments involving perceptual and cognitive information processing, control of motor performance, and changes in the electrical activity of the brain. The framework also provides insights into specific mechanisms that could account for why the cerebral specialization literature has been plagued with the sort of problems that have made theorizing in this domain difficult, such as the ease with which stimulus, instructional, and other task manipulations can change performance advantages from one to the other visual field, ear or hand; the difficulty of replicating data across laboratories and paradigms; and the wide range of within- and between-subjects individual differences usually observed on indices of cerebral specialization. In addition, the theory provides insights into mechanisms that might be responsible for patterns of task interference observed in the divided attention literature that are not easily accounted for by a limited-capacity model in which there is only a single pool of undifferentiated resources. Thus, the framework we are proposing has important theoretical and methodological implications for researchers in both the divided attention and cerebral specialization domains, and demonstrates the mutual need for these investigators to be aware of each other's work.

INTRODUCTION

Evidence from several disciplines suggests that the human brain is not bilaterally symmetrical with respect to either structure or function. The left hemisphere is typically described as the language hemisphere, and is alleged to be specialized for serial or analytic processing, while the right hemisphere is characterized as essentially mute and specialized for processing nonverbal information holistically. Evidence for this dichotomy derives from anatomical, physiological, and behavioral studies that have used both normal subjects and clinical populations such as "split-brain" patients and aphasics. However, despite the volume of available data, most previous research in this area can be characterized as little more than empirical demonstrations of either tasks or sets of stimulus materials that either do or do not appear to be "lateralized" for the particular individuals studied. In fact, it could be argued that the most frequent findings to emerge in well over 100 years of research are (a) the apparent capriciousness of the phenomena; that is, the ease with which relatively superficial changes of stimulus, instructional, and task parameters can readily switch a performance advantage from one to the other hemisphere, (b) the large amount of data that defy replication across laboratories and paradigms, (c) the wide range of individual performance differences observed on tasks that are supposed to be lateralized one way or another, even among populations suspected to be relatively homogeneous on this variable, such as right-handed males, (d) the lack of consistency within individuals in the degree of lateralization they show across time and tasks, and finally, (e) the absence of a global theory that can adequately explain the factors underlying even the existing regularities that have been observed.

In the present paper, we will demonstrate that an existing, well-formulated conceptualization of human information processing that views the brain in terms of multiple pools of resources, that is expressly equipped to embrace individual differences in performance, and that has a specific, well-developed methodology by which it can be tested, can be extended to the field of cerebral specialization to provide a framework from which much existing data can be better understood. Very simply, we will view the two cerebral hemispheres as separate and mutually inaccessible pools of finite resources that cannot be made available in different amounts at any particular point in time for a normal individual whose callosum is intact. The historical antecedents of our approach were developed by Kahneman (1973), Norman and Bobrow (1975), and others, in the context of an information processing framework that views the organism as having a single, undifferentiated pool of finite resources. This single-capacity model has been recently elaborated and extended by Navon and Gopher (1979) to allow for the possibility that there exist multiple pools of resources, and it is a subset of this multiple-resources approach that will be adopted throughout this paper.

In order to show how a multiple-resources framework may be both theoretically and methodologically relevant to the field of cerebral specialization, it will be necessary to proceed through several stages. We will first briefly review some of the other current models of the mechanisms responsible for the phenomena of cerebral specialization. Then, we will give an overview of both the single and multiple-resource models in which we will introduce and define the concepts they employ and discuss the methodological issues involved in testing theories of this sort. After we have discussed these background issues, we will analyze the results of a number of experiments from the cerebral specialization and divided attention literatures which have used diverse paradigms and dependent measures, in order to show that the data from these experiments can be most parsimoniously understood by considering a limited case of a multiple-resources approach in which there are only two types of resources--those deriving from the left and right hemispheres. Not only can these experiments be better understood and integrated from our framework than they can from any other currently existing view of cerebral specialization, but there are many respects in which the data from these experiments provide stronger support for the multiple-resources approach in general than do any of the data cited by Navon and Gopher (1979).

Current approaches to cerebral specialization. A number of different models have been used to try to explain the factors underlying cerebral specialization of function. The oldest and most popular involves the use of a primarily descriptive framework based upon the notion of direct access. This approach assumes that (a) the two cerebral hemispheres are differentially specialized; that is, they have different capabilities for processing certain types of information, and (b) the behavioral differences observed under conditions of, for example, visual half field presentations or dichotic listening, result from the fact that these task environments allow one or the other hemisphere to have more direct access, through anatomical pathways, to the stimuli that are to be processed for any particular task. Direct access of "hemisphere appropriate" stimuli is thus assumed to confer an advantage in either speed of processing or accuracy of processing or both. That is, according to this model, if a stimulus initially arrives at the "wrong" hemisphere, it must be transferred across the callosum for processing, which could result in a loss of quality and/or a loss of time. Within this approach, there are different opinions as to what the left and right hemispheres may be specialized for (e.g., verbal vs. pictorial material, analytic vs. holistic tasks, emotional vs. nonemotional stimuli, etc.), so that this class of "theorizing" has generated a large body of literature in an effort to understand the types of abilities and/or tasks and/or stimuli for which each hemisphere is better suited. However, the approach is difficult to reconcile with the individual differences that have been observed on indices of cerebral specialization (e.g., it cannot explain why all right-handed individuals do not demonstrate a comparable visual field advantage on a "left-hemisphere" task). In addition, an approach that specifies a strict dichotomy of function between the hemispheres has difficulty accommodating the ability of stimulus, instructional, and other subject and task manipulations to readily change performance advantages from one to the other hemisphere within individuals (e.g., Bever & Chiarello, 1974; Jonides, 1979; Klatzky & Atkinson, 1971; Moscovitch, 1973, 1976; Seamon & Gazzaniga, 1973; Shankweiler & Studdert-Kennedy, 1975; Springer, 1977; Thomas & Campos, 1978).

In contrast to a direct access approach, Marcel Kinsbourne and his colleagues (Bruce & Kinsbourne, Note 1; Kinsbourne, 1970, 1973) have proposed a <u>selective activation</u> hypothesis in which they assume that the hemispheres do not necessarily differ in their abilities, but rather, the involvement of a hemisphere in a task creates a gradient of attention across a sensory space (e.g., visual field), such that maximum attention is directed to the part of the sensory space most contralateral to the involved or "activated" hemisphere. Therefore, from the selective activation view, <u>any</u> stimulus presented contralaterally (i.e., with direct access) to the more activated hemisphere will be processed more efficiently than a comparable stimulus presented ipsilaterally to the activated hemisphere, regardless of whether that hemisphere hemisphere is "normally" inefficient at processing stimuli of that type. For example, selective activation predicts that the right hemisphere would be better able to process laterally presented verbal information if it were simultaneously listening to music or processing some other sort of nonverbal information.[1]

A number of dual-task experiments have been performed in an effort to test the selective activation hypothesis against the direct access approach (Hellige & Cox, 1976; Hellige, Cox, & Litvak, 1979; Kinsbourne & Cook, 1971). The logic underlying these experiments is that if a task, X, "activates" a particular hemisphere, then when that task is performed concurrently with a second task, Y, the performance of the activated hemisphere on Y should improve relative to the situation when Y is performed alone. Note that evaluating these ideas logically involves comparisons of performance between single and dual-task conditions. These dual-task experiments have provided little support for any parsimonious version of selective activation; indeed, many assumptions have been added on a rather ad lib basis to the original statement of the theory in order to explain the data generated from these experiments. For example, the data from a series of seven experiments (Hellige & Cox, 1976; Hellige, Cox, & Litvak, 1979), led to the conclusion that there were at least two different types of selective activation that could only be observed in the left hemisphere on tasks involving processing to a stage beyond early visuo-spatial processing. However, as will be seen, these dual-task experiments are particularly appropriate for testing a multiple-resources model, and their data provide singular evidence for the validity of the model's assumptions.

Kinsbourne and Hicks (1978) have recently proposed a revised model of cerebral specialization based upon the notion of functional cerebral distance. In this model, interference between two tasks is now predicted to be the most likely phenomenon for dual-task performance, while Kinsbourne's original prediction of facilitation for the activated hemisphere in a dual-task situation is assumed to be a special case of this more general theory. The model states that "...paired limbs (are) regarded as more highly interconnected than homolateral limbs, and these in turn (are) more highly interconnected than diagonally-paired limbs. Control of the right hand, right foot, rightward gaze, and voice form one functionally close cluster, and left arm, left leg, and leftward gaze form another (pg. 349)." This model was proposed primarily to explain performance decrements observed on lateralized motor tasks such as dowel balancing or finger tapping performed concurrently with a left or right hemisphere "load" task such as sentence repetition or memory for dot patterns. Thus, Kinsbourne and Hick's (1978) new theory addresses a very circumscribed set of data, and still requires all the modifications proposed by Hellige and his colleagues (Hellige & Cox, 1976; Hellige, Cox, & Litvak, 1979) in order to explain the pattern of results they obtained using perceptual and cognitive tasks.

In attempting to understand cerebral specialization of function there have been few efforts to use the theoretical machinery developed within the domain of cognitive psychology in general, and conversely, there have been few efforts within cognitive psychology to account for data from the cerebral specialization literature that are extremely germane to more general issues of human information processing. In the present paper, therefore, we have two primary concerns. First, we believe there is little to be gained at this point by repeated, ad infinitum attempts to demonstrate that particular types of stimuli or tasks or processing styles or subjects either are or are not lateralized. What is needed is a more theoretically motivated approach toward research that replaces the burden of discovering what is lateralized with the motivation of trying to understand how differences between the hemispheres contribute to the flexibility of the human information processing system. Second, we believe that investigators concerned with issues of attention, performance, and cognition in general can look to the cerebral specialization literature as a source of evidence for one of several proposals regarding human information processing that are currently contentious. Thus, we hope to be able to demonstrate that a theoretical framework existing within the domain of cognitive psychology can be readily extended to provide explanatory mechanisms sufficient to account for much of the data in the cerebral specialization literature, and in turn, that the cerebral specialization data provide strong support for this particular framework and some difficulties for its contenders.

As mentioned previously, the concepts we use throughout this paper were originally developed by a number of authors within the context of a single-capacity central interference model (Kahneman, 1973; Kantowitz & Knight, 1976; Norman & Bobrow, 1975, 1976). Navon and Gopher (1979) have recently written an elegant critique and review of the assumptions underlying single-capacity models and have extended these concepts to formulate a model of performance based on multiple pools of resources. The methodological implications of this multiple-resources model are particularly relevant to the interpretation of data from experiments in which comparisons between single and dual-task performance are made, such as those designed to evaluate both the selective activation and functional cerebral distance models. As has been amply demonstrated in the divided attention literature, these single to dual-task comparisons cannot necessarily be interpretated straightforwardly (Kantowitz & Knight, 1976; Navon & Gopher, 1979; Norman & Bobrow, 1976). Thus, the caveats that have evolved with respect to conducting such research as well as interpreting the resulting data are especially important for an understanding of data in the cerebral specialization literature that have been collected using dual-task methodlology. Indeed, we believe that without this theoretical machinery and its concomitant methodological guidelines, the continued use of multi-task situations to assess cerebral specialization cannot help our understanding of the phenomena. Therefore, we will next review a number of the basic concepts used by Navon and Gopher

(1979), Norman & Bobrow (1975), and others, and then describe how they may be fruitfully applied to the field of cerebral specialization. In particular, we will propose a limited case of the multiple-resources framework in which there are only two types of resources--those available from the right and left hemispheres. This is the simplest version of a multiple-resources model that one can begin with, yet even in its simplest form it can accommodate a respectable amount of data from both the cerebral specialization and divided attention domains.

SINGLE-CAPACITY MODELS OF INFORMATION PROCESSING

Although we will first describe a strict version of the single-capacity interference model, it should be kept in mind that most of the single-capacity concepts are applicable to each type of resource within a multiple-resources view. We begin with the assumption that the processing resources for any system are limited, and that all mental processes, whether automatic or under conscious control, must compete for resources from the same common pool. Implicit in this assumption is the idea that processes may occur in parallel without observed performance decrements, so long as the capacity available from the total pool of resources has not been "used up." For example, when the weather is clear and the traffic sparse, you can usually drive quite efficiently while simultaneously conversing as lucidly as if you were in your own living room.

Within this framework, cognitive organization is conceptualized as a set of quasi-independent processes that may interact with each other with respect to exchanging data and with respect to possible competition for a common pool of resources; the results produced by a particular mental process therefore depend upon the nature of the data that the process receives and upon the amount of resources that have been allocated to it. Figures 1a and 1c show several simplified versions of the hypothetical relationship between resource allocation and performance for a single task; these are called <u>performance-resource functions</u>. As Navon and Gopher (1979) have pointed out, a performance-resource function can be used to depict the relationship between performance and resources only when all other factors are held constant. These factors are called <u>subject-task parameters</u>, and they include such things as task difficulty, response complexity, visual field of presentation, exposure duration, stimulus type and quality, level of practice, visual acuity, sex, handedness, etc. In Figures 1a and 1c, the upper limit of available resources is depicted as L, the portions of the lines that are monotonically increasing indicate the regions in which additional units of resources affect performance so that it is <u>resource-limited</u>, and the horizontal portions indicate the <u>data-limited</u> regions in which additional increments in resources no longer affect performance. Norman and Bobrow (1975) suggested that whenever an increase in allocated resources can result in improved performance then the process involved and hence performance which is dependent upon it is resource-limited. For example, your ability to converse may worsen as you pay more attention to driving in order to negotiate a freeway during rush hour. However, whenever performance is independent of resource allocation then a process and hence any performance that is dependent upon it is data-limited. Data-limits can result from either environmental factors (e.g., the signal-to-noise ratio) or organismic factors (e.g., the existence or veracity of a memory representation). For example, even in an uncomplicated traffic situation, you would not be able to converse well with a passenger who spoke distinctly yet in a completely unknown or ill-remembered language.

