CONSCIOUSNESS AND COGNITION **5,** 288–326 (1996)
ARTICLE NO. 0020

# Mental Imagery as the Adaptationist Views It

JOHN R. PANI[1]

*College of Computing, Georgia Institute of Technology, Atlanta, Georgia 30332*

Mental images are one of the more obvious aspects of human conscious experience. Familiar idioms such as ''the mind's eye'' reflect the high status of the image in metacognition. Theoretically, a defining characteristic of mental images is that they can be analog representations. But this has led to an enduring puzzle in cognitive psychology: How do ''mental pictures'' fit into a general theory of cognition? Three empirical problems have constituted this puzzle: The incidence of mental images has been unpredictable, innumerable ordinary concepts cannot be depicted, and images typically do not resemble things well. I argue in this paper that theorists have begun to address these problems successfully. I argue further that the critical theoretical framework involves thinking of mental images as information within a cognitive system that is fundamentally adaptive. The main outline of the adaptationist framework was evident in the school of thought known as American Functionalism, but adaptationism has formed a consistent pattern of theorizing across many authors and decades. I briefly describe Functionalism and then present seven basic claims about imagery that were common in the years before the predominance of behaviorism. I then show how these claims have reappeared and been further articulated in modern cognitive psychology. I end with a brief integration of some of the basic elements of an adaptationist theory of imagery. 

Mental imagery is one of the more obvious components of human conscious experience. There nevertheless has been a basic theoretical puzzle concerning the relation of visual images to the information used in thinking: How does our ability to form ''mental pictures'' fit into a theory of cognition? I argue in this paper that we have begun to solve this puzzle by understanding mental images in the context of an adaptive use of information. It is not necessary to think of photographs or photocopies in this way, but description of adaptive cognition has been important to understanding the nature of mental images. I further argue that psychologists have been working toward an adaptationist account of imagery since before the turn of the century, with the main points provided by the school of thought known as American Functionalism (Angell, 1908; Dewey, 1903, 1933; James, 1890/1981). The adaptationist account of imagery is a theoretical framework that psychologists have progressively articulated as cognitive psychology has developed.

Insisting on the conscious aspect of imagery can make it difficult to refer to the work of modern authors, who typically avoid a construct of conscious representation (Horne, 1993). I treat authors' statements about imagery as referring to conscious imagery when it seems that they concern images in working memory (see Dennett, 1978; Ericsson & Simon, 1984). The main idea is that people are aware of imagery

[1] Correspondence concerning this paper should be addressed to John R. Pani, College of Computing, Georgia Institute of Technology, Atlanta, Georgia 30332.



1053–8100/96 $18.00

in normal thought processes and can describe it, either verbally or with various rating scales invented by psychologists (e.g., Paivio, 1969, 1971).

The remainder of this paper is organized into six sections. In the first, analog representation is briefly defined and then the basic empirical problems for a theory of mental imagery are described. I take the opportunity here to begin adopting a historical perspective. In the second section, there is a brief summary of the approach of American Functionalism to mental imagery. (I refer to adaptationist accounts of imagery as ''functionalist'' in this part of the paper, due to the initial focus on the historical school of thought.) In the third section, I articulate specific claims of the functionalists about visual mental imagery. In the fourth, I suggest that the functionalist approach to imagery is sufficiently compelling that it was implicitly adopted by E. B. Titchener, a metatheoretical opponent of functionalist thinking. In the fifth section, modern claims that support and advance an adaptationist view of mental imagery are discussed. In the sixth, I outline a modern synthesis of the adaptationist view of imagery. I close with a brief summary and conclusion.

## BASIC ISSUES FOR A THEORY OF MENTAL ANALOGS

### *Analog Representation*

A defining characteristic of mental images is that they can be analog representations (e.g., Bower, 1972; Kosslyn, 1980; Paivio, 1971; Shepard, 1978). People imagine ''in the mind's eye'' and ''relive'' past events. To say that images are analog is to say that there are representations in working memory that have the same form as perceptions of the things represented (e.g., Kosslyn, 1980). An individual may experience ''red'' in thinking about a fire truck somewhat as red is experienced in looking at the truck. Of course the isomorphism between an image and a perception need not be complete. The image of the truck may not show the shiny chrome that perception would reveal. When analog representation is visual/spatial, we speak of depiction.

That visual mental images may be depictive has been at the center of theory about imagery (e.g., Farah, 1988; Finke, 1989; Kosslyn, 1980, 1994; Pinker, 1984). For example, as the study of imagery accelerated after the era of behaviorism, a common formulation of the process of visual imagery was that initially perceptual ''sensory responses'' became conditioned to stimuli such as words (e.g., Mowrer, 1960; Staats, 1961; see also Skinner, 1953). Later hearing of a word would elicit the image of the item much as earlier looking at the item had elicited the direct sensory response. Paivio (e.g., 1969, 1971), who began the modern breakthroughs in the study of imagery, accepted this formulation with few reservations. More recently, Kosslyn (1980; also see 1994) has emphasized the ability of imagery to simulate continuous transformations of the visual field, such as ''scanning,'' ''panning,'' and ''zooming.'' The generation of mental images is described in terms of the creation of motion pictures (for discussion of motion picture techniques, see Hochberg, 1986).

### *Empirical Challenges for a Theory of Depictive Visual Imagery*

If the effectiveness of mental imagery is evaluated according to conventional standards for the fidelity of pictures, as the performance of a portrait painter or the quality

of a video system might be evaluated, imagery fails to live up to even the weakest expectations. Indeed, it has seemed to many thinkers that in the context of cognitive theory, the incidence and the internal structure of images are arbitrary. There typically has been agreement about the empirical facts; arguments about imagery through the years have centered on what conclusions should be drawn from the facts. Of course, the challenges for theory are pointed out energetically in works that have expressed skepticism about a theoretical construct of mental imagery (e.g., Anderson & Bower, 1973; Betts, 1909; Binet, 1903/1969; Brewer, 1974; Brown, 1958; Chase & Clark, 1972; Dennett, 1969; Fodor, 1965; Fodor, Bever, & Garrett, 1974; Hoernle, 1907; Humphrey, 1951; Pylyshyn, 1973, 1978, 1981; H. B. Reed, 1918b; Schiller, 1920; Stout, 1902–1903; Thorndike, 1907; Watson, 1913, 1914; Winch, 1908; Woodworth, 1906, 1915, 1938). Examination of these works suggests that the apparent arbitrariness of imagery is composed of three more focused problems for theories of mental imagery.

*Imagery is unpredictable.* It often has been difficult to find tasks or avocations that require particular forms of imagery. Certain avocations do require ''spatial ability,'' but exercise of such ability has a variable relationship to the use of visual images (e.g., Hampson & Morris, 1983; Lorenz & Neisser, 1985). Imagery has also seemed to be unpredictable for any one person when it is considered across time and across cognitive tasks. Because assignment of a causal role to an entity would seem to presuppose predictability in its occurrence, observations of this type have made many theorists doubt the usefulness of a construct of mental imagery (e.g., Watson, 1914; Winch, 1908).

*Actual mental content is independent of imagery.* Even were mental imagery entirely predictable, problems would remain. When imagery does occur, it generally does not provide what appears to be the *actual content* of thinking. Two traditions lead to this conclusion. The phenomenological study of consciousness revealed that thoughts compose a more or less coherent progression of conscious concepts which are not given in mental imagery (e.g., Ogden, 1911, 1923; Woodworth, 1906; the Wurzburg studies, see Humphrey, 1951; Mandler & Mandler, 1964; Titchener, 1909). Consider the question, ''Should a man be allowed to marry his widow's sister?'' The answer typically comes to people through an insight that is quite conscious. But that insight seems clearly different from any possible mental image (Brown, 1958; Woodworth, 1915).

Within a different tradition, if imagery is an analog representation, then it is logically clear that images cannot fully depict most concepts (e.g., Chase & Clark, 1972; Pylyshyn, 1973). The best-known example is the inability of images to depict categorical concepts (e.g., there cannot be a mental image of the generic concept 'food'). A number of examples of this type of observation are provided in Pylyshyn's (1973) famous paper. The truth value of a thought, that a chess piece is in a position to attack, and that one thing is to the right of another, are concepts that do not have a one-to-one relationship with any image.

