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WHAT THE MIND'S EYE TELLS THE MIND'S BRAIN: A CRITIQUE OF MENTAL IMAGERY¹

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This paper presents a critique of contemporary research which uses the notion of a *mental image* as a theoretical construct to describe one form of memory representation. It is argued that an adequate characterization of "what we know" requires that we posit abstract mental structures to which we do not have conscious access and which are essentially *conceptual* and *propositional*, rather than sensory or pictorial, in nature. Such representations are more accurately referred to as symbolic descriptions than as images in the usual sense. Implications of using an imagery vocabulary are examined, and it is argued that the picture metaphor underlying recent theoretical discussions is seriously misleading—especially as it suggests that the image is an entity to be perceived. The relative merits of several alternative modes of representation (propositions, data structures, and procedures) are discussed. The final section is a more speculative discussion of the nature of the representation which may be involved when people "use" visual images.

Cognitive psychology is concerned with two types of questions: What do we know? and How do we acquire and use this knowledge? The first type of question, to which this paper is primarily addressed, concerns itself with what might be called the problem of cognitive representation. It attempts to answer the question What is stored? by describing the form in which our knowledge or model of the world is represented in the mind. The second type of question attempts to deal more directly with certain limited-capacity psychological processes which create and manipulate the representations and generate

appropriate behavior from them (such as questions of limited attention and memory and "psychological cost" factors limiting performance).

The problem of cognitive representation has been approached by a wide variety of paths in the last half century. It is not the purpose of this paper to review this spectrum of alternative representations. We concern ourselves with one particular proposal—that cognitive representations take the form of mental images—which has recently exploded into fashion and with a number of alternatives which derive primarily from computer-simulation work.

MENTAL IMAGES

After almost 50 years of dedicated avoidance, mental imagery appears to be once again at the center of interest in many areas of psychology (Arnheim, 1969; Bower, 1972; Bugelski, 1970; Hebb, 1968; Holt, 1964; Horowitz, 1970; Paivio, 1969, 1971; Reese (1970); Richardson, 1969; Segal, 1971; Sheehan, 1972), although it is not without its

¹ Several of the arguments appearing in this paper were first developed in the course of discussions held with Marvin Minsky and Michael Arbib. Also, the careful critical reading given an earlier version of this paper by Allan Paivio has hopefully led to a more careful and balanced presentation. I am grateful to these people for their help but am not so optimistic as to expect that they will agree with all the arguments appearing in the final draft.

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detractors (Brainerd, 1971; Brown, 1958; Gibson, 1966; Neisser, 1972). It has returned not only as a phenomenon to be investigated but as an explanatory construct in cognitive psychology. It is of some interest, therefore, to ask whether anything new has been learned about mental images in the last decade and whether the critiques widespread early in the century have been satisfactorily countered.

Any analysis in the nature and role of imagery is fraught with difficulty. The concept itself proves to be difficult to pin down. Is a visual image like some conceivable picture? If not, then in what way must it differ? If it is like a picture in some ways, then must it always be a picture of some specific instance, or can it be generic (if such a notion is intelligible)? Could it, for example, represent abstract relations or must the relations in the image be of an iconic or geometric variety? Is an entire image available at once—as a spatially parallel static picture—or do parts of it come and go? If parts can be added and deleted at will, must such parts be pictorial segments (e.g., geometrically definable pieces or sensory attributes such as color) or can they be more abstract aspects? Could one, for example, conceive of two images of the identical chessboard with one image containing the relation “is attacked by” and the other not containing it? If so, then in what sense could such a relation be said to be “in the image”? Must images in some important sense be modality specific, as implied by such phrases as visual image, auditory image, etc.? And finally, must images always be conscious? Can one, for example, make intelligible the notion of an unconscious visual image?

The tumultuous history of the concept of imagery in both philosophy and psychology attests to the difficulties which such questions have raised in the minds of centuries of scholars. While contemporary psychologists have attempted to narrow the scope of the concept by operational definitions and multiple empirical and theoretical underpinnings, it is not clear that they have resolved the major *conceptual* ambiguities, circularities, and Rylean “category mistakes” which have plagued the notion in the past. In this paper we do not attempt a philosophical analysis

of the concept since that would take us too far afield from our primary objective, which is to analyze the role of imagery as an explanatory construct in cognitive psychology. In attempting this, however, it is impossible to avoid pointing out some of the conceptual problems implicit in contemporary uses of the term “imagery” to explain certain findings in psychology.

For the sake of avoiding any misinterpretations of the remarks in the remainder of this paper, it should be stressed that the existence of the experience of images cannot be questioned. Imagery is a pervasive form of experience and is clearly of utmost importance to humans. We cannot speak of consciousness without, at the same time, implicating the existence of images. Such experiences are not in question here. Nor, in fact, is the status of imagery either as object of study (i.e., as dependent variable) or as scientific evidence being challenged. There are many areas where the alternative to cautious acceptance of reports of imagery is the rejection of a whole area of inquiry (e.g., Hebb, 1960; Holt, 1964). Furthermore, the extensive experimental investigations of imagery in the last decade (exhaustively surveyed in Pavio, 1971) have been of unquestionable value in breaking through the earlier oppressive structures on what phenomena ought to be studied. The empirical regularities demonstrated are of high reliability and wide interest, both from a scientific and practical point of view. None of these empirical results are questioned. The main question that is raised is whether the concept of image can be used as a primitive explanatory construct (i.e., one not requiring further reduction) in psychological theories of cognition. A second and equally important issue is whether the commonsense understanding of this term contains misleading implications which carry over undetected into psychological theories.

Information and Experience

While most psychologists are willing to concede that not all important psychological processes and structures are available to conscious inspection, it is not generally recognized that the converse may also hold: that what is available to conscious inspection may

not be what plays the important causal role in psychological processes. This is not to imply that when a subject says that he does such-and-such a mental operation that he may be dishonest in his reports nor even that he himself is misled as to what he "actually" does. This is not the issue. If someone asks me how many windows there are in my house and then asks me to report how I went about answering the question, this report (subject to the usual methodological precautions) may be taken as an accurate report of what I *experienced* doing. The only trouble is that I must give such a report in the only language I have available for describing my awarenesses. A description in such a language may be entirely inadequate in meeting what Chomsky (1964) has referred to as "explanatory adequacy." The description may even fail to be mechanistic insofar as it may use terms such as "want," "guess," "notice," or "mind's eye," which, while they may faithfully reflect one's experience of doing the task, are inadequate as *primitive constructs* since they themselves cry out for a reduction to mechanistic terms.

Even if the description does not contain inadmissible terms, there is no guarantee that it will make sense as an *explanatory* scientific theory. An explanatory theory must meet different criteria of adequacy than would be demanded of an informal *descriptive* account. It must first be free of conceptual difficulties and internal contradictions. Then it must be shown to be capable of providing a mechanistic explanation for the widest possible domain of empirical evidence in a manner which reveals the most general principles involved. An explanatory account must ultimately appeal to universal mechanistic principles. Just because we *know* that we use certain mnemonic strategies, or that we say certain things to ourselves, or that we "see" certain objects in our "mind's eye" or "hear" ourselves rehearsing a series of numbers, etc., we cannot assume that the contents of such subjective knowledge can be identified with the kind of information-processing procedures which will go into an explanatory theory.

Perhaps these remarks can be made clearer if we sharply distinguish two senses of cognitive verbs like "see," "hear," or "image." In

one sense, they refer to information-processing functions—to the reception of information through the visual or auditory systems and the subsequent transformation or encoding of this information in interaction with stored information. In the case of imagery it may perhaps refer to the activation, retrieval, or reorganization of such information. Another very different sense of these terms is implied, however, when they are used to designate the conscious experience which may accompany such functions, that is, the conscious experience of seeing, hearing, or imaging (or examining an image in the "mind's eye"). In this sense of the word "image" one might claim that the image can be examined through introspection. Clearly, however, the information-processing function itself cannot. It is important to inquire whether the experience of imaging can reveal important properties of the information-processing functions or of the mental representation of information on which these processes operate. But we must not assume in advance that such observation will reveal the content of the mental representation. Not only does such observation present serious methodological hazards, it is not *prima facie* an observation of the functional representation (i.e., one that figures in the human information-processing function).

In discussing the question of introspective knowledge, Natsoulas (1970) warns,

It may turn out that, even though a useful informational relation (concomitant variation) exists between the contents of our awareness and the properties of mental episodes, they do not have the intrinsic properties which we take them to have [p. 91].