Note that the amount of resources required for optimal or data-limited performance under a given set of subject-task parameters can be less than L, which means that performance on a particular task can reach its maximum level before all the resources available for processing have been used up. Note also that performance on a task depends both on the amount of resources allocated to it and their relative <u>efficiency</u>. Efficiency is the amount of improvement in performance per unit of resource added, and hence is reflected in the slope of the function at any given point. In Figure 1a, for example, units of resources allocated to Task Y are twice as effective (i.e., produce twice as much increment in performance) as they are when applied to Task X. The efficiency of a resource may not be constant over the entire range of allocatable resources; e.g., if the task is data-limited the efficiency is zero (see Figure 1c, Task Z). The amount of resources needed to obtain a particular level of performance for a given task (X) is defined as the demand of that task, Dx (e.g., in Figure 1a, Task Y demands half as many resources as Task X to attain the same performance level, so that Dx = 2Dy).

Insert Figure 1 about here

The point on the performance-resource function at which a person is operating is a function of the person's intended level of performance, which in turn is a function of the utility for performing that task (see Navon & Gopher, 1979). Utility will be influenced by a person's motivation, level of arousal, expected gain, etc. A particular intended level is only possible if it lies on the performance-resource curve for that task and set of subject-task parameters. For example, if subject-task parameters are such that a task is data-limited at 80% accuracy (e.g., by setting threshold duration using the method of limits), then a subject may intend a level of 100% accuracy (perhaps because he or she is being paid $1.00 for every correctly detected target) but this intended level is not feasible under the circumstances. In contrast, in this situation performance could be only 50% accurate if, for reasons of utility (e.g., the subject becomes bored or distracted, or is receiving no payment) he or she has not allocated enough resources to achieve the maximum possible data-limited level of 80%.[2] In a single-task situation, the "extra" resources not applied to the task may remain unused and thus potentially available to be supplied to another task.

Limited-capacity processing with a single pool of resources: Performance on two or more concurrent tasks. The formulation outlined above implies that processes drawing from the same finite pool of resources will not interfere with one another until the amount of resources required by all exceeds L and at least one of the processes is operating within its resource-limited region. Interference between processes performed concurrently, whether symmetrical (i.e., Processes A and B mutually interfere with each other) or asymmetrical (i.e., A interferes with B but not the reverse) is assumed to imply that they both draw resources from a common pool. Symmetrical interference implies that both processes are resource-limited, whereas asymmetrical interference implies that the process interfered with is resource-limited while the other is data-limited.

According to a single-capacity model, these ideas can be tested by requiring that two or more tasks be performed concurrently, and observing the performance changes occurring for each as resources are differentially allocated between them. The joint performance function for two tasks between which resources are being allocated in different amounts is called a performance operating characteristic (POC; see Figures 1b and 1d). In generating a POC curve, all subject-task parameters are presumed to be held constant and only the amount of resources allocated to each task is varied (Kantowitz & Knight, 1976; Norman & Bobrow, 1976). A POC curve thus depicts joint performance plotted as a function of the set of alternative combinations of ratios of resource allocation (e.g., performance on Task X conjoined with Task Y is plotted as the ratio of resources allocated to each changes from 100%-0%, 90%-10%,...50%-50%...0%-100%). However, only one of these combinations is realized in any particular experimental situation. Therefore, in deriving a valid POC curve, the ratio of resource allocation is the only thing varied while parameters such as task difficulty, stimulus type, hand of response, and so on, are held constant. Consequently, in order to investigate the effects of these other parameters, it is necessary to generate a family of POC curves and compare differences in the shapes of the curves across the levels of the variables studied.

Note that performance tradeoffs between two tasks are a function of both the relative amounts of resources allocated and the relative efficiency of a "unit" of resource. That is, in the case where one unit of resources "released from" a difficult task improves performance on a concurrent easy task by two units, the same resource unit released from the easy task would only improve performance on the difficult task by half a unit. Therefore, in a single-capacity model, the relative efficiency of resources allocated between two tasks is reflected in the shape of the POC function, which in turn depends on the ratio of the slopes at any given point of the underlying performance-resource curves for each task (see Figures 1b and 1d).

Limitations of the strict single-capacity model. Navon and Gopher (1979) pointed out several assumptions implicit in using a POC curve to test a single-capacity interference model, questioned the viability of these assumptions, and proposed a multiple-resources model as a more reasonable alternative for describing the milieu in which human information processing takes place. They point out that for the single-capacity logic to work, one must make the following assumptions: (1) The demand for resources of two tasks when combined in a dual-task situation are additive, e.g., no additional resources are required to coordinate the tasks over and above what is necessary to perform each alone (Dx + Dy = Dxy). (2) The tasks remain independent when conjoined insofar as they use the same resources in the same way that they each do when performed alone, rather than the two combining to form a third, qualitatively different task. (3) The total amount of resources is fixed and not capable of expanding to meet task demands. (4) The allocation of resources between tasks can in fact be controlled and distributed at will in different proportions so that a POC curve can be obtained by varying these proportions. (5) When two or more tasks are combined, the system uses the full capacity available to it, so that an increase in resources applied to one task will necessarily result in an equal decrease in resources available to the other task, such that the resources used by the two tasks together equals L or the total amount, (i.e., there is *complementarity of supplies* such that the resources left over for Task X (Rx) are equal to L minus the resources used for Task Y (Ry)).

Navon and Gopher (1979) point out that even if one accepts a single-capacity model of human information processing, these assumptions may not always be justified. For example, the effect of combining two tasks on demand for resources may not be strictly additive. The joint demand for resources may be either greater or smaller than the sum of resources required to perform each task alone. When joint demand is greater than the resources required for the single tasks, the additional demand is a *concurrence cost* (Dxy > Dx + Dy). Examples of what might "cost" more resources in a dual as contrasted to a single-task environment are the coordination of processes for the two tasks, managing the joint resource allocation, competition for structures or their outputs when both tasks require them, etc. When the joint demand is less than the resource requirements of the single tasks, then the decrement in demanded resources is a *concurrence benefit* (Dxy < Dx + Dy). An example of what might facilitate joint relative to single-task performance is a situation in which both tasks use the product of the same process, so that when combined, that process only has to be executed once; that is, when there is a redundancy in the components of the tasks. It should be noted that Kinsbourne's (1970, 1973) selective activation theory essentially proposes that concurrence benefits in joint performance are to be anticipated whenever one or the other hemisphere is differentially activated or aroused by one of the two conjoined tasks.

The assumption of task independence is related to the additivity of demands assumption. If two tasks do not remain independent when combined, they may form a qualitatively different third task. If they do, the resource demands for this new task might very likely be quantitatively different from the sum of the demands for the original two tasks but not strictly for reasons of concurrence cost or benefit, since a qualitatively different third task precludes the concept of concurrence.

Related to the notions of independence and additivity is the assumption that capacity is fixed (L is a constant). It has been suggested that capacity might be able to expand to meet resource demands (Kahneman, 1973). However, it seems unlikely that capacity could expand indefinitely; a logically preferable alternative is that when performance increments are observed from single to joint performance, then either the tasks are not independent (i.e., a third, new task is being performed), or the demands are not additive (i.e., there is a concurrence benefit), or subjects had not been allocating the full amount of resources available to them in the single task situation, perhaps for reasons of differences in perceived utility. The possibilities of nonadditivity, nonindependence, and nonutilization of full capacity in the single-task situation have been cited as important reasons that inferences about underlying resource demands cannot necessarily be made by comparing single to dual-task performance (Kantowitz & Knight, 1976; Navon & Gopher, 1979).

Violations of any of the assumptions above could lead to noncomplementarity of supplies, an assumption essential for testing the single-capacity model. Recall that complementarity entails that resources released from one task can be used by the other, and that the system uses all its resources in the dual-task situation, such that $Rx = L - Ry$. If, for example, resources cannot be differentially allocated between two tasks (Assumption 4), then it would be impossible to observe complementarity because the ratio of resources allocated between the tasks would be a constant, despite differences in payoff conditions. A situation in which something of this sort might arise would be when a stimulus, by its mere presence demanded a certain amount of processing (i.e., its processing was nonoptional, see Navon & Gopher, 1979). If such a stimulus were present, it would not be possible to allocate fewer than the nonoptional amount of resources to its processing, regardless of payoffs or instructions to do otherwise.

Finally, an assumption that is basic to the limited-capacity idea in general is that performance is sensitive to resources. However, if performance on a task is data-limited, then adding more resources wouldn't improve performance and witholding resources wouldn't be deleterious until sufficient resources were witheld to place the task in its resource-limited region. This limitation is not crucial, however, provided that the other assumptions above are met, since as Norman and Bobrow (1975) point out, the POC curve for the data-limited task(s) would be flat across that region of resource allocation (i.e., no tradeoff in performance would be observed). It is the case, however that within a single-capacity framework a flat portion along a POC curve is always taken to imply that that task is data-limited. As will become clear, one of the major differences between the single and multiple capacity approaches is that from the latter point of view there are many reasons aside from data-limits that performance tradeoffs might not be observed.

MULTIPLE-POOL MODELS OF TASK INTERFERENCE

The fact that so much of the existing data in the divided attention literature could not be accounted for within a single-capacity model, particularly data from situations that seemed to demonstrate noncomplementarity of supplies, led Navon and Gopher (1979) to formulate an alternative model of human information processing and task inteference based upon the notion that there can be multiple pools of resources. The basic idea is that there is not a single pool of undifferentiated resources; rather, resources may be of a number of different types, each type with its own limited capacity. The types of resources demanded by a particular task will be a function of subject-task parameters such as those mentioned above; the particular subset of resources demanded by a task is referred to as its <u>resource</u>

composition. From an information processing point of view, the fact that the human system is highly adaptive and that individuals have at their disposal a large number of alternative means for achieving successful performance on any particular task has been widely acknowledged (Newell, in press). The idea that tasks may be performed with a variety of different resource compositions incorporates this flexibility into the multiple-resources approach. For example, suppose a subject has to be able to recognize a short list of visually presented nouns that are orthographically and phonemically distinct. Some subjects might use primarily phonemic and/or semantic information, others might remember the global shapes of the words or their referents, and still others might use a combination of these strategies, but the final level of performance attained might not differ for these different types of subjects. Thus, it is possible to obtain similar levels of performance from subjects who have used processing strategies and hence subsets of resources that are quite distinct.

It follows from the multiple-resource model that certain of the assumptions inherent in a single-capacity model may not hold for particular task combinations. For example, if one assumes there can be multiple pools of resources, then it logically follows that there could be complete, partial, or no overlap in the particular resources demanded by any two tasks (i.e., in their respective resource compositions). Thus, in a multi-pool situation, complementarity of supplies could only be observed if two tasks had complete overlap in their resource compositions and each task could only be performed with that particular combination of resources. If there were partial or no overlap in resource compositions, then complementarity of supplies would not necessarily hold. For example, when there is only partial overlap in demanded resources, then the resources freed from one task may be irrelevant to the other. In this case, while witholding resources from one task would decrease performance on it, there would not be a corresponding increase in performance on the other task. If one were assuming a single-capacity system was operational in this case, the erroneous inference would be made that the second task was data-limited, when in fact, the absence of a performance decrement was due to noncomplementarity of supplies: if a different type of resource had been available for use by the second task, performance could have improved. Similarly, if there were no overlap in resource compositions, then two tasks of increasing levels of difficulty could be conjoined without necessarily observing performance tradeoffs, and payoff manipulations designed to force a differential allocation of resources would be irrelevant. Thus in a multiple-resources model, the more similar the resource composition of two tasks, the greater the overlap in resource demand and the larger the amount of mutual interference that could be observed in a dual-task situation. Conversely, the smaller the overlap in the resource compositions of two tasks, the smaller will be the amount of tradeoff in performance that could be observed.

Navon and Gopher assume that a given task may be able to be performed by using one of several different resource compositions; however different combinations of resources may not all be equally efficient. For example, some resource compositions may demand more overall resources than others to produce equal levels of performance, and conversely, given a fixed amount of resources, a less efficient resource composition would produce poorer performance than a more efficient composition. If subjects are free to choose among several alternative resource compositions, and if they wished to maximize performance when required to perform two or more tasks concurrently, then their most reasonable option would be to choose the resource compositions with the least amount of overlap, regardless of their relative efficiency in the single-task situation.

