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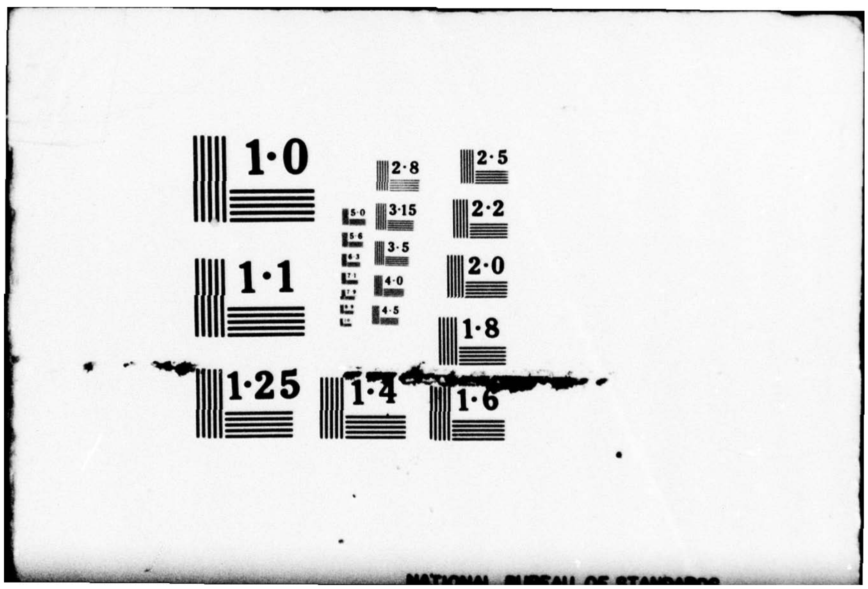
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Mental Imagery

The Status of Arguments Concerning Representations for Mental Imagery[1]

John R. Anderson
Department of Psychology
Yale University
New Haven, Connecticut 06520

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A review is provided of the recent debates over whether pictorial-like or propositional-like representations are most appropriate for visual imagery. The argument for a propositional representation has largely taken the form of an attack on the logical coherence of pictorial representations. These attacks have not been valid; one can develop a coherent dual-code model involving pictorial and verbal (non-propositional) representations. On the other hand, empirical demonstrations that are claimed to support pictorial representations fail to provide evidence that would discriminate such representations from propositional ones. It is argued that the failure of the anti-pictorial and the pro-pictorial arguments stems from a fundamental indeterminancy in deciding issues of representations. It is shown that wide classes of different representations can be made to yield identical behavioral predictions. In particular, this potential for mutual mimicry holds between propositional and dual-code (pictorial-plus-verbal) models. If one considers criteria such as parsimony and efficiency in addition to prediction of behavior, it may be possible to establish further constraints on representation. In particular, it may be possible to establish whether there are two codes, one for visual information and one for verbal, or whether there is a single abstract code. However, the conclusion of this paper is that, barring decisive physiological data, it will not be possible to establish the character of an internal representation -- e.g., whether it is pictorial or propositional.

Abstract

A review is provided of the recent debates over whether pictorial-like or propositional-like representations are most appropriate for visual imagery. The argument for a propositional representation has largely taken the form of an attack on the logical coherence of pictorial representations. These attacks have not been valid; one can develop a coherent dual-code model involving pictorial and verbal (non-propositional) representations. On the other hand, empirical demonstrations that are claimed to support pictorial representations fail to provide evidence that would discriminate such representations from propositional ones. It is argued that the failure of the anti-pictorial and the pro-pictorial arguments stems from a fundamental indeterminancy in deciding issues of representations. It is shown that wide classes of different representations can be made to yield identical behavioral predictions. In particular, this potential for mutual mimicry holds between propositional and dual-code (pictorial-plus-verbal) models. If one considers criteria such as parsimony and efficiency in addition to prediction of behavior, it may be possible to establish further constraints on representation. In particular, it may be possible to establish whether there are two codes, one for visual information and one for verbal, or whether there is a single abstract code. However, the conclusion of this paper is that, barring decisive physiological data, it will not be possible to establish the character of an internal representation--e.g., whether it is pictorial or propositional.

There is no need to document the historical importance of imagery to philosophical and psychological discussion nor the important place it has in current cognitive psychology. There is also no need to review the long debate over the status of the concept of imagery. Ample reviews of these matters exist in other places (e.g. Anderson & Bower, 1973; Bower, 1972; Bugelski, 1970; Fodor, 1975; Kosslyn & Pomerantz, 1976; Paivio, 1971, 1976; Pylyshyn, 1973; Richardson, 1969). This paper is concerned with analyzing some recent developments in the debate over the status of mental imagery. There are those (e.g. Cooper & Shepard, in press; Paivio, 1976; Kosslyn & Pomerantz, 1976), who argue that visual imagery is encoded in terms of properties that are quite spatial and modality specific. This position is referred to as the "imagery position." (This terminology will be continued here, although it is a potential source of confusion. The issue at stake is not whether imagery exists, but what mental representations underlie it.) On the other side of the issue are the propositional theorists (Anderson & Bower, 1973; Chase & Clark, 1972; Pylyshyn, 1973, 1976; Reed, 1974) who argue that imagery is encoded in an abstract propositional format and that this same format is used to encode verbal information. In contrast, the imagery theorists want to make a sharp distinction between the codes used for verbal and visual information. The principal purpose of this paper is to provide a critical analysis of the arguments given for both sides of this debate.

This paper will have the following structure: First, I will attempt to specify what a propositional theory is and what an imagery theory is; second, I will consider those arguments that have been made against an imagery position; third, I will consider those arguments that have been made for the imagery position; finally, I will take a more abstract look at these issues and consider what evidence might be useful in deciding between the two positions.

The central thesis of this paper is that arguments concerning the representation of information have been misdirected. Any claim for a particular representation is impossible to evaluate unless one specifies the processes that will operate on this representation. Arguments for or against a particular representation are only valid assuming a particular set of processes. These arguments are not valid assuming other processes. Pylyshyn (in press) has made this point that a theory must be considered as a representation plus process. As he writes:

> ...the appropriate subject of our analysis of representation should be not the representation per se but a representational system consisting of the pair (representation, process)...

Despite this common realization, Pylyshyn's conclusions about the representation for imagery will be different than mine.

Defining Our Terms

The Concept of a Proposition

It is classically accepted that there are three features that define a proposition (e.g., Frege, 1960). It is abstract; it has a truth value; and it has rules of formation. Abstractness is a concept originally defined with respect to sentences. A proposition can be denoted by a sentence but is more abstract than the sentence. It is not tied to the particular features of the sentence. Therefore, the attempts to equate "propositional" with "verbal" are fundamentally wrong. The notion of abstractness is related to a concept of invariance under paraphrase--see Schank (1972) or Norman & Rumelhart (1975). This is the idea that all linguistic paraphrases or cross-language translations would be assigned the same propositional representation. The concept of invariance under paraphrase is not part of the classical definition of a proposition and is in dispute (see Anderson, 1976; Woods, 1975). Nonetheless, it is the case that all propositional formalisms practice some degree of invariance under paraphrase.

The notion of truth values means that propositions are things about which it makes sense to inquire whether they are true or false. Propositions are analyzed as bearers of truth value in logic from which propositional representations were imported into psychology. However, use of propositional theories does not imply a psychological theory of meaning based on the concept of truth.

The structural aspect of propositions mean that there are an explicit set of rules for determining what is a well-formed proposition or not. In logic rules of inference are framed with respect to these structural properties. In psychology cognitive laws are formulated with respect to these structural properties (see Anderson, 1976; Anderson & Bower, 1973; Fredericksen, 1975; Kintsch, 1974; Norman & Rumelhart, 1975, for some examples of cognitive laws so formulated).

While there do exist agreed upon criteria for a propositional representation, these criteria lack the character of operational definitions. Therefore, it is not a cut and dry matter to decide if a particular representation is propositional. I will try to follow what has become standard usage in the propositional-imagery debate. This usage would include as propositional representations such things as Quillian's (1969) associative network, Schank's (1972) conceptual dependency, or Winograd's (1977) SHRDLU data base. In each case the representation is abstract, has at least minimal rules of formation, and the units of representation can be seen as having truth values. I mean to exclude arrays, pictures, S-R bonds, unstructured associations such as proposed by the British associationists, procedures, and simple list structures. With respect to the list structure possibility: Many computer implementations represent propositions as list structures. It potentially could be a problem to decide exactly when a list structure attains the status of a proposition, although this ambiguity does not seem to arise in practice. One possible criteria for propositional list structure is that it have clearly identifiable predicate and argument constituents.

The Concept of an Image

No one seems to deny that there is a phenomenon called mental imagery. On the other hand, there is considerable debate over whether there is a useful representational construct called an image. Just what an image is thought to be, however, is a sore point. Generally, image theorists ascribe to images properties very much like the properties that are given in phenomenological reports by subjects while experiencing a visual image. Thus, these theorists' use of the term "image" might be construed as an attempt by them to make phenomenological features the primitives of the psychological mechanism that accounts for these phenomenological reports and for other relevant data on use of imagery. In contrast, propositional theories must attempt to derive such imagery reports from mechanisms which do not have much in common with the phenomenological reports.

The paper by Pylyshyn (1973) was important in highlighting a number of issues concerning the role of an image as an explanatory concept. He argued that the underlying notion of an image is built on the metaphor of a picture:

> The whole vocabulary of imagery uses a language appropriate for describing pictures and the process of perceiving pictures. We speak of clarity and vividness of images, of scanning images, of seeing new patterns in images, and of naming objects or properties depicted in images. (p.8)

Pylyshyn and Anderson & Bower have criticized this picture-metaphor model of an image on many counts including that it makes predictions which have been empirically disconfirmed, that there are internal inconsistencies in the use of this model, that there are better models for many phenomena, and that the model involves many inelegant, unpalatable assumptions.

However, Kosslyn and Pomerantz (1977) and Paivio (1976) have argued that the picture-metaphor is a straw man, that few imagery theorists support such a metaphor in any literal sense. They concede that the picture-metaphor is not defensible. As Paivio writes:

> The wax tablet of picture metaphor is open to the kinds of criticisms that were directed at it over the ages. Today, however, they are largely directed at a straw man because no imagery researcher accepts the metaphorical view as a working theory. (p.2)

Kosslyn & Pomerantz write:

> Pylyshyn's attacks are based on a particular definition of imagery, namely the picture-in the-head hypothesis. We agree with Pylyshyn that this approach is untenable but fail to see what is gained by attacking such a strawman. No serious student of imagery holds this view. (p.57)

The problem is that imagery theorists have failed to say precisely what an image is. It is somewhat hard to debate about the status of an object when no one will specify what the object is. Both Paivio and Kosslyn & Pomerantz propose that an image of an object may be equated to the product of perception of the object, and they distinguish this representation from a picture. However, the current state of knowledge about perception is inadequate to decide the appropriate representation for an image. Also it is the case that the propositional theorists (e.g. Anderson & Bower, 1973; Palmer, 1975; Pylyshyn, 1973) want to equate the output of perception with a propositional representation. So they too endorse the claim that imagery and perception have the same representation.

Consider some of the other explications of an image offered by Kosslyn and Pomerantz:

> ...images are like surface displays generated on a cathode ray tube by a computer... (p.70)

> Images, once formed are wholes that may be compared to percepts in a template-like manner. (p.66)

What is a display on a cathode-ray tube or a template but another name for a spatial array of light information? What is a spatial array of light information but a picture? It seems that the picture-metaphor is the only available model of imagery. By "picture" I mean some format that represents information as a spatially structured array of light information. Consider the recent model by Kosslyn & Shwartz (1977). This computer simulation model is clearly the most concrete theory by anyone in the imagery camp. In this model, an image is represented by a set of points encoding the location in two-dimensional space of the contour points of an imaged object. Clearly, such a representation is "pictorial" in my sense.

Thus, it seems the picture metaphor is the imagery theory. Moreover, I think all sides have been premature in abandoning the picture metaphor. What I would like to do is to consider a semi-explicit picture model and show that it is not susceptible to the criticisms typically made of such a model.

What I want to defend is not simply a picture model, but that model as a part of a larger theory. This larger theory is basically the dual code model of Paivio (1971). He proposed that there are two types of information representations, visual and verbal. The visual representations I will equate with pictures. The verbal information will be equated with word strings. These words strings can be thought of as acoustic objects temporally structured, although this interpretation is not essential to what follows. What is important is that they not be interpreted as abstract propositions. I think it is a correct reading both of Paivio's exposition of his theory and of the attacks on it by the propositional camp that nothing in his theory can be considered abstract propositional. It is important that the theory I propose be faithful to the Paivio position. If it is, it definitely should be clear that I have not bolstered the power of a picture theory by sneaking in propositions.

A Verbal-Pictorial Dual Code Theory

The picture model I will discuss is also somewhat similar to the idea of Kosslyn and Shwartz. The principal difference is that my model is motivated purely to provide a counter-example to anti-imagery claims. Therefore, it contains some "outrageous" suggestions which I would probably want to modify were I to advance this model as a serious proposal. The point of the model is not its plausibility, but rather how a very "brazen" picture model cannot be disconfirmed. If this model is not subject to any difficulties, presumably models like that of Kosslyn & Shwartz, constructed with more concern for the prevailing sensitivities of the cognitive community, will also not be subject to decisive contradiction.

Images will be interpreted as <u>m</u> x <u>n</u> arrays of dots where each dot can be specified according to color and intensity. We will also have as a different storage medium (principally for verbal information) strings of words. There will also be directed associations that can connect strings and pictures.

Consider how we might represent the chessboard of an end game position in Figure 1. Figure 2 shows a possible representation. Note that the situation has been broken into a number of overlapping images connected by associations (arrows). This illustrates that a single external situation may be represented by a number of images. A possible motivation for this fragmentation is the fact that there may be capacity limitations on the amount of information that can be held in a single image. Note also that there are portions of the chessboard not represented. This illustrates the fact that images need not be complete. Note also that the black king is inaccurately located. This illustrates the fact that imaginal representations need not be veridical. Note also the verbal strings like "knight attacks king" are tagged to the images. This is one way of providing meaningful interpretations to the image.

Insert Figures 1 and 2 about here

A final feature to note of this representation is that the picture unit tends to segment out meaningful, coherent subunits of the picture.[2] This segmentation reflects the operation of perceptual procedures which encode and interpret the original object. One can think of these as perceptual chunks such as discussed by Chase & Simon (1973). So, as the imagery theorists would postulate, this representation is identified with the output of the perceptual routine.

The representation in Figure 2 seems a faithful embodiment of the dual code theory proposed by Paivio (1971). That is, there is a pictorial code, a verbal code, and connections between the two. Armed with this dual code model let us consider some of the criticisms that are made of images and of their role in dual code theories.