The recent literature on imagery abounds in examples which reveal that the investigator tacitly assumes that what is functional in cognition is available to introspection. Consider, for example, the widely held view (the so-called dual-code model) that the form of mental representations is either verbal or imaginal. This partition between two concrete modes has its roots in the persuasive fact that the only way in which we clearly experience our memory of cognitive events is through some form of sensory-motor image (including articulatory and acoustical images of words). Thus, for example, in a revival of a position associated with Berkeley and Hume, Bugelski

(1970) questions "whether there is such a thing as an abstract thought or abstraction [p. 1006]." The basis of his doubts are his experiments, using the Kent-Rosanoff Word Association Test, in which he finds:

If you say FLOWER, a categorical term, the subjects think of daisies or roses, and highly specific daisies or roses If you say DEMOCRACY, they report a variety of imagery, practically none of which refers to governmental operations. Government by the people becomes an image of a crowd at a political rally [p. 1006].

Drawing conclusions about the nature of cognitive representations from reports of experiences evoked by words may appear somewhat far-fetched (after all, what else could a subject report having experienced—other than images of objects or of other words?) until we examine the context in which Bugelski and his colleagues are working. The thrust of Bugelski's paper is to show the inadequacy of theories of learning and memory which rely exclusively on postulating associations among words. From this excess he adopts another equally untenable position (which is nowhere stated explicitly): that all learning and memory—and indeed all of cognition—takes place exclusively through the medium of either words or images. In fact, it appears that most modern psychologists working on imagery and learning have succumbed to the assumption that there are no forms of mental representation other than words and images. Thus Bugelski (1970) argues that the use of young deaf subjects who "have no language" provides an ideal test for the existence of imagery. He asserts, "If they truly have no speech or verbal capacity and can learn certain kinds of materials, for example, picture paired-associates, the conclusion that imagery was being used seems logically determined [p. 1004]." It is logically determined, of course, only if we accept that images and words exhaust the available forms of mental representation.

Similarly, Paivio (1969) pits his defense of imagery against the word-association approach, arguing that ". . . one can respond verbally to pictures as well as to words and so, by analogy, one's verbal response could just as logically be mediated by a 'mental

picture' as by 'mental words' [p. 242]." The parallel does indeed hold: whatever arguments may be marshalled in favor of mental words as mediators can be used equally well to support mental pictures. Thus adding images to the repertoire of mediators represents a logical extension of mediational accounts. What is unsatisfactory about this extension, however, is that no consideration is given to the possibility that cognition may be "mediated" by something quite different from either pictures or words, different in fact from anything which can be observed either from within or from without.

In spite of the prevalence of such views, a number of theorists, particularly those working in the information-processing tradition, have found it necessary to postulate forms of representation which differ radically from the form in which such information is presented to the senses or the way in which it is subjectively experienced. For example, many models of attention (e.g., Triesman, 1964) and memory (e.g., Norman, 1968) as well as all analysis-by-synthesis models (e.g., Neisser, 1967) require that representations differing from both the sensory pattern and the name or verbal description be available at some stage in the process. In the same spirit, the author argued some years ago (Pylyshyn, 1963) against the view that representations in short-term memory went directly from a visual to an auditory form as the information was "read" off the image. Instead, a coding continuum was proposed. Sperling (1963) also found evidence against the two-stage view. He showed that while information sufficient to identify a letter could be extracted from a display in about 10 milliseconds, it took over 300 milliseconds to name a letter. Sperling developed a model in which information between these two stages (i.e., visual and verbal) was held in a "recognition buffer memory." Not only is the information in this buffer neither in a visual nor an auditory form, it is not in any form which *could* be made conscious. Sperling (1967) comments,

This makes it indeed a mysterious component; it cannot be observed directly from within or from without! However, this inaccessibility should not surprise us. It is axiomatic that in any system which examines itself there ultimately must be some

part of the mechanism which is inaccessible to examination from within [p. 292].

This is indeed true; only perhaps the surprise ought to be that *any* of it should be accessible from within. One scarcely expects brain processes to be available to introspective examination, so why should one expect functional information to be thus accessible?

But 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. The problem is dramatized if we persist in using the common but utterly misleading metaphor of the “mind’s eye,” for then we have to account for the form of representation in the “mind’s eye’s mind” which clearly is not accessible to introspection.

Any attempt to bypass this difficulty by positing a direct associative link between a mental picture and a mental word meets with other difficulties. There are an infinite number of pictures to which a particular word applies. For example, there are an infinite number of rectangles of various shapes, sizes, colors, orientations, etc. When the mental word “rectangle” is elicited by the mental picture of a rectangle, it cannot be by virtue of an associative link between the two, since this would require that we postulate an infinite number of such links (one for each possible picture). The mental word “rectangle” is at best a response to what all the pictures of rectangles have in common, namely, their “rectangleness.” The problem arises because cognition must deal with pattern *types* and not *tokens*, and there is no limit to the variety of tokens corresponding to each type. Thus the relationship cannot be described by a finite list of associated picture-word tokens.

Propositions and Appearances

Although Bower (1972) appears to recognize the existence of such problems to the

extent of a passing admission that people do have concepts—and that these are different from either words or pictures—he nevertheless proceeds to develop an argument for a dual-code model of memory of the type earlier advocated by Paivio (1969). His arguments are of interest because they shed some light on the nature of some of the conceptual difficulties to which such models give rise. In his account, Bower (1972) make a distinction between memory for appearances (*how* things look) and memory for we what call facts (*what* things resemble). From this he argues,

This distinction between how something looked and what it looked like runs parallel to the distinction between cognitive memories, namely, images versus propositional memory. That is, we remember appearances in imagery, and we also remember propositions . . . the difference . . . is the same as the difference between a sighted versus a blind person’s knowledge of the visual world. In the auditory domain, it is the difference between my knowledge of how an orchestra symphony sounds and how I might try to describe it to a deaf person [p. 52].

Not only is this dichotomy not exhaustive, it also gives a misleading account of what it means to “know” such things as “how the orchestra sounds.” To make this clear, we need to draw some further distinctions. First, we must distinguish between the subjective experience of recalling the sound and the functional information which enables us to, say, make judgments of relative similarity of two instruments. The term *appearance* is surely meant to refer only to the former. An appropriately programmed computer could, no doubt, be made to produce similarity judgments among sounds but we might still be reluctant to describe it as “experiencing” the sound and therefore of being able to recall its appearance. It would, in general, even be unreasonable to require the computer to store the equivalent of a sound-recording trace of the stimulus, since this would soon tax the storage capacity of any machine. So even in this nonexperiential sense of appearance, it is still the case that the computer would not have access to the original pattern of stimulation when it made its similarity judgment. Thus there is no reasonable sense in which the computer would use the *appearance* of the original sound to make its

judgment. While a person might *experience* the appearance of the sound, it would similarly be unreasonable to suppose that he can make the similarity judgment because he has stored the original pattern of sensory stimulation (we shall return to this point later.)

Second, when Bower and others speak of nonimaginal memory as propositional, they imply the storage of actual utterances. But one must be careful not to equate a proposition with a string of words. A proposition is what a string of words may assert. A proposition is either true or false; the string of words is neither. A proposition may be asserted by any number of strings of words, in any language and in any modality. Furthermore, in the sense in which we use it when we speak of "propositional knowledge," it may involve no words of any kind. Thus when I look at the table in front of me, I see that there is a vase on it. I do not "see" patches of light or only an array of objects. My knowledge is enriched by (among other things) the proposition asserted by a sentence such as "The vase is on the table," even though I did not utter (audibly or otherwise) this or any other sentence. As Hanson (1958) argued "Knowledge of the world is not a *montage* of sticks, stones, color patches and noises, but a system of propositions [p. 26]." When we use the word "see," we refer to a bridge between a pattern of sensory stimulation and knowledge which is propositional. This is not to deny that there are such things as appearances, only that if they have a role to play in cognition, the nature of such a role is at present a complete mystery. We cannot even talk about appearances without, in fact, talking about the propositional content of the appearances. And as Wittgenstein wisely reminded us, in such circumstances it is best to remain silent on the subject.

Failure to grasp the difference between the appearance of visual images and knowledge leads to various logical confusions. For instance, it leads Bugelski to conclude that the only reason deaf children should recall visual patterns is because they used visual images which, judging by his use of the term, means that they could recreate the appearance of the pattern by reactivating something like the original sensory stimulation. By such

an account each time the image is recalled, it must be "seen" anew since deaf children presumably do not possess the appropriate code (i.e., an auditory image of words) with which to represent the proposition as a subvocal sentence. If this were so, deaf children (who, incidentally, very likely have a language of some kind) would be left wallowing in appearances without a single item of knowledge to which the ascription "true" or "false" was even applicable!