Testing the models. It should be clear that only one point on a POC curve can be obtained from any particular combination of two tasks; the entire curve must be derived by holding all other factors (e.g., level of difficulty) constant and insuring that what is actually varied between tasks across different experimental conditions is the subject's resource allocation ratio (see Sperling & Melchner, 1978, for an excellent example of this methodology). From the single-capacity view, the possibility exists that two tasks when conjoined demand fewer than L resources for optimal performance, so that from this view the absence of performance decrements reflects the fact that the tasks are data-limited and are competing for an abundant resource supply, as contrasted to providing evidence that either (a) capacity can expand indefinitely to meet task demands or (b) one or both tasks are "automatic" in nature and do not compete for a finite supply of resources (Posner & Klein, 1973). From the multiple-resources view, the further possibility exists that two tasks when conjoined may demand entirely, partially, or none of the same resources, so that valid interpretations of a lack of tradeoff between two tasks, even with a properly derived POC, are impossible in the latter two situations. The amount of tradeoff observable depends on the similarity of the resource compositions of the two tasks.

In general, the multiple-resources model may be tested against the single-capacity model by deriving a family of POCs for different sets of task pairs. For example, suppose that in the joint performance function of Tasks X and Y a plateau of 70% accuracy was reached for X that did not change even when subjects were induced to allocate more resources to X at the expense of Y. The single-capacity interpretation of this would be that a 70% level of accuracy represented the maximum data-limited performance for Task X for that particular set of subject-task parameters. Suppose, however, that X was now paired with Z, instead of Y, and there was every reason to believe that Y and Z were equally difficult and were otherwise similar in terms of subject-task parameters. If under these circumstances the same resource allocation ratio that produced 70% accuracy for X when paired with Y produced 100% accuracy for X when paired with Z, then clearly a level of 70% accuracy could not represent the data-limited performance level for X. This type of data would be evidence in favor of a multiple-resource model in which X and Z had more similar resource compositions than X and Y, so that resources released from Z could be used to improve performance on X while those released from Y could not. In other words, if a performance plateau for one task conjoined with a second disappears when the first is conjoined with a third, and the second and third are comparable in some a priori sense, then "such a plateau cannot be held as a manifestation of local insensitivity of performance to resources in general, but rather to a particular type of resource (Navon & Gopher, 1979, pg. 248)." In the following sections, we will discuss data from the cerebral specialization literature that strongly argue in favor of this multiple-resources view.

EXTENSION OF THE THEORY TO THE TWO CEREBRAL HEMISPHERES

Since the anatomical division of the brain invites consideration of a naturally occurring division of resources, we believe that the concepts discussed above may be used to provide explanatory mechanisms sufficient to account for a variety of data in the cerebral specialization literature. Further, we believe that the cerebral specialization literature provides data that favor a multiple-resources view over a single-capacity approach.

We shall use the term "process" to refer to a mental or physical operation requiring the use and coordination of one or more mechanisms from within a hemisphere (e.g., encoding, retrieval, transformation of representations, and responding are all processes).[3] Now, suppose each hemisphere constitutes a separate collection of mechanisms that require resources to operate. We propose that the amount of resources or capacity of each hemisphere is fixed, limited, and inaccessible to the other hemisphere, and that the resources within each hemisphere are undifferentiated. Thus, although there may be many different mechanisms in each hemisphere and many types of perceptual, motor, and cognitive processes using those mechanisms, the processes performed within a hemisphere all draw on (compete for) the same fixed amount of resources. Therefore, we are proposing a conceptualization that is a limited case of a multiple-resources model in which there are only two pools of resources--right hemisphere resources and left hemisphere resources.

Successful performance of a task will require the coordination of several processes, and the combination of processes required (i.e., the resource composition of the task) may use mechanisms that draw exclusively on right hemisphere resources, or exclusively on left hemisphere resources, or may require that resources be be drawn from both hemispheres. In addition, a given task may be performed with a variety of resource compositions that may each draw on the resources of the two hemispheres in varying amounts. However, each combination of resources may not be equally efficient. For example, depending upon such things as the current supply and demand of resources, personal predelictions, etc., a subject may choose to encode a stimulus either linguistically or spatially, but these different encodings may be more or less useful for the task at hand.

We believe that most tasks should be able to be performed in their entirety by either hemisphere using its own mechanisms and resources, but that the resources from each hemisphere might not be equally efficient, and so performance levels attainable for a given task by each hemisphere may not be equal. Thus, the hemispheres may or may not be equally competent in performing a given task for several reasons. First, there may be tasks for which the processes used by the two hemispheres are the same or similar, but different amounts of resources are required by each hemisphere in order to attain equal levels of performance. For example, the motor coordination for right versus left-handed finger tapping might involve similar processes in the left versus right hemisphere, respectively, but a right-handed person usually requires more right than left hemisphere resources to attain the same performance level for each hand. Second, there may also be tasks for which the required processes or mechanisms are different in the two hemispheres, but the resources applied to those processes are equal in amount and efficiency. For example, the right hemisphere might remember the shape of a noun about as well as the left hemisphere could remember its name, so that both could perform about equally well on a noun recognition task by applying equal amounts of resources to qualitatively different processes. Finally, we believe that there are probably tasks for which the most efficient or even possible resource composition consists of processes that draw resources from one hemisphere exclusively, i.e., that there are tasks that can be performed most efficiently if at all by using the resources of only one hemisphere. For example, although the processes involved in right and left-handed finger tapping may be similar in the two hemispheres, right hemisphere resources cannot be used for right-handed tapping. Similarly, there is evidence dating from as early as 1861 to suggest that the posterior part of the left inferior frontal gyrus (Broca's area; Broca, 1861, 1865) is responsible for speech production (i.e., vocalization) in most right-handed individuals, especially males (see also Sperry, 1974; Wada, Clark, & Hamm, 1975). Therefore, for right-handed individuals, tasks requiring motor control of the right hand or speech production may demand mechanisms and hence resources that are specific to the left hemisphere and only the left hemisphere. When a task has a component such as a motor response that can only be performed by using the resources of a particular hemisphere, we will refer to that task as one whose resource composition includes hemisphere-specific resources. In contrast to simple lateralized motor tasks or speech production, the data in the cerebral specialization literature suggest that there are probably very few if any cognitive tasks for which this is true.

Implications for single-task performance. An important implication of having separate and mutually inaccessible pools of resources is, of course, that the performance-resource functions for a given individual or population of individuals performing in a particular stimulus and task domain may not be the same in the two hemispheres. That is, the amount of resources required from each hemisphere to attain a certain level of performance will not necessarily be equal for any given task, type of stimulus, instructional set, or subject. Thus, a given task may be performed with more than one resource composition, each of which may draw on the resources of the two hemispheres in varying amounts, and each of which may be differentially effective with respect to performance. If one resource composition draws primarily on left hemisphere resources and a second draws primarily on right hemisphere resources, then both the lower and upper bounds of effective resource allocation (i.e., the region in which performance is sensitive to resource allocation) as well as the relative efficiency of increments in resources may differ in the two hemispheres. For example, Figures 2a-2d depict a series of performance-resource functions for each hemisphere for each of five tasks (A through D and Y). In Figures 2a-2c, it is assumed that Tasks A-C can each be performed by drawing resources exclusively from either one or the other hemisphere; that is, it is assumed that there are at least two different resource compositions that can be used to perform the tasks, each of which draws exclusively from one hemisphere's supply. In Figure 2a, the functions for Task A are identical: the hemispheres use their resources with equal efficiency (i.e.,the slopes of the performance-resource functions are equal), attain data-limited performance by expending an equal amount of resources, and have data-limited performance levels that are equally good. An example of such a task might be simultaneous presentation of visually distinctive letters, words, shapes, faces, etc., to either visual half field that are to be matched on the basis of physical identity. Such a task may be performed in a variety of ways (analytically, holistically, in serial or parallel, using visual or phonemic or other codes, etc.), but since it is a relatively "low-level" task it makes some sense that the resources deployed by either hemisphere would in fact be equally efficient, and there is some evidence that they are (Bevilacqua, Capitani, Luzzatti, & Spinnler, 1979; Moscovitch, Scullion, & Christie, 1976). Thus, identical performance-resource functions should not be taken to imply equality of process; in fact, this framework generally obviates the need to discuss hemispheric performance with reference to dichotomies of process.

Figure 2b depicts a task for which resources are applied with equal efficiency in the two hemispheres, but more overall resources are required by the right hemisphere to attain a particular level of performance (e.g., finger tapping for right-handed individuals), and Figure 2c depicts a task for which the efficiency of the resources in the two hemispheres is widely disparate, as reflected by the difference in slopes (e.g., music discrimination tasks, name matches of successively presented abstract words, face recognition, etc.).

Finally, Figure 2d depicts a set of curves which pertain to a situation in which performance of the task requires a hemisphere-specific resource, i.e., in this case, no matter how many right hemisphere resources are available, they are irrelevant to performance. Note that the curves in Figure 2d are implicit in any approach that assumes a strict dichotomy of process or function between the hemispheres, whether it be a dichotomy dictated by hand of response, choice of stimulus materials (verbal or nonverbal), or "cognitive style" (e.g., analytic vs. holistic processing). That is, the relationship between resources and performance depicted in 2d is applicable to any approach in which it is assumed that there can be such a thing as having a stimulus which, via half field or dichotic techniques, initially arrives at the "wrong" hemisphere and consequently needs to be transferred across the callosum for processing.

Insert Figure 2 about here

In summary, we assume that most perceptual and cognitive tasks can probably be performed with more than one resource composition, each of which may use more or less right and left hemisphere resources. If this is true, then instructional manipulations such as asking subjects to use imagery vs. verbal rehearsal to remember a search set (Seamon & Gazzangia, 1973) or task manipulations such as varying the length of time a stimulus must be held in memory (Bevilacqua, Capitani, Luzzatti, & Spinnler, 1979; Moscovitch, Scullion, & Christie, 1976) will most likely affect the resource composition used to perform the task, and therefore the particular visual field advantage that is manifested. Similarly, we expect that such individual differences as level of expertise (Bever & Chiarello, 1974; Hirskowitz, Earle, & Paley, 1978), degree of hemispheric "dominance" as reflected by behavioral measures of various motor competences (Thomas & Campos, 1978), sex, handedness (Levy & Reid, 1976, 1978; Witelson, 1976, 1977), and so forth, are subject parameters that must have implications for the type of resource compositions that are even available and that could be used most efficiently to perform under a given set of task parameters.

An assumption fundamental to our approach is that each hemisphere has the same total resource capacity and furthermore, the amount of resources available to be supplied to a given task at any particular moment is always equal in both hemispheres, whether or not these resources are required by the particular resource composition of that task. That is, we specifically disavow the idea that different amounts of resources can be available in either hemisphere, or that the hemispheres can be differentially activated or aroused. Thus, we propose that the capacity limit of the left hemisphere (L-LH) is equal to the capacity limit of the right hemisphere (L-RH) and their sum is equal to L (L-LH + L-RH = L). We further propose that if a subject consciously or unconsciously increases his or her arousal level, attention level, motivation, etc., that the effect is to increase <u>equally in each hemisphere</u> the amount of resources that can be supplied to a task or set of tasks at that moment. For example, if L is equal to 100 units of resources, then the limit of the right and left hemisphere would each be 50 units (L-LH = L-RH = 50). If a subject were operating at an 80% level of attention, arousal, etc., then a total of 80 units of resources could be supplied to a task (40 from the right hemisphere and 40 from the left). Thus, if a subject wished to perform a task whose resource composition required 45 units from the left hemisphere and none from the right in order to reach a particular intended level of performance, it would be necessary to increase his or her overall arousal level to at least 90%, rather than 45%, so that the 45 units necessary would all be available from the left hemisphere. In this case, there would also be 45 units of resources available in the right hemisphere that could remain unused or else supplied to another task. Therefore, in a single-task situation, hemispheric differences in performance are assumed to be a function of the demand for resources at a particular intended level and differences in their efficiency, and are not a function of differences in the available supply, which is assumed to be equal in both hemispheres.

Implications for dual-task performance. If interference between two tasks depends upon the similarity among the resources each demands, then a strong prediction of an independent-resources approach to cerebral specialization is that a task demanding resources from primarily one hemisphere should not interfere with a second task demanding resources from primarily the other hemisphere, regardless of the difficulty of either of the tasks. If two such resource-independent tasks are performed concurrently, one of the tasks could be made increasingly more difficult and still not affect performance on the second task. That is, performance tradeoffs would not be observed because of the lack of overlap in resource demands between the two tasks, and not because one or both tasks were data-limited, as would be inferred from a single-capacity model. Conversely, within this framework, if two tasks draw resources from primarily the same hemisphere, then there should be a tradeoff in performance between them as a function of shifts in resource allocation, provided that at least one of the tasks is sensitive to resource allocation; i.e., provided that at least one of the tasks is resource-limited. In other words, with subject-task parameters held constant, two tasks drawing on the resources of the same hemisphere have complete overlap in their resource demands and it should be possible to observe tradeoffs in performance, whereas two tasks drawing resources from opposite hemispheres have no overlap in resource demands and tradeoffs should not be observed. Finally, a task or set of tasks that each demanded resources from both hemispheres would have partial overlap of resource demands so that performance tradeoffs would be observed only when there was a scarcity of the overlapped resource. In Figures 2a-2d, we have drawn the performance-resource curve for a task (Y) which for illustrative purposes is assumed to demand resources exclusively from the right hemisphere. It can be seen that when Task Y is conjoined with Tasks A-D, the POC curves appropriate for describing joint performance pertain to tradeoffs in the right hemisphere only.