*Images are poor copies.* The third problem is that images seem more often than not to be poor copies. Even if people are ''vivid imagers,'' their imagery typically is little like what is seen in a motion picture, or even in a scrapbook. To borrow some well-known terms, visual images often are vague, fleeting, and fragmentary,

and sometimes they ''picture'' the wrong thing altogether (e.g., Boring, Langfeld, & Weld, 1935). Thus, even if imagery were more predictable, and if it could in principle depict the real content of thought, it nevertheless would often fail to do so. The overall situation was summed up by Buhler: ''Anything so fragmentary, so sporadic, so thoroughly at the mercy of chance when it enters consciousness as the images in our thought experiences, cannot be regarded as the carrier of the close-fitting and continuous thought content'' (quoted in Humphrey, 1951, p. 57).

*What Can Be Depicted?*

The claim that concepts generally cannot be depicted (the second problem noted above) raises the question of what *can* be depicted. The standard answer has been, ''Those things which are concrete.'' Indeed, this answer has been well supported by subject ratings of the imagability and concreteness of different things (Paivio, 1969, 1971). The claim about concreteness seems based on the fact that visual images can be mapped on to visual sensation (as in the image of the red fire truck), and visual sensation can be mapped onto structure in the optic array (Gibson, 1966). Assuming the mapping is one-to-one, it can be reversed. This means that things which can be specified in the optic array can be depicted in visual images (for one view of this class of objects, see Gibson, 1979). This assertion suggests a means of evaluating whether a visual image depicts a concept: Examine whether the spatial properties of the image have a one-to-one mapping with the referent of the concept. That is, if the structure of an image were instead the structure of a picture, would it be unambiguous what the picture represented?

Given that mental imagery may in principle depict some things, there are a number of conceivable replies to the claim that most concepts cannot be depicted. First, image theorists might accept the description of the content of concepts, but then maintain that images actually may depict such things (i.e., that the meanings of the concepts can be specified in the optic array). It does not appear that any recognized theorist has held this view, although Gibson's (1979) theory of affordances could be adapted to a claim of this type (consider also Freyd, 1987). Perhaps the statement closest to this view is Galton's (1883) formulation of the generic image. He suggested that an image could have generic reference if it resembled all members of a class in terms of essential properties of the class, at the same time that the image resembled no exemplar of the class in detail. The modern concept of prototypes for basic and entry level categories makes this view reasonable in many respects (Jolicoeur, Gluck, & Kosslyn, 1984; Rosch, 1978; see below).

A second attempt to close the gap between images and concepts begins with agreeing that images cannot depict what is purported to be the content of most concepts. To solve the problem, the image theorist denies the validity of the description of the concept. The image is said to be all that the person actually is aware of, and the concrete referent of the image is said to exhaust the meaning of the concept. Many writers (e.g., Brown, 1958; Fodor et al., 1974; Humphrey, 1951; Kosslyn, 1980) imply that this was Titchener's (1909) view and that he was representative of early authors. I will argue that this was not Titchener's view and that it certainly was not the standard one. It is only theorists who came from the behaviorist tradition who

have adopted this approach to imagery. Thus, Bugelski (1970) asks, ''If communism is not an image of a bust of Karl Marx or a red velvet wall with a yellow hammer and sickle, what is it?'' (p. 1011). There was a similar logic in early behaviorism (e.g., Watson, 1919), in which all representation was equated with patterns of peripheral behavior (which might be ''covert'').

*The Functionalist Response to the Empirical Challenges*

The functionalist alternative for image theory contains two basic themes. First, it is emphasized that structural isomorphism between two things is not adequate for making one of them represent the other. As James (1909/1975) noted, eggs resemble each other but do not represent each other. Mental images represent, in part, because they are given meanings. But if the meaning of an image is something in addition to its structural isomorphism, the image is symbolic. It then is clear that images in principle have the same power to represent concepts as any symbol has (e.g., a mental word). Theoretical effort can be concentrated on the question, why is an analog image employed as a symbol in some instances? Second, the incidence and the internal structure of images are said to vary with the need for information in the task at hand. Both of these themes contrast with the typical criteria used to evaluate a system that produces pictures (e.g., a camera). A mental image is evaluated not on the consistency or quality of its resemblance to perceptions, but on whether it provides useful information.[2]

## GROWTH OF AMERICAN FUNCTIONALISM AND THE PSYCHOLOGY OF MENTAL IMAGERY

The initial landmark in the empirical study of mental imagery was furnished by Galton (1883). He discovered striking variability in the amount of visual imagery that people used and in the pictorial quality of that imagery. Furthermore, scientists and academicians seemed to be the most deficient in visual imagery. These people are presumably the most skilled at cognitive activity, so that if imagery is unnecessary for them, image theorists are presented with a challenge. Galton's explanation of this phenomenon involved two components. First, visual imagery is only necessary when a person is thinking about intrinsically spatial things. This claim could not stand alone, as accomplished geometers and painters, and people generally adept at visual perception and memory, could be found who got along without much visual imagery. The second component of Galton's explanation was that visual imagery is only necessary in more inventive, less routine, exercises of thought. This appeal to special uses of ''the visualizing faculty'' is one of the consistent features of the functional approach to imagery.

A second significant event in the early imagery psychology was the publication of James's *Principles of Psychology* (1890/1981). It would be difficult to overestimate the influence of James. Such important figures as Dewey, Angell, Woodworth,

[2] If photography is considered as an art form, or in its various branches of expertise (e.g., photojournalism or technical illustration), photographs also must be understood in terms of goal-directed information processing. It is only in thinking of the raw technology that cameras are just machines for making copies.

and Thorndike, among many others, enthusiastically credited his influence upon them (Evans, 1981). Much of James's chapter on imagination was given over to establishing the variability in sensory modality and in pictorial quality of different people's imagery. He professed his own imagery to be rather poor (although his appreciation of visual things was strong), and there were no direct references to a visualizing faculty. Throughout this work, James was at pains to deny that mental representations function through a resemblance to their referents.

James appealed often to the concepts of sensation and image in building his theory of mind, but he recognized the challenges for theories of imagery. For example, he pointed out that if a generic image were a schematic image of a type of thing, the individual would be unable to discriminate a generic concept from a sketchy memory of a particular thing. It was important to recognize that images occur in an active mind that has a cognitive relation to its environment and uses representations in the pursuit of goals. Images occur in relationships of meaning and cognitive use. Resemblance is only part of what makes an image work, and extensive resemblance may almost never be necessary. A conscious ''fringe'' can symbolize a meaning (see Mangan, 1993), and a vague and fragmentary image often can function as well as a highly pictorial one.

As functionalism grew into a recognized school of thought, it came to be associated with a form of theorizing in which phenomena were approached with the questions of ''How?'' and ''Why?'' in addition to the structuralist's ''What?'' (Angell, 1907). Functionalism was much influenced by the evolutionary theory of Darwin and the application of this theory to psychology by Spencer (1881) and others (see James, 1890/1981). Boring (1950) considers that Galton was a functionalist, and there is agreement that in its broader scope functionalism characterized most of the American centers of psychology (including Chicago, Clark, Columbia, and Yale), as well as the direction of American psychology (for example, J. B. Watson was a student of Angell's; see Boring, 1950; Heidbreder, 1933; Keller, 1973). Most historians of psychology agree, however, that functionalism took definite form and inspiration under James (e.g., 1890/1981), and that its best expression came from the Chicago school under Dewey (e.g., 1896, 1903, 1910, 1916) and Angell (e.g., 1907, 1908). Hilgard (1956) and Hilgard and Bower (1966) give excellent descriptions of functionalism during its later development.

As the study of mental imagery progressed, most introspective studies showed a great deal of variability in imagery (e.g., Fernald, 1912). The low degree of isomorphism between images and conceptual content was a commonplace observation. Titchener's (1909) description of his own imagery is the best known example. A fairly characteristic description of the ordinary memory image was given by Ladd (1894). Memory images are typically ''meagre and schematic'' (p. 254); they are less intense than perceptions, less rich, they elicit less feeling, almost no motor reaction, and (because of processing capacity limitations) they occur in fragments that can only represent complex memories over time.

The observations of mental set by the Wurzburg school were generally accepted (see Gibson, 1941). The very active debate that arose over the observation of imageless thought by the Wurzburgers, and others, centered around one question: whether there is a nonsensory *conscious* medium of thought (see, e.g., Angell, 1897,

1906, 1911a; Book, 1910; Calkins, 1909; Clarke, 1911; Ogden, 1911, 1923; Titchener, 1909, 1911, 1912; Stout, 1898; Washburn, 1915; Watt, 1911; Woodworth, 1906, 1915, 1938). This debate solidified the approach to mental images that had begun with Galton and James. Downey (1929) summed up the general situation: ''The image was reconceived, not as a static hard existence, but a fluid fleeting thing, moulded by every exigency of the momentary task'' (p. 37).