Criticisms of Picture Theory

Images are Pre-interpreted

One frequent criticism made of imagery theories is that images behave as if they were interpreted whereas pictures (just arrays of light information) cannot:

> ...one's representation of a scene must contain already differentiated and interpreted perceptual aspects. In other words, the

> representation is far from being raw, and so to speak, in need of 'perceptual' interpretation. (Pylyshyn, 1973, p.10)

> We would argue that people store perceptual interpretations of scenes rather than 'raw, unanalyzed, textured details' of such scenes. (Anderson & Bower, 1973, p.453).

Pylyshyn points out some of the many ways in which our memory for an image behaves as if it were interpreted. We can immediately retrieve an image directly from a meaningful description like "my living room." This is not to be expected if we had to scan through a series of pictures. However, it is a feature of the representation in Figure 2 that it can be accessed via verbal labels. The associative interconnections between strings and pictures basically provide this conceptual indexing.

Pylyshyn also notes that we can access meaningful parts of an image such as "the light fixture in my dining room" and that when we forget part of an image we tend to lose a meaningful part and not a physical portion of the picture that might cross many meaningful units. However, the representation in Figure 2 is organized into meaningful units--producing access to meaningful parts and a potential for loss of meaningful parts.

It is argued that it is wasteful to perceptually analyze a scene but to store only the raw scene rather than the analysis. The scene analysis will have to be performed again when the scene is retrieved. There are two remarks that can be made about this objection. First, perceptual interpretation does not seem very costly for the human system. So it is relatively insignificant whether it has to be performed again. Second, there is no reason why the output of the perceptual process might not be a representation like that in Figure 2--that is, segmented into subpictures with relations indicated among these subpictures, but the structure of the subpictures not analyzed.

It is clear from considering these objections that the representation in Figure 2 is "interpreted." This interpretation is provided by the network of associations. So, there is nothing incompatible between the concepts of a picture memory and an interpreted memory.[3]

Capacity Limitations

It is argued that the storage demands to encode these pictures would be enormous and exceed the capacity of the brain. However, given current ignorance about the capacity of the brain this remark has virtually no force. It is also possible in the dual code model of Figure 2 to reduce the storage demands by choosing a crude grid or by incompletely representing the objects. It is also worth considering the storage demands of alternatives to a picture model. For instance, consider the Baylor (1971) model advocated by Pylyshyn. This model requires separately representing every vertex, line, surface, and object (and some of these redundantly) in Baylor's I-space and S-space.

The demands of such a representation also seem very large. The simple fact may be that there is a great deal of information in an image and any representation of an image will have to acknowledge this fact.

Representation of Vagueness

Information can be represented vaguely in a picture, but it is claimed that the character of the vagueness does not match the character of vagueness in introspective reports of images. A picture can be of poor resolution but the vagueness of human images seems inexplicable in terms of simple resolution. For instance, Pylyshyn points out that we may be able to recall what objects were in the room without recalling their exact spatial location. A poor resolution picture of the room is more likely to preserve relative spatial information than to preserve object identity.

However, this is not an insurmountable problem with the picture metaphor. Consider again the representation in Figure 2: It is possible to have two subpictures of the chessboard sections without encoding their relative spatial location or with only encoding the relation as "beside," not specifying whether to the right or left.

Anderson & Bower (1973) also wondered how it is that one could remember that a lamp was in the room without being able to recall any details about the appearance of the lamp. This phenomenon has multiple possible explanations within a dual code model. It is possible that we have stored the verbal label "lamp" rather than the picture in our scene description. Another possibility is that we have stored a picture but have also tagged that picture with "uncertain" or some other label to indicate we should not take the visual details seriously. This might be done if the transmission of information from the scene to the lamp encoding was not accurate. Yet another possibility is that we have replaced the actual lamp with a picture of a prototypical lamp. Recognizing that this is a prototypical lamp, the system is not willing to use this as a basis for reporting details about the particular lamp we saw. It might be more efficient to use a prototypical lamp than the actual lamp if it was easier to transmit information from the internal representation of a prototype than from an external scene. The possibility of an uncertain lamp or prototypical lamp illustrates an important possibility that has not been frequently recognized in the debate over imagery. This possibility is that there is internal information (i.e., the uncertain lamp or prototype) which subjects cannot report.

Metaphors are Misleading

Another criticism that Pylyshyn levels against the picture metaphor is that it is misleading, that it causes people to postulate mental processes from analogy to operations we can carry out on pictures:

> For example, one misleading implication involved in using the imagery metaphor is that what we retrieve from memory when we image, like what we receive from our sensory systems, is some sort of undifferentiated (or at least not fully interpreted) signal or pattern, a major part of which (although perhaps not all) is simultaneously available. This pattern is subsequently scanned

> perceptually in order to obtain meaningful information regarding the presence of objects, attributes, relations, etc. (p.8)

However, it is an open question whether the metaphor is misleading. In particular, results such as those of Kosslyn (1973) on scanning or Shepard (1975) on mental rotation of images would seem to imply the metaphor leads one in quite fruitful paths.

Semantic Effects in Picture Memory

Anderson & Bower made much of the evidence that pictures are remembered better when they can be interpreted. DeGroot (1965) finds better memory for meaningful chess positions. Wiseman & Neisser (1971) find better memory for Mooney pictures that subjects manage to meaningfully interpret. Bower & Karlin (1974) report similar results. Goldstein and Chance (1970) have shown poorer memory for snow flakes, which permit little meaningful structuring, than for faces which do. These results are certainly contrary to claims (e.g. Bugelski, 1971) about the mnemonic superiority of the image system, but they really say little about whether pictures are used as a medium of storage. It is quite possible that pure pictures are a poor storage medium. It may be that some meaningful structure as in the chessboard of Figure 2 is needed for good memory. Perhaps retrieval schemes require verbal labels to provide access routes.

Summing Up the Picture Metaphor

In conclusion, it has not been shown that there is anything incoherent, contradictory, or impractical in using pictures as a representational format. Whether pictures are suitable depends on the processes that one assumes operate on them. To be sure, one can assume inadequate processes for a picture representation (e.g., a forgetting process that consisted of fading rather than loss of meaningful subparts) as did Anderson & Bower, Pylyshyn, and even some of the image theorists. But, then again, one need not.

Propositional Representations

Besides the supposed empirical and logical inadequacies of picture theories an independent line of argument against them is that picture representations are unnecessary. This argument has two subclaims. First, it is argued that a propositional representation is essential on independent grounds. Second, it is argued that a propositional representation can handle all the phenomena ascribed to a pictorial representation. Therefore, on grounds of parsimony it is unnecessary to assume pictorial representations in addition to propositional representations. This argument would have some validity if both subclaims were true. However, the first subclaim has not been established.

Are Propositional Representations Necessary?

Pylyshyn argues that it is necessary to propose a propositional code to explain how it is that people can describe pictures in words or create pictures to illustrate verbal material. Similar proposals for an interlingua have been made by Clark & Chase (1972), by Anderson & Bower (1973) and by Fodor (1975). The abstract propositional code would serve as a neutral format into which and out of which pictorial and verbal information could be translated. It serves as a "half-way house" for the process of translating between the two peripheral codes. As Pylyshyn (1973) writes:

> ...the need to postulate a more abstract representation--one which resembles neither pictures nor words and is not accessible to subjective experience--is unavoidable. As long as we recognize that people can go from mental pictures to mental words or vice versa, we are forced to conclude that there must be a representation (which is more abstract and not available to conscious experience) which encompasses both. There must, in other words, be some common format or interlingua... (p.5).

However, this argument is flawed with a serious internal inconsistency. It is argued that to translate from code 1 to code 2 it is necessary to translate code 1 into a new code, code 3, and from code 3 to code 2. However, if true, this would lead to an infinite regress. To translate from code 1 to code 3, a new code 4 would be needed and so on. It is simply not the case that it is necessary to have a propositional or any other intermediate code for translation. By careful analysis, it might be possible to show that an interlingua makes the translation process more efficient, but such an analysis has not been forthcoming.

Another argument used by both Anderson & Bower and by Pylyshyn is that a propositional code is needed to represent meaning. For instance, Pylyshyn argues that one needs this code to represent a relation like "attacked-by" in a chessboard. His example inspired Figure 2 which shows this information can be represented by verbal strings. The "meaning" can be contained in the processes that interpret the strings.

Anderson & Bower argue that a propositional code is needed to deal with the considerable evidence that subjects tend to remember only the meaning of sentences and not their exact wording. So, for instance, subjects show confusion about whether they heard an active sentence or the passive equivalent (Sachs, 1967). There are any number of explanations of the phenomena which do not require postulations of a propositional code. First, one could propose that subjects represent these sentences in memory by pictures (e.g. a picture of a boy hitting a girl). Such pictures would represent the meaning but not the original form. Another possibility is that subjects convert various sentences to a common string format. So all sentences might be represented as active. The processor, knowing this, would be smart enough not to use the form of the string in memory as a basis for judging the form of the string that was studied. Another possibility is that the exact string heard is stored in memory but the processor does not pay attention to the difference between active and passive sentences because normally this is not important.

Power of a Propositional Code

It seems to be a generally accepted claim that any well-specified set of information can be represented by a set of propositions.[4] Thus, propositions can represent any information in an image or in a sentence or information from any other source. One might argue from this fact that propositional representations are appropriate for representing images. To my knowledge, no one has explicitly made this argument although Kosslyn and Pomerantz ascribe it to Pylyshyn. The counter argument is obvious: Even if all information can be represented propositionally, it does not follow that the propositional representation will lead to the correct empirical predictions.

The power of propositional representations has been used by Kosslyn and Pomerantz to argue against them:

> The problem with propositional theories, on the other hand, is that they may be too powerful. They possess no inherent constraints, and the theorist must add restrictions onto his theory to make it conform with experimental observations. The propositional language is so powerful that one can use it to formulate almost any kind of theory that one desires, predicting with equal ease, it would seem, any experimental finding or its converse. (p.62)

I will return to this question of the plasticity of representations later in this paper to give it a more thorough examination. However, at this point a specific rejoinder is required to this criticism: A representation without any process assumptions is not a theory. By making different process assumptions it is possible to have quite different theories with the same propositional representation. We cannot test representations but only representation-process pairs. It is not an argument against a representation-process theory that there happens to be a different theory with the same representation but different process that makes the opposite prediction.

Propositional Representations and Inference-Making

It is sometimes assumed (e.g., Anderson, 1976; Anderson & Kline, 1977; Fodor, 1975; Pylyshyn, 1973) that there is a particular affinity between propositional representations and the task of making inferences. The claim is that propositional representations are particularly well-suited for the operation of inference making. Propositions, because of their abstract truth-bearing character only represent what is necessary to judge the validity (or plausibility) of an inference. There can be, therefore, a reduction in the complexity and/or number of inference rules if they are formulated in terms of propositions. For instance, most propositional systems would represent active and passive sentences identically. Anything that follows from an active also follows from a passive. A propositional system avoids the need to have separate inference rules for actives and passives. This is probably the reason why almost every artificial intelligence program for making inferences uses some variety of a propositional data base.

However, these considerations do not force the conclusion that human inference making is done in terms of abstract propositions. It may be the case that while artificial intelligence programs are capable of such abstraction, humans are not. In fact, there is some evidence that the human system is not capable of such abstraction: It has been shown that semantically-irrelevant linguistic details of an argument affect the time and success of making a valid conclusion (e.g. Clark, 1969; Rips & Marcus, 1976). While these data can be interpreted within a propositional model, they do serve to deflate claims about the advantage of propositional representations in abstracting out only truth-relevant information for inference making.

Pro-Imagery Arguments

So far, we have considered arguments against imagery theories and arguments for propositional representations. These two types of arguments define the "anti-imagery" position. Now I would like to turn to the consideration of the arguments that have been made for imagery theories. By "imagery theories," I mean theories based on the picture metaphor. As noted earlier, this is the only explicit interpretation available for the concept of an image.

Computational Advantages of Imagery Representations

Kosslyn and Pomerantz argue that, while the same information can be represented via propositions or images, it is easier to perform certain types of computations on images. Therefore, images have a computationally useful function. It is further assumed that, if something is useful, it is likely to be found in the human head. I will be making a similar argument for efficiency considerations later in this paper. A basic problem is that claims about one representation being more efficient than another are always based on implicit assumptions about the processes to be used with the two representations. With other process assumptions these claims may no longer be valid.

Kosslyn & Pomerantz present an example to make their point. They contrast two formats for representing geographical information: a map with cities on it versus a chart of intercity distances. The first is thought of as similar to an image representation and the second as more similar to a propositional representation. They claim that these are "isomorphic" to each other in all important respects since they contain identical information and either one can be generated from the other (p.60). (This is not totally true in that north-south orientations cannot be recovered from the chart.) They claim that different types of computations are appropriate to the two representations:

> If we want to know quickly whether three cities fall on a straight line, we consult a map; if we want to know the total distance of an air flight from New York to Los Angeles to Miami we consult the chart. (p.61)

However, these claims are only true assuming a particular algorithm on a particular device. There is a relatively simple algorithm for solving the first problem given chart distances: See if two of the distances sum to the third. In some implementations, this algorithm would be more efficient than any map scanning operation. Conversely, if it were difficult to add the distances, but one had a string marked off so as to translate string length into miles, the second problem might be better solved with the map.

So it is not possible to decide issues of efficiency of a representation without knowledge of the procedures that will be operating on them. However, later I will be arguing a point somewhat similar to Kosslyn & Pomerantz which is that efficiency considerations may lead to the need for specialized representations. In contrast to Kosslyn & Pomerantz, I do not think we can decide on the nature of the specialized representations.

Arguments Based on Introspection

Introspections probably provide the most intuitively compelling evidence for the existence of a picture-like image code and for the distinction between this code and a verbal code. Many people find introspection about the picture-like quality of imagery extremely striking. Of course, there are those who report little or no such introspective experience. Informal count seems to indicate that these non-picture-imagers tend to be the doubters of imagery theory. As scientists, however, we must go beyond the intuitive force of our internal experiences and ask what is the logical force of the presence or absence of such introspective reports. The introspective reports are data that require explanations like any other data. However, there is no reason to suppose that the best representation to account for verbal reports of picture-like properties of an image is a picture.[5] A computer program could be written to deliver such reports from a propositional data base (for instance, see Moran, 1973). The tendency to assume a picture representation to account for reports of pictures illustrates a wide-spread fallacy in discussions of representations that the best way to explain data with property P is to assume a representation with property P.