Note that just as in the single-capacity model, if two tasks draw resources from the same hemisphere the amount of decrement observed on either task when both are being performed concurrently will depend upon the amount of resources required by each. For example, a task demanding relatively few resources (i.e., a task that is data-limited relatively soon) may show no performance decrements when performed concurrently with a second task as compared to a more difficult task that demanded more resources for optimal performance. Examples of these types of results from dual-task experiments already exist in the cerebral specialization literature.

ANALYSIS OF EXPERIMENTAL RESULTS

Many of the dual-task experiments conducted within the field of cerebral specialization have been designed to test Kinsbourne's selective activation hypothesis (Kinsbourne, 1970, 1973), and they involve comparing the single and dual-task performance of each hemisphere on tasks that are assumed to be lateralized in a particular manner. We will refer to tasks that employ lateral presentations vs. those that do not as target and load tasks, respectively.

There are two types of results we wish to address in these experiments. The first concerns differential changes in the target task performance of each hemisphere as a function of whether the task is performed alone or conjointly with a load task (e.g., differences in the length of time a dowel can be balanced in either hand as a function of whether or not there is a concurrent sentence repetition task to be performed). The second type of data we wish to address concerns differences in patterns of interference observed across different pairs of target and load tasks (e.g., interference on noun naming as a function of whether the load task involves remembering nouns or dot patterns). Although both types of data have been collected in an effort to observe activation effects and to delineate the conditions under which they occur, they provide very good evidence for the validity of a multiple-resources approach to information processing in general. That is, with few exceptions, the existing data conflict with selective activation predictions insofar as performance decrements have been observed where increments have been predicted and increments have been observed when there should have been no change in performance. Similarly, the results often conflict with a model that assumes the target and load tasks draw resources from a common pool insofar as increments or decrements in target task performance have been observed in one but not both hemispheres, and different patterns of interference on target task performance have been observed as a function of the particular load task used. However, the data that apparently conflict with either a selective activation or a single-capacity model are easily accommodated within a multiple-resources approach. To do so, we assume that subjects are not generally operating at their full capacity in the single-task situation, and that the dual-task situation is either in fact more difficult (i.e., demands more resources) or is perceived as being potentially more difficult (i.e., instructions to perform two tasks conjointly alters the utility for allocating resources). Thus, for reasons of shifts in either utility or demand, we assume that subjects increase their attention in the dual as compared to the single-task conditions. This increase in attention provides an increase in available resources that is equal in both hemispheres. Thus, since the supply of resources to both hemispheres is equal, changes in target task performance that occur from the single to the dual-task situation will reflect (a) differences between the hemispheres in the slopes of the performance-resource curves for the target task, and (b) the degree of overlap that exists in the resource demands of the target and load tasks. This assumption--that subjects generally increase their attention when going from a single to a dual-task situation--is applicable to a large group of experiments whose data are otherwise in apparent conflict. In addition, we believe it is a plausible assumption because in none of the dual-task experiments that have been performed has any kind of incentive been used to insure that subjects were performing at the maximum levels possible in either the single or dual-task conditions.

Dual-task experiments involving lateralized motor tasks. In order to illustrate how an increase in attention that provides an equal increase in the resources available within each hemisphere can lead to differential performance changes in the two hemispheres, we will first discuss one of the simplest of the dual-task experiments (Kinsbourne & Cook, 1971). The target task was dowel balancing, which is a motor activity that can be reasonably assumed to require primarily the resources of the hemisphere contralateral to the hand being used (e.g., right-handed balancing uses primarily left hemisphere resources). The performance measure is the length of time the dowel remains balanced. Kinsbourne and Cook (1971) found that right-handed subjects could balance a dowel longer with their right than with their left hand. These data imply that there could be both a difference in slope (efficiency) and optimal attainable performance (data-limits) for the two hemispheres.

In Figure 3, we show a set of performance-resource curves that could underly the single-task performance of each hand observed by Kinsbourne and Cook (1971). While these curves reflect Kinsbourne and Cook's assumption that right-handed balancing demands exclusively left hemisphere resources and vice versa, they also incorporate the differences in efficiency of resources implied by their data. Note that the function for the right hand (left hemisphere) is drawn with a steeper slope than that for the left hand (right hemisphere), which implies that for right-handed individuals, the right hand can perform this task more efficiently than the left at the expense of fewer resources. Therefore, if both hands are drawing an equal number of resources from their respective hemispheres, the right hand will always be better than the left. In addition, the curves imply that the left hemisphere becomes data-limited sooner than the right (i.e., it can attain maximum performance with fewer resources). Thus, even in a single-task situation, an equal increase in resource allocation to dowel balancing by both hemispheres would not have the same effect on performance for each. For example, after the point of resource allocation where the left hemisphere became data-limited (i.e., after the 30% allocation level), an increase in allocated resources would not change performance in the right hand, while the left hand could continue to improve until it reached its data-limited performance level.

Insert Figure 3 about here

For their dual-task condition, Kinsbourne and Cook (1971) had subjects repeat a short sentence aloud while simultaneously balancing the dowel in either hand, the assumption being that sentence repetition would require primarily left hemisphere resources. From the single-capacity framework, if the added sentence repetition task is detrimental at all it should either be so equally for both hands or else it should be more detrimental to the left hand than to the right. From the selective activation framework, repeating a sentence should activate the left hemisphere so that right-handed balancing would improve relative to the single-task condition; left-handed balancing should be unaffected by this manipulation. Contrary to either of these expectations, Kinsbourne and Cook (1971) found that in the dual-task conditions, the amount of time the dowel could be balanced decreased in the right hand and increased in the left. Thus, there was no "activation" or facilitation of right hand (left hemisphere) performance yet there was a significant improvement in left hand (right hemisphere) performance with a concurrent left hemisphere load.

From our framework, whenever resource allocation is increased to insure that the hemisphere primarily involved in the load task has sufficient resources to attain a particular intended level of performance, then there is an equal amount of extra resources made available in the hemisphere not involved in the load task that can be applied to the target task to potentially improve its performance. This implies that in both single and dual-task conditions, the level of attention in each hemisphere is equal across the balancing trials for each hand. That is, assume that in the single-task situation, subjects did not use all available resources to balance the dowel, and initial performance levels were at the point on Figure 3 represented by the vertical dashed line (i.e., the intended level of performance was less than the maximum attainable). If the sentence repetition task demanded more left hemisphere resources than were "left over" from right-handed dowel balancing in the single-task situation (i.e., as the figure is drawn, more than 70% of the left hemisphere's resources), then right-handed balancing would suffer when the tasks were conjoined (i.e., Dx + Dy > Dxy). However, since we are assuming there cannot be differential levels of arousal between the hemispheres, then when the left hemisphere is using resources for sentence repetition, the right hemisphere is in a position of having a supply of resources available for balancing (or any other task, for that matter) which is more abundant than the supply it had in the single-task condition, and so its performance improves.[4]

These types of differential changes in the target task performance of each hemisphere are not limited to situations in which the preferred or dominant hand (i.e., the right hand of right-handed subjects) is initially better able to perform the target task, since they are attributable to the overlap in the resource compositions of the target and load tasks. For example, Smith, Chu, and Edmonston (1977) required right-handed subjects to perform haptic discriminations of Braille symbols with either hand, and found that they performed better with the left (i.e., right hemisphere (left hand) resources were more efficient than left hemisphere (right-hand) resources, so that the performance-resource curves would be similar to those of Figure 3, with the labels reversed). Subjects then performed the haptic task while music was simultaneously being played into their left or right ear, on the assumption that at least for musically naive subjects, right hemisphere resources are generally required for music processing (Bever & Chiarello, 1974; Hirshkowitz, Earle, & Paley, 1978). According to our framework, if music demands primarily right hemisphere resources, it could only interfere with left-handed discrimination performance and might actually improve the performance of the right hand. These are exactly the results obtained by Smith et al. (1977), and our explanation of them is similar to that offered for Kinsbourne and Cook's (1971) data, except that in the present case the two tasks demand right rather than left hemisphere resources. Music played to the right hemisphere demands enough resources to force a tradeoff with other tasks requiring right hemisphere resources, while simultaneously causing an increase in the supply of left hemisphere resources that can be applied to another task. Further, listening to music seems to be a good example of a case in which the mere presence of a stimulus demands resources. That is, music seems to be processed "automatically" if it is presented to the right hemisphere. In contrast, when the music was played to the left hemisphere, there was no change in discrimination performance for either hand. The most likely reason for this is that since there was no response required to be made to the music there was no reason for the left hemisphere to either attempt to process it or to transfer the information to the right hemisphere for processing, and so this condition was effectively the same as if the haptic task were being performed alone. That is, since the left hemisphere may not normally be involved in music processing, the mere presence of music does not demand its resources; if a response had been required, the outcome might have been different.

In the two examples just discussed, when a concurrent load task utilized the resources of the same hemisphere as the hand performing a lateralized motor activity, the performance of that hand declined relative to the single-task situation, whereas performance was improved for the hand controlled by the hemisphere opposite to that being used for the load task. These results argue against a simple selective activation hypothesis of cerebral specialization, since the improvements in performance occurred in the hemisphere opposite to that predicted and the decrements occurred in the hemisphere that was supposed to have improved. They also argue against a simple single-capacity interference model, since the load tasks did not produce the same performance changes for each hand (however, see Lomas & Kimura, 1976, for a case in which the motor performance of both hands was interfered with by a concurrent verbal load).

There are also examples of interference with the performance of the hand contralateral to (controlled by) the hemisphere involved in the load task with no concomitant improvements in the ipsilateral hand. This sort of finding is also difficult to explain using either selective activation or single-capacity concepts, but from a multiple-resources view it could arise if either the ipsilateral hand was data-limited to begin with or if subjects were initially operating at full capacity. For example, Lomas and Kimura (1976) found that repeating nursery rhymes interfered with movements by the right hand or arm but not the left when the manual activity involved tapping keys in a particular sequence. Similarly, Summers and Sharp (1979) found right but not left hand inteference when finger tapping was conjoined with a verbal load task.

The studies discussed thus far have used only a single level of load difficulty. According to our framework, if motor control of the right hand and the processing of the load task both draw primarily on left hemisphere resources, then increasing the difficulty of the load task should increase the amount of interference with the right hand. Hicks (1975) found that when the load task was sentence repetition, increasing the phonetic difficulty of his sentences (e.g., by using tongue twisters) further increased the amount of interference with the right hand for dowel balancing, but still did not decrement left hand performance. Hicks, Provenzano, and Rybstein (1975) found a similar effect for typing.

If the motor task requires complex sequential activity in which both hands are to be coordinated, then a decrement in the performance of both hands may be observed with a concurrent verbal load (Hicks, Bradshaw, Kinsbourne, & Feigin, 1978; Summers & Sharp, 1978). Since performance of complex sequential motor tasks may not be controlled entirely by the contralateral hemisphere (Wyke, 1971; Lassen, Ingvar, & Skinhoj, 1978), the resource compositions of these tasks may be such that they draw from both hemispheres in varying amounts, so that the patterns of interference observed will depend upon the degree of overlap in the resource requirements of the motor and load tasks. However, since so little is known about hemispheric responsibility for processes involved in complex motor activities requiring sequencing and coordination across hands, we would prefer to discuss a number of experiments in which there is some independent evidence that can be used to infer what the degree of overlap between the target and load tasks might be.

Dual-task experiments involving laterally presented perceptual and cognitive tasks. Hellige and his colleagues (Hellige & Cox, 1976; Hellige, Cox, & Litvak, 1979) have performed an extensive series of experiments using visual half field techniques in single and dual-task situations in an attempt to delineate the conditions under which activation effects occur. Their general procedure involves presenting right-handed subjects with a target stimulus to either visual field, preceded by either none or a varying number of load stimuli to be held in memory and recalled after the target task trial. Subjects are instructed to give equal weight to both tasks in the dual-task conditions, so that each experimental condition reflects one point on a POC curve.

These experiments are especially appropriate for testing a multiple-resources framework, because patterns of interference can be compared across sets of task pairs. In particular, we will discuss what happens to noun naming accuracy as a function of the resource composition of two different concurrent load tasks of varying levels of difficulty--remembering either 2, 4, or 6 nouns vs. remembering the location of 4, 7, or 11 dots in 3 x 3, 4 x 4, or 5 x 5 matrices (Hellige & Cox, 1976, Experiment 2; Hellige, Cox, & Litvak, 1979, Experiment 1). We will adopt Hellige and Cox's (1976) assumption that remembering nouns requires primarily left hemisphere resources, and since memory for dot patterns has been shown to elicit a LVF-RH advantage for most right-handed individuals (Kimura & Durnford, 1974; Levy & Reid, 1976, 1978), we will also concur with their assumption that remembering dot patterns requires primarily right hemisphere resources. Thus, from our view, the extent to which remembering nouns or dot patterns can interfere with any other concurrently performed target task will depend on the extent that the target task demands left or right hemisphere resources, respectively. In contrast, from the selective activation view, concurrently remembering nouns should improve the left hemisphere's naming accuracy relative to the single-task condition while not affecting the naming performance of the right hemisphere, whereas remembering dot patterns should produce the opposite results; i.e., right hemisphere improvements with no change in left hemisphere performance. As can be seen in Figure 4, these selective activation expectations were not realized. Moreover, the two load tasks had very different effects on noun naming performance: remembering dot patterns seemed not to affect the naming accuracy of either hemisphere, remembering 2 or 4 nouns did not affect left hemisphere naming accuracy but improved right hemisphere accuracy, and remembering 6 nouns decreased the naming accuracy of both hemispheres. While it is difficult to account for these results parsimoniously from either a selective activation or a single-capacity model, they are nicely illustrative of a multiple-resources model in which different patterns of interference between tasks are expected to occur as a function of the amount of overlap in their resource demands. For example, considering just the demands for left hemisphere resources, when the nouns to be named are presented to the left hemisphere, a concurrent noun memory load provides maximal overlap with the naming task demands while a concurrent dot pattern load provides minimal overlap. In the former case we could expect to see tradeoffs in performance whereas in the latter we could not, regardless of how difficult the dot pattern task became. In the remainder of this section, we will discuss in more detail how the multiple-resources approach can account for the patterns of interference obtained across these two different dual-task conditions.