## FUNCTIONALIST ASSERTIONS ABOUT MENTAL IMAGERY

Seven basic statements about representation and mental imagery gradually became standard in the functionalist account of thinking. In the following, these seven ideas are described in turn.

### *Mental Representations Are Produced According to the Need for Them*

The function of consciousness is to provide representation of the world for a system of adaptive activities, including thinking and behavior (e.g., Angell, 1908). Conscious interests and goals are joined with objective perception, or with mental imagery, to guide action. A series of actions may be carried out to continuously alter the environment, or representation in thinking, until the interest is satisfied or a goal is reached (e.g., Dewey, 1933). In this view, representation is for the purpose of directing action, and representation is generally produced by action in the context of interests and goals.

Among the classical expressions of this view, James (1890/1981) defined mentality as the choosing of means in the pursuit of goals. Similarly, even the most ordinary perceptions were said to depend upon attention, in which an active person selects among alternative courses of cognition on the basis of interests and goals. Dewey (1896) pointed out that representation and action simultaneously enable each other. Just looking at something requires complex motor action, and action requires the guidance of perception. Dewey urged psychologists to realize that stimuli and responses are not ontologically distinct. There is only a functional distinction between two types of sensorimotor event. Some sensorimotor events are perceptions of a situation relatively early in an experience; they correspond to the term ''stimulus.'' Other sensorimotor events are responsible for the development of the experience into perception of a more inclusive and complex situation with a particular outcome and value for the person. These latter sensorimotor events correspond to the term ''response'' (see also Angell, 1907; MacDougall, 1911).

This view implied that images should not be conceived as isolated mental objects with fixed properties. An image provides representation in the adaptive regulation of activity, and this more or less local role will influence the structure of the image. Attention to the specific functions of imagery provided flexibility in the interpretation of its observed structure (see below). A good example of functionalist thinking in the interpretation of imagery is in papers by Kuhlmann (1906, 1907, 1909; see also Comstock, 1921).

### *The Need for Imagery Varies with the Novelty or Difficulty of a Task*

Conscious representation is not needed to facilitate adaptation if there is an appropriate act already prepared for a situation (e.g., Angell, 1908; Dewey, 1903, 1916;

James, 1890/1981; MacDougall, 1911). In other words, consciousness serves to control action when it cannot progress automatically, or by habit. Novelty, difficulty, or conflict in a problem will bring representations potentially useful for guiding action into consciousness. The converse, a reduction of conscious representation with practice, was a hypothesis ''. . . held by all psychologists of repute'' (Angell, 1907, p. 72).

Book (1910) showed in a study of the acquisition of typewriting skills that early stages of the skill involved rather static, well-formed, mediating imagery. This was most obvious for a set of subjects who usually had the keyboard hidden from sight. The imagery eventually disappeared as direct eye/hand production mechanisms were consolidated and higher order sequences were acquired. A wide range of empirical papers included the argument that imagery only occurs in novel or difficult cognitive tasks (e.g., Clarke, 1911; Comstock, 1921; Fernald, 1912; Fisher, 1916; Fox, 1914; Kuhlmann, 1906, 1907; H. B. Reed, 1918a; Rowe, 1910). Numerous theoretical works of the period urged the hypothesis (e.g., Angell, 1908; Gore, 1903; Langfeld, 1916; MacLennen, 1902). In Judd's (1907) words:

> When an object is to be handled time and time again . . . then perception must be organized as compactly as possible, and imagery becomes a hindrance rather than a help; it therefore gives way to direct forms of organization. No better illustration than this could be found of the fact that the development of all experience is in the direction of the perfection of functions. (p. 240)

### *Images Are Symbols*

There is a symbolic relation between an image and its referent. Two different images that refer to the same thing are functionally identical for the thinking person. There should not be a general expectation that an image will closely resemble its referent. The requirement is that the image have the right reference, and there is more to reference than resemblance.

Numerous theoretical discussions claimed that imagery was symbolic (e.g., Angell, 1908; Hollingworth, 1911, 1926, 1928; James, 1890/1981; Titchener, 1909, 1911, 1915). James, for example, suggested that images should be considered to be symbols in a sort of cognitive algebra. Just as symbols are used to perform algebra, a thought process can be carried forward without the imaginal symbols being explicitly converted into their meanings. Angell (1907, 1908) used the idea that meaning provides the essential identity of images to locate the stable conceptual world in the midst of the effervescent imagistic one. The referential meanings of images are more constant than the images themselves are. Hollingworth (1928) argued, along with many others, that only trained introspectionists could accurately describe most cases of imagery, because the layman is only concerned with getting the meanings of images. People are ordinarily unconcerned with the nature of the images that help cognition to progress. Philosophers of mind (e.g., Hoernle, 1907) who were skeptical about the importance of the analog nature of mental imagery nevertheless believed that images serve as mental symbols.

An example of the assertion that imagery is symbolic is the treatment of the generic image. Leading theorists (e.g., Angell, 1908; James, 1890/1981; Titchener, 1915)

denied that there could be a representation that had generic reference just because it was an analog representation. Introspection, however, made it obvious that images are of common use when categories are represented. Theorists asserted that it was a symbolic function which made images capable of generic representation.

> . . . a blurred picture is just as much a single mental fact as a sharp picture is; and *the use of either picture by the mind to symbolize a whole class of individuals is a new mental function,* requiring some other modification of consciousness than the mere perception that the picture is distinct or not. (James, 1890/1981, p. 695; italics in the original)

It was supposed that a wide range of images, including ones depicting individual exemplars, could help to represent generic concepts. Fisher (1916) provided extensive introspective data on the acquisition and use of category concepts. Her findings supported the functionalist view of symbolic imagery.

Many theorists interpreted the data showing individual differences in imagery (see Griffitts, 1927; James, 1890/1981) to mean that motoric/kinesthetic gesturing or mimicry, auditory/verbal naming or describing, and visual picturing are functionally equivalent types of representation in many circumstances (e.g., Colvin, 1910; Fernald, 1912; James, 1890/1981). In addition, different degrees of completeness of each type of representation were generally accepted as being functionally coordinate. A common interpretive statement about reported imagery was that it ''carried the meaning'' of thoughts (e.g., Clarke, 1911; Comstock, 1921; Titchener, 1909).

There were numerous reviews of appropriate methodology for the study of mental imagery (Angell, 1910; Colvin, 1909; Fernald, 1912; Titchener, 1901). These reviews suggested that researchers not use methods that involved inferring the nature of imagery from indications of what a person was thinking about. For example, it was not considered fruitful to count the relative frequency of visual metaphors in a prose passage in order to ascertain the propensity of the author for visual imagery. Nonvisual images (or no conscious representation at all) could have served as representation in thinking during composition of the prose.

### *The Importance of an Image Is in Its Implications*

The next functionalist assertion introduces an additional aspect of meaning. In particular, the meaning of an image is related to its implication for further activity. The general idea was crucial to James' (e.g., 1907/1975, 1909/1975) pragmatic theory of knowledge and to his radical empiricist ontology (e.g., 1912/1976). In pragmatism, the meaning of a concept is in the conceivable experiential or behavioral consequences that are specific to the occurrence of the concept. An image symbolizes something if the consequences of the image are those that would follow from the thing itself being in mind. Langfeld (1916) took a similar view:

> The image may be an almost perfect likeness of an object. In most cases, however, it is not; and often it is so far removed from the original object that to say that it means the object seems on the face of it almost absurd. But . . . a hundred different images can introduce almost the same reaction, and if the reaction is the meaning then a hundred different images can in this sense stand for the same meaning. (pp. 181–182)

Other clear statements of this view were made by MacLennen (1902) and Gore

(1903; see also Dewey, 1916). Langfeld and MacLennen argue that images are generally in the background of attention because it is the implications of the images that are of primary interest.

The best empirical work relevant to this position was by Kuhlmann (1906, 1907, 1909; see also Comstock, 1921; Crosland, 1921; Fisher, 1916). For example, in a study of recall of auditorally presented conversations, Kuhlmann (1909) reported that the predominant form of recall involved initially vivid visual imagery that would establish a mental context that had been imagined at encoding. The auditory recall followed, and the visual imagery would immediately become vague or absent. At points of difficulty in recall, such as at turning points in the conversation, the visual images would recur and help to set the auditory recall going again. In this instance, imagery would be idiosyncratic, and there is no compelling reason to believe that an effective image would have to faithfully resemble particular objects. The image must provide a mnemonic cue for a single individual at a particular moment during recall.