Arguments for Imagery From Experimental Demonstration

Most imagery theorists do not base their position on such introspective evidence--at least not publically. Rather, they will marshall a large series of experiments to support their position. Therefore, it is important to consider some of the classes of data presented and to evaluate the ability of these to decide issues of internal representation. An early class of data concerned the supposed superior mnemonic capacity of the imagery system--better memory for pictures or for imaginable words, better memory under instructions to image, etc. The culmination of the line of evidence is Paivio's (1971) book which provides an extensive review. It appears that reliance on such data is waning. One reason for this waning is that further evidence has indicated that the pictorial material is not superior to verbal material. First of all, verbal material when "deeply processed" can display similarly high levels of memory (Anderson & Bower, 1973; Anderson, 1976; see Craik & Lockhart, 1972 for a general discussion of levels of encoding). Second, the good memory for pictorial material only seems to apply when that pictorial material can be meaningfully interpreted (Anderson & Bower, 1973; Bower & Karlin, 1974; Goldstein & Chance, 1971; Mooney, 1959; Wiseman & Neisser, 1971).

There now appears to be a second generation of research to support the imagery approach. This research is more concerned with operations on images in immediate memory rather than the treatment of images in long-term memory. The logic of this research has been succinctly analyzed by Shepard and Podgorny (in press). The attempt is to show that when subjects process objects mentally the functional consequences for behavior are quite similar to those when subjects process the actual objects. This is evidence that the mental or imaginal representation of an object is the same as the perceptual representation. Shepard and Podgorny note that this equivalence need not imply that either representation is picture-like. However, the frequent interpretation of such an equivalence is that the imaginal representation must be picture-like because (assumption) the perceptual representation is picture-like. At this level, the logic of these experiments is not at all compelling because many theorists (Anderson & Bower, 1973; Palmer, 1975; Pylyshyn, 1973; Winston, 1970) would reject the notion of a picture-like representation for the products of perception and rather assert a propositional representation. In this section I would like to focus on some of the specific demonstrations and see if they have any additional force beyond this general argument. I will not have room to consider all types of data that have been enumerated in such papers as Kosslyn & Pomerantz (1977), Paivio (1975), and Shepard & Podgorny (in press). However, I will consider a representative subset. This will be enough to make a general point.

Mental Rotations

One of the most influential phenomena uncovered in recent research in cognitive psychology has been that of mental rotation (see Metzler & Shepard, 1974; Cooper & Shepard, in press). The basic finding is that the time to decide that one object is a rotation of another object is a monotonic, and often linear, function of the amount (degrees) of rotation. This is taken as evidence that subjects mentally rotate an image of one object of the pair into congruence with the other object. The continuous nature of the function is taken as evidence that the subject must go through all or many intermediate states in rotating the object. In the Kosslyn & Shwartz simulation, the image is moved through a series of small changes in orientation.

It is a simple matter to propose a propositional model which mimics this image model. The model would involve a propositional description of an object and of its orientation in space. Just as Kosslyn & Shwartz compute a series of small changes in their image so a series of small changes can be computed in the propositional representation. Given that it is so easy to produce the phenomenon in a propositional model, one might wonder why propositional theorists (e.g. Anderson & Bower, 1973) have been so loathe to propose it and why most find the image account more appealing than the propositional account. Consider Kosslyn & Pomerantz's criticism of the propositional account:

> The imagery account seems somewhat plausible and relatively straightforward. The propositional account seems less satisfactory: Aside from the problem of not knowing how to represent the letters in the first place, it is not clear why rotation is gradual in such a system. It should be especially easy to rotate an image 180° because all the relations could simply be reversed (e.g., right becomes left). To rotate an image 45° should be more difficult, because more complex substitutions must be implemented. Nevertheless, subjects take longer to rotate an imaged object 180° than 45°. It appears that people do not (or cannot) skip from one orientation of an image directly to another, but must proceed gradually. Such a prediction does not follow from basic concepts of propositional representation.(p.69)

But one can ask why rotation of the image must be gradual. Why should it be computationally harder in the image model to calculate a 180° step than a 1° step? In terms of number of CPU cycles there would be no differences in a simulation program like that of Kosslyn & Shwartz. It is no less ad hoc to propose this limitation on the image model than it is to propose it for the propositional model.

<u>Effects of Image Size and Complexity</u>

Kosslyn (1975) has found that subjects take longer to verify that an imaged object has a certain property if they are instructed to make the image of the object small. Kosslyn argues that there is a "grain" limitation on the mental image and that it is difficult to properly represent the details of a small image. He relates this to the supposed perceptual fact that it is difficult to discriminate details of small objects when presented. (However, Kosslyn has not established that there is this perceptual phenomenon over the range of sizes he is manipulating.) Kosslyn has also shown that there is a complexity limitation on an image--that it takes longer to verify that an object has a certain property when it is imaged along with a more complex object.

These results can be accounted for by a propositional model which assumes that a subject activates fewer propositions to represent an object when instructed to image it small and that he can activate fewer propositions when he must represent another complex object. However, Kosslyn and Pomerantz argue that this propositional account

> ...seems less satisfactory than the imagery account: Why should people access less information about an object when asked to "image it small." This seems ad hoc; a propositional model would not lead one to expect such effects. (p.71)

However, it is no less ad hoc to propose that small images suffer a grain limitation. A priori, one might have supposed that smaller images have smaller grain. It is entirely ad hoc to propose a complexity limitation on an image. A property frequently ascribed to images (e.g. Cooper, 1975) is that they can be processed in an unlimited capacity parallel manner. In contrast, there does exist a propositional model (ACT - Anderson, 1976) which incorporates a complexity limitation on the number of propositions that may be active.

This limitation was motivated on grounds entirely independent of Kosslyn's result.

There is nothing intrinsic to an image or to a propositional representation which would have led one to predict Kosslyn's results of size and of complexity. Either representation requires additional, non-trivial process assumptions to predict these results. There is no justifiable basis for calling one set of assumptions more arbitrary than the other.

<u>Judgments of Magnitude</u>

There are experiments (e.g. Moyer, 1973; Paivio, 1975) which show that when one is judging two mental objects with respect to a dimension on which they vary, reaction time decreases with the separation of these objects on that dimension. In a model experiment, Paivio (1975) had subjects judge which of two items (e.g. a lamp or a zebra) was larger. In one condition Paivio presented the words and in another condition Paivio presented a picture of the objects in their true size ratio. Reaction time to make this judgement decreased in either case as the items named or depicted increased in size disparity. Paivio's picture condition provides the needed control to support his claim that he is getting the same effect with word-cued representations as he would get with picture-cued representations. (It is somewhat disturbing, however, that the size of the effect is about twice as large with word-cued judgments as it is with picture-cued judgments.) Paivio argues that this is evidence that picture information is represented in an analogue image format rather than a discrete propositional format.

There is some dispute about the exact mechanisms underlying these comparative judgements (Banks, Clark, and Lucy, 1975; Holyoak, 1977). However, a more relevant point to the issue at hand is that there is nothing incompatible with the notion of a propositional model and the idea that judgement time can vary with object magnitude. Magnitudes can easily be represented in a propositional model as arguments of propositions. (It is easy to provide predicate calculus treatments of many physical and mathematical domains that deal in continuously varying quantities.) There is no reason why the distance effects reported could not come from a process defined on these propositional representations. Of course, there is no reason to have expected the effect. However, there is no reason to have expected the effect given an image representation, either. The reason to have expected the effect comes from a knowledge of the results obtained in perception. However, as noted earlier, the products of perception can either be represented in a picture format or a propositional format.

<u>Unlimited Capacity Image Processing</u>

There are a number of experiments (Cooper, 1975; Nielson & Smith, 1972; Smith & Nielson, 1970) which lead to the conclusion that images can be matched to perceptual objects as templates or in an unlimited capacity parallel manner. For instance, Nielson & Smith (1970) find subjects unaffected by complexity in recognizing faces when they have encoded the faces as whole units but not when they have encoded the faces as verbal strings. This finding has been used as evidence for image over propositional representations. However, there is nothing at all incompatible in having propositional representations and parallel processes. The ACT model (Anderson, 1976) is an example of a propositional system in which all basic processes are parallel and some are of effectively unlimited capacity. The spreading activation of Quillian's (1969) TLC model can be conceived of as an unlimited capacity parallel process (but see Collins & Loftus, 1975).

There are two aspects of this phenomenon that are potentially troublesome, however. The first is the possibility that unlimited capacity parallel processes can be obtained with encodings of visual information but not with verbal encodings. If one abstract propositional encoding underlies all memory, it would be hard to see why different principles would govern the representation when it encodes information from different sources.

Second, the very phenomenon of truly unlimited capacity parallel processing is puzzling. I know of no well-understood device that could make recognition discriminations such as found above without an increase in processing time after some bound on object complexity was exceeded. There is sometimes expressed a belief that analogue processes, because of their continuous nature, provide an infinite amount of information. However, discriminability limitations on a system's ability to respond to small differences imply a finite bound on the amount of information per analogue process.(xxxx)

It is possible to have a computational system that appears to have "unlimited capacity" within a certain range. For instance, one can have a large number of parallel processors only some of which are used on simple problems. The greater difficulty of more complex problems can be masked by recruiting the unused processors. A complexity effect would only be observed for problems that were sufficiently complex to exhaust the available processors.

Template matching is frequently given as an example of unlimited capacity parallel processing. However, templates have only a certain fineness of discrimination. Faced with distinguishing among objects that require finer discrimination, either a template matching program will make errors or more computational resources will have to be allocated to permit a finer grid to be computed.

There are a number of possible responses to reports of unlimited-capacity parallel processing of images. One would be to give up the principle of finiteness of human computing resources. A better response is to assume that the complexity has not been pushed far enough--that we are still in the range where the capacity of a finite set of parallel processes has not been fully exploited. A third response is to quibble with the demonstrations of unlimited parallel processing. It may be that less information is being processed about the more complex objects but that the tests fail to bring out evidence for this degradation in processing.

Consider the experiment by Cooper and Podgorny (1976) on recognition of Attneave polygons: they varied the number of points in the polygons from 6 to 24 and obtained no effect of this measure of complexity on recognition time. As distractors, they used transformations of the target polygons with some of their points perturbed. There were no more errors made to distractors for polygons of greater complexity. This was used as evidence against the possibility of a less careful processing of the more complex shapes. However, the more complex distractors also had more points perturbed. Therefore, one would have to remember a smaller portion of the points from the more complex figures to achieve the same probability of detecting a distractor.

Cooper & Podgorny had subjects rate similarity of the distractors to the targets. The distractors were, on the average, of equal similarity for the targets of different complexity. Apparently, more points have to be perturbed in a more complex polygon to achieve the same difference in judged similarity. However, to have shown unlimited capacity processing they should not have used distractors of equal similarity but rather distractors that had the same number of points perturbed and by the same amount. This would be a test of whether all the information in the target was being processed in the complex figures. To perform the experiment in this manner would mean that distractors of greater similarity would have to be used for more complex stimuli. Cooper and Podgorny found that there were more errors for more similar distractors. So, presumably in the prescribed experiment they would find that subjects were not performing as well with more complex figures, arguing against unlimited parallel processing.

General Analysis of the Problem of Discriminating Among Representations

I have been arguing that the many examples proposed by image theorists do not provide greater evidence for an image representation than they do for a propositional representation. In each case it was found that evidence for a particular representation was really evidence for a particular process and that there was no good reason to associate the process with a particular representation. (There were important second order complications with the unlimited capacity issue.) Similar difficulties were also shown with the arguments given by propositional theorists. I would like to formalize the general point that these examples illustrate. This general point is that it is not possible for behavioral data to decide uniquely issues of internal representation. The reason is that one cannot just test questions about a representation in the abstract. One must perform tests of the representation in combination with certain assumptions about the processes that use the representation. That is, one must test a representation-process pair. One can show that, given a set of assumptions about an image representation and a set of processes that operate on it, one can construct an equivalent set of assumptions about a propositional representation and its processes. Or one can be given a propositional theory and construct an equivalent imagery theory. In fact, it is possible to establish a more general claim: Given any representation-process pair it is possible to construct other pairs with different representations whose behavior is equivalent to it. These pairs make up for differences in representation by assuming compensating differences in the processes.

The argument that I will give to establish this claim has been changed somewhat from an argument to the same point given in Anderson (1976). It has been changed both to make the claim more general and to try to make it clearer why it is possible to achieve equivalences among different representations.

Note to typesetter: [I] should be set in script.

Suppose one had a theory of internal representation, [I]. This theory would specify a set (probably infinite) of possible internal representations which we can denote $I_1, I_2, \ldots, I_n \ldots$. However, a theory which only specifies internal representations says virtually[6] nothing about behavior and therefore is not testable by itself. One must specify some processes that operate on these internal representations in order for behavior to occur. It is useful to discriminate among three types of processes. There are encoding processes which map external stimuli, S_i, into internal representations, I_j. These encoding processes will be denoted by the function E. The operation of encoding a stimulus can be represented $E(S_i)=I_j$. Second, there are processes of internal transformation which can be represented by the function T. The notation $T(I_i)=I_j$ represents a transformation from internal representation I_i to I_j. Finally, there are decoding processes specifying how internal representations are manifested as responses. So if state I_i results in response R_j, this will be denoted $R_j=D(I_i)$.

This is a quite general framework for representing cognitive theories and I do not think it blurs any significant issue involved in the image-propositional controversy. Figure 3a represents a possible scheme of information processing within this framework. We have three stimuli S_i, S_j, and S_k being presented, not necessarily at the same time. By the encoding process E, these result in internal representations I_i, I_j, and I_k. I_i and I_j result by T in an intermediate internal representation I_m. To preserve the notation of T mapping one representation into another, we will assume that a conjunction of internal representations is itself an internal representation. So $T(I_i \& I_j)=I_m$. There are other transformations illustrated which occur at various points of time: $T(I_j)=I_n$, $T(I_n \& I_k)=I_p$. Finally, the decoding process maps I_m and I_p into response R.

Insert Figure 3 about here

If we restrict ourselves to behavioral data, we cannot directly observe the internal processes, E, T, and D nor the internal representations. All we observe is that at various times the stimuli

S_i, S_j and S_k arrive and that sometime later response R is emitted. The question of interest is whether behavioral data (i.e., observation of the contingencies between such events and the time of these events) are adequate to constrain a theory of internal representation. Such a theory of representation will be part of a model, M, that also specifies the processes that operate on the representation. It will be argued that models with very different theories of representation can perfectly mimic the behavioral predictions of M. These alternative models will compensate for differences in the representation by different assumptions about the processes. Therefore, these models are not discriminable from M on the basis of behavioral data. Therefore, the representation assumed by M is not discriminable from the very different representations assumed by the other models.

Let [I] be a specification (e.g., a grammar) of the possible representations $I_1, I_2, \ldots$ under M. [I] by itself is not a very interesting theory of representation. For instance, to assert that our representation was predicate calculus would not be very informative unless we had some idea what events would lead to a representation like give(John, Mary, ball). It would be a very different theory of representation if this formula were used to represent the meaning of "Fred eats pizza" than if it were used to represent "John gives the ball to Mary." That is, we want a theory of representation to specify how various inputs are represented. A theory of representation should include the encoding process, E. This forces a connection between our representation and the external world. Let us refer to the pair $\langle [I],E \rangle$ as M's theory of representation. The pair $\langle T,D \rangle$ will be M's theory of the processes that operate on the representation. What I will show is that given a different theory of representation $\langle [I]^*,E^* \rangle$, one can embed that theory in a different model M^* with different processes $\langle T^*,D^* \rangle$ and have M^* mimic M in all its predictions about behavioral data.