Insert Figure 4 about here

It seems reasonable to assume that as single tasks, more resources are required to remember 6 nouns than are required to remember 2 nouns, and similarly, that more resources are required to remember the locations of 11 dots than are required to remember the locations of 4 dots. This assumption is borne out by the level of recall obtained on these tasks in the dual-task conditions: The percent of nouns recalled decreased from 96.0% in the 2-noun condition to 59.1% in the 6-noun condition, and the percent of correctly reproduced dot patterns decreased from 87.3% for 4 dots to 18.0% for 11 dots (see Figure 4). From a single-capacity point of view, the heavier memory load conditions of both the noun and dot pattern tasks should yield more interference with any concurrent target task than the lighter load conditions. Moreover, from the single-capacity view, since overall performance on the dot pattern task was worse than performance on the noun task (47.9% vs. 73.7% accuracy), then when these two tasks are conjoined with the same target task the former should produce more interference than the latter. In contrast, from the multiple-resources view, the patterns of interference with target task performance that these two load tasks could produce will depend on the degree to which their resource compositions overlap with that of the naming task. We thus need to make explicit some assumptions concerning the underlying resource composition of the noun naming target task.

At the very least, a noun naming task requires that the visually presented nouns be processed to some level of representation that includes a phonemic code or a motor program for generating such a code, and then the motor program for vocalizing the processed information must be executed. Thus, for the sake of simplicity, we will suppose that there are at least two components to this task; we will refer to them as perceptual decoding and verbal output. While the former may involve a variety of different processes (e.g., visual analysis and recognition of features or letters, retrieval of lexical or phonemic information, etc.), we will not be concerned with these processes individually.

Since it is known that even for right-handed individuals, the right hemisphere is capable of some rudimentary linguistic analysis and identification of familiar nouns (Day, 1977; Moscovitch, 1973; Sperry, 1974) we will assume that both the left and right hemispheres have at least one resource composition sufficient for perceptual analysis of nouns, but that the left hemisphere's resources are generally more efficient. This argument is similar to that previously made for the motor tasks; both the left and right hemispheres have resources that allow control of the right and left hands, but depending on the type of motor activity, these resources are not equally efficient. Thus, just as a motor task performed by the right hand necessitates considering a different performance-resource curve than the same motor task performed by the left hand, presenting a stimulus to the left visual field may entail considering a different performance-resource curve than presenting the same stimulus to the right visual field or to the fovea. We are therefore treating visual field of presentation much as we treated the two hands; it is a task parameter that must be considered and held constant when deriving POC curves or discussing resource compositions.

As discussed previously, in contrast to the perceptual decoding aspects of verbal analysis there are good reasons to believe that for right-handed individuals a task requiring speech production is one of the few whose resource composition includes a resource specific to the left hemisphere. Thus, when a noun is presented to the left hemisphere for the purpose of naming, there exists a resource composition exclusive to that hemisphere which is sufficient for performing both the perceptual decoding and verbal output components of the task. Conversely, when a noun is presented to the right hemisphere, there may be a resource composition exclusive to the right hemisphere sufficient for any task that did not require naming (e.g., recognition, categorization) but when verbal output is a requirement right hemisphere trials constitute a <u>task</u> whose resource composition includes resources from both the right and left hemispheres.

According to this analysis of noun naming, the performance-resource functions of each hemisphere that underly perceptual decoding of verbal stimuli would be similar to those shown for Task C in Figure 2c, while functions for the verbal output would be similar to those for Task D in Figure 2d. Therefore, on right visual field-left hemisphere naming trials, both components of the task may draw exclusively on left hemisphere resources, and naming accuracy will be entirely a function of the availability of left hemisphere resources. Thus, on right visual field (left hemisphere) naming trials conjoined with a noun memory load, we expect no decrement and certainly no increment in naming performance until the resources required by both the target and load tasks exceeded L-LH. When this point is reached, there should be a decrement in either naming performance or recall accuracy or both. Conversely, we do not expect to observe performance tradeoffs on left hemisphere naming trials when the load task demands primarily right hemisphere resources (e.g., the dot pattern memory task), because that would be a case in which there was no overlap in the resource compositions of the two tasks. The data are entirely in accord with these predictions. In the 6-noun load condition there was a large decrease in accuracy for both the load and right visual field naming tasks. Thus, we assume it is at this point that there are no longer sufficient left hemisphere resources to perform either task at data-limited levels; i.e., there is a scarcity of left hemisphere resources. However, even though the performance levels of the most difficult dot pattern task were more than 40% worse than those of the 6-noun memory condition in which left hemisphere naming accuracy was detrimentally affected, the left hemisphere's naming accuracy was not affected by the difficulty of the dot pattern task. While it is very difficult to explain this lack of tradeoff from a single-capacity view, the multiple-resources view accounts for this result straightforwardly because of the differences in resource overlap between the two dual-task conditions. Further, since if it is true that left hemisphere performance on noun naming is data-limited relatively soon (Figure 2c), then even though increasing right hemisphere resource demands to comply with the requirements of the dot pattern load task would automatically increase the left hemisphere's allotment (allocation) of resources to devote to the noun naming task, we would not expect to see any increment in its naming accuracy, and in fact there was none.

In contrast to the right visual field (left hemisphere) naming task, naming performance on right hemisphere trials will be affected by the availability of resources in both hemispheres, since right hemisphere resources can be used for perceptual decoding while left hemisphere resources must be used for verbal output. Left visual field-right hemisphere naming trials conjoined with noun or dot pattern load tasks thus constitute a situation in which there is only partial overlap in resource compositions between target and load tasks. Thus, for example, on LVF-RH trials there will be no decrement in naming performance with a concurrent left hemisphere load until there is a scarcity of the overlapped resource, i.e., left hemisphere resources. In fact, with a 2 and 4 noun load there was an increase in accuracy on LVF-RH noun naming task analogous to the performance increase in the left hand observed in the motor experiments, and our explanation of this is similar to the one offered for the improved motor performance. That is, since there cannot be differential increments in resources between the two hemispheres, then as more left hemisphere resources were allocated to perform the increasingly difficult verbal load task, more right hemisphere resources were available for the perceptual decoding aspects of the target task, and performance could continue to improve on the LVF-RH trials until perceptual decoding became data-limited since the left hemisphere is now receiving a higher quality data representation. In contrast, since remembering 6 nouns produces a scarcity of left hemisphere resources, we observe a decrease in target task performance on right hemisphere trials in this condition. That is, although the right hemisphere may be sending very high quality data to the left hemisphere, when remembering six nouns, the left hemisphere does not have sufficient resources for verbal output to name the nouns at data-limited levels of accuracy (e.g., as in the 0 and 2 noun load conditions). Thus, any time the resources available in the left hemisphere for verbal output are scarce noun naming will become less accurate, regardless of the visual field of presentation, because performance on LVF-RH noun naming trials requires a resource composition that draws in part from the left hemisphere.

When remembering dot patterns is the load task, we do not expect to see an improvement in the right hemisphere's naming accuracy, since the surfeit of right hemisphere resources made available by the concurrent 2 or 4 noun memory load that had enabled right hemisphere accuracy to improve are now required for the dot pattern task. Moreover, the fact that the dot pattern load did not decrement right hemisphere naming accuracy implies that sufficient right hemisphere resources were "protected" (Navon & Gopher, 1979) to maintain the right hemisphere's minimum attainable performance for noun naming. That is, since subject's instructions were to pay attention to both tasks equally, when noun naming was conjoined with remembering dot patterns, there was some utility associated with being able to attain some level of performance on both tasks, even if it is minimal.

We have thus far discussed a number of experiments involving perceptual and motor performance whose results conflict with the predictions of a selective activation approach to cerebral specialization. There do exist target tasks for which the predictions of a simple activation hypothesis have been confirmed (i.e., an increase in target task performance was obtained in the hemisphere that was presumed to also be processing the load task). For example, Kinsbourne (1970, 1973) discusses several experiments in which a concurrent verbal load increased the accuracy with which the left hemisphere could detect gaps relative to the single-task situation in which gap detection produced a right hemisphere advantage. However, neither Gardner and Branski (1976) nor Boles (1979) were able to replicate this finding; in fact, in an experiment that closely duplicated Kinsbourne's procedure the opposite finding was obtained: A concurrent verbal load slightly increased performance on LVF-RH trials and slightly decreased performance on RVF-LH trials. Note the similarity between this pattern of results and those obtained by Kinsbourne and Cook (1971), Hellige and Cox (1976), and Smith et al. (1977).

Hellige and his colleagues have observed improved target task performance in the hemisphere presumed to also be processing the load task in two paradigms involving the use of random polygons: a polygon recognition task (Hellige & Cox, 1976, Experiment 1) and a same-different physical identity task in which one of the polygons was held in memory (Hellige, Cox, & Litvak, 1979, Experiment 3). In both cases, the polygons were either processed more accurately on right hemisphere trials in the single-task situation or else by both hemispheres equally well, but with a concurrent 2 or 4 noun load, they were processed more accurately on left hemisphere trials. Within the multiple-resources framework, the construct of a concurrence benefit could account for improvements from the single to the dual-task situation in the performance of the hemisphere whose resources are required to process both the load and target tasks (i.e., in a complete overlap situation). However, we feel that invoking this construct for these data is a bit ad hoc at this point, since the cognitive mechanisms used in processing polygons are not well understood. That is, whether a left or right visual field advantage is observed in tasks using polygons as stimuli has been shown to be a complex interaction of the association value of the polygons, the length of time they are held in memory, and their complexity as indexed by number of points (Dee & Fontenot, 1973; Hannay, Rogers, & Durant, 1976). Therefore, it appears that polygons may be able to be processed with a variety of different resource compositions using varying amounts of right or left hemisphere resources, and that the particular resource composition used can be easily changed by manipulating subject-task parameters. It is not clear, therefore, just what sort of process could be common to both noun memory and polygon recognition that could be beneficially shared when these two tasks are conjoined to produce a concurrence benefit. Thus, it might be more reasonable to look for concurrence benefits between two tasks whose processing mechanisms are more clearly understood and are less labile than are those of polygon recognition before this construct is invoked as the mechanism underlying performance improvements between single and dual-task situations when the tasks involved both draw resources from primarily the same hemisphere.

Dual-task experiments involving nonlaterally presented cognitive tasks. We have discussed several experiments from the cerebral specialization literature whose data can be used to support a multiple-resources approach. There also exist dual-task experiments outside this domain in which the lack of performance tradeoffs observed could have been due to the fact that the processes involved in the tasks employed demanded varying amounts of resources from different hemispheres.

A good example of this is an experiment conducted by Rollins and Thibadeau (1973), who compared recognition memory performance for different types of stimuli across two levels of a concurrent verbal task. Four groups of subjects learned one of four different stimulus lists while either listening to or shadowing auditorially presented verbal passages. The stimuli to be remembered were either concrete nouns presented auditorially, the same concrete nouns presented visually, pictures depicting the referents of the nouns, or pictures of fictitious characters that were not readily labeled.

Relative to the nonshadowing dual-task situation, the shadowing task interfered most with recognition of the auditorially presented words, to a lesser extent with recognition of visually presented words and pictures of objects, and not at all with recognition of the fictitious characters. A similar pattern of interference with recognition was obtained by Allport, Antonis, and Reynolds (1972), who used shadowing verbal passages as a load task and auditorially presented words, visually presented words, or colored photographs as the stimuli to be remembered. Both sets of data argue against a single-capacity model and in favor of the hypothesis that the two cerebral hemispheres are independent resource pools that a subject might be able to take advantage of when performing concurrent tasks. That is, if alternative resource compositions exist for each task that could be combined to yield a minimum amount of overlap in resource demands, these particular resource compositions may be used to reduce the amount of interference between tasks in the dual-task situation. For example, in the case of the Rollins and Thibadeau (1973) experiment, assume that simply hearing a verbal passage demands some left hemisphere resources (much as simply hearing music demands some right hemisphere resources), whereas shadowing a verbal passage demands a great deal of left hemisphere resources. The four different recognition tasks each vary in the extent to which right hemisphere resources could be comandeered to help separate the resource compositions of the shadowing and recognition tasks.