### *Imagery Becomes Abstract*

The abstractness of imagery increases with a person's experience in thinking about a particular topic. Concern with the abstraction of imagery tended to include discussion of generic images. It commonly was suggested that after repeated experience with a type of object, images would retain only the properties essential to the type. Galton (1883) produced composite photographs as examples of spatial abstraction. The discussion most often cited was Huxley's (1879; quoted in James, 1890/1981). Apart from generic images, there was a consistent belief in a process of progressive abstraction. One of the clearest statements was by Ladd (1894). Because his view captures much of the early thinking about abstraction, I will briefly describe it.

Ladd believed that the most important factor leading to abstraction is the ongoing need for a ''condensation'' of representation. The need for condensation can be seen by tracing how a sensory experience is taken up into the flow of cognitive processing. Thus, a ''presentation'' (i.e., an immediate sensory experience) might first become a memory image, one form of ''idea.'' Ordinarily, this image will be schematic. In addition, if the remembered object is extended in time or space, or is complex, then there is a need for some part of the object to be taken as representative of the whole. To dwell on the whole would slow down cognitive processing too much. These abstracted images can then become ''concepts,'' thus taking on a more general signification. Further abstraction will be a part of this change of function, so that any nongeneral properties of the represented things will be dropped from the images. Concepts can then be related together by ''judgments.'' These are instances of propositional thinking. In a judgment, the individual ''affirms a relation'' between two things (such as concepts). Then, judgments can be combined into ''reasoning,'' where a higher order judgment is sought through the intermediary of successive related judgments (e.g., the judgment ''Socrates is mortal'' is sought through the intermediary of ''All men are mortal,'' etc.). Ladd suggested that cognitive processing would be too slow and inefficient if representation was not condensed. There must be a progressive selection and abstraction of bits and pieces of material to serve as repre-

sentations for a much broader and deeper object of thought. A view emerges in which there is a threshold for any image beyond which it is a visual/spatial symbol rather than a picture to be examined. As for the everchanging representations themselves: ''If one arrives at the other side of the stream in safety, one does not notice or remember how each floating block of ice felt, as it was touched lightly with the toes—one's eyes and interests being set *on that other side*'' (Ladd, 1894, p. 284, italics in the original).

Other authors made similar points (e.g., Judd, 1907; MacDougall, 1911). Book's (1910) description of learning to type demonstrated the need for a condensation of imagery. Novices depend on imagery to aid them in finding each key. Experts have skills which allow them to type from just the visual perception of the copy and the appropriate motor set in relation to the keyboard. During the development of these skills, imagery must abbreviate, become more purely symbolic, more inclusive in its reference to the keyboard, and eventually drop out altogether, as the skill increases in speed and scope.

Binet (1893/1966) provided a fascinating interview study of blindfold chess playing. He concluded that while amateurs have highly pictorial imagery, experts have imagery that is abstract in the extreme. The chess board is not imaged, and images of the pieces do not distinguish between black and white nor between the different shapes. There is a purely ''geometrical'' representation in which a few locations and motions are used to symbolize possible moves. Binet's explanation was that the players' imagery paralleled their abilities in perception. The expert is no longer impressed by the invariant concrete properties of the game, and attention and imagery respect only that which cannot be assumed.

Fisher (1916), in a study of the development of category representations, reported that early in learning, images for categories of objects were likely to be images of various separate items. Later, a single schematic visual image would stand for the whole set. Eventually words would tend to be used instead of images, and finally no conscious representation would be needed.

Another relevant line of research was exemplified by Clark (1916). She presented subjects with lists of words and found that words that did not evoke memory of a particular event tended to evoke images that were more abstract (e.g., the imaginal background might be absent). However, studies of this type yielded conflicting results (see the references in Clark).

In James's (1890/1981) ideomotor theory of action, the earliest developmental stage of performing an act involves imaging the act itself. In later stages, increasingly remote perceptions of the external conditions related to the need for the act are sufficient to elicit it. As James put it: ''Consciousness deserts all processes where it can no longer be of use. The tendency of consciousness to a minimum of complication is in fact a dominating law'' (Vol. 2, p. 1107).

### *The Visualizing Faculty*

A claim that became increasingly common during the prebehaviorist era of psychology concerned what is currently called spatial (or visual) cognition. Spatial cognition was generally subordinated to the novelty/difficulty principle: Imagery will

occur to provide information when useful cognitive actions are not otherwise prepared. Many psychologists noted that this process would consistently produce depictive visual imagery when unpracticed cognition concerned spatial properties of things.

Betts (1909) was an influential proponent of spatial cognition. This is somewhat ironic because he worked at Columbia and shared Woodworth's (e.g., 1906) and Thorndike's (1907) decidedly anti-image convictions. Betts devised one of the well-known cube tests: If a 3-in. cube is painted red and then cut into 1-in. cubes, how many of these smaller cubes will have zero, one, two or three red sides? Betts' results compelled him to grant that imagery was important in cases of cognition where immediate perception would be valuable. Particularly after Betts's demonstration, theorists associated spatial cognition with reliable elicitation of visual imagery. Thus, Angell (1910) stated that: ''Tests on geometrical forms are peculiarly successful in throwing visual imagery into the foreground'' (p. 76). Another effective task was said to be asking detailed questions about the concrete properties of arbitrary arrays of objects that were previously shown for a brief time. Fernald (1912) concurred with Angell after her extensive research on the imagery involved in a variety of cognitive tasks. When Griffits (1927) sought ''visualization'' tests, he developed a battery of tests composed of Betts' cube problem and other unfamiliar or complex geometrical problems. This was one of the earliest attempts to construct a test of spatial ability.

### *Representation Becomes Contained in Activity*

The progressive abstraction of conscious representation in thinking may leave aspects of activity, such as shifts of attention, or kinesthetic sensations or images, as the only conscious representation in thinking. In considering this assertion it is important to realize that there was a rich tradition that related action to cognition. Consider two examples.

As noted above, a classic paper by Dewey (1896) rejected the atomistic view of sensory ''stimuli'' and motoric ''responses'' that follow one after the other. Both perceptions and behaviors are simultaneously sensorimotor. Even very simple instances of perception require sophisticated motoric cooperation of the eyes, the head, and the posture of the body. So called stimulus–response pairs actually are coordinations of two or more sensorimotor events.

Theorists often referred to action in attempts to explain the consciousness of personal states. James and Lange (see James, 1890/1981) reduced feelings of emotion to patterns of activity and sensation within muscular and autonomic response systems (so that, for example, there would be no special ''anger'' sensation). This view was further developed by Dewey (1894, 1895), who also reduced feelings of effort to felt aspects of the motoric system (Dewey, 1897). The attempt in such cases as these was to integrate personal states into the logic of a cognitive system that was geared to adaptive action.

Feelings of activity were commonly reported in introspective analyses, and representative functions were commonly attributed to those feelings. James (1890/1981), for example, claimed that acquaintance with the self was given for him in ''bodily

processes, contained primarily within the head'' (p. 287). Judd (1907), Titchener (1909, 1911, 1915), and Washburn (1915), among many others, believed that active response to perceptions and images could later serve alone as mental representation. Such representations might stem from characteristic motor sets (e.g., feelings of preparation), motor accompaniments, or motor or attentional responses and were said to function symbolically (except, perhaps, by Washburn, 1915). Many authors considered these ''conscious attitudes,'' perhaps in very condensed form, to be the conscious aspect of the imageless thoughts. One of the main goals of Book's (1910) paper was to support this view; typing need only have the right ''feel'' for an expert (see also Rahn, 1913). It was believed generally that expertise and the condensation of representation were important determiners of the use of action as representation. It also was believed that motor images or acts could symbolize anything (e.g., Colvin, 1910; Hollingworth, 1928).

## TITCHENER AS A FUNCTIONALIST

Modern discussions of imagery show little awareness of the earlier functionalist work on the problem. However, the structuralist Titchener is cited often. The famous introspective passages from Titchener's treatise on thinking (1909), and the empirical papers of his students (e.g., Clarke, 1911; Comstock, 1921; Okabe, 1910), are routinely used to prove that the mental images people generate are inconsistent with a theory in which all concepts are represented by images (e.g, Brown, 1958; Fodor et al., 1974; Humphrey, 1951; Kosslyn, 1980). Such rhetorical uses of Titchener's introspections do not, however, constitute a description of his theoretical views of imagery. Titchener has been treated so many times as the major image theorist of the prebehaviorist era that it is important to outline his views in the context of the functionalist approach to imagery.