Preservation of Internal Distinctions

It is not the case, however, that any theory of representation can be made part of a model M^* that mimics M. The theory of representation must satisfy a condition called *preservation of internal distinctions:* One theory of representation $\langle [I]^*,E^* \rangle$ preserves the internal distinctions of another theory $\langle [I],E \rangle$ if (a) there is a one-to-one mapping f from [I] to $[I]^*$ such that: (b) f has a computable inverse which will be called f^{-1}, (c) f^{-1} will map the encoding of S in the mimicking theory, $E^*(S)$, into the encoding of S in the target theory, E(S), i.e., $E(S)=f^{-1}(E^*(S))$ for all S. The fact that the mapping is one-to-one assures that any distinctions among representations in [I] will be preserved in distinctions among representations in $[I]^*$. The fact that $E(S)=f^{-1}(E^*(S))$ assures that E and E^* assign corresponding representations to the same stimuli. One consequence of these requirements is that for S_i and S_j if $E^*(S_i)=E^*(S_j)$ then $E(S_i)=E(S_j)$. That is, the encoding process E^* does not fail to preserve any of the distinctions among stimuli that are preserved by the process E. It will prove to be necessary that f have a computable inverse to guarantee that process assumptions $<T^*,D^*>$ of the mimicking model M^* can be computed. One would not want to propose processes which could not be computed and hence (by Turing's thesis or Church's thesis--see Minsky, 1967) were not capable of specification.

While the condition of preservation of internal distinctions excludes some representations from the guarantee of mimicry, it is not so severe as to exclude all interesting possibilities from mimicry. In particular, we could have a propositional model mimic a picture model. The mapping f in this case would transform the picture into a complete propositional description. (I assume it has been generally conceded that all the information in a picture can be propositionalized.) It is also the case that a propositional model can be mimicked by a dual code model like Figure 2. In this case, f would map a propositional representation into a dual code representation that contained the same information.

One might wonder under what conditions the mapping would have a computable inverse. If E and E^* are primitive recursive (Minsky, 1967), a mapping f can be constructed with a computable inverse f^{-1}. One can simply make $f=E^* \bullet E^{-1}$ where $E^* \bullet E^{-1}$ denotes the combination of applying first the inverse of E and then E^*. Similarly, $f^{-1}=E \bullet E^{*-1}$. If E and E^* are primitive recursive E^{-1} and E^{*-1} will be computable and hence f and f^{-1} will be computable.[7,8] Note that the above argument establishes that f and its inverse are computable by showing one way to compute f, i.e., $E^{*} \bullet E^{-1}$. It does not mean that this is the best or only way to compute f. For instance, in mapping from a picture representation to a propositional representation there would be no need to map to the external stimulus by E^{-1} and then to the propositional representation by E^{*}. A more direct propositional encoding of the picture should be possible.

It should also be noted that for any theory of representation <[I],E> where E has a computable inverse, there is at least one other representational theory that will mimic <[I],E>. This is the theory that assigns to each stimulus a representation isomorphic to that stimulus. For this theory, the mapping $f=E^{-1}$ satisfies the condition of preservation of internal distinctions. Since E need only be restricted to primitive recursive to have a computable inverse, this means virtually any theory, not just imagery and propositional, can be mimicked.

A final feature to note is that if the map f from [I] to $[I]^{*}$ is a function (i.e. its inverse is 1-1) then there is a potential for mutual mimicry. That is, theories using <$[I]^{*}$,E^{*}> can be mimicked by theories using <[I],E> as well as the converse. I would argue that this mutual mimicry holds between dual code theory and propositional theory because it seems that one can define a 1-1 function from a dual code representation to a propositionalization of it.

<u>Proof of Behavioral Mimicry</u>

It remains to be established that there exists the potential for mimicry given a 1-1 map f. I will show something stronger--not only is it possible to mimic the observable behavior of M using <[I],E> with a model M^* using $<[I]^*,E>^*$, but it is possible to produce a set of internal operations on the representations in $[I]^*$ isomorphic to the internal operations on [I]. Figure 3b illustrates this. This is important. Since the mimicking model goes through the exact same steps, not only will it reproduce the same behavior, it will reproduce the same time relationships. That is, it will mimic such things as reaction times.

After all these preliminaries, it only takes a few brief remarks to establish that E^*, T^* and D^* will mimic E, T, and D just as Figure 3 illustrates. If the encoding operation E maps the stimulus S into I then E^* maps S into f(I). By its construction, the map f was guaranteed to convey on E^* this mimicry of E. It is also possible to construct the elements T^* and D^* to achieve mimicry of T and D. That is, if T maps I_x into I_y, T^* will map $f(I_x)$ into $f(I_y)$ and if D maps I into R, D^* will map f(I) into R. One T^* to achieve this can be constructed as $f \bullet T \bullet f^{-1}$ where this denotes the operation of f^{-1} on the internal representation, then the operation of T, then the operation of f. Since f, f^{-1} and T are computable, so is T^*. If $T(I_x)=I_y$, then $T^*(f(I_x))=f \bullet T \bullet f^{-1}(f(I_x))=f \bullet T(I_x)=f(I_y)$. That is, if T maps I_x into I_y, T^* will map $f(I_x)$ into $f(I_y)$. Similarly, we can designate D^* as $D \bullet f^{-1}$. D^* will also be computable.

One might object to the complicated specification of T^* as

$f \cdot T \cdot f^{-1}$ and of D^* as $D \cdot f^{-1}$. However, it does not follow that these are the simplest specifications of T^* or D^*. This demonstration has the character of an existence proof. I have shown that there exists at least one process pair $\langle T^*, D^* \rangle$ which will combine with the representation $\langle [I]^*, E^* \rangle$ to yield mimicry of M. For all we know, there is a $\langle T^*, D^* \rangle$ which is much simpler than $\langle T, D \rangle$ from M. This argument establishes nothing, one way or the other, about the relative parsimony of the two simplest models for representations [I] and $[I]^*$. The point of this section is to establish that there are not purely behavioral criteria for distinguishing between the two theories. Certainly, if it could be shown for some T that its simplest T^* mimic was $f \cdot T \cdot f^{-1}$, there would be parsimony grounds for rejecting it. However, in actual examples such as the forthcoming illustration, there has always turned out to be simpler T^* specifications. A more thorough evaluation of parsimony, an unfortunately subjective concept, comes later in the paper.

A similar remark can be made about time relationships. To guarantee M^* can mimic M we must assume the time for each step of T^* in Figure 3 is identical to the time for the corresponding step of T. For this to be so and since we are only assured of one specification of T^* as $f \cdot T \cdot f^{-1}$, we have to assume that the time for M^* to perform the sequence $f \cdot T \cdot f^{-1}$ can be made identical to the time for M to perform T. This can be done by assuming that M^* can compute T faster than M and also can rapidly compute f and f^{-1}. Thus, by speeding up the operation of M^* we can always place its operations in time step with M. We might be prevented from such speed-up proposals if we had adequate knowledge about possible physiological implementation but we do not. (An evaluation of the potential of physiological criteria also follows.) Moreover, as it seems we can usually construct T^* more simply than its formally guaranteed specification, the need for such speed-up proposals does not seem to arise in practice.

In concluding this argument, I refer the reader back to Figure 3a and 3b which capture its essence. That shows how there can be an isomorphism between the operations on two distinct representations in M and M^*. Some people have the feeling that if the operations are isomorphic the distinction between M and M^* becomes almost meaningless. I would like to endorse this attitude. It embodies an important claim of this paper: At a useful level of abstraction there need be no difference in the behavior of systems that use a wide range of representations. In particular, there need be no difference in the behavior of a system which uses a propositional versus a pictorial representation.[9]

Another counterargument to this argument about representational indeterminacy is that it misses an important distinction. While it may be true that a propositional representation can be modified to accomodate data predicted by a dual-code theory (or vice versa), the counterargument goes, it is still the case that one theory predicted the result and the other theory was modified. There are some points that need to be made here. First, in practice, it is often not the case that one representation rigorously predicted the result. Rather it is the case that we "intuit" the result as being implied by the representation. Second, in those uses of fairly rigorous predictions, the derivation depends critically on process assumptions. Therefore, it is not evidence for the representation per se, but for a representation-process pair. It is correct to take this predictive power as evidence for that representation-process pair. However, it certainly seems incorrect to take the outcome as evidence for the representation in abstract since conjoined with other process assumptions the representation would lead to very different predictions. Finally, it is wrong to conclude from a theory's failure to predict a result that the theory-builder should do anything more than appropriately modify his theory. Any theory proposed today must be wrong in many aspects. Any worthwhile theory is based on and accounts for a good range of data. Therefore, the appropriate response to inevitable discrepancy usually should be modification of the theory not abandonment. The appropriate reason for abandoning a theory rather than modifying it is when an alternate theory is developed that much more parsimonously accounts for the data. The parsimony disadvantage of a theory may arise from modifications to account for discrepant results. However, such modifications also may not leave the theory at any parsimony disadvantage.

A natural reaction to this argument is to view it as "so much blind formalism." But considered in the light of the prior discussion about attempts to discriminate between propositional and imagery representation, the argument seems more compelling. That discussion contained frequent evidence for the central claim of this formal argument: Differences in representation can be compensated by differences in the processes that operate on these representations. I would also like to apply this formal argument to a specific case:

Example of Equivalence

This argument has been made in quite abstract terms. This abstractness was required to be able to establish the generality of the point about non-identifiability. However, it is hard to recognize the force of the argument because of its abstractness and also because of the importation of the terminology of primitive recursive functions and the need to create such formal constructions such as $T^{*}=f{\bullet}T{\bullet}f^{-1}$. Therefore, I will go through an example of how this result can be mapped into the reality of a contemporary psychology experiment.

The task I have chosen is rotation of letters as studied by Cooper and Shepard (1973). I will sketch out an imagery model (representation plus process) of this phenemena, a propositional representation, and use the above analysis to construct a process which, operating on the propositional representation will mimic the behavior of the imagery model. I will assume that the imagery representation [I] of a letter is a two-dimensional matrix encoding in terms of 1's and 0's whether particular squares are filled in. This is basically the stimulus display presented. Therefore, the encoding process for an imagery model is one of identity--i.e., E = I. We assumed stored in memory is an upright representation of the letter. A test object is presented and encoded into its matrix form. In the Cooper & Shepard paradigm the presented object is usually not in upright form. The subject must decide whether the presented object matches a letter or is a mirror image of a letter (e.g. R vs. Я). We assume that the matrix representation of the presented object is rotated until it is in upright form. This corresponds to T, the process of internal transformation. It is easier to tighten our application of the formalism if we assume the rotation proceeds in discrete steps (as is done by Kosslyn & Shwartz in their simulation). So, in each discrete time unit, matrix M_1 is transformed into matrix M_2 where these two are related by a small angle of rotation around an axis through the center of the matrix. We can denote this as $M_2=T(M_1)$. It should be obvious how to spell out the operation T (e.g., as a computer program). The decoding operation applies when the rotated matrix are in upright orientation. There is a technical difficulty in deciding when the matrix is upright, but I assume as others have that there are features which will allow one to decide that a character is upright before one has recognized it. The recognition operation consists of computing a complete match between the rotated matrix and the stored matrix. This is measured by the number of 0-1 correspondences in the two matrices. If the stimuli offer a close enough match, a positive response is emitted and, if not, a negative response is emitted. Let $O(M_1, M_2)$ be some scaling of the distance between the filled cells of M_1 and the closest filled cells of M_2. Then we have D defined with respect to the prototype letter matrix M_p:

$$D(M) = \text{YES iff } O(M, M_p) \geq C$$
$$= \text{NO iff } O(M, M_p) < C.$$

The above may or may not correspond to one's favored interpretation of an imagery model for this task. For present purposes of illustration it is irrelevant whether it does.

Insert Figure 4 and Table 1 about here

Let us now develop a propositional representation for letters. Figure 4 represents the letter R in standard orientation and Table 1 gives its propositional code representation. The main proposition, COMPOSE (R, S1, S2, S3, S4, S5, S6) defines R in terms of its component line segments. Other propositions define these line segments according to their shape and terminal points. Others give the length of the segments. Others give the angles between straight lines. Of particular interest is the proposition AXIS (R, P3) which identifies P3 as giving the axis of orientation for the letter R and the VECTOR-ANGLE propositions which identify the locus of all the crucial points relative to this axis propositional code. To complete our propositional representation we need to specify E^* the encoding process. This is the operation by which one goes from the external stimulus (e.g., a matrix) to a propositional encoding in terms of lines. This process is basically one of picture parsing for which there do exist available algorithms (e.g., Duda & Hart, 1973). Assuming clean displays and a small repertoire of line types this would be a simple algorithm. The algorithm would become more difficult as the displays deviated from these assumptions. (One remark about this picture parser: It could not recognize the stimulus configurations before parsed. Therefore, if Figure 4 were an encoding of a stimulus array, the R in the propositions would be replaced by an arbitrary term or node.) The above may or may not correspond to one's favorite propositional model for letter representation. As with the imagery model this does not matter for purposes of illustration. No endorsement should be inferred for either model.

Now we have to proceed with the construction of the mimicking processes T^* and D^* for the propositional model. The first thing to note is that we can create the requisite map f between [I] and $[I]^*$ as $E^* \bullet E^{-1}$. Since E was the identity transformation we have $f=E^*$. Its inverse f^{-1} will be E^{*-1} or a transformation that goes from a propositional encoding like that in Figure 4 to a matrix encoding. Such a function is clearly computible. The other condition required for preservation of internal distinctions is that $E(S)=f^{-1}(E^*(S))$. Since E is the identity and f^{-1} is E^{*-1} this can be rewritten as $(S=E^{*-1}(E^*(S)))$ which is clearly true.

Now let us consider construction of T^* the process of internal transformation of the representation. We have from the formal results that $T^*=f \cdot T \cdot f^{-1}=E^* \cdot T \cdot E^{*-1}$. T^*, as a specification of input-output, might seem quite complicated. It might seem to require applying E^{*-1} mapping the propositional representation to its matrix form, applying T doing the matrix rotation, and then applying E^* to map from the matrix back to the line drawing. But consider the final effect of this--there will be a change only in the angle in the VECTOR-ANGLE propositions. This change in angle of orientation could be directly computed. This example illustrates an important fact of the formal analyses. One should not reason from a complex specification guaranteeing the existence of an input-output relation to the conclusion that the computation of this relation is complex. So, in conclusion, T^* will compute small changes in the angle of orientation in step with the small rotations performed by T. To remind the reader of an earlier point (p. xxx): It is no more arbitrary to assume small slow changes in an orientation parameter than to assume small slow changes of rotation.