A priori, an auditorially presented list of words to be remembered provides the least amount of flexibility in processing strategies and is the recognition condition most similar in terms of resource overlap to both the listening and shadowing tasks. Since shadowing requires more resources than listening, there is a large decrement seen in recognition of the auditorially presented words. In contrast, if pictures of fictitious characters that are difficult to label could be processed using almost exclusively right hemisphere resources, then there would be little or no overlap in the resource compositions between the recognition task and either of the two concurrent auditory tasks, so that increasing the resource demands from listening to shadowing would have little or no effect on recognition of these unfamiliar pictures. These two situations--complete vs. no overlap of resource demands between tasks--are analogous to the right visual field naming trials conjoined with either the noun or dot pattern load tasks that we discussed earlier. Finally, visually presented words or pictures of easily labeled objects may demand some degree of left hemisphere resources, but these types of stimuli might also provide an opportunity to help separate the overlap in demand between resource compositions used for shadowing vs. recognition and thus mitigate to some extent the interfering effects of joint performance. That is, if these visually presented stimuli can be processed as patterns rather than as strictly linguistic entities or referents with labels, then a situation of only partial overlap could exist between the resource demands of the recognition and shadowing tasks. Although treating words and pictures of familiar objects as visual patterns by using a greater amount of right hemisphere resources than "normal" may not as a rule be the most efficient deployment of resources for these stimuli, in this type of dual-task situation it is beneficial.

Electrophysiological measures of cerebral specialization. Some recent data from electrophysiological studies of cerebral specialization also support an independent-resources approach. In the first of these, Poon, Thompson, and Marsh (1976) recorded visual evoked potentials to letter pairs presented to either visual field as subjects decided whether a letter pair had occurred, which is a low level detection task that should be performed equally well by both hemispheres and require relatively few resources, or as they decided whether the letters in a pair were both vowels or consonants, which is a higher level linguistic decision task that we might expect demands primarily left hemisphere resources. They found no difference in evoked potential amplitudes between the hemispheres for the low level detection task, but found that the amplitudes were higher overall in the language task, and within that task, that the amplitudes were higher in the left hemisphere than they were in the right hemisphere. Within the context of our approach, we would say that the evoked potential amplitude recorded to task relevant stimuli should vary directly with the amount of resources required by the task from each hemisphere--in this case, they were highest for the more difficult task when recorded from the hemisphere that was doing most of the processing on that task. While we realize that this may appear to be a rather simple-minded and naive explanation for what are undoubtedly complex relationships between physiological indices of cerebral specialization and information processing during higher level cognitive tasks, a full discussion of these issues is not appropriate in the present context. However, a recent study by Shucard, Shucard, and Thomas (1977) corroborates our claim that the amplitude of the evoked potential can reflect the amount of resources being used by each hemisphere during tasks which vary in difficulty and which therefore can be assumed to require different amounts of resources.

In their study, Shucard et al. (1977) used auditory evoked potentials to pairs of tones as the dependent measure of hemispheric involvement in one of three different behavioral tasks: A baseline task in which subjects had to press a response button simultaneously with both hands whenever they heard a click, a verbal detection and comprehension task in which they heard verbal passages and were required to respond whenever they heard a particular word, and a musical theme detection task, which required the subjects to press the buttons whenever they heard a particular theme in a Bach fugue. In all three tasks, the tone pairs to which the evoked potentials were recorded were superimposed on the binaurally presented task materials, and subjects were told to ignore them and only pay attention to the primary detection task. Thus, in this experiment, we have an interesting situation; the experiment may be construed as a dual-task environment in which subjects are making a conscious effort to respond to one of the three primary behavioral tasks while the second, irrelevant, tone "task" requires (evokes) a presumably automatic response from the brain. Again, the tones are an example of a stimulus which by its mere presence demands and receives resources. Whereas in the Poon et al. (1976) study the evoked potential amplitudes recorded to task-relevant stimuli varied directly with the resources required from each hemisphere, in the Shucard et al. (1977) study, the evoked potential amplitudes recorded to task-irrelevant stimuli varied inversely with the amount of resources required by each hemisphere for the primary task. For example, in the baseline condition, there were no amplitude differences in the evoked responses of the two hemispheres. In the verbal condition, the evoked response to the tone pairs--particularly the response to the second tone--was lower in amplitude in the left hemisphere than it was in the right hemisphere, while the reverse was true in the music condition.[5] From our framework, if performing the verbal task did in fact require primarily left hemisphere resources, then there would be fewer resources (neurons) "left over" to respond to the task-irrelevant tone pairs. Thus, the evoked response may be an important and sensitive measure of the relative utilization of resources between the two hemispheres, as well as being a measure of the allocation of resources within a hemisphere for tasks of varying levels of difficulty.

DISCUSSION

We have described the simplest possible version of a multiple-resources model, in which the existence and number of resource pools has been tied to the anatomical structure of the brain. In so doing, we have been able to account for a large set of data involving perceptual and cognitive information processing, control of motor performance, and changes in electrical activity within the brain. Thus, by assuming that the left and right hemispheres together comprise a system in which there are two pools of mutually inaccessible, finite resources that cannot be made differentially available, we have been able to explain data from experiments employing distinctive and converging measures of cerebral specialization, as well as data from experiments in which issues of cerebral specialization were not of primary concern. Further, these experiments provide strong evidence against the idea that there is only a single, undifferentiated, pool of resources, because "...the multiple resources hypothesis cannot be tested with just one pair of tasks; it requires that several task pairs exhibit disparate behavior (Navon & Gopher, 1979, pg. 248)." The data we have described provide exactly that sort of evidence.

In viewing the two hemispheres as separate pools of resources, we have formulated a cohesive framework that provides a number of insights into the specific mechanisms that could account for why the cerebral specialization literature has been plagued with the problems we mentioned earlier. These include the fact that stimulus, instructional, and other task manipulations readily change performance advantages from one to the other visual field, ear, or hand; the difficulty that exists in replicating results across laboratories and paradigms; the wide range of individual differences observed on indices of cerebral specialization; and the lack of consistency within individuals in the degree of lateralization manifested across time and tasks.

With respect to the first issue, we regard manipulations of stimulus materals, exposure durations, instructions, and other such factors as variables included in the subject-task parameters. These parameters are generally assumed to produce variations in performance, so that manipulating them necessitates considering the possibility that the resource compositions used and hence the underlying performance-resource functions that are relevant may have changed. Thus, variations in performance that occur as a function of these types of task manipulations are, generally speaking, to be expected. For example, instructing subjects to process a stimulus one way or another could change the relative efficiency of using one or another of the resource compositions available as processing options, and thereby change the particular composition that subjects choose to employ. While the sorts of explanations offered by our approach to account for hemispheric differences in performance don't particularly contradict those offered by other investigators, the explanations we offer are an integral part of our framework and are relevant to the entire range of such task manipulations, rather than being able to only address data obtained from a single experimental paradigm.

Second, the difficulties involved in obtaining reliable, replicable data in this field may similarly reflect the fact that tasks can usually be performed with a number of different resource compositions, each of which draws in varying amounts from the resources of the two hemispheres. Tasks that admit of an assortment of resource compositions will tend to be easily influenced by parameter manipulations and may thus produce the most variable results across different populations of subjects. That is, if a task can be performed with a variety of resource compositions, and if subjects differ in the particular types that are available to them as well as in the relative efficiency of each type for performance, then it is no wonder that a phenomenon obtained in one laboratory may fail to be replicated in another. For example, suppose a task like noun recognition could be performed using either primarily left or right hemisphere resources for strategies involving, respectively, phonemic or shape information. If these strategies were more or less equally efficient for some individuals, while being differentially efficient for others, then the particular visual field advantage obtained in an experiment will be a function of the relative proportions of these different types of individuals that have been sampled. Thus, in addition to the fact that tasks vary in the extent to which they demand resources from one or another hemisphere, we assume that subjects vary in the extent to which the resources of one or the other hemisphere will be efficiently applied to performance. Indeed, the most ubiquitous "problem" in the cerebral specialization literature has been the wide range of within- and between-subjects individual differences that have been observed. Attempts have been made to relate these differences to sex (Hannay, 1976; Hannay & Malone, 1976b; Levy & Reid, 1978; Lomas & Kimura, 1976), handedness (Hardyck & Petrinovich, 1977), writing posture (Levy & Reid, 1976, 1978), native language (Teng, Lee, Yang, & Chang, 1979), cognitive abilities (Bogen, 1975; Zaidel, 1979), learning disabilities (Witelson, 1976, 1977), depression, and schizophrenia (Greenberg, 1979). From our framework, all of these factors are included as subject variables in the subject-task parameters. That is, we recognize that individual differences in the factors above are important parameters of information processing, so that it is probably most proper to speak in terms of degrees of lateralization (Shankweiler & Studdert-Kennedy, 1975; Thomas & Campos, 1978) for a given individual under a particular set of circumstances. A multiple-resources view is easily applicable to an individual's performance; moreover, it does not demand that that individual be, for example, strongly "left hemisphere language dominant" across all possible sets of stimulus, instructional, and task manipulations.

Although we are not, at present, concerned with the specific factors responsible for individual differences, there are some investigators who have hypothesized about the mechanisms that may be involved (e.g., Levy and Reid (1976, 1978) suggest that sex differences in cerebral specialization are due to the differential effects of male and female hormones on the development of the nervous system). However, it seems reasonable that individuals can and do differ in the degree to which they are able to involve the resources of the hemispheres in flexible and varying amounts when performing under a particular set of subject-task parameters. Thus, the fact that individuals do differ so widely implies that efforts to delineate what the hemispheres are specialized for may yield conclusions that depend as much upon the particular subjects chosen for study as they do upon whatever experimental environment those subjects have encountered.

Our approach suggests that continued efforts to discover which stimuli, tasks, cognitive styles, etc., are or are not lateralized may be a fruitless endeavor, since the division of labor between the hemispheres is malleable within and between subjects. A more appropriate point of view from which to conceptualize research may be to address how this malleability contributes to the flexibility and efficiency of human information processing. For example, we live in a world in which the amount of potential information to be processed at any particular time is enormous. It may be that having independent pools of resources allows us to process more information simultaneously by limiting the amount that one type of process can interfere with another. That is, if there were only a single, undifferentiated pool of resources, all processes could potentially interfere with each other, whereas if there were at least two types of resources, then there would be minimal interference between processes that could take advantage of these independent resources. Thus, the availability of different resource compositions for processing information may allow for flexibility in processing by providing an opportunity to minimize interference between processes executed simultaneously.

The multiple-resources approach also demonstrates the mutual need of researchers in cerebral specialization and divided attention to be aware of each other's work. For example, as mentioned previously, there are data in the divided attention literature demonstrating either no performance tradeoffs or else "strange" patterns of task interference which could easily be due to both the degree of overlap in the left vs. right hemisphere resource requirements of the tasks as well as to the differing efficiency of resources in the two hemispheres (Allport, Antonis, & Reynolds, 1972; McLeod, 1978; Rollins & Thibadeau, 1973). Similarly, there are a growing number of investigators in the area of cerebral specialization who are attempting to use dual-task methodology to ascertain whether certain processing mechanisms are located in one or the other hemisphere, or how certain task variables, such as memory requirements or required depth of processing, affect performance on tasks presumed to demand the resources of one or the other hemisphere (McFarland & Ashton, 1978; Rizzolatti, Bertoloni, & Buchtel, 1979; Summers & Sharp, 1979). These investigators are explicitly or implicitly using either single-capacity or multiple-resources ideas in interpreting their results. They thus need to become aware of the implicit assumptions they are making and of the consequent methodological issues involved when these assumptions are made. These issues include adequate control of resource allocation, the problems involved in making comparisons between single and dual-task conditions, and the possibility that there is more than one resource composition by which a task can be performed. With respect to this latter point, investigators of cerebral specialization who are using dual-task methodology need to carefully consider whether different possible resource compositions exist that could be used to perform each of their experimental tasks, and whether or not these will be employed at the expense of efficiency for the sake of the utility gained by minimizing resource overlap. For example, McFarland and Ashton (1978) used polygon recognition as a task presumed to require right hemisphere resources and noun recognition as a task presumed to require left hemisphere resources. As we have previously shown, there are many studies indicating that both of these tasks can be performed with a variety of strategies that use the resources of either hemisphere in different proportions (Dee & Fontenot, 1973; Hannay & Malone, 1976a; Hannay, Rogers, & Durant, 1976; Hellige & Cox, 1976; Hellige, Cox, & Litvak, 1979). Thus, combining these tasks may not produce interpretable data in terms of underlying resource requirements, because subjects have so many processing options.

We would urge that investigators of cerebral specialization adopt the strategy of (a) using populations of subjects that have shown the largest and most consistent performance differences between the hemispheres (e.g., right-handed males with no familial history of left-handedness who use a normal rather than an inverted writing posture; Levy & Reid, 1976, 1978), (b) using within-subjects designs, (c) carefully controlling resource allocation in both single and dual-task conditions through various payoff schemes, (d) carefully controlling resource demands by adding tasks or increasing their difficulty in the dual-task situations, and (e) looking at patterns of interference or noninterference across carefully chosen sets of task pairs.

With respect to the last point, we feel that investigators should try to use tasks that either logically or empirically admit of resource compositions that draw primarily from one or the other hemisphere, and for which the processing options are few. Otherwise, when two tasks whose resource compositions draw from both hemispheres are paired, the results may be difficult to interpret. In summary, it may be more informative to study the performance of a few individuals on a carefully selected set of task pairs when resource allocation between tasks is carefully controlled then to try to determine such things as the relationship between lateral "dominance" and scholastic achievement in 4,143 Chinese (Teng et al., 1979).