In the pages that are so often cited, Titchener (1909) makes it clear that images are not identical to their meanings and that meanings are important. For example, he refers to the images that he describes as ''impressionist notes'' (p. 13) and says of the problem of generic imagery that: ''What is abstract and general is not the idea, the process in consciousness, but the logical meaning of which that process is the vehicle'' (p. 15). In another work, Titchener (1911) states that,

> Thought and reasoning . . . can go on in terms of internal speech, in terms of conscious attitudes, . . . and in terms of images. The attitude is as symbolic as the word, and the image may be as symbolic as the attitude; all that thought requires is a system of mental symbols. (p. 521–522)

Similarly,

> What we do when we exchange ideas in ordinary conversation, is to indicate the object of the ideas . . . we have not the least desire or occasion to go behind the topic of thought to the psychological vehicle of that topic . . . But this question, of the mental stuff of which thought is made, is precisely the question that a descriptive psychology of thought has to answer. (p. 511)

Titchener (e.g., 1909, 1911, 1915) often gave explanations of mental representation that involved metaphor, unique ecological association, or characteristic functional

context. Arnheim (1969) and Paivio (1971) credit Titchener with advocating a symbolist view of imagery. Indeed, Arnheim credits Titchener (1909) with understanding representation with the subtlety of one schooled in the visual arts and with providing ''the voice of a new era'' (p. 107) in the study of representation.

Titchener (1909, 1911, 1915) accepted unequivocally the functionalist doctrine that imagery would be more likely to occur in novel or difficult cognitive problems. This fact, and others in the same vein, prompted Angell (1911b) to claim that Titchener was moving toward functionalism in practice and promoting his pure structuralism only in form. Titchener's most succinct statement of his view of imagery is in his *Beginner's Psychology* (1915; e.g., the various sections on memory).

Humphrey (1951) claimed that the Titchenerian position on imagery was logically inconsistent. The critical assertion in Humphrey's analysis was that the Titchenerian concept expressed in the terms ''vehicle'' and ''carrier'' of meaning (e.g., as they are used in the above quotations) only sets the problem of meaning back a step. Humphrey believed that a structuralist theory of meaning could only add meanings to images in the form of sensations or other images. And Titchener did suggest that it might be such a context that would allow an image to have a certain meaning, somewhat as James (1890/1981) had earlier discussed the ''fringe of consciousness'' (see Mangan, 1993). Humphrey suggested that there is no justification for speaking of an image carrying a meaning in this theory: There can only be a conglomeration of sensations and images, and the conglomeration is as meaningless as the image by itself would be.

The source of the disagreement is that Humphrey argues the case for the phenomenologists who are concerned to describe conscious meanings (e.g., Woodworth, 1906). Titchener certainly did not succeed in locating these *sui generis* conscious contents. But of course he frankly disbelieved in them and was attempting to provide an alternative account of the reported conscious events. The account he provided was the functionalist one. It is a symbolic mapping of images to referents that is the source of meaning in thinking.

To understand Titchener, it is important to realize that he did banish meaning from psychology, but that this was not because he considered meaning unreal or unimportant. Titchener's view is reminiscent of Chomsky's (1965), when he said that the grammar of a language could be analyzed without knowledge of the semantics of the language. Titchener insisted that the discipline called ''psychology'' should consist of psychophysics in conjunction with a reductionist description of conscious contents (e.g., 1898; 1912; 1915). With the unequivocal successes of Weber and Fechner in the background, Titchener believed that sensations and images were the elements of consciousness and that psychology should expend its efforts in describing their structure and the pattern of their occurrence. Logical description of the meanings of mental symbols would be provided by philosophers, much as they were providing a formal logical calculus. In his research, meanwhile, Titchener looked for the sensory or imaginal ''carriers'' of meaning (e.g., 1915).

Titchener was wrong about much. For example, modern cognitive psychology has made it clear that even the most hardened empirical psychologist must be as interested in the formal description of meaning as any philosopher might be (e.g., Sachs, 1967; Bransford & McCarrell, 1974; Brewer, 1974; Brewer & Treyens, 1981; see

Schwartz & Reisberg, 1991). However, there was never any danger that Titchener would build a theory of imagery on the premise that images provide conceptual content merely through structural isomorphism between an image and a referent. When the topic of a debate, or the need to write for a general audience, led Titchener to set aside his metatheoretical rhetoric, he consistently espoused functionalist theoretical claims.

## FUNCTIONALISM IN THE MODERN PSYCHOLOGY OF MENTAL IMAGERY

Most research on mental imagery in the prebehaviorist era was quite poor methodologically. Statistical techniques now taught to undergraduates were generally unheard of. Concepts crucial for conducting informative experiments, such as response bias, had not been developed sufficiently. And fundamental methods for controlling experimental presentations, such as the use of norms in constructing word lists, were years in the future. The disappearance of the study of mental imagery, and the continuation of the study of learning, can be explained by saying that psychologists turned to areas in which immediate progress could be made through experiment.

In contrast, the current psychology of mental imagery has had well known success in the laboratory. Behaviorism would not have become predominant if experimental results available today were known in the early period (e.g., Bower, 1972; Brooks, 1968; Kosslyn, 1975; Paivio, 1969; Shepard & Metzler, 1971; see Finke, 1989). Nevertheless, as theories of mental imagery have developed, numerous independent statements have established a pattern in which the functionalist approach to depiction in mental imagery is again standard.

In the following, I reconsider the seven consistent claims of functionalists about mental imagery. In this case, however, the examples are drawn from modern sources. I refer to the theoretical framework as ''adaptationist,'' because that is clearly the term preferred by modern psychologists (e.g., Anderson, 1990). I do not mean to imply that all of the authors cited below agree with each other on every aspect of mental imagery. Nor is it true that every author is clearly an adaptationist on every point. But if the spectrum of modern work on the nature of mental imagery is examined, the outlines of an adaptationist framework for image theory are unmistakable.

### *Mental Representations Are Produced According to the Need for Them*

Mental images are considered by current cognitive theorists to provide information in goal-directed cognition. It is recognized that the need for information will vary with the task and that the structure of imagery will vary accordingly. As a consequence, imagery often will have minimal resemblance to concrete objects. A clear example of this approach was provided by Huttenlocher (1968). She found that people tend to image a spatial array when solving three term series problems (e.g., ''Sam is taller than John. Tom is shorter than Sam. Who is tallest?''). Huttenlocher discusses this phenomenon in terms of a goal-directed use of selective imagery. For example, the identification of the three terms may be accomplished through visualization of the names stated in the problem. The spatial array may resemble the problem situation only at the level of ''ordered things.''

In Kosslyn's (1980, 1994) view, the ordinary image is global (i.e., lacking in detail). It likely will be a figure without a ground. If parts of an object need to be imaged with greater specificity, this occurs at the expense of other parts of the object, due to the limited capacity of attention and working memory. Changes in imagery are enacted in the service of goal-directed cognition. Arrival at a goal may involve much changing of images, none of which is a good picture by typical standards of pictorial fidelity.

In their discussion of mental rotation, Cooper and Shepard (1973) note that the rotation paradigm was explicitly designed to be a task which demanded imagery (see also Corballis, 1988; Takano, 1989). They suggest that mental rotation may occur in discrete steps, that the imagery of many people appears to have a strong kinesthetic component (so that visual imagery may not be necessary), and that the imagery is schematic, perhaps being no more specific than would be needed to differentiate mirror reflections of two objects (as demanded by the task). An explicitly analytical and task-specific approach to images in mental rotation was proposed and supported empirically by Just and Carpenter (1976).

*The Need for Imagery Varies with the Novelty or Difficulty of a Task*

The idea that imagery will disappear with practice, but recur if a problem becomes difficult, has been proposed often in the modern study of imagery. Humphrey (1951) accepts Fisher's (1916) finding that visual imagery is prevalent in the early stages of concept learning, is replaced by language, and then disappears altogether. Because Humphrey's criticism of Titchener can be read as a criticism of the construct of imagery as a whole, it is instructive to note that when Humphrey provides his own ideas about imagery, he adopts an adaptationist point of view.

A well-known thought experiment is Shepard's (1966) observation that trying to count the number of windows in one's dwelling will elicit spatial imagery. One critical property of this task is its novelty. The number of windows cannot simply be remembered, because it never was explicitly encoded. The goal (the number) can, however, be obtained through the process of counting. Counting employs representation of each window, and the set of windows has been encoded in terms of one's perceptual experiences. Mental imagery makes this information available in thinking. A similar logic is evident in the experiments of Brooks (1968). In order to require the use of visual imagery, he had people describe in serial order the types of corners (convex or concave) on block letters. Like counting windows, Brooks's procedure requires a novel description of a spatial pattern. This description can only be obtained, for most people, through the processing of information encoded in terms of perceptual experience.