There are even more serious difficulties involved in drawing the distinction between appearances and propositions if we carry this dichotomy through to the area of thinking. The role of experienced images (i.e., appearances) in thinking is by no means clear since even if we make the assumption that the contents of our experiences reveal theoretically useful psychological processes, it still remains true that very little (if any) of the thinking is carried by such processes. Thus, as Humphrey (1951) points out, while the process of thinking ". . . may involve sense-resembling processes of a particular modality . . . this is the cart, not the horse. The primary 'work' when one thinks a proposition such as 'Russia is East of Britain' is imageless . . . [p. 106]." Natsoulas (1970) concurs with this view, arguing that even though thinking can involve a succession of imaginal awarenesses, "In undergoing the image, however, one does not have the thought. One has it in noticing something about what is imaginally presented. Such noticings are, or course, propositional . . . [p. 99]."

The same could also be said about the role of imaging in other cognitive tasks, including the learning of paired associates. For suppose one maintains that a subject learns a pair such as *boy-play* by forming an image of a small boy throwing a ball. Later when the stimulus word *boy* is presented, the same image is retrieved. By examining this image, so it is argued, the subject is able to produce the correct response *play*. The problem remains, however, to explain why the subject in this case chooses to respond *play* and not *throw* or *ball* or *catch* or any of an unlimited number of words equally appropriate to that image. Presumably it is because

he remembers more than is contained in the image. In fact, this shows that the bulk of the work of learning and recalling the pair of words is carried out by a process to which we do not have conscious access, but which may, in some unspecified manner, make use of the propositional information that *boy* and *play* are related by predication.

Before leaving this discussion of knowledge as propositional, we must pause to reemphasize the difference among pictures, sentences, and propositions. Both pictures and sentences must be interpreted before they become conceptual contents. This is because there are an indefinite number of both pictures and of sentences which are cognitively equivalent. This is not true of propositions as logicians use this term. For example, the philosopher Frege (1960) in his seminal work on predicate logic (first published in 1879) cites the example of two sentences which are paraphrases of one another and comments,

... I call the part of the content that is the same in both the *conceptual content*. Only this has significance for our symbolic language; we need therefore make no distinction between propositions that have the same conceptual content [p. 3].

Thus propositions are to be found in the deep structure of language and not in its surface form. But this is still not sufficiently abstract for our purposes since it might be taken to imply that each proposition is expressible by *some* sentence in a natural language. This is not, however, a necessary condition for our use of the term. We claim that it is still useful to think of propositional knowledge even when the concepts and predicates in such propositions do not correspond to available words in our vocabulary. Such concepts and predicates may be perceptually well defined without having any explicit natural language label. Thus we may have a concept corresponding to the equivalence class of certain sounds or visual patterns without an explicit verbal label for it. Such a view implies that we can have mental concepts or ways of abstracting from our sense data which are beyond the reach of our current stock of words, but for which we *could* develop a vocabulary if communicating such concepts became important (e.g., for a professional musician, painter, or wine taster). This is not

an unreasonable position to hold in view of the fact that conceptual categories are necessary not only for communicating but also for *acting* on the environment. Thus perceptual or motor events which are functionally equivalent with respect to indicating or leading to functionally similar changes in the organism's environment might become represented as unique nonverbal mental concepts (for a discussion of such an action-oriented view, see Arbib, 1972). Such a view is in agreement with Newell and Simon's (1972) position that postulating a single set of internal symbol structures provides the most parsimonious account for both thought and the deep structure of language. It also receives support from evidence (e.g., Macnamara, 1972) that children develop conceptual or semantic structures prior to learning the related linguistic signs.

In spite of the inexpressibility (for a particular individual at a particular time) of propositions containing such nonverbal concepts, there are nevertheless some good reasons for still referring to such knowledge as propositional or descriptive. Just as cognition requires propositions which stand in a type-token relation to sentences, so also does it require something which stands in a type-token relation to pictures or sensory patterns. This something is best characterized as a descriptive symbol structure containing perceptual concepts and relations, but having the abstract qualities of propositions rather than the particular qualities of pictorial images. Furthermore, to refer to a representation arising from sensory stimulation as being propositional, as we have been advocating, is to imply (a) that it does *not* correspond to a raw sensory pattern but, rather, is already highly abstracted and *interpreted*, (b) that it is not different in principle from the kind of knowledge asserted by a sentence, or potentially assertable by some sentence, (c) that it depends on the classification of sensory events into a finite set of concepts and relations, so that what we know about some event or object is formally equivalent to (i.e., can be reduced to) a finite (and, in fact, relatively small) number of logically independent descriptive propositions. The above implications, as we shall see in the next section, are

desirable and yet difficult (if not impossible) to convey using the picture vocabulary of the imagery literature.

Picture Metaphor

In this section we try to make explicit some of the implications of using the imagery vocabulary. To begin, consider what the terms "image" or "imagery" mean to most psychologists who write on the subject. Some writers have suggested that images are related to conditioned sensations (Staats, 1968), to "indirect reactivations of former sensory or perceptual activity [Bugelski, 1970, p. 1002]," or that they are "a faint subjective representation of a sensation or perception without an adequate sensory input [Holt, 1964, p. 255]," or "the occurrence of perceptual processes in the absence of stimulation which normally gives rise to perception [Hebb, 1966, p. 41]," or imagery is defined as "the ability of a subject to generate or synthesize a sensory-like datum in the absence of physical stimulation [Weber & Bach, 1969, p. 199!]."

Such definitions, however, are not used directly in the empirical research. As Paivio (1969) rightly points out, "Both images and verbal processes are operationally defined and the concern is with their functional significance . . . [p. 243]." However, the importance of the informal notions of imagery in psychological theories should not be underestimated. What makes it possible to give a consistent and systematic interpretation of the empirical findings is not the individual predictions (e.g., high-imagery sentences are recalled more easily than low-imagery sentences) nor the operationally defined terms (imagery as the rating assigned to a stimulus), but the highly persuasive intuitive notions of what images are, what causal effects they may exert, and how we can manipulate them in our mind.

This can be seen clearly if we consider that various different experimental paradigms require different operational definitions of the construct *image*. Thus in research in which the effects of various mnemonic strategies are compared (e.g., instructions to use images as opposed to other methods), there is one definition of image ($image_1$). In experiments in-

vestigating the influence of different stimulus attributes (e.g., high- versus low-imagery words) there is another operational definition ($image_2$). Other research procedures involve the adoption of still other definitions of the theoretical construct *image*. The identity of these various constructs ($image_1 = image_2 = \dots$) does not, however, follow from any of the operational definitions nor from the results of the experiments (although, of course, similar patterns among empirical correlates of the various manipulations of imagery gives one some grounds for believing that they are related).

The unity of these constructs, and consequently the coherence of the notion of imagery rests on a metatheoretical assumption. This assumption, in turn, rests on the persuasiveness of subjective experience and on the ordinary informal meaning of the word *image*. In this context the term relies heavily on a picture metaphor. 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.

There is, of course, nothing wrong with using metaphors: Virtually all theoretical ideas in science derive from some relatively familiar metaphor. However, not all metaphors are equally appropriate and some may even be harmful by discouraging certain kinds of fundamental issues being raised and by carrying too many misleading implications.

For example, one misleading implication involved in using the imagery vocabulary 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. This "image retrieval before perception" view is phenomenally very powerful and is implicit in the everyday sense of the word "image." It is also present in all

the illustrative examples used by psychologists to persuade their colleagues of the reality of images. For example, in discussing the use of the "one-bun" rhyming mnemonic used by his subjects, Bugelski (1968) states,

The most convincing evidence regarding imagery comes from the reports of many Ss who expressed the belief that they did not know some or any of the words when either the original learning or recall test began. They would then mumble the numeral, state the rhyme word, and then report "oh, yes, hen-ski." They asserted that the "little hen on skis" had to appear before they could report "ski" [p. 332].

Atwood (1971) is quite right when he states, "The most elementary question which can be asked about mnemonic visualization is the following: does the mnemonic image actually involve the visual system [p. 291]?" Using a method of selective interference, he gathers evidence which leads him to conclude that to a large extent it does. He writes,

Verbal material may be recoded into a visual image (e.g., during application of a mnemonic device) and encoded into memory as a primarily visual schema. During recall, the schema is *decoded visually* and then recoded once again into verbal symbols [p. 297, italics added].

Similarly Bahrck and Boucher (1968) argue in favor of an "image retrieval before perception" view. They write,

if one is asked to recall the color of a couch in the living room of a friend's home, however, it is likely that the verbal transformation occurs at the time of recall, and is based upon stored visual information [p. 417].