Now let us consider the construction of $D^*=D \cdot f^{-1}=D \cdot E^{*-1}$. This could be interpreted as a process which transformed the propositional encoding into a matrix format and applied the decision function D. However, D^* could be defined directly with respect to the propositional encoding. Some propositional matching algorithm (e.g., Anderson, 1976) could be used to obtain the degree of structural match between the probe and the prototype. There would also have to be a scaling of the match between the lengths and angles in the prototype and the probe. The only difference between a letter and its mirror image, once rotated into congruence would be the value of the vector-angles. Thus, we can define a function O^* mapping the disparity between R_p, the prototype representation, and R, a particular representation. We can define D^* as:

$$D^*(R) = \text{yes iff } O^*(R_p, R) \geq C^*$$
$$= \text{no iff } O^*(R_p, R) < C^*.$$

For this application O^* need not be constructed to produce an identical metric on differences between stimuli as O produces. The prototypes and their mirror images will be quite different by either O^* and O and hence D^* and D will agree as to which are same or different. If the task were to discriminate among very similar stimuli, care would have to be taken to get O and O^* correspond in the metric they imposed. That they can be made to so correspond is a consequence of the general result on equivalence.

This example illustrates how one can generate a propositional model to mimic an imaginal model. An example of the reverse could also be given. I hope the reader will agree that the propositional model produced by this algorithm is plausible relative to the plausibility of the imagery model from which it was derived. By my own subjective estimate, it seems more plausible.

Possible Responses to Non-Identifiability

There are at least two justifiable responses to this result about non-identifiability. One is to simply try to develop some model, imagery or propositional, that is compatible with the data and not to worry about distinguishing it from all possible models with other representations. The fact that there is no explicit model, imagery or propositional, that even comes close to accounting rigorously for the available data should indicate that this is a substantial goal in itself. The second approach is to look for other criteria besides behavioral data for selecting among representations. Personally, I find myself leaning toward the first response. I would like to state a defense of the first response and then turn to a detailed discussion of the second.

There are a number of ways to proceed in research. One is to proceed with a strongly empirical bent, with little guidance from a general theoretical framework. The hope of this approach is that a theory will somehow emerge from the empirical work. Sometimes results on non-identifiability are used to defend this empirical orientation over a more theoretical orientation. They should not be so used. There are two types of theoretical approaches and non-identifiability results only argue against one.

The theoretical approach damaged by non-identifiability results is that which attempts to discover the "true" theory. This cannot be done if we cannot decide on issues like propositional. vs. imaginal or serial versus parallel (Townsend, 1974). However, one can proceed in a less ambitious theoretical direction. This is to formulate a more-or-less complete model without a commitment to discriminate it from all other possible models. Non-identifiability results imply that there are other models which will generate the same predictions. However, the important fact is that many models will not generate the same predictions. One's non-unique model is perfectly capable of being tested and proven wrong. In proving it wrong one would also be proving wrong all of its equivalent models. It is no mean feat to come up with a model capable of accounting for the existing range of empirical facts. I think it is a fair statement that no current model handles the existing range of results on imagery. Producing such a model seems a more worthwhile endeavor than deciding among the grand contrasts such as imagery versus propositional.

Other Criteria for Identifiability Besides Behavioral

The argument to this point is that behavioral data do not provide a basis for deciding between imagery and propositional theories. The range of possible theories is so great that for any imagery theory there will be a mimicking propositional theory and vice versa. Past work that has claimed to decide between propositional and imagery theory rested on implicit "ground rules" about what were the acceptable variations in these theories. However, to date there are no compelling reasons to accept these ground rules. I have argued that by violating these rules in quite acceptable ways one could get one type of structure to account for data claimed to be uniquely explainable by another type of structure. Indeed, the representational issue has proven so slippery because the ground rules change over time and from researcher to researcher. If it were possible to justify some constraints on the range of possible theories then behavioral data might be able to achieve unique identifiability. This last section will consider these types of non-behavioral criteria for constraining theories. These are physiological criteria, the criteria of parsimony and plausibility, and the criteria of efficiency and optimality.

Physiological Criteria

An obvious additional constraint comes from physiological data. If we could open the brain and observe it operating on pictures or on propositions it seems that the issue would be settled. There are two problems with this solution, one serious and one not, but both worth considering. The non-serious objection is to argue that observations of brain functions have the same problem of interpretation that behavioral data do. Suppose, not just to be bizarre, we observed an *m* x *n* grid of data encoded on the brain's surface and that this corresponded to a picture of an object. This observation is a datum that a theory must account for. It would be possible to attribute that datum to some source other than the fact that such a grid was actually neurally encoded. That is, reports of neural observation can be doubted just as introspective reports are doubted. However, such a level of skepticism is clearly unacceptable, whereas the skepticism about the introspective reports is acceptable. It is of interest to note that direct observation always has had a privileged status as a means of determining the state of an object, even though it must be handled with some caution (e.g. the stick that appears crooked in the water). Unless there is good reason for believing otherwise, the working assumption of all men, including scientists, is that there is a 1-1 correspondence between the structure of a visual percept and the structure of the object perceived. The problem with behavioral data such as introspection is that it is not direct observation of the objects under consideration.

The serious reason for challenging physiological data is that it does not provide anything like direct observation of the mental objects. Use of it tends to require more perilous chains of inferences than use of behavioral data. No neuroscientist has found anything like direct evidence for propositions or images. This is not to say that such data are impossible to achieve in principle, only that it is unlikely. This is also not to say that the more indirect data do not provide constraints on a psychological theory. (See Fodor, 1975, for a discussion of the difficulty in reducing the concepts of cognitive psychology to physiological concepts.) However, such indirect data cannot decide between image or proposition.

The principle physiological data cited for an imagery theory concern hemispheric asymmetry in information processing. It is claimed that the right hemisphere is better adapted for spatial tasks and that the left hemisphere is better adapted for linguistic and analytic tasks. Part of the evidence for this hemispheric differentiation comes from experiments showing selective loss of abilities with damage to one of the two hemispheres. (Blakemore, Iverson, & Zangwill, 1972; Kimura, 1963; Meier & French, 1965). Evidence for specificity of function is also found in split-brain patients (Gazzaniga & Sperry, 1967). Also behavioral experiments (e.g. Giffen, Bradshaw, & Nettleton, 1972; Klatzky & Atkinson, 1971) have shown differences in the speed with which tasks can be performed which are presented to the right visual field (and hence directly to the left hemisphere) versus those presented to the left visual field (and hence directly to the right hemisphere). Tasks that involve an important verbal component are performed better when presented to the right visual field while visual tasks do better in the left visual field.

These studies on hemispheric specialization really provide very little evidence on the form of information representation. One could propose that all information has a propositional form but that propositions encoding visual information are stored in the right hemisphere and propositions encoding verbal in the left. Another possibility suggested by Anderson & Bower (1973) was that rather than having the data differentially stored one could have procedures differentially stored. That is, procedures for performing verbal tasks would be in the left hemisphere and procedures for spatial tasks, right hemisphere. Both types of procedures could take propositional information as their data.

A recent experiment by Patterson & Bradshaw (1975) is particularly interesting. They found evidence that the right hemisphere performs gestalt, template-like operations on visual stimuli whereas the left hemisphere is responsible for more analytic operations on visual stimuli. In an experiment that involved easy discriminations between a test face and a memorized face, they found a left visual field advantage. A right visual field advantage was found in a task requiring a difficult discrimination. In both cases, the memorized faces were learned under identical procedures. So, it does not so much seem that there is differential storage of visual information in the right hemisphere as there is differential ability to perform certain types of operations. If so, the data on hemispheric asymmetries lose all ability to discriminate among types of representation.

<u>Parsimony and Plausibility</u>

I would like to put together the criteria of parsimony and plausibility because I believe that plausibility is just an extension of parsimony--the parsimony of the theory when integrated with our general sense about nature and human cognitive functioning. These criteria have some promise of discriminating among theories of representation. As I will argue, it may prove possible to decide on grounds of parsimony and plausibility whether there are two distinct representations, one typically used for pictorial information and one typically used for verbal information, or whether there is just one representation for all information. That is, I think we may be able to decide between a dual-code model versus an abstract model. However, I am not optimistic that parsimony and plausibility will be of much help in establishing the nature of the representation. That is, even if we can decide in favor of a dual code model, there seems little hope for deciding that one code is verbal and one pictorial. Similarly, if we decide for an abstract code, I see little hope of establishing that the code is propositional. So perhaps we might be able to establish whether a distinction should be made between codes but not be able to identify the character of the internal codes.

Propositional representations offer a potential advantage in terms of the parsimony of the theories that are formulated in terms of them. Because both verbal and pictorial information are abstracted *into a common representation*, it is only necessary to propose one set of psychological laws governing the processing of that information. This potential parsimony of propositional theories also offers a means for their rejection on the basis of an extensive research program. If it can be shown that different laws govern the processing of information depending on its source (verbal or visual), this would be evidence against a propositional theory. Any single piece of evidence of this sort would not be devastating for a propositional theory. The earlier theorem guarantees that a propositional theory can always be made to account for such perturbations. For instance, one could suppose that the processes which operated on a propositional representation depended on what was encoded--verbal or visual information.[10] However, any extensive use of such clearly ad hoc explanations would pose a fatal strain on the propositional theory in terms of its plausibility and parsimony.

There is some data relevant to whether similar laws hold for pictorial and verbal information. The generation of research that attempted to show superior memory for pictorial information is an example of research with this logic. However, as noted earlier, there is now reason for doubting the force of this work. A current candidate which is more promising is the work of Cooper and others discussed earlier indicating that there may be different complexity functions describing matching of verbal and non-verbal information. If this research were interpreted as Cooper advocates, it would be a serious strain on the plausibility-parsimony of the propositional model with its single abstract trace.

On the other side of the fence, I can report my work looking for interference phenomena with visual vs. verbal material (Anderson & Paulson, in press). Here evidence is found that the same principles of interference apply to the two sets of material (verbal descriptions versus faces) and that the absolute size of the interference effects may be quite similar. It is also found that verbal and pictorial information mutually interfere with each other. Similar results have been reported by Pezdek (1975). It is true that there have been frequent reports of greater interference of presenting two sets of information in the same modality rather than different modalities

(Atwood, 1971; Kroll, 1975; Salthouse, 1974, 1975; but see Anderson & Bower, 1973). However, these results can be interpreted as resulting from the greater similarity of the content in the same-modality condition rather than use of the same modality per se. For instance, a propositional encoding of two arbitrary objects in the visual modality may overlap in such features as color, shape, and size; whereas, there would not be the potential for such overlap between two objects in different modalities. This possible explanation was noted by Kosslyn & Pomerantz (1977). Of relevance here is the fact that these modality effects are strongest over short retention intervals. Encodings of peripheral perceptual properties of a stimulus are likely to be lost rapidly. Perceptual properties provide the content on which two stimuli presented in the same modality are most likely to overlap.

A question that has been subject to considerable research is whether visual and auditory information have the same short-term retention characteristics (see Kroll, 1975, for a review). It has become apparent in this field that subject strategies, particularly with respect to rehearsal, are sufficiently complex to prevent any simple answer to this question. I fear a similar fate may await research on other issues. It has been argued (e.g. Newell, 1973) that the human cognition is so complex and interactive that it not possible to address simple issues of the system, that it is necessary to build and test complex models that embody a combination of many assumptions. It is fear of this possibility that causes me to doubt whether plausibility and parsimony will yield any answer to questions about the underlying representation.

Efficiency and Optimality

It seems a reasonable assumption that the human system processes information in a way to maximize the efficiency and optimality of its performance. This means that a constraint on any theory is that it not propose the system is processing information inefficiently. It unfortunately is not always a trivial matter to decide how the efficiency of the system should be measured in absence of detailed knowledge of its physiological implementation. Anderson & Kline (1977) proposed that the efficiency of a system can be measured in terms of the efficiency of its computer simulation. If some such proposal were accepted, it would be possible to place considerable constraint on a theory. However, it is unlikely that there is going to be general consensus in the field about such a definition of efficiency. Nonetheless, it seems possible to apply very general (non-implementation-specific) notions of efficiency to impose some constraints on theories of mental representation.

One very general consideration leads to an interesting conclusion about mental representations. It is the case that well-designed systems tend to have special representations for the kinds of information they have to process frequently. These representations are designed to facilitate the kind of computations useful for this kind of information. For instance, we know from physiological evidence that visual and auditory information are given very different encodings at initial neural levels.

Another good example comes from an advanced computer language like INTERLISP (Teitleman, 1976). INTERLISP has list structures which are useful for encoding symbolic structures (like propositions), arrays which are useful for encoding dimensionally organized information (like pictures), and even some string capabilities useful for encoding sequential information (like verbal input). The array and string capabilities are additions to the original LISP (McCarthy, Abrahams, Edwards, Hart & Levin, 1962) which only had list structures. These additions were forced by the practical needs of doing various types of information processing operations in LISP. It is the case that information encoded in arrays or strings can be represented in lists but at a severe cost to efficiency of processing.

This INTERLISP example leads one inescapably to a tri-code theory. That is, it seems clear that the human must process three kinds of information--visual-spatial, verbal-sequential, and abstract-propositional. The INTERLISP example reinforces a belief that the kinds of information representations optimal for these three domains are different. So, it would seem that there would be a strong survival advantage pushing in the direction of three separate codes with the potential for intertranslation among them. Personally, I find this a priori argument for a tri-code theory quite compelling. It is interesting, however, that it leads to the opposite a priori conclusion than parsimony. On the a priori parsimony criterion we gave the advantage to a pure propositional theory.

Consideration of efficiency points in the direction of useful empirical and theoretical studies. Consider once again the complexity results reported by Cooper. The data reported would seem to indicate that matching of pictorial material is not affected by complexity but that matching of verbal material is. This is a study aimed right at the question of efficiency of operating on different types of representation. It is perfectly possible to mimic these results with a single propositional representation given the earlier formal argument. However, to do so would require proposing that when matching verbal information the system holds back on using its potential for unlimited parallel processing. Besides its already mentioned lack of parsimony, this assumption seems outrageously inefficient.

Even if it were not the case that spatial processing was unlimited capacity parallel, it seems possible to establish that a propositional model would have to be made inefficient to mimic a dual code model and a dual code model would have to be made inefficient to mimic a propositional model. Suppose it were the case, as it is in the INTERLISP analogy, certain computations could be made much more rapidly on spatially organized information. We could mimic these computations with a propositional representation but this would require proposing that the propositional computations proceeded much faster when processing spatial information than non-spatial information.