The major difficulty with an independent-resources approach to cerebral specialization is one that also exists for the broader multiple-resources framework of Navon and Gopher (1979). That is, it should be clear that there cannot be a single, crucial experiment that would support the approach we have proposed and disprove the competing alternatives. In particular, just as the single-capacity model can be rendered as a limited case of the multiple-resources framework (i.e., complete overlap of resource compositions yields the same predictions in both theories), the model of cerebral specalization we have proposed can subsume the competing theories by delineating the conditions under which the same predictions would be made. For example, if the resource composition of a task were such that it demanded a hemisphere-specific resource, we would make the same general predictions as a direct access approach. Similarly, invoking the construct of a concurrence benefit (with, hopefully, a reasonable hypothesis about the nature of the specific processes or mechanisms that could be shared between tasks) would allow us to account for instances in which an improvement in joint relative to single-task performance was observed between tasks requiring the resources of the same hemisphere. The predictions of a selective activation model are thus also subsumed within our approach. How, then, is the theory to be tested, and why, then, should it compel support? Although we acknowledge these as difficult questions, we agree with Navon and Gopher's approach to both of these issues. "In practice, the way to reject the notion of multiple resources, like any other elaboration in conceptualization, is to repeatably demonstrate that simpler approaches suffice to capture (the) empirical phenomena (pg. 249)." It should be patently clear at this point that a simpler formulation of the mechanisms responsible for cerebral specialization phenomena that meets this criterion does not currently exist. Moreover, at least one reason to compel acceptance of what is admittedly a relatively complex and difficult point of view is that when "...the most parsimonious view of the field seems to have proved inadequate; the remaining alternatives are either to augment, patch, and hedge that view to the point that it barely resembles its original form, or to substitute it altogether with a broader, and necessarily more complex, view (Navon & Gopher, 1979, pg. 248)." The second factor that we hope will compel serious consideration of the present proposal is that it represents an effort to bring theoretical structure and concomitant methodological guidelines to an endeavor which has been sorely deficient in both.

In summary, increasing numbers of investigators of cerebral specalization (Hellige & Cox, 1976; Hellige, Cox, & Litvak, 1979; Kinsbourne, 1973; Kinsbourne & Hicks, 1978; Moscovitch, Scullion, & Christie, 1976) have each come to adhere to many of the assumptions and conclusions regarding the interpretation of their data which we have been able to derive from our multiple-resources theory. None of these investigators, however, have tied their assumptions together within a broad theoretical framework, so that like much of the cerebral specialization literature, their data have been explained on an experiment-by-experiment basis. The advantage of our approach is not only that it provides a cohesive theoretical structure, but in addition, it provides explicit guidelines for testing it.

We believe that the approach we have outlined can describe a larger set of data more coherently than any other existing theory. Further, the notion of multiple resource pools in general has been successfully applied to information processing domains usually considered to be outside the sphere of cerebral specialization issues. By extending this approach to cerebral specialization, therefore, it might be possible to effect a marraige between several heretofore disparate domains.

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FOOTNOTES

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1. Throughout this paper, we will be purposefully guilty of a certain degree of anthropomorphism in our use of such phrases as "the ability of the hemispheres," "the resources used by the right hemisphere," "processing on left hemisphere trials," "the right hemisphere allocates resources when it listens to music," etc. Strictly speaking, when behavioral methodology such as visual half field presentations is employed, one does not know for certain "where" information is being processed, and it is most proper to speak of, for example, "processing or resource allocation on right visual field trials." It is a bit more proper to discuss the hemispheres directly when more direct measures of their processing are used, such as the evoked

cortical potential. However, while we do not wish to ascribe homunculi to either hemisphere, we find it easier to conceptualize and address the issues by referring to the hemispheres directly rather than via their respective visual fields, hands, or ears.

2. We assume that in an uninstructed single-task situation, subjects will allocate only the amount of resources they deem necessary to perform the task at hand (Friedman & Bourne, 1976). These amounts of resources will not necessarily be equal to the the amounts required for optimal performance; the actual amount allocated can vary as a function of a subject's motivation, attention, etc. Therefore, without appropriate experimental controls, we cannot necessarily assume that the amount of resources allocated will be the same in a single-task situation as it is in a dual-task situation. Thus, we agree with Kantowitz and Knight's (1976) assertion that the resource allocation functions in a single-task situation are not "merely a limiting case of double stimulation that arises when all of the resource is allocated to one task and none of it to the other (pg. 405)."

3. Note that we are maintaining a distinction between the mechanisms a process uses and the resources required by them. Therefore, our framework as well as Navon and Gopher's combines two previously disparate views of interference effects in information processing and performance. Capacity interference is interference caused by competition for resources, where resources are defined in terms of attention or capacity. Structural

interference is interference caused by competition for a particular mechanism, which may only be able to perform one task at a time, regardless of the amount of resources available to it. The reader is referred to Navon and Gopher (1979) and Wickens (Note 4) for a more complete discussion of these issues.

4. From our framework, there is actually another possible explanation for this pattern of results, given the performance-resource functions displayed in Figure 3. If we a priori assume that in the single task situation the subjects were allocating all of their resources to the balancing task, then the left hemisphere performance decrement could be due to either a "pure" tradeoff in resource allocation between the dowel balancing and sentence repetition tasks or there could have been a concurrence cost in addition to a resource tradeoff, and we could not be sure how much of the decrement was due to trading resources and how much was due to concurrence cost. Similarly, given that all resources are a priori assumed to have been used in the single task situation, an improvement in the left hand could only be attributed to a concurrence benefit.

We prefer the explanation given in the text for several reasons. First, there is no intuitively appealing reason, such as shared mechanisms, why a sentence repetition task demanding resources from the left hemisphere when conjoined with a dowel balancing task demanding resources from the right hemisphere should produce a concurrence benefit, so that using the concept of a concurrence benefit in this case seems a bit ad hoc. It seems more reasonable that an improvement in performance was due to an increase in the amount of resources applied to the balancing task by the right hemisphere as a result of the level of arousal it was forced to assume because of the left hemisphere's involvement in the sentence repetition task. As a rule, if subjects' intended level of performance does not necessitate comandeering all available resources in a single task situation, it should be possible to improve their performance by offering suitable inducements. It should further be noted that performance-resource curves in general are plotted as a function of the total resources potentially available to the system as a whole (L). That is, the concept of a performance-resource function was developed within a single-capacity model and does not reflect the pools from which the resources necessary to perform the are being drawn.

5. Shucard, Shucard, and Thomas (1977) recorded from T3-Cz and T4-Cz (International 10-20 system, Jasper, 1958), while Shucard, Shucard, Cummins, and Thomas (Note 3) in a replication study, recorded from T3-A1A2 and T4-A1A2 sites. Cz is considered to be a relatively active site, while A1A2 (linked mastoids) is considered to be a relatively inactive site. When the results of both studies are considered together, they indicate that the amplitude differences betwen the two hemispheres were due to a <u>decrease</u> in amplitude at T3 (left temporal) relative to T4 (right temporal) during the verbal condition, with the reverse holding during the music condition (see Shucard, Shucard, & Thomas, 1977,

and Shucard, Shucard, Cummins, & Thomas, Note 3, for details).

FIGURE CAPTIONS

Figure 1. Performance-resource functions depicting the relationship between percent of total resources allocated and performance for three hypothetical tasks (Panels a and c), and the POC functions depicting joint performance as a function of the ratio of resources allocated between Tasks X and Y (Panel b) vs. Tasks Y and Z (Panel d).

Figure 2. Hypothetical performance-resource curves for five tasks (A through D and Y). For Tasks A, B, and C, there exists a resource composition exclusive to both hemispheres that can be used to attain some level of performance. Tasks D and Y require a hemisphere-specific resource.

Figure 3. A set of performance-resource curves that could underly right and left-handed dowel balancing performance for right-handed subjects. The curves assume that only the resources of the hemisphere contralateral to the hand performing are relevant to performance.

Figure 4. (a) Data obtained by Hellige and Cox (1976, Experiment 2) for noun naming conjoined with a noun memory load. (b) Data obtained by Hellige, Cox, and Litvak (1979, Experiment 1) for noun naming conjoined with a dot pattern memory load.

FIGURE 1

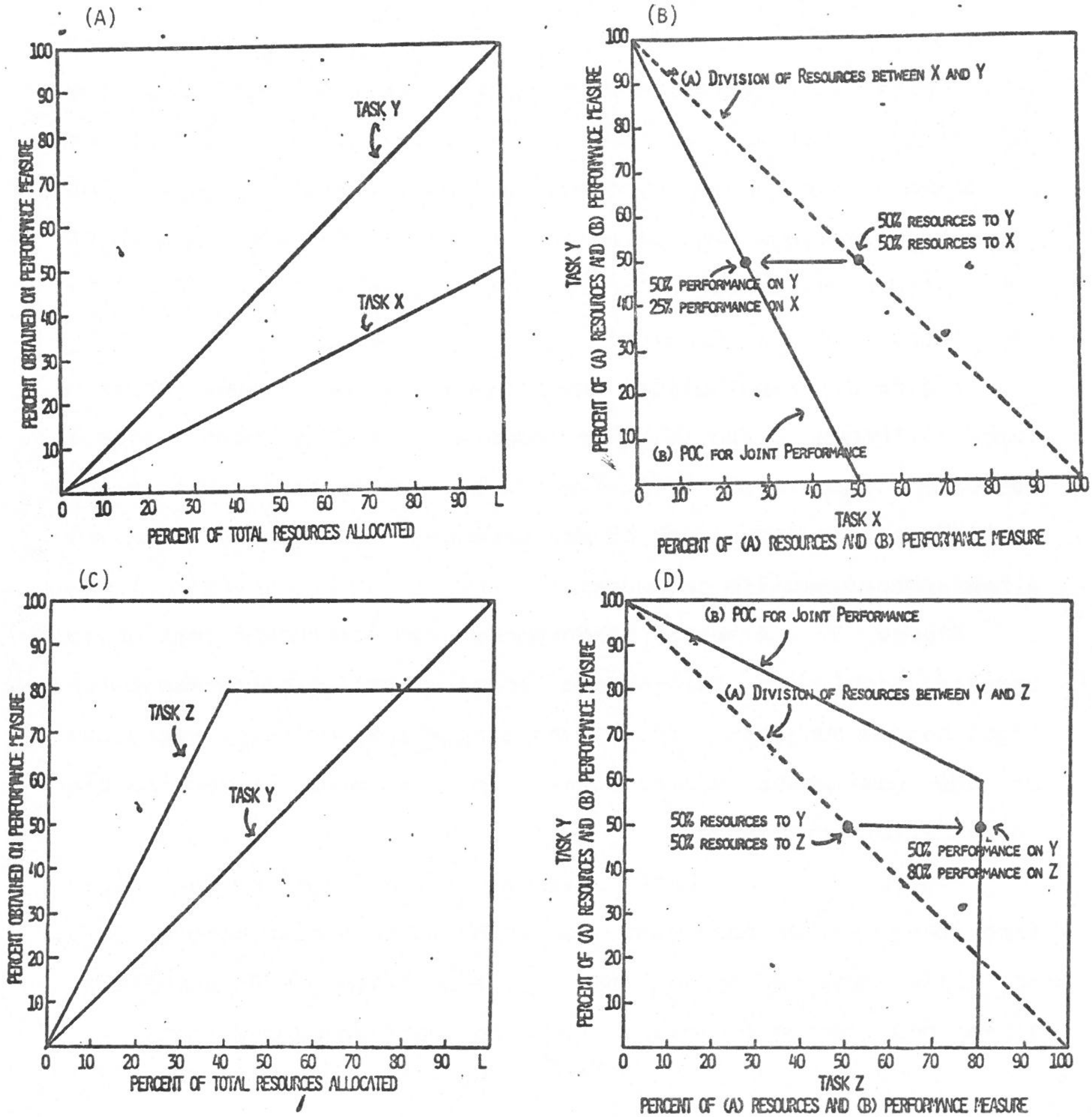
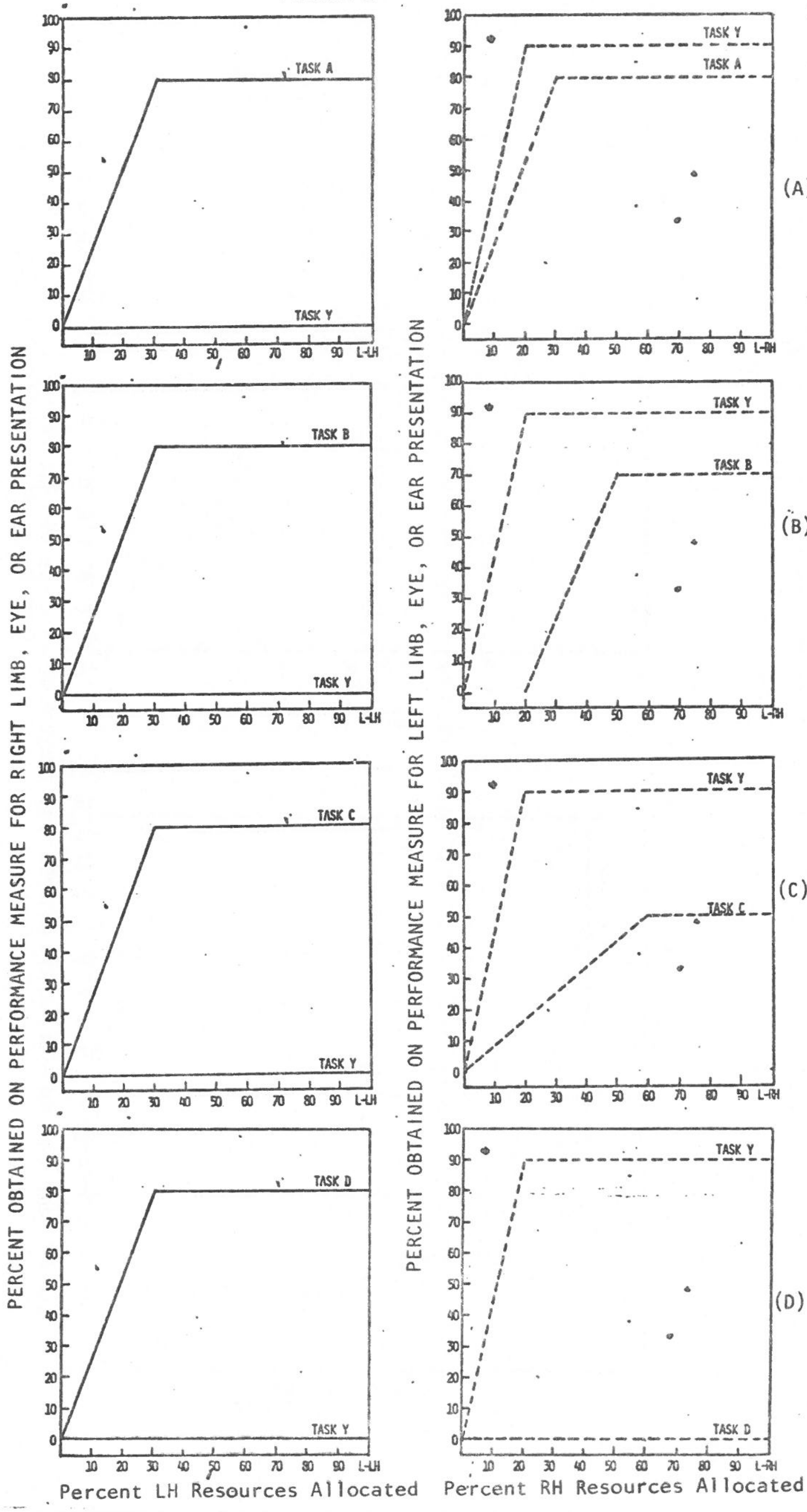
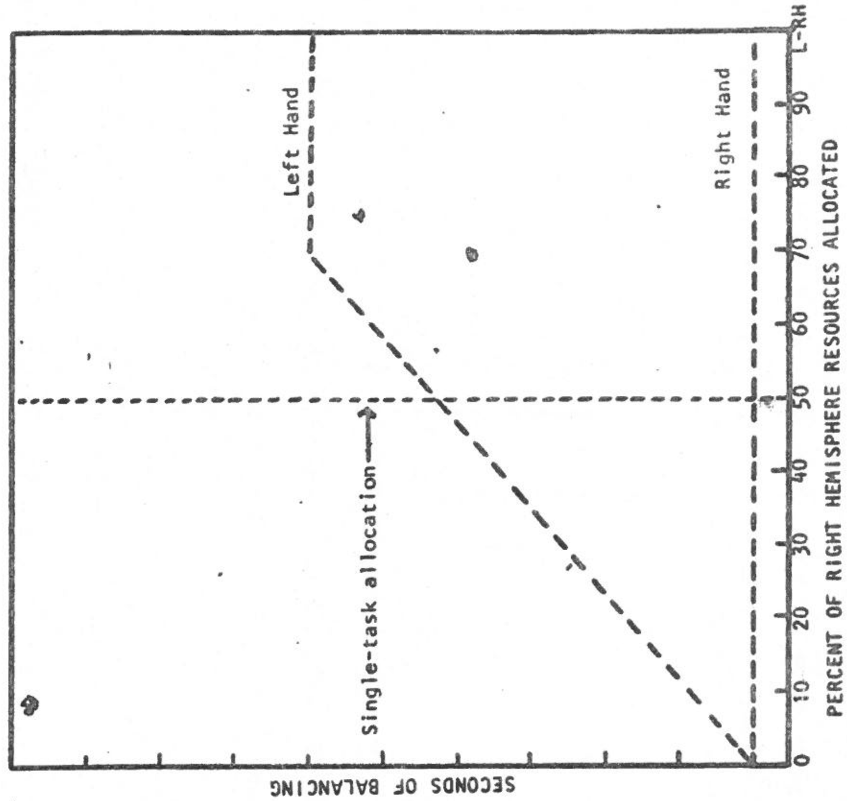