This is exactly the same type of argument which Shepard (1966) used,

... if I am now asked about the number of windows in my house, I find that I must *picture* the house, as viewed from different sides or from within different rooms, and then count the windows presented in these various mental images [p. 203].

The view depicted in the above quotations, though phenomenally quite sound, presents serious problems if it is taken as an explanatory account of the process of retrieving pictorial information (i.e., information initially acquired visually) from memory. This is because however metaphorically one interprets the notion of picturing a recalled scene in one's mind, the implication is always that

whatever is retrieved must be perceptually interpreted (or re-perceived) before it becomes meaningful. In other words, the appearance of a memory image precedes its interpretation by the usual perceptual processes, such as those resulting in figure-ground distinctions, object individuation and identification, and the abstraction of attributes and relationships among elements of the scene. But what can serve as the input to such a perceptual process? Whatever it is, it must be very much like the pattern of sensory activity which takes place at various levels of the nervous system when some sensory event token occurs.

Such a position, however, runs into many difficulties. First, in supposing that information received through the senses is stored in memory and retrieved at a later date in an uninterpreted form, we place an incredible burden on the storage capacity of the brain. In fact, since there is no limit to the variety of sensory patterns which are possible (since no two sensory events are objectively identical), it would require an unlimited storage capacity.³ Second, such a view creates severe difficulties for the retrieval process. Since the sensory events are stored in "raw" form, retrieval can occur by one of two means. Either one retrieves an image by some sort of scanning process in which putative candidates are placed before the mind's eye to determine whether they are appropriate, or else the images are tagged by some gross labels and associatively retrieved by a multiple-sort key. The first of these is unreasonable on several grounds. Perceptual processes in the "mind's eye" appear to be no faster than the usual perceptual recognition processes, so the time for an exhaustive search would be prohibitive.

³ This claim does not depend on any assumptions about how information is encoded, so long as we hold that what is stored in some encoding of the particular stimulus token. Thus it holds for all types of encoding of the sensory pattern token including analogical ones such as holograms. It does not, however, apply to a view which has humans storing *procedures* which construct a representation anew from a finite set of primitive symbols each time a stimulus is encountered. Thus we are able to *discriminate* an unlimited number of stimulus patterns (e.g., numbers) even though we cannot store an unlimited number of such (encoded) patterns. This issue is discussed in Pylyshyn (1973) and in Fodor, Bever, and Garrett (in press).

Furthermore, the conscious awareness, which suggested image storage in the first place, also reveals that we directly retrieve the correct information without a series of false attempts.

The second alternative is implausible on the grounds that we can retrieve information about a whole scene or any part of it by addressing aspects of the *perceptually interpreted content* of the scene. Even if we confine ourselves to the retrieval of phenomenal images, we can argue that the content of such images must be already interpreted—in spite of the fact that we seem to be “perceiving” them as we would novel stimuli. This must be so because retrieval of such images is clearly hierarchical to an unlimited degree of detail and in the widest range of aspects. Thus, for example, I might image a certain sequence of events at a party as I recall what happened at a certain time. Such images may be quite global and could involve a whole scene in a room over a period of time. But I might also image someone’s facial expression or the jewel in their ring or the aroma of some particular item of food without first calling up the entire scene. Such perceptual attributes must therefore be available as interpreted integral units in my representation of the whole scene. Not only can such recollections be of fine detail but they can also be of rather abstract qualities, such as whether some people were angry. Furthermore, when there are parts missing from one’s recollections, these are never arbitrary pieces of a visual scene. We do not, for example, recall a scene with some arbitrary segment missing like a torn photograph. What is missing is invariably some integral perceptual attribute or relation, for example, colors, patterns, events, or spatial relations (we might, for example, recall who was at the party without recalling exactly where they were standing). When our recollections are vague, it is always in the sense that certain perceptual qualities or attributes are absent or uncertain—not that there are geometrically definable pieces of a picture missing. All of the above suggest that 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. The argument is not simply that retrieval of images would involve a bewildering cross-classification system while retrieval in other forms of representation would not. The point is that because retrieval must be able to address perceptually interpreted content, the network of cross-classified relations must have interpreted objects (i.e., concepts) at its nodes. Thus storing images at these nodes as well is functionally redundant. This does not mean, of course, that what we retrieve cannot be further processed. We shall examine several ways in which such representations can reasonably be thought of as being processed further after retrieval (e.g., by the application of operations such as counting). The argument is simply that they are not subject to *perceptual* interpretation the way pictures are interpreted.

Our attack against the notion of an image being an entity to be perceived need not, of course, appeal to phenomenal observations. Consider, for example, the following argument. There are denumerably many logically independent propositions true of any scene or of any physical object (including a real picture). Since the brain can store only a finite (in fact, relatively small) amount of information about any one scene, we might ask about the nature of this selected finite subset. One possible answer is that the stored representation is a pictorial image of limited resolution (i.e., one which can effectively be replaced by a finite two-dimensional grid, each element of which contains a selection from a finite set of attributes). But this is unsatisfactory not only because it still leaves too much information (we can easily show, because of the fineness of some of the details recalled, that the overall resolution of any pictorial representation would still have to be rather high), but because such an approach results in the wrong *kind* of information being selected. Thus, as we argued in the previous paragraph, we are more likely to recall such things as which objects were present without recalling their exact relations than we are to recall all the detailed information but with low precision.

We may assume, then, that the representation differs from *any conceivable* picture-like entity at least by virtue of containing only

as much information as can be described by a finite number of propositions. Furthermore, this reduction is not reasonably accounted for by a simple physical reduction such as that of limited resolution. What type of representation meets such requirements? A number of alternative forms of representations are discussed in a subsequent section. For the present, it suffices to point out that any representation having the properties mentioned above *is much closer to being a description of the scene than a picture of it*. A description is propositional, it contains a finite amount of information, it may contain abstract as well as concrete aspects and, especially relevant to the present discussion, it contains terms (symbols for objects, attributes, and relations) which are the *results* of—not inputs to—perceptual processes. Of course, to say that the representation was a description without being more specific about the nature of such descriptions still leaves it vulnerable to some of the types of criticisms which we have directed against images. Both images and descriptions carry too much undesirable excess meaning; for example, the latter may imply a fixed-order of access, as in reading, which is certainly unwarranted. “Descriptions” of the type we have in mind are never accessed in a fixed serial order in any of the systems which we will examine later. Apart from the arguments made above and those which we mentioned earlier in discussing knowledge as being propositional, the notion of a description gains its greatest advantage from the fact that it has been formalized in a number of areas (e.g., in computer-simulation models). In such contexts the representations provide a formally adequate amount of certain types of cognitive activity while, at the same time, corresponding closely to what we intuitively mean by the term “description.”

The mental representation differs from what is inferred from the conscious image in many ways. For example, to use an illustration cited earlier, while two visual images of a chessboard may be pictorially identical, the mental representation of one might contain the relation between two chess pieces which could be described by the phrase “being attacked by” while the representation under-

lying the second image might not (cf. Simon & Barenfeld, 1969). For this reason, it would be reasonable to expect that the mental representation of a configuration of pieces on a chessboard would be much richer and highly structured for a chess master than for an inexperienced chess player. This view is supported by de Groot (1966) who found that chess masters could recall an authentic board position much better than inexperienced players (after viewing it for 5–10 seconds) in spite of the fact that their *visual* memories were no better (as measured, say, by their ability to recall chessmen randomly placed on a board).

As another example, it would be quite permissible, according to the view which we have been presenting, to have a mental representation of two objects with a relationship between them such as “beside.” Such a representation need not contain a more specific spatial-relation term such as “to the left of” or “to the right of.” It would seem to be an unreasonable use of the word “image,” however, to speak of an image of two objects side by side without one of the relations between them being either “to the left of” or “to the right of.” (The fact that children, who are especially adept at “visual imagery,” frequently have difficulty in discriminating a figure such as a letter from its mirror image, suggests that their mental representation of such figures suffers precisely from such a lack of explicit differentiation of the relations “to the left of” or “to the right of” in favor of a more general relation such as “adjacent to” or “away from the center.”) Similarly, we could have a mental representation of a triangle which might consist of a structure in which the symbol “triangle” was hierarchically linked (by the relation “has as parts”) to three representations of lines which were, in turn, linked to each other via relations labeled “connected to.” Such a network (which resembles many of the artificial intelligence data structures—see below) need not contain relations of the type “at an angle of n degrees to.” On the other hand, there is considerable uncertainty (as dramatized by the debate between Locke and Berkeley) regarding the possibility of having an image corresponding to the above representation,

namely, of a triangle which is "neither oblique nor rectangular, neither equilateral, equicrural, nor scalenon; but all and none of these at once."