Similarly, we could mimic computations (e.g., abstract inferences) appropriate for propositional operations with operations on spatial representations. However, this might require proposing the spatial operations occurred faster on abstract than spatial information. Either way, the parameters describing rate of information processing would not be invariant across material. We would be forced to propose that sometimes operations were not performed as rapidly as they could.

These considerations lead to recommendations for more research of the Cooper variety--where one looks at processes on different information, trying to argue that the processes cannot be performed by the same mechanisms proceeding at the same rate on the same information representations. Rather there are specialized representations with specialized processes for special types of information. Whether in fact this will be the conclusion of such research is still up in the air. It may turn out that there really are remarkable invariances in processing rates across types of information.

It is worth noting that if efficiency considerations do indicate the existence of multiple representations, they will do little to indicate the character of the differences among the representations. As noted in this paper's discussion of Kosslyn & Pomerantz (p.xxx) on this point, we cannot decide whether a particular representation is efficient without knowing the kinds of processes that will operate on it. However, we may be able to use efficiency considerations to decide that a distinction among representations needs to be made. So, the conclusion on this score is similar to that from parsimony: It may be possible to decide that there are different representations without deciding how they are different.

Conclusion

To summarize the conclusions of the paper:

1) The picture metaphor is the only current explicit interpretation of the image theory.

2) The frequent criticisms made of the picture metaphor are not valid. One can have a viable dual code model involving picture and verbal representations (Fig. 2).

3) The arguments for the necessity of a propositional representation are far from compelling. The best have to do with the utility of such a representation for inference making.

4) The arguments for imaginal representations based on introspections, computational considerations, empirical results, and physiological considerations are not convincing.

5) It is not possible to decide between imaginal and propositional representations strictly on the basis of behavioral data.

6) The criteria of parsimony and efficiency may allow a decision about whether there are different types of internal representation or just one abstract representation. This would be based on a research program which investigated whether verbal and visual information displayed similar properties.

There are a number of reactions to the possibility that we may not be able to identify the nature of the information representation. A frequent one among my colleagues is disbelief and/or dismay--this would imply that cognitive psychology is not possible. However, I think the implication of this possibility is not that cognitive psychology should be abandoned but rather that it should undergo a slight change. Our goal should be to develop some model capable of accounting for human intelligence--that is, predicting behavior in a wide variety of situations where human intelligence is manifested. The fact that it may be indistinguishable scientifically from other quite different models need not be a source of unhappiness. In fact, it is possible to take comfort in such equivalences. If a particular model is equivalent to many other models, we can be more confident in its basic truth. Even if the physical implementation directly described in our model proves false of the human brain, there are many other ways that model could be true. The possibility of equivalent models also offers computational advantages. Just as is the case in the wave and particle models of light, one version of the model might be useful for certain computations and another version of the model for other computations. It is also worthwhile to note with respect to this example from physics that scientists were able to make progress without unique identifiability.

The function of science is to discover what is the case not to prescribe what should be the case. If equivalence and non-determinacy seem to be the case we should not be timid about acknowledging that possibility.

Footnotes

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2. The segmentation is meaningful for myself. I admit to being a chess duffer.

3. It might be argued that the representation in Figure 2 is really a propositional representation. This could be argued on one of three bases: the use of word strings like "knight attacks king", the use of the associative network structure, or because of the procedures which we assume will use this information. There are two responses to this remark. The first is to note that if one agrees that this representation is faithful to dual code models and insists it is propositional, one would be conceding that there is no difference between dual code and propositional models. This amounts to conceding the main point that I will be arguing for in the paper.

However, I think a stronger response is justified to this argument. None of the three bases for calling Figure 2 propositional seems very good:

a) There has been a standard distinction in the literature between word strings and propositions which are thought to be more abstract.

b) Associative structure has never been considered equivalent to a propositional structure.

c) Standard definitions of what a proposition is (abstract, has rules of formation, has a truth value) make no reference to the procedures that use this information.

Moreover, there seems to be consensus that Paivio's dual code theory is not propositional. Still, one could, if he wanted to, extend the notion of a propositional representation to Figure 2 without being in outright violation of any explicit definition of what a proposition is. However, to do so would seem to be violating basic "sincerity conditions" on scientific discourse. We have to respect the conventions of usage in the scientific community.

4. This conjecture about the universality of propositional representation can be seen as related to a conjecture known as Church's thesis or Turing's thesis (Minsky, 1967). This is the thesis that any well-specified behavior can be computed by a recursive function or Turing Machine. Given that any well-specified information should be capable of entering into well-specified computations and given that the recursive functions can be represented in predicate calculus, a propositional-based language, there is a sense in which it would follow from Church's thesis that any well-specified information can be propositionalized. However, this argument implies a rather unsatisfactory way of propositionalizing information. Therefore, I think it is better to let this conjecture stand as an independent claim. It is explicitly accepted by Kosslyn & Pomerantz (1977).

5. For instance, if a person reports to us, "My mind is swarming with ideas," would we want to assume a mental representation of a swarm of bees?

6. The hedge "virtually" is inserted because we can assume that, whatever its representation, there are certain behaviors of which a system is logically incapable--for instance, solving the halting problem (see Minsky, 1967). Note these "logical" predictions about behavior would be true of all representations and so do not provide a way of discriminating among them.

7. The class of primitive recursive functions is very large but is a subset of the recursive functions which can be computed on a general purpose computing device equivalent to a Turing machine. One way of thinking of the difference between primitive recursive functions and all computable functions is that it is possible to place time bounds on the amount of computation required to perform a primitive recursive function whereas such time bounds do not always exist for more general recursive functions. The class of primitive recursive functions is quite powerful, nonetheless. It is difficult to imagine that any process computed by the brain is more powerful than primitive recursive. So under very minimal assumptions about its nature, f will have a computable inverse.

8. If E or E^* map more than one input into the same value I or I^* the inverse of E or E^* can map I or I^* into any of these inputs. This use of inverse may not be totally conventional but is what is needed for the argument.

9. The point of this formal analysis was to show that one cannot decide issues of representation in the abstract, that one must also specify the processes that operate on the representation. It might be asked whether this point can be turned around. Is it possible to decide issues of process in the abstract? Could we get two very different processes to mimic each other by choice of structure in the way it was shown that two structures could mimic each other by choice of process? The situation is not exactly symmetric in that it is not possible to assign a structure for a process in the way it was possible to assign a process for a structure. A process must specify the structure of its input and of its output. Nonetheless, there probably is considerable indeterminacy in process assumptions. We can have two processes mimic each other by changing the processes with which they interact. For instance, we can get different processes T and T^* to mimic each other by changing the encoding processes, E and E^*, and the decoding processes, D and D^*. Thus, it may not be possible to test one process without specifying the processes with which it interacts.

10. This can be a fairly plausible assumption for certain processing formalisms such as production systems (e.g., Anderson, 1976). A production cannot apply unless the content of the information meets certain specifications. Thus, we might have certain types of productions that only applied to propositional representations that had verbal content or to propositional representations that had pictorial content.

References

Anderson, J.R. *Language, memory, and thought*. Hillsdale, N.J.: Lawrence Erlbaum Assoc., 1976.

Anderson, J.R. & Bower, G.H. *Human associative memory*, Washington, D.C.: Hemisphere Press, 1973.

Anderson, J.R. & Kline, P. Design of a Production System. Paper presented at the Workshop on Pattern-Directed Inference Systems, in *Sigart Newsletter*, June, 1977.

Anderson, J.R. & Paulson, R. Interference in memory for pictorial information. *Cognitive Psychology*, in press.

Atwood, G. An experimental study of visual imagination and memory. *Cognitive Psychology*, 1971, *2*, 290-299.

Banks, W.P., Clark, H.H. & Lucy, P.D. The locus of the semantic congruity effect in comparative judgments. *Journal of Experimental Psychology: Human Perception and Performance*, 1975, *1*, 35-47.

Baylor, G.W. A treatise on the mind's eye. Technical report. Institute of Psychology, University of Montreal, Canada, July, 1971.

Blakemore, C., Iversen, S.D., & Zangwell, O.L. Brain Functions. *Annual Review of Psychology*, 1972, *23*, 413-455.

Bower, G.H. Mental Imagery and Associative Learning. In L. Gregg, (Ed.). *Cognition in Learning and Memory*. New York: Wiley, 1972.

Bower, G.H. & Karlin, M.B. Depth of processing pictures of faces and recognition memory. *Journal of Experimental Psychology*, 1974, *103*, 751-757.

Bugelski, B.R. Words and things and images. *American Psychologist*, 1970, *25*, 1002-1012.

Chase, W.G. & Clark, H.H. Mental operations in the comparison of sentences and pictures. In L. Gregg (Ed.). *Cognition in Learning and Memory*, New York: Wiley, 1972.

Chase, W.G. & Simon, H.A. The mind's eye in chess. In W.G.

Chase (Ed.). Visual Information Processing. New York: Academic Press, 1973.

Clark, H.H. Linguistic processes in deductive reasoning. Psychological Review, 1969, 76, 387-404.

Collins, A.M. & Loftus, E.F. A spreading-activation theory of semantic processing. Psychological Review, 1975, 82, 407-428.

Cooper, L.A. Mental transformation of random two-dimensional shapes. Cognitive Psychology, 1975, 7, 20-43.

Cooper, L.A. & Podgorny, P. Mental transformations and visual comparison processes: Effects of complexity and similarity. Journal of Experimental Psychology: Human Perception and Performance, 1976, 2, 503-514.

Cooper, L.A. & Shepard, R.N. Chronometric studies of the rotation of mental images. In Chase, W.G. (Ed.) Visual Information Processing. New York: Academic Press, 1973.

Cooper, L.A. & Shepard, R.N. Transformations on representations of objects in space. In E.C. Carterette and M. Friedman (Eds.), Handbook of Perception. Volume VIII. Space and Object Perception. New York: Academic Press, in press.

DeGroot, A.D. Thought and choice in chess. The Hague: Mouton, 1965.

Duda, R.O. & Hart, P.E. Pattern classification and scene analysis. New York: Wiley, 1973.

Fredericksen, C. Representing logical and semantic structure of knowledge acquired from discourse. Cognitive Psychology, 1975, 7, 371-458.

Frege, G. Uber Sinn und Bedetung. Zeitschrift fur Philosophi und philosophiche Kritik (P. Geach & M. Black Eds. and trans.). Translations from the philosophical writings of Gottlob Frege. Oxford: Basil Blackwell, 1960, 56-78.)

Fodor, J.A. The language of thought. New York: Thomas Y. Crowell, 1975.

Gazzaniga, M.S. & Sperry, R.W. Language after section of the cerebral commissures. Brain, 1967, 90, 131-148.

Giffen, G., Bradshaw, J.L., & Nettleton, N.C. Hemispheric asymmetry: A verbal and spatial encoding of visual stimuli. Journal of Experimental Psychology, 1972, 95, 25-31.

Goldstein, A.G. & Chance, J.E. Visual recognition memory for complex configurations. Perception and Psychophysics, 1971, 9, 237-241.

Holyoak, K.J. The form of analogue size information in memory. Cognitive Psychology, 1977, 9, 31-51.

Kimura, D. Right temporal damage. Arch. Neurol., 1963, 8, 264-271.

Kintsch, W. The Representation of Meaning in Memory. Hillsdale, N.J.: Lawrence Erlbaum Assoc., 1974.

Klatzky, R.L. & Atkinson, R.C. Specialization of the cerebral hemispheres in scanning for information in short-term memory. Perception and Psychophysics, 1971, 10, 335-338.

Kosslyn, S.M. Scanning visual images: Some structural implications. Perception and Psychophysics, 1973, 14, 90-94.

Kosslyn, S.M. Information representation in visual images. Cognitive Psychology, 1975, 7, 341-370.

Kosslyn, S.M. & Pomerantz, J.R. Imagery, propositions, and the form of internal representations. Cognitive Psychology, 1977, 9, 52-76.

Kosslyn, S.M. & Shwartz, S.M. A data-driven simulation of visual imagery. Cognitive Science, 1977, 1, 265-296.

Kroll, N.E.A. Visual short-term memory. In J.A. Deutsch & D.Deutsch (Eds.), Short-term memory. New York: Academic Press, 1975.

McCarthy, J.; Abrahams, P.W.; Edwards, D.J.; Hart, T.P. and Levin, M.I. Lisp 1.5 programmers manual, Cambridge, Mass.: MIT Press, 1962.

Metzler, J. & Shepard, R.N. Transformational studies of the internal representations of three dimensional objects. In R.L. Solso (Ed.). Theories of Cognitive Psychology: The Loyola Symposium. Hillsdale, N.J.: Lawrence Erlbaum Assoc., 1974.

Minsky, M.L. Computation: Finite and infinite machines. Englewood Cliffs, New Jersey: Prentice-Hall, 1967.

Moran, T.P. The symbolic imagery hypothesis: A production system model. Unpublished PhD Dissertation, Carnegie-Mellon University, 1973.

Moyer, R.S. Comparing objects in memory: Evidence suggesting an internal psychophysics. Perception and Psychophysics 1973, 13, 180-184.

Meier, M.J. & French, L.A. Lateralized deficits in complex visual discrimination and bilateral transfer of reminiscence following unilateral temporal lobectomy. Neuropsychologia, 1965, 3, 261-272.

Newell, A. You can't play 20 questions with nature and win: Projective comments on the papers of this symposium. In W.G. Chase (Ed.). Visual Information Processing. New York: Academic Press, 1973.

Nielson, G.D. & Smith, E.E. Imaginal and verbal representations in short-term recognition of visual forms. Journal of Experimental Psychology, 1973, 101, 375-378.

Norman, D.A., Rumelhart, D.E. and the LNR Research Group. Explorations in Cognition. San Francisco: Freeman, 1975.

Paivio, A. Imagery and verbal processes. New York: Holt, Rinehart, and Winston, 1971.

Paivio, A. Perceptual comparisons through the mind's eye. Memory and Cognition, 1975, 3, 635-647.

Paivio, A. Images, propositions, and knowledge. In J.M. Nicholas (Ed.). Images, Perception, and Knowledge. The Western Ontario Series in the Philosophy of Science. Dordrecht: Reidel, 1976.

Palmer, S.E. Visual perception and world knowledge: Notes on a model of sensory-cognitive interaction. In D.A. Norman & D.E. Rumelhart (Eds.), Explorations in Cognition. San Francisco: Freeman, 1975, pp.279-307.

Patterson, K. & Bradshaw, J.L. Differential hemispheric mediation of nonverbal visual stimuli. Journal of Experimental Psychology: Human Perception and Performance, 1975, 1, 246-252.

Pezdek, K. Cross-modality integration of sentence and picture memory. Paper presented at the annual meeting of the Psychonomic Society, Denver, 1975.

Pylyshyn, Z.W. What the mind's eye tells the mind's brain: A critique of mental imagery. Psychological Bulletin, 1973, 80, 1-24.