(A)
TASK Y
TASK X
PERCENT OBTAINED ON PERFORMANCE MEASURE
PERCENT OF TOTAL RESOURCES ALLOCATED
(B)
(A) DIVISION OF RESOURCES BETWEEN X AND Y
50% RESOURCES TO Y
50% RESOURCES TO X
50% PERFORMANCE ON Y
25% PERFORMANCE ON X
(B) POC FOR JOINT PERFORMANCE
TASK Y
PERCENT OF (A) RESOURCES AND (B) PERFORMANCE MEASURE
TASK X
PERCENT OF (A) RESOURCES AND (B) PERFORMANCE MEASURE
(C)
TASK Z
TASK Y
PERCENT OBTAINED ON PERFORMANCE MEASURE
PERCENT OF TOTAL RESOURCES ALLOCATED
(D)
(B) POC FOR JOINT PERFORMANCE
(A) DIVISION OF RESOURCES BETWEEN Y AND Z
50% RESOURCES TO Y
50% RESOURCES TO Z
50% PERFORMANCE ON Y
80% PERFORMANCE ON Z
TASK Y
PERCENT OF (A) RESOURCES AND (B) PERFORMANCE MEASURE
TASK Z
PERCENT OF (A) RESOURCES AND (B) PERFORMANCE MEASURE

FIGURE 2



TASK A
TASK Y
TASK B
TASK C
TASK D
(A)
(B)
(C)
(D)
L-LH
L-RH
PERCENT OBTAINED ON PERFORMANCE MEASURE FOR RIGHT LIMB, EYE, OR EAR PRESENTATION
PERCENT OBTAINED ON PERFORMANCE MEASURE FOR LEFT LIMB, EYE, OR EAR PRESENTATION
Percent LH Resources Allocated
Percent RH Resources Allocated

FIGURE 3


Left Hand
Right Hand
Single-task allocation
SECONDS OF BALANCING
PERCENT OF RIGHT HEMISPHERE RESOURCES ALLOCATED
0
10
20
30
40
50
60
70
80
90
L-RH

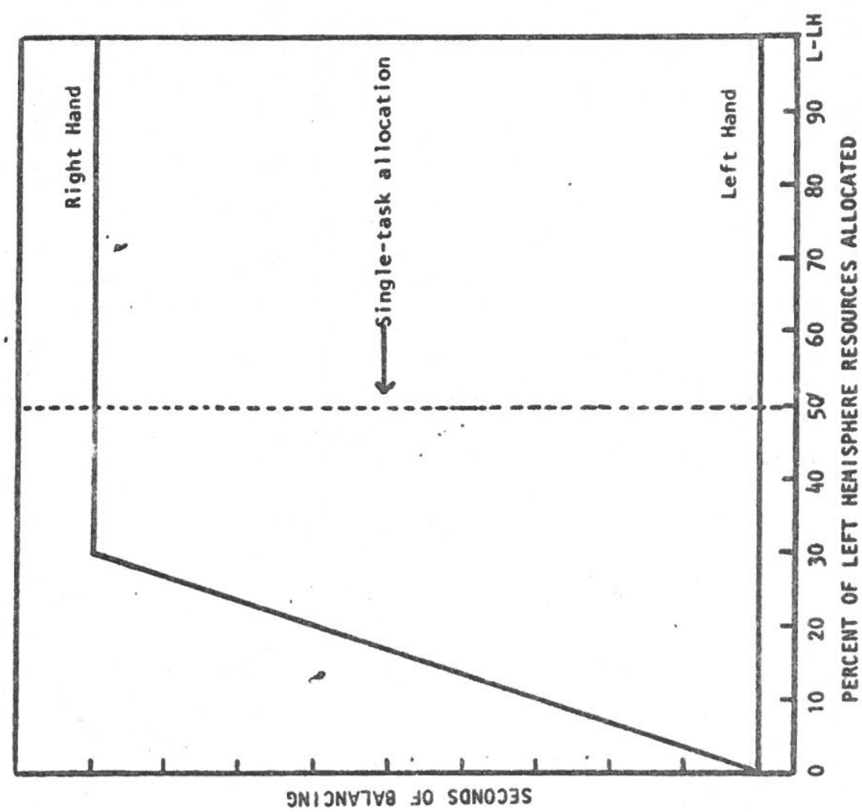
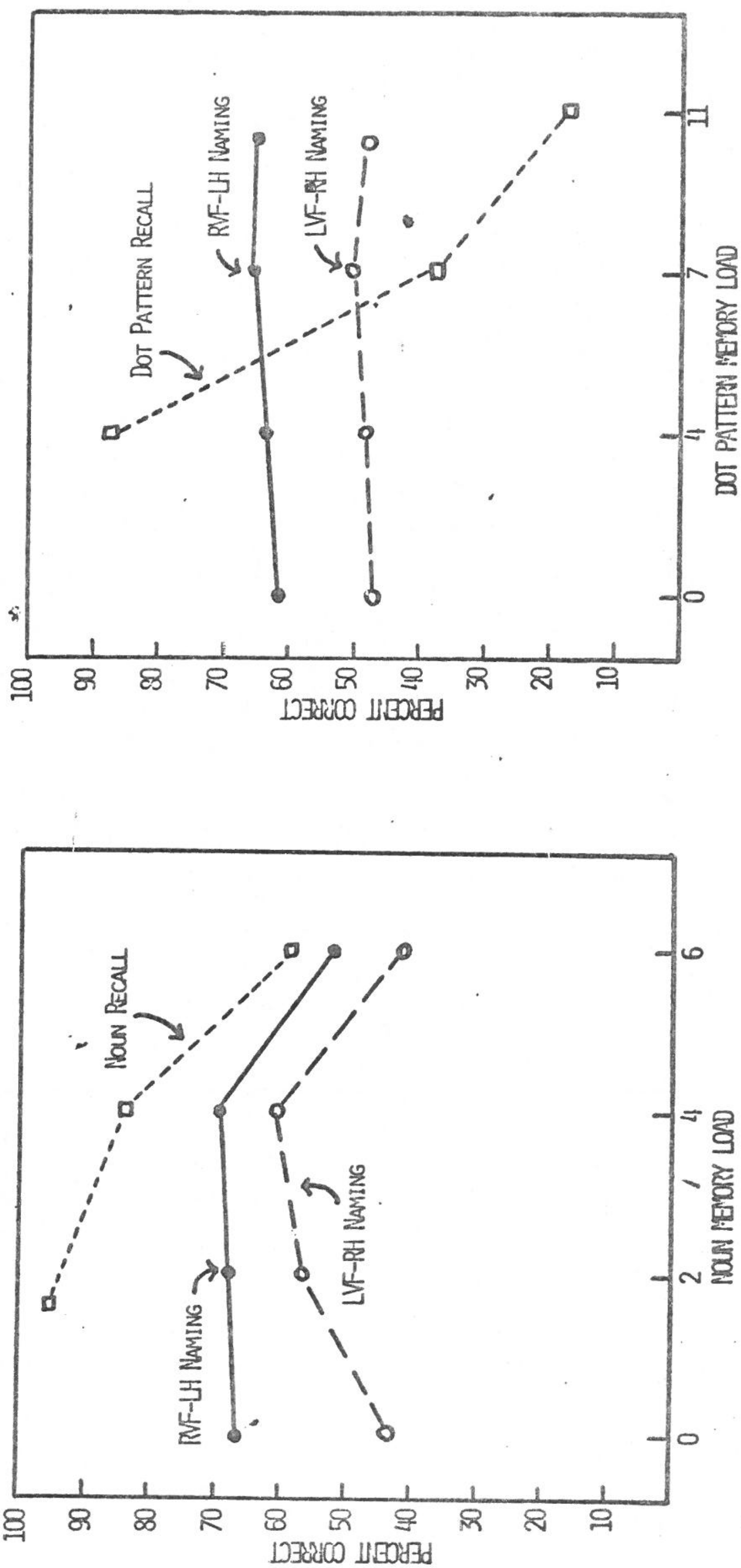

Right Hand
Left Hand
Single-task allocation
SECONDS OF BALANCING
PERCENT OF LEFT HEMISPHERE RESOURCES ALLOCATED
0
10
20
30
40
50
60
70
80
90
L-LH

FIGURE 4


DOT PATTERN RECALL
RVF-LH NAMING
LVF-RH NAMING
PERCENT CORRECT
100 90 80 70 60 50 40 30 20 10
0 4 7 11
DOT PATTERN MEMORY LOAD
NOUN RECALL
RVF-LH NAMING
LVF-RH NAMING
PERCENT CORRECT
100 90 80 70 60 50 40 30 20 10
0 2 4 6
NOUN MEMORY LOAD

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