To summarize, then, we have argued that the functional mental representation is not to be identified with the input to a perceptual stage but rather with the output of such a stage, inasmuch as it must already contain, in some explicit manner, those cognitive products which perception normally provides. If we could think of functional (rather than phenomenal) "images" in this sense, we would have removed the disturbing duality of "image" and "mind's eye," while, at the same time, we would have answered some of the puzzling classical questions referred to earlier: An "image" *qua* representation in our sense can certainly be selective, generic, abstract, and even unconscious inasmuch as the cognitive products of perception can be all of these.

ALTERNATIVE FORMS OF REPRESENTATION

In this section we briefly examine three approaches which have been used in theoretical studies of the representation problem for cognition. The approaches are closely related and are distinguished primarily by the research areas in which they are developed and by the descriptive formalisms which they employ, although there are one or two more significant differences among them which we shall try to draw out. The first approach involves the use of propositions and usually relies on deductive proof procedures for processing them. The second approach derives primarily from work in computer simulation of cognition and in artificial intelligence. The form of the representation is called an information or data structure and is frequently described in terms of directed graphs. The third approach represents concepts in terms of procedures. These three types of approaches are described below.

Propositional Representations

Because of the availability of the predicate calculus as a formal language for expressing the contents of knowledge, propositions have been widely used—especially by students of artificial intelligence—as an explicit form of

representation. This form has the great advantage that well-known mathematical systems for manipulating formal sentences can be applied to the representations to derive their logical entailments.

In its simplest form, such an approach assumes that what a person knows can be represented by a finite list of propositions or axioms (although, to repeat again an earlier point, this must not be taken to imply that tokens of actual sentences in some natural language are stored). Rules of deductive reasoning can then be applied to this list to generate all the logically valid propositions which follow from the initial "premises." Herein lies one of the attractions of this approach: It is generative in the sense that an unlimited number of "beliefs" can be deduced by a straightforward mechanical procedure from the initial representation. Thus it ought to allow an indefinite number of questions to be answered about the knowledge represented.

Question-answering systems, in fact, have been developed which represent their data base in the predicate calculus and which use a theorem-proving procedure for retrieving information (e.g., Green & Raphael, 1968). The question to be answered is converted to a proposition to be proven in the system. A constructive proof of this proposition then provides the answer. For example, a constructive proof that there exists an object (in the formal sense of this term, including mathematical objects such as numbers) which satisfies certain conditions would actually identify such an object. Slagle's question-answering system DEDUCOM and the more comprehensive MULTIPLE (Slagle, 1971), which can be applied to a wide spectrum of problems from playing chess to solving problems in logic, both use an explicit propositional data representation. The Stanford Research Institute robot "Shakey" (Raphael, 1968) operates by storing its "knowledge of the world" in propositional form and using a theorem prover to respond to commands. For example, the command to push two large blocks together is transformed into a proposition to the effect that there exists a path of travel which leads to the desired state with two large blocks together, given the present

conditions and known constraints. A constructive proof of this proposition would derive a path satisfying the requirements, which would then be converted into a sequence of overt motions by the robot.

In spite of considerable success with this form of representation of knowledge in a variety of artificial intelligence applications, it does have some serious limitations. In addition to the general problems associated with the use of the predicate calculus to represent knowledge of a changing environment (e.g., the "frame problem" discussed by Raphael, 1971), there are additional problems which appear when we think of such a system as a model of human cognition. In order for such a system to have "psychological reality" it must take cognizance of empirical data concerning the psychological complexity of various cognitive tasks (for a discussion of this point, see Pylyshyn, 1973). In other words, it must account for empirical data such as that made available by chronometric analyses of a variety of recall, verification, and the problem-solving experiments. Theorem-proving processes, as well as the specific propositions posited to constitute the representation of knowledge, must reflect the relative complexity of various cognitive tasks as inferred from empirical studies. In addition, the system must display similar *intermediate states of knowledge* as subjects do in solving a problem or answering a question. For example, part way through attempting to answer a question, a subject may have the answer to some other related questions. An adequate model should account, in a general way, for such sequences of partial solutions. It is not clear at this stage in our understanding of theorem-proving schemes whether a uniform proof procedure is capable of meeting such requirements. If it were to do so, however, it would have to be molded to fit empirical data in at least two ways: (a) by the selection of starting propositions (which may include derivable theorems as well as independent axioms) and (b) by the selection of an appropriate proof method. These are discussed below.

Consider that there are an indefinite number of sets of base propositions which can serve as logically equivalent representations

(i.e., from which the same ultimate set of propositions can be derived). From the standpoint of a logician, the smallest number of simple logically independent axioms would be preferred. From the standpoint of a psychologist interested in describing a mental representation of knowledge in a certain domain, this is only one criterion. He is interested in the simplest representation which accounts not only for what is known, but also for empirical evidence concerning such properties as accessibility. Thus while it is logically immaterial which of two propositions, "A is larger than B" or "B is smaller than A," is contained in the representation, the two are not equivalent from a psychological point of view. Which proposition is expressed in a problem description affects how difficult the problem is to solve (Clark, 1969). One could point to the fact that the predicate "is smaller than" is *marked*, that is, it has both a nominal and a contrastive sense. From this one could argue that the sentence "B is smaller than A" may be psychologically represented by three propositions, such as "A is larger than B," "B is small," and "A is small" (Clark would represent it as "A is small; B is small+" where "small+" signifies "smaller to a greater degree"). Indeed, such a hypothesis appears to fit the available empirical evidence (Clark, 1969).

Another potential source of development may come from studies in computational complexity as applied to theorem-proving systems. For example, as it stands, one of the difficulties of a logic-based model of cognition is that if any pair of propositions in the representation is contradictory, the whole system breaks down (since anything can be proven in a system in which both p and $not-p$ are axioms). If we had a measure of derivational complexity—or a measure of the distance of a derivational path between two propositions—which was based on psychological considerations, the problem of contradictions could be dealt with. In this case, it might be reasonable to tolerate contradictory propositions so long as the derivational path between them exceeded a certain minimum value. Such a proposal was, in fact, made recently (Arbib, 1969). If we distinguish, as do Simon and Newell (1956), between logical

entailments (all statements derivable from the axioms) and psychological entailments (all statements which are evidently true, to a person, as a consequence of the axioms), then we have the basis for an interesting extension of a predicate calculus model of cognition. We would identify the psychological entailments as those statements derivable from the base set by a path of less than a certain critical length.⁴ Such a system would have the interesting consequence that it would allow a person to hold contradictory beliefs and to make contradictory statements without being aware that they were contradictory!

Data-Structure Representations

The idea of general data or symbol structures grew out of several pioneering achievements in computer science. One was the work of the group at the Carnegie Institute of Technology beginning in the late fifties which led to the first list-processing system known as the Information Processing Language (see the historical notes in Newell & Simon, 1972). Another was the work on computer graphics which was pioneered at the Lincoln Laboratory at Massachusetts Institute of Technology (Roberts, 1965; Sutherland, 1963). Both of these were attempts to represent information in a manner best suited to the processes which would operate on it. The design of *appropriate* data structures is one of the central tasks of computer science, and many difficult problems, such as that of processing graphical data for display on an oscilloscope screen, were solved only after clever new forms of representation were developed. An appropriate representation for a particular information-processing application is one which (a) contains symbols which

designate the functionally important and most invariant *aspects of the environment which is being represented* and (b) gives the processes access to a variety of units of data, from individual primitive symbols through overlapping subsets of related symbols up to the entire representation. There must, in other words, be a facility whereby symbols can designate symbol structures in which individual symbols can designate still other symbol structures, etc., in both a hierarchical and heterarchical fashion.

A wide variety of data structures have been developed for different purposes. They are usually depicted as directed graphs in which nodes represent symbols (which may, in turn, designate other symbol structures or objects in the environment or even programs) and links represent relations of various types (i.e., the links may be labeled according to the type of relationship they represent, e.g., "is connected to," "is a part of," "is an instance of," or "has the property"). Because such representations are extremely varied in form as well as in the way they function in different systems, and because they are rather common in the information-processing literature, they are not discussed in any detail in this paper. For further elaboration, the reader is invited to consult the historical papers of Sutherland (1963), Roberts (1965), or the papers contained in Minsky (1968) where a variety of data structures are discussed. Reitman (1965), Newell and Simon (1972), and Frijda (1972) also present a discussion of the use of simple list structures in psychological theories. Such data structures meet many of the basic requirements for a cognitive representation: Only functionally relevant aspects of the environment are mapped onto the representation, distinct representations mean functionally distinct stimulus *types*, and relations among stimulus types can be accounted for by relations among representations (i.e., by the presence or absence of nodes or links in the underlying data structure). In fact, the contents of data-structure representations may be viewed as *propositional*. By identifying links with predicates and nodes with designating expressions (or in some cases with other propositions), we can generate a finite

⁴ An even simpler way to deal with contradictions might be to adopt a proof procedure which blocked all derivations relying on contradictory premises. Although such an approach would prevent a knowledge base containing contradictory premises from degenerating, it would allow the base to contain both p and *not* p , which seems psychologically unreasonable. Instead it would seem more reasonable not to allow such a minimal pair but to allow certain cases of p and q even though *not* p is derivable from q (e.g., those cases in which the derivation exceeded the critical length).

set of propositions (e.g., "line *X* is part of figure *A*") which exhaustively describes the knowledge which the system has of the environment.