Kosslyn and his colleagues (Kosslyn, 1980, 1981; Kosslyn, Murphy, Bemesderfer, & Feinstein, 1977; Kosslyn & Jolicoeur, 1980) have pointed out that imagery will occur more consistently in novel cognitive tasks. As the world becomes ''propositionally'' encoded, perhaps into categorical knowledge, imagery will become unnecessary. Kosslyn and Jolicoeur (1980) show that verification of statements such as ''Canaries have yellow feathers'' will lead to reports of a greater dependence on visual imagery when the stated property has a lower association strength to the stated object.

Brewer and Pani (1983) suggest that mental imagery often is elicited by questions that require people to generate ''personal memories.'' Questions such as ''Who was the first person you saw after you entered the building today?'' or ''What was the last sporting event you attended?'' easily produce reports of vivid imagery. Events that are recalled as personal memories have been recently or vividly experienced but have not been previously recalled or considered in more categorical terms.

Chi, Feltovich, and Glaser (1981) review a number of studies of problem solving and present data suggesting that novices at physics problems concentrate on immediate concrete properties in their attempts at solution. Experts, on the other hand, are able to translate physical features into abstract categories and procedures. Perhaps similarly, children turn to concrete devices, such as counting on their fingers, when arithmetic problems become difficult (Siegler & Shrager, 1984). Children also are more likely to talk to themselves when problems are more difficult (Berk, 1994). With learning, this private speech is abbreviated and becomes a sort of muttering. With mastery, there is only internal speech (or, perhaps, no speech at all).

Paivio (1971) reviews a number of studies of paired associate learning which show that spontaneously produced mediators are prevalent in the early trials of learning and tend to drop out in later trials. He considers this reduction to be basic to mental representation. A similar view was put forward by Osgood (1953; see also Watson, 1919). A modern expression and development of this view in terms of production systems has been provided by Anderson (e.g., 1983).

Kaushall and Parsons (1981) show that slopes of response time that imply mental rotation approach zero as subjects become practiced. Tarr and Pinker (1989) obtained a similar pattern of results in their investigation of object recognition across changes of orientation. Recognition time was affected by changes of orientation until subjects were practiced. More generally, the novelty/difficulty principle appears often as authors seek to explain the incidence of mental imagery (e.g., Hintzman, O'Dell, & Arndt, 1981; Pani, 1982; Richardson, 1969; Slee, 1980).

Authors concerned with conscious representation as a whole have endorsed versions of the novelty/difficulty hypothesis. Baars (1988) suggests that conscious representation is generated to reduce uncertainty within an established set of alternatives. As expertise develops, uncertainty is reduced, and conscious representation no longer is needed. Hampson and Morris (1983) propose that in the absence of expertise, conscious representation is required for integrating lower level activities into an organized response to a situation. As appropriate higher level skills are consolidated, consciousness is no longer needed to aid in this organization.

### *Images Are Symbols*

Many recent authors have argued that mental images function as a type of symbol. Arnheim (1969) and Schwartz (1981) support this argument by discussing the conventional concrete representations that function in a purely symbolic way. Schwartz, for example, mentions traffic signals and mathematical symbols. Fodor (1975) also argues that images function symbolically. He begins by assuming that thought can go forward through linguistic representation. He then asks where visual imagery could be successfully substituted for linguistic entities. He suggests that images can function wherever they are intentially produced to have reference to things. Given

the importance of intention, there may be minimal use of the potential of images to depict things.

Modern developments in the psychology of categorization (see Mervis & Rosch, 1981; Neisser, 1987; Rosch, 1978; Smith & Medin, 1981) imply that an image of an exemplar of a category, or an abstract image that had the general form of the ''best examples'' of a category, can be useful in thinking about generic concepts. This especially is true for basic level, subordinate, and entry level categories (Jolicoeur et al., 1984; Rosch, Mervis, Johnson, Gray, & Boyes-Braem, 1976). The use of exemplar or exemplar-like information as representative of categories is clearly an example of representations functioning in a symbolic role.

Werner and Kaplan (1963), and subsequently Paivio (1971), have spoken of the ''concretization'' of abstract concepts (also see Arnheim, 1969). The idea is that certain concrete situations or events illustrate particularly well essential properties of abstract concepts. A person might, for example, represent ''infinity'' by imagining the open space beyond distant galaxies. Shepard (1978) has argued that imagery of this general type has been important to many scientific discoveries. Because such representations cannot fully depict their objects and/or have generic reference, the representations function in part by being symbolic.

The fact that spatial representations may exemplify abstract concepts has recently been developed into a major new statement about the source and representation of concepts of all kinds (e.g., Johnson, 1987; Lakoff & Johnson, 1980). Cognitive Linguistics is one recognizable discipline within this effort (e.g., Langacker, 1988; Talmy, 1988). It is claimed that elementary perceptual concepts such as ''container'' underlie the comprehension of, or at least communication about, abstract concepts such as ''agreement.'' Thus, an individual ''enters into'' an agreement but may try to ''back out'' again. It also has been suggested that a person's understanding of relatively large domains of knowledge may be based upon metaphor. For example, the set of possible relationships between lovers may be conceptualized in terms of the metaphor ''journey.'' A relationship may ''get off to a good start,'' ''proceed rapidly,'' ''hit a snag,'' or ''end up on the rocks.'' These linguists and philosophers observe that language is filled with concrete expressions such as ''come to the point,'' ''take a position,'' and ''adopt a new perspective.'' Serious discussion of the use of perceptual knowledge as a source of metaphor in the understanding of more abstract concepts reverses the historical trend to separate perceptual and conceptual knowledge. This discussion implies that insofar as imagery may be useful in representing perceptual knowledge, it may also be useful in representing knowledge in general.

In his studies of creativity, Finke (1990) encourages subjects to consider abstract shapes and to manipulate and synthesize them in imagination in order to represent novel objects and systems. The resulting configurations would nearly always be ambiguous if seen out of context. Clearly, the reference of mental images in this instance depends on the intentions and interpretations of the imagers. To them, the images are abstract depictions of definite things.

### *The Importance of an Image Is in Its Implications*

One of the welcome consequences of the modern reexamination of analog representation in cognitive theory is the clear understanding that representations only can work in conjunction with processes that operate upon them (e.g., Anderson, 1978;

Johnson-Laird, 1983; Kosslyn & Pomerantz, 1977; Larkin & Simon, 1987; Palmer, 1978; Pylyshyn, 1978; Shepard, 1975). The processes ''interpret'' the representations. Similar distinctions are those between stimulus information and response information (e.g., Garner, Hake, & Eriksen, 1956) and between stimulus and perceptual set (see Gibson, 1941; Haber, 1966). The general form of the argument is that the response to a representation is necessary to defining the information content, or meaning, of the representation.

Anderson (1978) used this formulation of representation, and the flexibility of Paivio's (1971) associative model of imagery, to show that verbal and spatial imagery could represent concepts of all kinds. In his discussion of cognition with respect to a chess game, Anderson suggests that images will have the required meanings if associative connections between the images carry the appropriate implications.

Studies of the relationship of imagery to learning and memory (see Bower, 1972; Paivio, 1969, 1971) have stressed the role of imagery in establishing a variety of associative connections. Bower's (1972) studies of paired associate learning suggest that imagery which relates associates together into a unitary term greatly improves learning over rote rehearsal. The person has much freedom in just what image is invented. The constraints are that the image be memorable and a good retrieval cue.

Recent cognitive theory has stressed the importance of diagrammatic spatial representation in human reasoning. Johnson-Laird (1983) accounts for a complex pattern of experimental results by proposing that people construct and examine diagrammatic mental models when thinking through verbally presented syllogisms (e.g., ''None of the authors are burglers; Some of the chefs are burglers; What conclusion(s) can be drawn?''; see also Huttenlocher, 1968). Koedinger and Anderson (1990) suggest that experts in geometry organize their knowledge around a set of basic diagrammatic configurations. Cheng and Simon (1995) suggest that scientific discovery often takes place through examination of relationships simplified into diagrammatic form (see also Larkin & Simon, 1987). In all these theories, there is a knowledge system that provides the basis for the construction of images and a processing system that reads task-specific information from the images. The images by themselves would be hopelessly ambiguous and perfectly useless. In the context of the processing systems, the images provide useful and efficient information for sophisticated reasoning (see Johnson-Laird, 1983; Larkin & Simon, 1987).