Pylyshyn, Z.W. Imagery and artificial intelligence. In W. Savage (Ed.) , Minnesota studies in the philosophy of science, Vol. IX. Minneapolis: University of Minnesota Press, 1976.

Pylyshyn, Z.W. The symbolic nature of mental representations. In S. Kaniff (Ed.), Objectives and Methodologies in Artificial Intelligence, in press.

Quillian, M.R. The teachable language comprehender. Communications of the ACM, 1969, 12, 459-476.

Reed, S.K. Structural descriptions and the limitations of visual images. Memory and Cognition, 1974, 2, 329-336.

Richardson, A. Mental imagery. New York: Springer, 1969.

Rips, L.J. & Marcus, G. How prior beliefs affect implication. Carnegie Symposium on Cognitive Processes in Comprehension, May, 1976.

Salthouse, T.A. Using selective interference to investigate spatial memory representation. Memory & Cognition, 1974, 2, 749-757.

Salthouse, T.A. Simultaneous processing of verbal and spatial information. Memory & Cognition, 1975, 3, 221-225.

Shepard, R.N. Form, formation, and transformation of internal representations. In R. Solso (Ed.). Information Processing and Cognition: The Loyola Symposium. Hillsdale, N.J.: Lawrence Erlbaum, 1975.

Shepard, R.N. & Podgorny, P. Cognitive processes that resemble perceptual processes. In W.K. Estes (Ed.). Handbook of learning and cognitive processes

Hillsdale, N.J.: Lawrence Erlbaum Assoc., in press.

Smith, E.E. & Nielson, G.D. Representations and retrieval processes in short-term memory: Recognition and recall of faces. Journal of Experimental Psychology, 1970, 85, 397-405.

Teitleman, W. INTERLISP reference manual. Xerox Palo Alto Research Center, 1976.

Townsend, J.T. Issues and Models concerning the processing of a finite number of inputs. In B.H. Kantowitz (Ed.), Human Information Processing: Tutorials in Performance and Cognition. Hillsdale, N.J.: Lawrence Erlbaum Associates, 1974.

Winston, P.H. Learning structural descriptions from examples. MIT Artificial Intelligence Laboratory Project AI-TR-231, 1970.

Wiseman, S. & Neisser, U. Perceptual organization as a determinant of visual recognition memory. Paper presented at meetings of the Eastern Psychological Association, Spring, 1971.

Woods, W.A. What's in a link: Foundations for semantic networks. In D.G. Bobrow and A. Collins (Eds.), Representation and understanding: Studies in cognitive science. New York: Academic Press, 1975.

Table 1

A Propositional Encoding of the Letter in Figure 4

COMPOSE(R,S1,S2,S3,S4,S5,S6)	ANGLE(S1,S2,90)
STRAIGHT(S1,P1,P2)	ANGLE(S2,S3,90)
STRAIGHT(S2,P1,P3)	ANGLE(S2,S4,180)
STRAIGHT(S3,P3,P4)	ANGLE(S3,S4,90)
STRAIGHT(S4,P3,P5)	ANGLE(S3,S5,117)
STRAIGHT(S5,P4,P6)	AXIS(R,P3)
HALF-CIRCLE(S6,P2,P4)	VECTOR-ANGLE(P1,90)
LENGTH(S1,10)	VECTOR-ANGLE(P2,63)
LENGTH(S2,20)	VECTOR-ANGLE(P4,0)
LENGTH(S3,10)	VECTOR-ANGLE(P5,270)
LENGTH(S4,20)	VECTOR-ANGLE(P6,315)
LENGTH(S5,23)	
LENGTH(S6,31)	

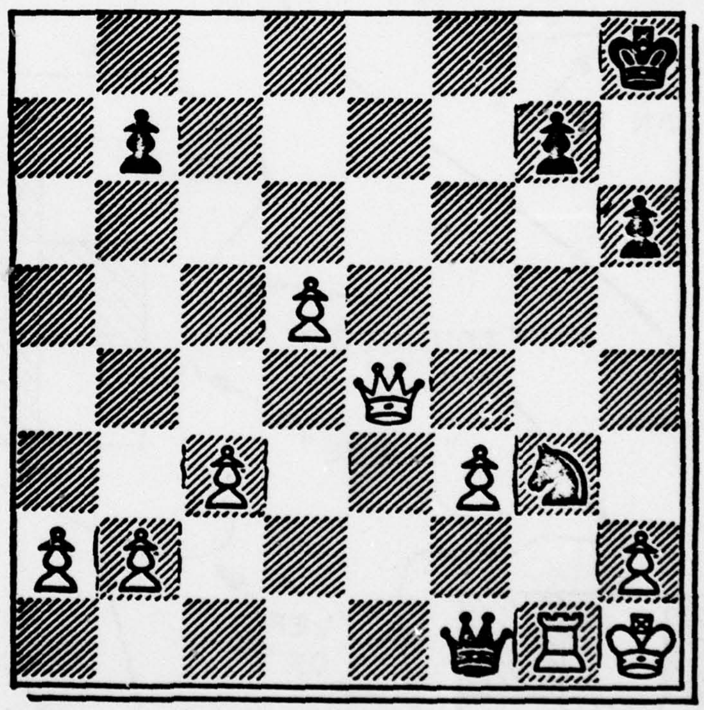
Figure Captions

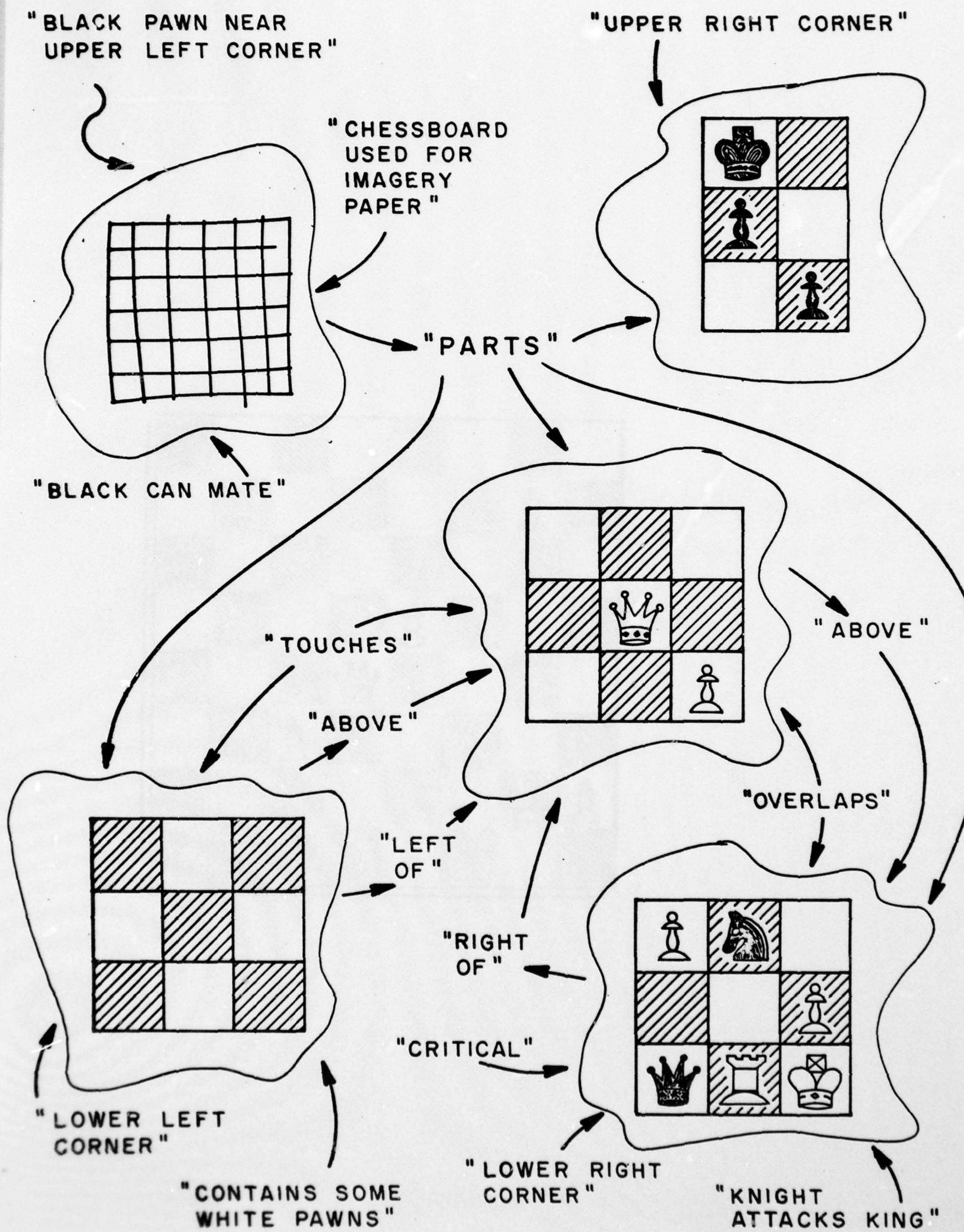
Figure 1. A end game chess position.

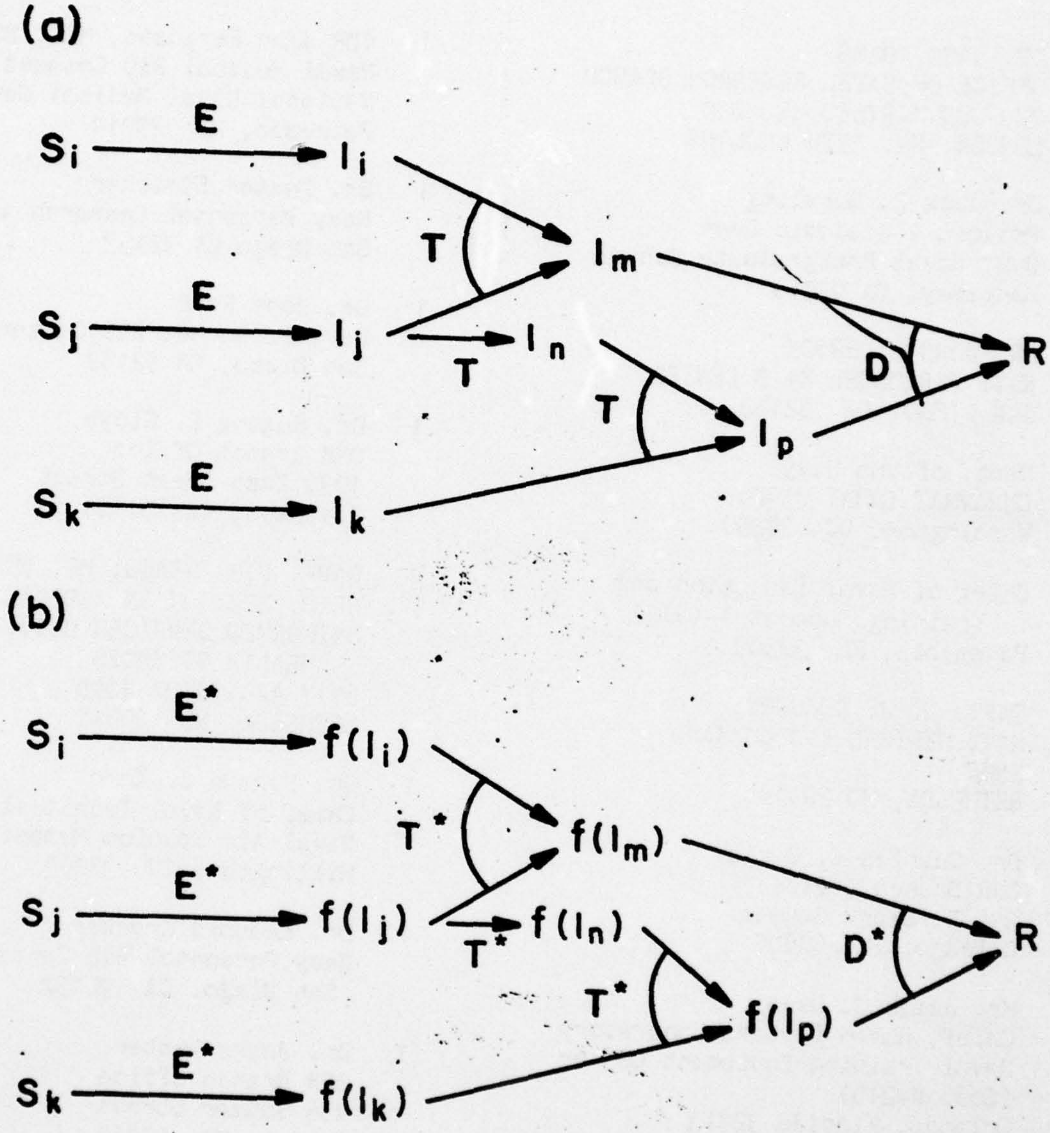
Figure 2. A dual code representation of the chess board in Figure 1.

Figure 3. (a) A representation of the transformation of information representations in model M.
(b) A representation of the transformation of information representations in model M^* which mimics M.

Figure 4. The letter R whose propositional coding appears in Table 1.