In spite of the close relation between data structures and propositions, there are a number of important differences between them. A list of propositions has little inherent structure. While certain relations among the propositions may be implicit in the way in which various symbols occur in them or the way in which the propositions tend to be used in groups to prove theorems, this structure is of a rather indirect and limited kind. Relations among terms are much more explicit in data-structure representations because of the explicit access relations provided by the system of links. This usually makes the data-structure network more useful and natural for artificial intelligence applications.

Procedural Representations

The third form of representation which we shall examine is one in which concepts and facts are represented in terms of rules or procedures. The view that what is stored is a system of rules or a procedure is an attractive one on many grounds and has enjoyed popularity in a number of circles (see, e.g., Davies & Isard, 1972; Miller, Galanter, & Pribram, 1960; Pylyshyn, 1973; Winograd, 1972). An obvious argument in favor of a rule description is on the grounds of descriptive economy: a small number of rules can cover a wide domain of instances. Another argument is the intuitive idea that what we know when we have learned something (say a concept) is how to use it. This is related to the notion of operational meaning and to the position (made famous in the 1930s by Rudolf Carnap) that the meaning of a word is bound to the method by which statements containing the word are checked for truth or falsity.

Intuitively, it seems clear that at least part of what we know when we have learned a concept includes a set of specific procedures for determining whether a particular token is an instance of the concept as well as a set illustrating how the program makes use of a variety of specific situations. In other

words, we not only know facts but also how to take certain actions relevant to the facts. From such considerations it is possible to argue that the representation of certain concepts is nothing more than the set of such procedures. We shall take the position that while this claim is undoubtedly true, it may also be somewhat misleading in its usual interpretation. We shall return to this point in the latter part of this section.

One of the earliest proposals for including procedural predicates in a propositional system was made by McCarthy (1959) and has been the source of several subsequent developments. The most successful recent attempt to exploit the notion of procedural representation is a system for understanding natural language developed by Winograd (1972). Winograd's system is a computer program which maintains a sophisticated model of the knowledge which a robot needs to operate in a limited environment. The robot is assumed to be equipped with an eye and a hand. Its simulated environment consists of a collection of blocks of various sizes and colors which it can manipulate. The system can enter into a dialogue with a person concerning this environment. It can understand declarative English sentences about the environment and add the information conveyed to what it already knows. It can interpret and simulate the execution of commands related to manipulating objects in the scene (i.e., it can change the representation of the location of objects: There are no actually physical objects, and the machine does not have a real perceptual motor device). It can also answer a wide range of English questions both about the scene and about its own actions. While the most impressive aspect of this system is the way in which the various subsystems work together to produce intelligent behavior, our concern here is only with the question of how the system represents its knowledge. This knowledge includes not only knowledge of objects in the scene, but also knowledge of grammar, semantics, and deductive logic. For simplicity we will concern ourselves with only one aspect of the total system—that which illustrates how the program makes use of procedural information in its representation.

The form of representation adopted by Winograd contains aspects of both the data structure and the propositional forms of representation discussed earlier. Recall that one of the defining characteristics of data structures is the presence of explicit access links which enables the tracing of paths through the structure in a straightforward data-governed manner. In contrast, one of the defining characteristics of the propositional representation is that inquiries to it are dealt with by a neutral and uniform proof procedure whose operation does not depend on either the inquiry or the data. Each of these two approaches has its advantages. In the data-structure case, by making as many as possible of the relations among concepts and among substructures explicit in each representation, we gain considerable access efficiency. It is no longer necessary to refer to the entire data base and to perform complex computations to go from one substructure to another, since much of this has been done for us in advance. In the propositional representation, going from one set of propositions to another is done by a single uniform proof algorithm which, being independent of the data, must consider the entire data base as being relevant to all deductions.⁵ On the other hand, the uniform proof method allows us to get at a wide range of questions, including ones not initially anticipated, without making changes in the way the data is represented. This gives the propositional representation an important advantage over data structures.

Winograd proposed an alternative representation combining the efficiency of the "relationship-as-part-of-the-representation" characteristic of data structures with the generality and descriptive-uniformity characteristic of deductive propositional systems. This is done by adopting a theorem-proving deductive system in which the procedures to be

used are not neutral with respect to the data to which they are applied, but rather, the data-base representation contains directions as to how to go about proving assertions about particular concepts in the data base. In effect, the propositional knowledge contained in the representation is expressed in an imperative rather than in a declarative language. As an example, take the proposition which might be expressed in English as something like "An object is an X (e.g., chair, sentence, thesis) if it has property x or property y but not property z ." Instead of this assertion, we would have a hierarchical, goal-oriented, and partially ordered sequence of procedures which might be interpreted something like,

If you wish to show that an object is an X , then check first whether it has property z : Do this by trying the following procedures . . . or, if they fail, by trying the following. . . . If any of these succeed return a FAIL. If they fail try next to show that the object has property x or y by referring to all assertions mentioning these properties or all procedures having these properties as a consequent. . . .

Such an imperative or procedural representation is able to state a specific order in which to try out tests, to recommend heuristic short-cut procedures, to specify procedures in terms of goals, and to suggest sections of the data base in which to search. Furthermore, new procedures do not have to be attached to a particular place in the representation (i.e., linked to a particular concept) but may simply be added without relating them directly to the rest of the data base. The general instruction to "try proving that . . ." will locate relevant procedures. The way they are stated makes it possible to see when procedures are relevant. Such an approach is made possible by the availability of a general goal-directed imperative language called PLANNER (Hewitt, 1971). The resulting system provides a powerful and efficient representation of knowledge capable of accommodating both facts and data-dependent ways of relating facts. It is, however, essentially heuristic in nature, that is, it depends primarily on logically incomplete short-cut methods. While, if all else fails, it *could* be made to resort to a uniform

⁵ The distinction between a uniform proof procedure and a data-dependent one is subtler than this discussion might suggest. By adding selected theorems to the data base or by ordering or otherwise marking the premises in some fashion, a uniform proof method can be made to behave very much like a data-dependent one although it might in practice be rather difficult to mold such a system to behave in some particular desired manner.

proof method, this is considered to be unnecessary. The basic procedures are designed to be "sensible" methods of going about relating things and may even suggest at some point that the goal is likely to fail so the system should give up looking any further.

Such a procedural representation is an extremely attractive idea from many points of view, both as an approach to constructing artificial intelligence devices and as an approach to the problem of cognitive representation. Elsewhere (Pylyshyn, 1972, 1973) the author has argued that one has to be particularly careful in selecting the procedures which are to define the representation. One can get into difficulties by taking the most obvious heuristic procedures such as one might infer, for example, from an analysis of think-out-loud protocols. While it is beyond the scope of this paper to present these arguments here, it might be appropriate to indicate briefly what these difficulties are.

As was argued in connection with our earlier discussion of imagery, it is unlikely that processes of which we are aware will turn out to be useful in an explanatory theory. We have already pointed out several ways in which criteria of adequacy for an explanatory account are rather different from those which might be appropriate for an informal descriptive account. If it is to serve as an explanatory account of what a person knows when he has mastered a certain concept, the representation of that concept very likely has to contain procedures more abstract and general than those moment-by-moment procedures which a subject is aware of using. This comes about because the theorist's task in accounting for how a certain concept is represented involves more than simply describing the procedures which a person might use to assign an instance to that concept *in certain typical situations*. The fact that as novel instances are presented to him, a subject can keep coming up with clever new heuristic procedures for assigning those instances to concepts (e.g., for deciding whether strings of words are sentences), and may even resort to external mnemonic aids as the task becomes difficult, suggests that his representation of the concept is not limited to a finite list of such consciously available procedures.