### *Imagery Becomes Abstract*

It is characteristic of modern discussions of visual imagery to assert that it is fragmentary and schematic (e.g., Anderson, 1978; Bower, 1972; Hebb, 1968; Paivio, 1971). Kolers (1983) and Baddeley (1990) suggest the sketch pad as an appropriate metaphor for imagery. Numerous examples of abstract imagery were cited above, but certain additional examples are of interest. Schwartz (1981) develops a case for the necessity of an interpretive mechanism for mental representations and describes the freedom that is thereby granted to the forms that imagery may take. He points out many well-known examples of visual representation that are only abstractly depictive and/or that incorporate purely symbolic forms of representation. Examples are maps in various projections, musical notation, graphs, gestures, schematic draw-

ings, chess diagrams, and cubist portraits. Arnheim (1969) argues that images that are not depictive in detail, or that are otherwise vague, fragmentary, or minimally formed, may be perfectly adequate representations. In amodal perception, and in much modern art, the way in which things are not shown, or are left vague, can contribute directly to the power of the perception or representation. It is often the ''hints and flashes'' (p. 107) of essential structure that capture a particular event in a visual representation.

Research by Kosslyn and Schwartz (described in Kosslyn, 1980) implied the occasional occurrence of a ''blink'' transformation, a discontinuous shift in the part of an object represented in a mental image. In order to account for subjects' preferences for the blink, Kosslyn (1980) concluded that people opt for the least expenditure of time and effort in imagery. Sometimes that will be provided by the generation of an image representing a discontinuous shift of perspective, rather than an image representing a continuous transformation. This discussion fits the functionalist claim that there will be abstraction for the sake of efficiency.

It is noteworthy that there has been little suggestion in the modern era that mental imagery becomes increasingly abstract with experience. Discussions of change in imagery have focused on the disappearance of images altogether. Discussion of abstraction has focused on the efficiency of imagery and the need for information at particular moments. The lack of discussion of progressive abstraction probably is due to the rarity of efforts to link problem solving, learning, and mental imagery within single research efforts.

### *The Visualizing Faculty*

The claim that thinking about concrete properties of things will lead to visual spatial imagery is common in the current psychology of imagery. One manifestation of this claim has been the attempt to relate performance on spatial abilities tests with individual differences in the reported vividness of imagery. There has been little success in this effort (see Lorenz & Neisser, 1985; Hampson & Morris, 1983; Paivio, 1971; Richardson, 1969). Other components of the adaptationist view of imagery make this lack of success seem reasonable. Surely Binet's (1893/1966) masters at blindfold chess would have rated their imagery as nonvivid.

Neisser (1970) used Barratt's (1953) research with spatial abilities tests, and the counting-windows thought experiment (Shepard, 1966), to argue that visual imagery is specially suited to representing spatial properties (see also Slee, 1980). The importance of novelty or difficulty to the generation of mental imagery is quite often associated with claims for a specialized spatial cognition. The counting windows task is effective for generating imagery both because it is a problem for which we have little conceptual preparation and because we have spatial knowledge of the windows available to provide information for counting.

The leading proponent of a specialized spatial cognition has been Shepard (e.g., 1978, 1984). He and his colleagues (e.g., Cooper & Shepard, 1973; Shepard & Feng, 1972; Shepard & Metzler, 1971; see Shepard, 1975, 1978) have studied tasks similar to those in traditional spatial abilities tests and typically have used patterns of reaction time as the basis for inferring use of mental imagery. For example, Shepard and Feng

adapted ''mental paper folding'' from a spatial abilities test and demonstrated that latency to response varied directly with the number of surfaces that would have to be moved if the task were to be performed physically. Shepard (1978) quotes Galton's (1883) statement that visual imagery is especially well suited for representing spatial properties and infers imagery in cases where concrete material being thought about is ''complex and hard to describe'' (p. 127). More recently, Shepard (1984, 1994) has suggested that human evolution has determined that certain invariant properties of the 3D world are readily represented in human perception and imagination.

*Representation Becomes Contained in Activity*

Neisser (1976, 1978) has argued that the anticipation of useful information is critical to effective perception. He goes on to say that the exercise of perceptual anticipations in the absence of their perceived objects constitutes the process of mental imagery. Perceptual anticipation does not normally include mental images, but it does include action. As we turn to greet someone who has appeared at the door, we orient our body, direct our gaze, focus our attention, and then respond to what we see. Thus, Neisser's description of mental imagery ties it closely to the exercise of organized activity. Goodman (1982) also argues for such a position, and Kosslyn (1994) has moved in this direction. The identification of anticipation with practiced perception makes Neisser's description of imagery consistent with the claim that thinking takes place as pure action after cognition is practiced. That is, what Neisser calls an anticipation, Titchener would have called a conscious attitude.

A difference between Neisser's (1976, 1978) view and the early one (e.g., Book, 1910; Titchener, 1909, 1915) is that while the early psychologists emphasized the sensory nature of active representation, such that thinking might still ''feel'' like one is perceiving the object of thought, Neisser is almost totally concerned with the unconscious information processing that is involved in perception. Neisser's view helps to make sense of the early stress on activity as representation. The early view helps to explain why perceptual anticipations can seem, phenomenally, to be a kind of spatial awareness.

Kolers (e.g., 1983; Kolers & Smythe, 1979) was another modern voice urging that mental imagery be considered a type of action. Although he never worked out a theory of mental imagery, Kolers made it plain that he thought the starting point of such a theory should be concepts of organized action. He likened visual imagery to sketches on a pad, where the sketch is not constrained to resemblance by paper or pencil, but by the current skills and concerns of the person producing the sketch.

> . . . The image as symbol need not resemble either a perceptual experience or external reality. Such correspondence as is reported between image and perceived object is due not to any special characteristics intrinsic to the process of imaging, but to the purposes and needs to which the imaging is put. (Kolers & Smythe, 1979, p. 181)

A number of authors have pointed to a distinction between visual and spatial mental imagery (e.g., Baddeley, 1976). It has been shown, for example, that the behavior of congenitally blind subjects in standard imagery experiments implies the use of spatially analog, but not visual, mental imagery (e.g., Carpenter & Eisenberg, 1978; Kerr, 1983; Marmor & Zabeck, 1976). Farah, Hammond, Levine, and Calvanio

(1988) support the distinction by demonstrating dissociations among a variety of imagery tasks for a subject with brain damage. The existence of purely spatial imagery may be related to the claim that mental imagery can take place as a type of action.

A recent development in the study of mental imagery is demonstration that the typical person is better able to imagine events when imagination can exploit familiar motor patterns (see Loomis, Da Silva, Fujita, & Fukusima, 1992; Parsons, 1987; Rieser, 1989, 1993). It may become possible to explain some of the intuitions about the motoric ''feel'' of mental imagery in terms of the special properties of imagery associated with practiced behavior.

## OUTLINE OF A MODERN ADAPTATIONIST VIEW OF MENTAL IMAGERY

In this section of the paper, I sketch a modern integration of the adaptationist framework for mental imagery. I concentrate on one theme within adaptationism, the idea that information that might have been depicted in mental imagery often is not. I begin by stating a few basic assumptions about mental imagery and its development. In general, these are borrowed from well-known discussions of thinking and skilled behavior (e.g., Anderson, 1983; Duncker, 1945; Fitts, 1964; Newell, 1990; Simon, 1981; Woodworth, 1938). I then suggest a set of categories of unimaged information related to the use of mental imagery.

### *The Reason for Images*

Thinking is purposive. Each conscious representation in thinking is an attempt to generate useful information in movement through a problem space. Production of a new representation is controlled both by the current representation of the state of the world (in perception and/or thinking) and by a hierarchical set of goals (Newell, 1990; Simon, 1981). A goal at one level may be to give someone directions to a building, a more local goal may be to remember walking a particular route to the building, and a memory of what comes after the blue skyscraper may be generated to facilitate reaching the goals (e.g., Anderson, 1983). Higher goals have longer time spans and correspond to a greater variety of individual experiences than do lower goals (Newell, 1990).

The operations that produce representations are organized in such a way that they accomplish qualitatively distinct logical, mathematical, spatial, and other cognitive functions (e.g., generating exemplars of categories, counting, moving through an imagined environment). In many cases, operations may satisfy heuristics (Kahneman, Slovic, & Tversky, 1982; Newell & Simon, 1972). And when goals are superordinate, perhaps to the degree that they are best described as interests or predispositions, then the operations may be associative.