"BLACK PAWN NEAR UPPER LEFT CORNER"
"UPPER RIGHT CORNER"
"CHESSBOARD USED FOR IMAGERY PAPER"
"PARTS"
"BLACK CAN MATE"
"TOUCHES"
"ABOVE"
"ABOVE"
"OVERLAPS"
"LEFT OF"
"RIGHT OF"
"CRITICAL"
"LOWER LEFT CORNER"
"CONTAINS SOME WHITE PAWNS"
"LOWER RIGHT CORNER"
"KNIGHT ATTACKS KING"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Sj
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Navy

4 DR. JACK ADAMS
OFFICE OF NAVAL RESEARCH BRANCH
223 OLD MARYLEBONE ROAD
LONDON, NW, 15TH ENGLAND

1 Dr. Jack R. Borsting
Provost & Academic Dean
U.S. Naval Postgraduate School
Monterey, CA 93940

1 DR. JOHN F. BROCK
NAVY PERSONNEL R& D CENTER
SAN DIEGO, CA 92152

1 Dept. of the Navy
CHNAVMAT (NMAT 034D)
Washington, DC 20350

1 Chief of Naval Education and
Training Support)-(01A)
Pensacola, FL 32509

1 CAPT. H. J. CONNERY
NAVY MEDICAL R&D COMMAND
NNMC
BETHESDA, MD 20014

1 Dr. Charles E. Davis
ONR Branch Office
536 S. Clark Street
Chicago, IL 60605

1 Mr. James S. Duva
Chief, Human Factors Laboratory
Naval Training Equipment Center
(Code N-215)
Orlando, Florida 32813

4 Dr. Marshall J. Farr, Director
Personnel & Training Research Programs
Office of Naval Research (Code 458)
Arlington, VA 22217

1 DR. PAT FEDERICO
NAVY PERSONNEL R&D CENTER
SAN DIEGO, CA 92152

Navy

1 CDR John Ferguson, MSC, USN
Naval Medical R&D Command (Code 44)
National Naval Medical Center
Bethesda, MD 20014

1 Dr. Dexter Fletcher
Navy Personnel Research and Development
San Diego CA 92152

1 Dr. John Ford
Navy Personnel R&D Center
San Diego, CA 92152

1 Dr. Eugene E. Gloye
ONR Branch Office
1030 East Green Street
Pasadena, CA 91101

1 CAPT. D.M. GRAGG, MC, USN
HEAD, SECTION ON MEDICAL EDUCATION
UNIFORMED SERVICES UNIV. OF THE
HEALTH SCIENCES
6917 ARLINGTON ROAD
BETHESDA, MD 20014

1 Dr. Norman J. Kerr
Chief of Naval Technical Training
Naval Air Station Memphis (75)
Millington, TN 38054

1 Dr. Leonard Kroeker
Navy Personnel R&D Center
San Diego, CA 92152

1 Dr. James Lester
ONR Branch Office
495 Summer Street
Boston, MA 02210

1 Dr. William L. Maloy
Principal Civilian Advisor for
Education and Training
Naval Training Command, Code 00A
Pensacola, FL 32508

1 Dr. Sylvia R. Mayer (MCIT)
HQ Electronic Systems Div.
Hanscom AFB
Bedford, MA 01731

Navy

1 Dr. James McBride
Code 301
Navy Personnel R&D Center
San Diego, CA 92152

2 Dr. James McGrath
Navy Personnel R&D Center
Code 306
San Diego, CA 92152

1 DR. WILLIAM MONTAGUE
NAVY PERSONNEL R& D CENTER
SAN DIEGO, CA 92152

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NATIONAL NAVAL MEDICAL CENTER
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1 Library
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Code 2627
Washington, DC 20390

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CHIEF OF NAVAL EDUCATION &
TRAINING SUPPORT
PENSACOLA, FL 32509

1 Office of Naval Research
Code 200
Arlington, VA 22217

1 Scientific Director
Office of Naval Research
Scientific Liaison Group/Tokyo
American Embassy
APO San Francisco, CA 96503

Navy

1 SCIENTIFIC ADVISOR TO THE CHIEF
OF NAVAL PERSONNEL
NAVAL BUREAU OF PERSONNEL (PERS OR)
RM. 4410, ARLINGTON ANNEX
WASHINGTON, DC 20370

1 DR. RICHARD A. POLLAK
ACADEMIC COMPUTING CENTER
U.S. NAVAL ACADEMY
ANNAPOLIS, MD 21402

1 Mr. Arnold I. Rubinstein
Human Resoureces Program Manager
Naval Material Command (0344)
Room 1044, Crystal Plaza #5
Washington, DC 20360

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Chief of Naval Education and Training
Code N-5
NAS, Pensacola, FL 32508

1 A. A. SJOHOLM
TECH. SUPPORT, CODE 201
NAVY PERSONNEL R& D CENTER
SAN DIEGO, CA 92152

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Office of Chief of Naval Operations
OP-937E
Washington, DC 20350

1 CDR Charles J. Theisen, JR. MSC, USN
Head Human Factors Engineering Div.
Naval Air Development Center
Warminster, PA 18974

1 W. Gary Thomson
Naval Ocean Systems Center
Code 7132
San Diego, CA 92152

Army

1 DR. JAMES BAKER
U.S. ARMY RESEARCH INSTITUTE
5001 EISENHOWER AVENUE
ALEXANDRIA, VA 22333

1 DR. RALPH DUSEK
U.S. ARMY RESEARCH INSTITUTE
5001 EISENHOWER AVENUE
ALEXANDRIA, VA 22333

1 DR. FRANK J. HARRIS
U.S. ARMY RESEARCH INSTITUTE
5001 EISENHOWER AVENUE
ALEXANDRIA, VA 22333

1 Dr. Milton S. Katz
Individual Training & Skill
Evaluation Technical Area
U.S. Army Research Institute
5001 Eisenhower Avenue
Alexandria, VA 22333

1 Dr. J. E. Uhlaner
Chief Psychologist, US Army
Army Research Institute
6933 Hector Road
McLean, VA 22101

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U.S. Army Research Institute
5001 Eisenhower Avenue
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Bolling AFB, DC 20332

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CNET LIAISON OFFICER
AFHRL/FLYING TRAINING DIV.
WILLIAMS AFB, AZ 85224

1 Dr. Ross L. Morgan (AFHRL/ASR)
Wright -Patterson AFB
Ohio 45433

1 Research Branch
AFMPC/DPMYP
Randolph AFB, TX 78148

1 Dr. Marty Rockway (AFHRL/TT)
Lowry AFB
Colorado 80230

1 Brian K. Waters, Maj., USAF
Chief, Instructional Tech. Branch
AFHRL
Lowry AFB, CO 80230

Marines

1 Director, Office of Manpower Utilization
HQ, Marine Corps (MPU)
BCB, Bldg. 2009
Quantico, VA 22134

1 DR. A.L. SLAFKOSKY
SCIENTIFIC ADVISOR (CODE RD-1)
HQ, U.S. MARINE CORPS
WASHINGTON, DC 20380

CoastGuard

1 MR. JOSEPH J. COWAN, CHIEF
PSYCHOLOGICAL RESEARCH (G-P-1/62)
U.S. COAST GUARD HQ
WASHINGTON, DC 20590

Other DoD

12 Defense Documentation Center
Cameron Station, Bldg. 5
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Attn: TC

1 Military Assistant for Human Resources
Office of the Director of Defense
Research & Engineering
Room 3D129, the Pentagon
Washington, DC 20301

1 Dr. Harold F. O'Neil, Jr.
Advanced Research Projects Agency
Cybernetics Technology, Rm. 623
1400 Wilson Blvd.
Arlington, VA 22209

1 Director, Research & Data
OSD/MRA&L (Rm. 3B919)
The Pentagon
Washington, DC 20301

1 DR. ROBERT YOUNG
ADVANCED RESEARCH PROJECTS AGENCY
1400 WILSON BLVD.
ARLINGTON, VA 22209

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1 Dr. William Gorham, Director
Personnel R&D Center
U.S. Civil Service Commission
1900 E Street NW
Washington, DC 20415

1 Dr. Andrew R. Molnar
Science Education Dev.
and Research
National Science Foundation
Washington, DC 20550

1 Dr. Thomas G. Sticht
Basic Skills Program
National Institute of Education
1200 19th Street NW
Washington, DC 20208

1 Dr. Vern W. Urry
Personnel R&D Center
U.S. Civil Service Commission
1900 E Street NW
Washington, DC 20415

1 Dr. Joseph L. Young, Director
Memory & Cognitive Processes
National Science Foundation
Washington, DC 20550

Non Govt

1 PROF. EARL A. ALLUISI
DEPT. OF PSYCHOLOGY
CODE 287
OLD DOMINION UNIVERSITY
NORFOLK, VA 23508

1 Dr. John R. Anderson
Dept. of Psychology
Yale University
New Haven, CT 06520

1 DR. MICHAEL ATWOOD
SCIENCE APPLICATIONS INSTITUTE
40 DENVER TECH. CENTER WEST
7935 E. PRENTICE AVENUE
ENGLEWOOD, CO 80110

1 MR. SAMUEL BALL
EDUCATIONAL TESTING SERVICE
PRINCETON, NJ 08540

1 Dr. Gerald V. Barrett
Dept. of Psychology
University of Akron
Akron, OH 44325

Non Govt

1 Dr. Kenneth E. Clark
College of Arts & Sciences
University of Rochester
River Campus Station
Rochester, NY 14627

1 Dr. Norman Cliff
Dept. of Psychology
Univ. of So. California
University Park
Los Angeles, CA 90007

1 Dr. Allan M. Collins
Bolt Beranek & Newman, Inc.
50 Moulton Street
Cambridge, Ma 02138

1 Dr. John J. Collins
Essex Corporation
201 N. Fairfax Street
Alexandria, VA 22314

1 Dr. Meredith Crawford
5605 Montgomery Street
Chevy Chase, MD 20015

1 Dr. Nicholas A. Bond
Dept. of Psychology
Sacramento State College
600 Jay Street
Sacramento, CA 95819

1 Dr. John Seeley Brown
Bolt Beranek & Newman, Inc.
50 Moulton Street
Cambridge, MA 02138

1 DR. C. VICTOR BUNDERSON
WICAT INC.
UNIVERSITY PLAZA, SUITE 10
1160 SO. STATE ST.
OREM, UT 84057

1 Dr. John Carroll
Psychometric Lab
Univ. of No. Carolina
Davie Hall 013A
Chapel Hill, NC 27514

Non Govt

1 Dr. Richard L. Ferguson
The American College Testing Program
P.O. Box 168
Iowa City, IA 52240

1 Dr. Victor Fields
Dept. of Psychology
Montgomery College
Rockville, MD 20850

1 Dr. Edwin A. Fleishman
Advanced Research Resources Organ.
8555 Sixteenth Street
Silver Spring, MD 20910

1 Dr. John R. Frederiksen
Bolt Beranek & Newman
50 Moulton Street
Cambridge, MA 02138

1 DR. ROBERT GLASER
LRDC
UNIVERSITY OF PITTSBURGH
3939 O'HARA STREET
PITTSBURGH, PA 15213

1 DR. JAMES G. GREENO
LRDC
UNIVERSITY OF PITTSBURGH
3939 O'HARA STREET
PITTSBURGH, PA 15213

1 Dr. Barbara Hayes-Roth
The Rand Corporation
1700 Main Street
Santa Monica, CA 90406

1 Dr. Donald Dansereau
Dept. of Psychology
Texas Christian University
Fort Worth, TX 76129

1 DR. RENE V. DAWIS
DEPT. OF PSYCHOLOGY
UNIV. OF MINNESOTA
75 E. RIVER RD.
MINNEAPOLIS, MN 55455

1 Dr. Ruth Day
Center for Advanced Study
in Behavioral Sciences
202 Junipero Serra Blvd.
Stanford, CA 94305

1 MAJOR I. N. EVONIC
CANADIAN FORCES PERS. APPLIED RESEARCH
1107 AVENUE ROAD
TORONTO, ONTARIO, CANADA

Non Govt

1 DR. LAWRENCE B. JOHNSON
LAWRENCE JOHNSON & ASSOC., INC.
SUITE 502
2001 S STREET NW
WASHINGTON, DC 20009

1 Dr. Arnold F. Kanarick
Honeywell, Inc.
2600 Ridgeway Pkwy
Minneapolis, MN 55413

1 Dr. Roger A. Kaufman
203 Dodd Hall
Florida State Univ.
Tallahassee, FL 32306

1 Dr. Steven W. Keele
Dept. of Psychology
University of Oregon
Eugene, OR 97403

1 LCOL. C.R.J. LAFLEUR
PERSONNEL APPLIED RESEARCH
NATIONAL DEFENSE HQS
101 COLONEL BY DRIVE
OTTAWA, CANADA K1A 0K2

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Human Factors Research, Inc.
6780 Cortona Drive
Santa Barbara Research Pk.
Goleta, CA 93017

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Hunter Lab.
Brown University
Providence, RI 82912

1 Dr. Donald A Norman
Dept. of Psychology C-009
Univ. of California, San Diego
La Jolla, CA 92093

Non Govt

1 Dr. Jesse Orlansky
Institute for Defense Analysis
400 Army Navy Drive
Arlington, VA 22202

1 MR. LUIGI PETRULLO
2431 N. EDGEWOOD STREET
ARLINGTON, VA 22207

1 DR. PETER POLSON
DEPT. OF PSYCHOLOGY
UNIVERSITY OF COLORADO
BOULDER, CO 80302

1 DR. DIANE M. RAMSEY-KLEE
R-K RESEARCH & SYSTEM DESIGN
3947 RIDGEMONT DRIVE
MALIBU, CA 90265

1 Dr. Mark D. Reckase
Educational Psychology Dept.
University of Missouri-Columbia
12 Hill Hall
Columbia, MO 65201

1 Dr. Joseph W. Rigney
Univ. of So. California
Behavioral Technology Labs
3717 South Hope Street
Los Angeles, CA 90007

1 Dr. Andrew M. Rose
American Institutes for Research
1055 Thomas Jefferson St. NW
Washington, DC 20007

1 Dr. Leonard L. Rosenbaum, Chairman
Department of Psychology
Montgomery College
Rockville, MD 20850

1 DR. WALTER SCHNEIDER
DEPT. OF PSYCHOLOGY
UNIVERSITY OF ILLINOIS
CHAMPAIGN, IL 61820

Non Govt

1 DR. ROBERT J. SEIDEL
INSTRUCTIONAL TECHNOLOGY GROUP
HUMRRO
300 N. WASHINGTON ST.
ALEXANDRIA, VA 22314

1 Dr. Richard Snow
School of Education
Stanford University
Stanford, CA 94305

1 Dr. Robert Sternberg
Dept. of Psychology
Yale University
Box 11A, Yale Station
New Haven, CT 06520

1 DR. ALBERT STEVENS
BOLT BERANEK & NEWMAN, INC.
50 MOULTON STREET
CAMBRIDGE, MA 02138

1 Mr. D. J. Sullivan
c/o Canyon Research Group, Inc.
741 Lakefield Road
Westlake Village, CA 91361

1 DR. PATRICK SUPPES
INSTITUTE FOR MATHEMATICAL STUDIES IN THE SOCIAL SCIENCES
STANFORD UNIVERSITY
STANFORD, CA 94305

1 Dr. Kikumi Tatsuoka
Computer Based Education Research Laboratory
252 Engineering Research Laboratory
University of Illinois
Urbana, IL 61801

1 DR. PERRY THORNDYKE
THE RAND CORPORATION
1700 MAIN STREET
SANTA MONICA, CA 90406

1 Dr. Benton J. Underwood
Dept. of Psychology
Northwestern University
Evanston, IL 60201

Non Govt

1 DR. THOMAS WALLSTEN
PSYCHOMETRIC LABORATORY
DAVIE HALL 013A
UNIVERSITY OF NORTH CAROLINA
CHAPEL HILL, NC 27514

1 Dr. Claire E. Weinstein
Educational Psychology Dept.
Univ. of Texas at Austin
Austin, TX 73712

1 Dr. David J. Weiss
N660 Elliott Hall
University of Minnesota
75 E. River Road
Minneapolis, MN 55455

1 DR. KEITH WESCOURT
INSTITUTE FOR MATHEMATICAL STUDIES IN
THE SOCIAL SCIENCES
STANFORD UNIVERSITY
STANFORD, CA 94305

1 DR. SUSAN E. WHITELY
PSYCHOLOGY DEPARTMENT
UNIVERSITY OF KANSAS
LAWRENCE, KANSAS 66044