Rather, he is able to creatively generate new heuristic procedures from a representation which, while it is most likely procedural, is itself more abstract than a list of the procedures he is aware of using on specific occasions. The underlying abstraction characterizes what Chomsky (1965) has called the subject's *competence* and is discussed in some detail in Pylyshyn (1973). While it is procedural, a competence characterization is not heuristic. It attempts to be complete, that is, to describe the mental representation in a manner which accounts for all the cognitive distinctions in a certain theoretical domain which could be made considering all conceivable circumstances.

INFORMATION PROCESSES AND IMAGERY

The discussion so far has been concerned primarily with the question of how knowledge might be represented in memory. Let us now consider the issue of how we might characterize the representations and the processes which are involved when a person is engaged in what he calls imaging. Before we can proceed with these rather speculative suggestions, we must introduce some general remarks regarding differences in levels of knowledge or in types of representation which enter into various stages of cognition. This, in turn, leads us to consider different levels of accessibility or of activation of these representations.

In his excellent analysis of the nature of complex systems, Simon (1969) makes it clear that there are powerful reasons, both from the point of view of the evolution and operation of a system and from the point of view of the scientist's ability to understand the system, for it to be organized in a hierarchical fashion. Such reasons can be used to argue that in studying cognition we ought to distinguish levels of knowledge. What a person knows would then be described as being hierarchically organized. Levels of this hierarchy might be distinguished, for example, on the basis of universality or permanence (in relation to external modifiability). Thus we might distinguish among universal and innate properties of cognition, properties which develop gradually with maturation and general experi-

ence, properties having to do with particular domains of knowledge (including domain-specific operational knowledge concerning how to deal with certain concepts), and properties having to do with particular instances, that is, representations arising from particular events, or novel constructions generated in the course of solving a particular problem or in generating some particular overt behavior. It is reasonable to expect that these levels of knowledge may have to be treated in a somewhat different manner within a cognitive theory. One of the virtues of a theory such as Winograd's (1972) system for understanding natural language that it incorporates a distinction among levels of knowledge very much like the one outlined above.

Another general consideration, also related to Simon's (1969) arguments for hierarchical organization, which suggests that one might usefully treat some classes of representation in a somewhat distinct manner, has to do with questions of efficiency of access. Efficiency may be gained through the use of levels of activation or accessibility, with a few items being highly accessible and larger numbers being progressively less accessible.

As an example of the notion of hierarchical accessibility, consider the following: Suppose a process (computer or human) makes use of a certain repertoire of n items of information, numbered from 1 to n . Suppose further that the currently active subprocess makes repeated reference to Items 2, 3, 5, and 7, and that at the present moment an operation is being performed on Item 3. In such a situation there is considerable virtue in arranging for the sets $\{1, 2, 3, \dots, n\}$, $\{2, 3, 5, 7\}$, and $\{3\}$ to be differentially available or to be at different levels of preparedness or activation. Thus, for example, in some computers Item 3 might be placed in the accumulator or other special register; Items 2, 3, 5, 7 might be placed in some designated common-communication area; while the remaining items would remain in general memory. Of course, items need not in any sense be moved about; they might simply be placed in some more ready state (e.g., in the computer example, the addresses of the items might be listed in some stack). We might then identify

such an active or ready state with a cognitive buffer or a *workspace*.

Such a workspace would have several additional values. It would provide a stage at which items closely related to a particular item being processed could be held in readiness. This corresponds to the well-known psychological phenomenon sometimes referred to as redintegration, wherein retrieval of part of a structure of related items (e.g., recall of one word of a sentence) results in the recall of the whole structure. It would also provide a stage at which a representation being recalled could be restructured into a form more appropriate for a particular task at hand (more appropriate, that is, than the form in which it was originally stored).

This workspace would also be useful as a stage at which general computational processes are applied to representations. For example, consider what would have to happen when the concept of *number* and that of *window* and of *my house* are being related to one another to answer a question regarding the number of windows in my house. It would be unreasonable to hold that "number of windows in my house" is a static term in my store of explicit knowledge. Indeed it *could not* be the case in general since there is no limit to the number of propositions of the type "number of X s is N " which a person potentially possesses (since there is no limit to the number of designating expressions such as X which he could generate). Answering a question such as the one regarding number of windows, therefore, must depend on the application of a concept of a number to generate a counting procedure which would, in turn, generate the appropriate concept "number of windows in my house." In fact, this is very similar to the way in which Winograd's (1972) system would answer such a question.

The point of this illustration is to suggest that cognition requires the interaction of abstract concepts such as that of *number* with less abstract ones such as *window* and even more particular ones such as *my house*. Considerable computation must occur in the course of such interactions during which the concepts should be in some state of recruit-

ment. It is useful to think of such a stage, in which several concepts are simultaneously active, as one in which the concepts are held in a buffer or workspace.

It might be remarked that the process of activating a representation or of "placing it in the cognitive workspace" is invariably constructive since most, if not all, concepts are constructive or generative (cf. Niesser, 1967). That is, a complete representation may not simply be placed in a state of alert, but rather a static instance, undoubtedly more specific in its detail than individual stored concepts, may be constructed from such concepts. It would even be reasonable to suppose that a more detailed representation may be generated in the workspace than is, in fact, called for by a particular cognitive task. In this way a savings in number of separate access steps to the main memory may be achieved by retrieving extra information at each access cycle.

Such considerations might suggest that we are tending towards the view (favored, e.g., by Chase & Clark, 1972) that while picture-like entities are not stored in memory, they can be constructed during processing, used for making new interpretations (i.e., propositional representations) and then discarded. This approach views the content of the workspace as a *model* which satisfies the stored propositions. There is little harm in using the metaphor in this context so long as one can resist the temptation of assuming that the relation of the model to its cognitive representation is like the relation of any physical object to its representation. In fact, the possible descriptive interpretations that can be given to a model is a small subset of those which can be given to a physical object. This is because only a small subset of the properties of a model are relevant to its functioning as a *model*. Which particular properties are relevant can only be determined by referring to the description from which the model was constructed. Thus while a physical model or analog has many properties not contained in, or, in fact, derivable from, the stored representation (e.g., with a physical model of a molecule, one could determine its weight, color, taste, angular momentum, etc.), these are not used as bases for making inferences

from the model. In fact, so long as the physical object is being used as a *model*, all inferences drawn from it were entailed by the propositional representation (plus other stored knowledge) from which it was constructed. Thus the model introduces no new information although it serves the invaluable function of making what was implicit in the description more explicit, accessible, and manipulable. This, of course, is of central importance in cognition. For example, by using heuristics which operated on a diagram, Gelernter's (1963) geometry-theorem-proving system was able to achieve a 200-fold savings in number of search operations. Nevertheless, if we accept the above argument regarding the way in which a model functions, we see that the particular extended physical nature of the model is irrelevant since the model functions like a highly selective abstract and interpreted *percept*—in other words, like a description again.⁶ Its importance arises from the fact that it makes possible certain kinds of restructuring and reconstruction of descriptions. But we do not require a picture-like entity to do this. Symbolic descriptions too can be manipulated so as to make various aspects more accessible to certain inquiries. Furthermore, such an approach has the advantage that it does not require positing two qualitatively different entities, one, an abstract propositional-descriptive structure serving for memory representations and the other a picturelike entity with implications of concreteness, spatial extent, and simultane-

⁶ In fact, the Gelernter system mentioned above, which is famous for its use of diagrams, never actually draws a diagram at all but merely constructs an internal representation of one. Furthermore, the representation need not be pictorial at all since, as Gelernter (1963) puts it "... the only information transmitted to the heuristic computer ... is of the form: 'Segment AB appears to be equal to segment CD in the diagram,' or 'Triangle ABC does not contain a right angle in the diagram [p. 139].'" Such properties are not only propositional, but highly abstract (i.e., are true of a large set of possible diagrams). Admittedly, however, the "diagrams" do bear something of a type-token relation to the original description insofar as they achieve consistency and some degree of completeness by making arbitrary commitments with respect to certain aspects which are unspecified in the original description (e.g., approximate magnitudes).

ous availability (all of which must be metaphorically interpreted since none of these terms are intended to apply literally to brain structures) serving in thinking. To make the latter remarks more concrete, we shall devote the next section to describing a system which uses that approach.

Information-Processing Model

An excellent illustration of the way in which higher and lower level representations might be handled in a cognitive theory and of the use of something like a cognitive workspace is to be found in the recent work by Baylor (1972).⁷ Baylor's system is a cognitive theory designed to characterize (by simulation) the psychological processes involved in solving certain kinds of "block visualization tasks." An example of such a task is the following: "The four narrow sides of a 1-inch \times 4-inch \times 4-inch block are painted red. The top and bottom are painted blue. The block is then cut into 16 1-inch cubes. How many cubes have both red and blue faces? How many have no painted faces?"

Baylor's work is in the best tradition of information-processing theories and is clearly free of the conceptual difficulties discussed earlier in this paper. Yet, it is addressed directly to the phenomenon of imagery. Because of this, it sheds some light on the question we are currently examining, namely, what is the nature of the information-processing function which accompanies imaging? Consequently, we shall examine his system in some detail.

In a manner somewhat analogous to the "dual-code" schemes in the imagery literature, Baylor distinguishes between what might roughly be described as "factual" knowledge and the more "pictorial" or "imaginal" knowledge. This distinction, as we shall see, is quite different from Bower's distinction between propositions and appearances. Baylor's distinction is made precise in his system. As we examine it in detail, we will find that the difference between the

two types of knowledge is not at all a difference in kind but rather a difference in arrangement which results in somewhat different *access relations* in the two cases.

The distinction arises in Baylor's theory through his postulate of two separate but closely related systems in which information about the problem environment is represented. These are called the S space (for symbolic factual information) and the I space (for imaginal information). The idea was to represent in the S space, "information that is true about pieces and their components *in general*"; and to store in the I space, information that is true for a *specific* piece and its components [Baylor, 1972; see Footnote 8]. In fact, this is not quite accurate since various processes do affix problem-specific information (such as about the color of various faces) to the S-space representation. Such information is, however, represented in a more global manner than it is in the I space as we shall see later.

The S space consists mainly of a data-structure showing how certain atoms are interrelated hierarchically. The atoms are faces, edges, and vertices and are distinguished only as being top, bottom, left, right, front, or back. Thus this structure corresponds rather closely to the statements which we would make about blocks in general *without being able to label or to point to certain particular points on some arbitrary three-dimensional block*. Consequently, the structure does not refer to any *particular* edge or vertex. As a result, many distinct vertices receive the same designation (e.g., TOPVERT) and many particular vertex on a block would be referred to by various designations (e.g., the "top" vertex of the "left" edge of the "front" face would also be the "front" vertex of the "left" edge of the "top" face).

In contrast to this description of a base block, the I-space representation does have attributes and relations which depend on a three-dimensional frame of reference. Thus in I space, vertex atoms such as TOPVERT are assigned attribute values which are symbols for a particular vertex on a block (say, V_1) while edge atoms such as LEFTEDGE are assigned symbols which refer to a particular line on a block (say V_1-V_2). When-

⁷ Quotations in the present paper are from an unpublished report with the same title which was issued in three parts by the Université de Montreal, Institute de Psychologie, 1971.

ever two atoms refer to the same edge or vertex of a block, these atoms would be assigned the same attribute value. In addition, the I-space structure not only displays relations such as "is a part of" (as was the case in the S space) but also certain spatial relations such as "is above," "is in front of," or "is to the left of." Thus the I-space representation captures more of the structure of the integrated physical object than does the S-space representation which is constrained to follow closely the type of verbal description in which block visualization problems are originally stated.

The two representations continue to be distinct but closely related as the problem-solving process continues. As more blocks are created in the I space (by slicing the original base block), each is assigned a cross-reference to the S-space block, while at the same time a list is kept in the S space of the blocks created in the I space. Also, if certain faces of a block are painted, the color names are assigned directly to particular faces (say, $V_1-V_2-V_3-V_4$) on the I-space block, while in the S space the reference to the I-space block is assigned a list structure description such as "(SIDES COLOR RED) AND ((TOP BOTTOM) (COLOR BLUE))."

Thus much of the information is, in effect, stored twice, once as a direct attribute of particular atoms in I space and again as a general attribute of the block in the growing structure of "factual" knowledge represented in S space. The main difference between these two forms of representation is that certain information is represented directly in the I space whereas it would have to be deduced indirectly from the S-space representation (perhaps in some cases only with the aid of additional knowledge concerning the properties of three-dimensional objects). This means certain operations, such as counting, can be applied directly to objects in I space but not to those in S space. In other words, the main difference between S-space and I-space representations is in the relative accessibility of different aspects of the information to different psychological processes.

In Baylor's system the S space and I space are only roughly hierarchical in our sense of hierarchy of knowledge. Furthermore, much

of the higher level knowledge (e.g., the concept of a *slice* or of *number*) is implicit in the permanent operators built into the system. Also, because of the limited domain of application of the system, the range of its higher level knowledge is rather limited. If the system had been a more general theory of cognition, the S space might have included a great deal of information about geometry and about three-dimensional blocks in general, while the I-space representation would still have been the same, since it is adequate to solving block-visualization problems. Of course, other types of tasks might demand a different I-space representation which would then have to be constructed from the S-space information. The main principle of the cognitive workspace, however, does apply to the I-space representation: The data structure in I-space is both more specific than that in the S space and is in a form more appropriate for applying typical operators needed in solving the block visualization task.

It is not difficult to think of phenomenal correlates of many aspects of Baylor's theory. Indeed, the system was designed to bear a close relation to a subject's "thinking-out-loud" protocol produced while he was solving a block-visualization problem. Such a protocol is naturally couched in the language of experience, with persistent references to images and operations on the imagined objects. Thus Baylor's work is proposed as a bridge between certain aspects of the consciously accessible phenomena of cognition (in a restricted domain) and the requirements of an information-processing level of analysis. Such requirements necessitate the development of precise and logically sound (noncontradictory) definitions of constructs. It is of interest, then, to see what happens to the picture metaphor when it is subjected to such demands.

Consider the formal nature of such notions as "image," or "reading an image" in Baylor's system. In his conclusions, Baylor makes the following summary statement:

But what do these various techniques tell us about the use of visual mental imagery in the human thought processes? For one thing, *visual mental imagery is just another representational system*, albeit one that happens to be very convenient for

structuring information that was at one time "known" and encoded through the visual system. . . . Most importantly, perhaps, the processes identified to read the images (in $\frac{1}{2}$ -3 secs.) are composed of the same kinds of elementary processes identified elsewhere for generating and testing, comparing, counting, and the like [Baylor, 1972; part III, p. 51; see Footnote 8].

In other words, the image has lost all its picturelike qualities and has become a data structure meeting all the requirements on the form of a representation set forth in earlier sections. In fact, it can be put directly into one-to-one correspondence with a finite list of propositions. Thus the representation corresponding to the "image" is more like a *description* than a picture: There is nothing in the representation corresponding to the notion of "appearance." Similarly, "seeing the image" has been replaced by a set of common elementary and completely mechanical operations, such as that of testing for the identity of two symbols. The only reason that this could be done, of course, is that the I-space representation is in a canonical form in which tokens of a common type have a unique representation. Furthermore, only functionally relevant information is contained in the representation (e.g., size, coordinates of vertices, etc., are not represented, nor are spatial relations of diagonal elements). Recall that these were among the considerations which eliminated the concept of an image as an entity to be perceived.

Notice also that such a reformulation of the construct of imagery eliminates all reference to *perceptual* processes. But virtually all the informal definitions of imagery quoted earlier mention *perception* as being involved in imagery. Consequently, it is very tempting to conclude that Baylor's I-space representation has little to do with the authors cited mean when they use the term "image." However, one could still argue that there is some functional similarity between the way in which the I-space representation plus its associated processes function in Baylor's theory and the way images function in the more informal theories (or the way the term *image* is used by subjects in the protocols). But notice that in interpreting processes in the system in terms of phenomenal descriptions, one is, in fact, redefining what the informal terms

shall mean whenever they are used in an explanatory-theoretical capacity. And there is surely nothing wrong with this. But at the same time, it should be pointed out that words like image are undergoing a strange but essential transformation. They are being wrenched from their metaphorical context and are being given a role in a new formal system. This system then can shelter them from the excess meaning which they invariably carry in the informal theoretical context.

In the new formal context it also becomes possible—indeed compelling—to ask certain fundamental questions which had been blocked when phenomena were described with words and phrases such as "image," "unitization," "spatial representation," "comparison of images," "reading an image," etc., serving as primitive (i.e., irreducible) constructions. It becomes possible to explore such formerly inaccessible questions as, What goes on in the "mind's eye?" *Why* can certain kinds of stimuli be more readily recalled? *Why* do certain mnemonics work? *Why* do certain classes of recall and performance tasks interfere or result in systematic confusions? The *why* in each of these questions could not be approached until the image metaphor is replaced by a fine detail information-processing model whose relation to the experience of imagery, by the way, is really quite a secondary matter. It is, in fact, significant that in this more formal model the experience of imaging has no causal role. It remains, at most, a source of ideas suggesting what processes might be required in the model.

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