The representations used in thinking depend on an individual's abilities to generate sequences of representations that lead to goals. These abilities, in turn, depend on the individual's experience with things and tasks in a given domain (e.g., Pani, Jeffres, Shippey, & Schwartz, in press a). For example, the counting windows task forces visual/spatial imagery because of the limitations that most people have on the representations and operations that can provide the number of windows. If a person could generate a set of words that referred to the set of windows, the words would be

adequate as input to the operations of counting. But the necessary information has been encoded only in terms of relatively concrete perceptual experiences.

Assuming that an individual has a goal, that a path to it has been found, and that the same or a similar problem arises again, there is pressure toward greater efficiency of representation (e.g., Anderson, 1983; Carlson & Lundy, 1992; Newell, 1990). This pressure comes from two sources. First, there are limits on the capacity of attention and working memory coupled with an effort to focus on what may be useful information (Kosslyn, 1980). People invest little time and attention in what can be assumed or appears to be irrelevant. Second, there is learning. There is a tendency not to produce representation that previously was not useful (i.e., there is a benign form of forgetting), and there is greater fluency in the repetition of what was useful. This learning is part of the larger domain of skill learning, and is a type of implicit memory, in which the efficiency of organized activity improves with repetition (see Graf & Masson, 1993). The two sources of efficiency interact in a cyclic fashion. The operation of selective attention in the present influences generation of representations in the future, which then provides a new basis for the efficient operation of selective attention (e.g., Kotovsky, Hayes, & Simon, 1985).

The pressure toward efficiency is sufficiently important that there is an emotional state, boredom, that responds to uninformative events. In contrast, Piaget has suggested that the tendency to seek out moderate novelty is a driving force in cognitive development (Ginsburg & Opper, 1969). Such novelty evokes the feeling of ''interest'' that is the opposite pole to boredom (Simon, 1981; Lenat, 1977).

### *Components of Perception and Mental Imagery*

The capacity for mental imagery is the ability to ''relive'' perceptual experience (Brooks, 1968; Finke, 1989). To begin with, mental images often are pictorial: They have internal structures the same as conceivable projections of the optic array to the eye. However, there is much more in visual perception than the visual field, and there is much more in mental imagery than the recording of pictorial structure. Explanation of the generation of mental images rests on a description of all of the components of imaging (see below).

Obviously there are fundamental differences between perception and imagery. Perception is constrained by the architecture of the sensory systems always to make available a great deal of ecological information. In perception, for example, a colorful object always is seen to have its color, even if little attention is paid to it. Mental imagery is not constrained in this way for properties of objects that are cognitively separable (e.g., Garner, 1974). If a person can separate shape from color, then it is possible for the image of the object to be colorless (see Joseph & Proffitt, 1994). In sum, description of the separable components of imaging helps to define the manner in which it may become selective and efficient. In the following, I list basic components of the act of imaging.

*Separable structures within things.* People consider the world to be structured hierarchically: Scenes include separate objects, and objects are formed from separate parts (Biederman, 1987, 1990; Biederman, Mezzanotte, & Rabinowitz, 1982; Brewer & Treyens, 1981; Kosslyn, 1980; Palmer, 1975a,b). In addition, people are

able to represent scenes and objects at global levels of structure (Biederman, 1987, 1990; Kosslyn, 1980; Marr & Nishihara, 1978; Navon, 1977; Palmer, 1975a); we can recognize a giraffe made from a few pipe cleaners (Marr & Nishihara, 1978) or a face made from pieces of fruit (because the global structure of the face is preserved; Palmer, 1975a).

In a similar way, visual memory and imagination are quite often dependent upon simple forms of spatial organization (Chambers & Reisberg, 1992; Hinton, 1979; Palmer, 1977; Pani, 1993, 1994; Proffitt & Gilden, 1989; S. K. Reed, 1974; Tversky, 1981). For example, people will remember North and South America as being perfectly aligned north and south when actually they are related diagonally (Tversky, 1981). (The shift in imagination amounts to more than 2000 miles; see also Piattelli-Palmarini, 1994.) Maps that show the actual configuration of the continents may have been seen thousands of times, but an efficient form of organization has overridden any tendency toward accurate encoding and reproduction (Tversky, 1981). As a second example, people understand rotational motion in terms of circular paths in parallel planes that are aligned along an axis. If an individual fails to organize a given rotation in this way, then it will be unimaginable, or, if it is seen to rotate, it will look to be an incoherent motion (Pani, 1993, 1994; Pani, William, & Shippey, in press b). In both of these examples, the essential encoding of the structure is in terms of simple geometric elements in simple relation to each other.

*Actions related to images.* Many aspects of action related to mental imagery have been observed over the years. First, there is the control of attention. The distribution of attention in time and space is different for a looming skyscraper than for an ant walking across a table. In many cases the control of attention may be the analog of eye and head postures and movements encoded in perception (Kosslyn, 1980, 1994; Neisser, 1976, 1978). There also is inhibition of motor activity in varying degrees. The more that a person concentrates on a thought, the more that other activities must be suspended (Kahneman, 1973). Given that representations succeed each other, and individual representations may have beginnings, middles, and ends, thinking has an abstract shape and rhythm.

*Recognition.* Recognition adds categorization and identification to visual structure (Biederman, 1987; Hummel & Biederman, 1992; Farah, 1990; Neisser, 1994). Recognition does not generally require a particular view of an object (e.g., Biederman & Gerhardstein, 1993). It succeeds with a variety of views, with visual structure that has been reduced to context-free schematic contours, and with objects that are partially occluded or otherwise incomplete (Biederman, 1987, 1990; Hummel & Biederman, 1992). Considering mental images in the context of theories of object recognition gets at the core of what has been meant over the years by the claim that all images are symbolic. The question arises: What variety of mental images can contribute to the ''recognition'' of the thing that is imaged?

It is important not to confuse recognition with the use of processes of recognition in mental imagery. I will use the term ''interpretation'' (see Pylyshyn, 1973) to mean the application of processes of recognition to the use of a mental image.

*Propositions.* People often make judgments or decisions that relate a current representation to the ongoing task. These can be expressed in sentences and are well described as conscious propositions (see Pylyshyn, 1973). Quite often these proposi-

tions point to the operation that will follow the representation. In navigating city streets, a person may look up at a building, recognize it as a landmark, and add, ''Now I turn right.'' Generally, the task of navigating through a problem space will result in such propositions (e.g., ''This is the best one.'' ''Not this again.'' ''Almost done.''). Explanation of the consciousness of propositions is even more unsettled than explanation of the consciousness of mental images; the debate over imageless thoughts never was decided. It is clear, however, that although propositions may at times depend on mental images, the propositions are not the same as the images (e.g., one image may have many propositions; see Pylyshyn, 1973).

### *Efficient Mental Imagery*

*Elimination of images.* One effect of experience in the use of imagery is the complete disappearance of images from thinking about certain things. An elementary example of this is the elimination of imagery that was necessary only during initial exploration of a problem (e.g., deciding among alternative routes in an unfamiliar city). Much material suddenly becomes irrelevant after a course of action has been decided (Anderson, 1990; Kotovsky et al., 1985).

More generally, it is common in thinking that the particular means employed to reach a goal are unimportant after the goal has been reached. In later thought within the domain, the goal is remembered, and the representations that formed the means are not repeated. If an individual did count the windows in his or her dwelling (perhaps in order to purchase new window shades), it probably would be done just once. If the need for the number were to recur, the number would be recalled directly (see Anderson, 1983; Carlson & Lundy, 1992; Kosslyn, 1980; Tarr & Pinker, 1989).

Recall of the conclusion of a thought process may not always be immediate. The number of windows that were counted may not be remembered right away. Reinstantiating the cognitive context in which the goal was reached would facilitate recall of it (Roediger & Srinivas, 1993; Tulving & Thomson, 1973). For example, recall of the last window would be an effective retrieval cue. Of course the individual is not counting the windows again, but remembering that the windows had been counted. Any mental images that were generated would be based on the earlier counting, but the function of the images would be different (they are now mnemonic), the information required from the images would be different (they now must cue the number), and the images would be different (certainly fewer).

*Redundant information.* If imagery may be selective, then there is a question of how redundant sources of information can substitute for each other. For example, it is known that scene information encoded early disambiguates global object information encoded later (Palmer, 1975b; see also Biederman et al., 1982). Disambiguation by context is important in the consideration of goal-directed cognition, where goals may set the context of objects that are considered later (Fitts, 1964; Gibson, 1941). In general, as learning and context make individual representations more predictable, less attention and internal detail are needed for those representations. A basic demonstration of this type of tradeoff was provided by Miller, Heise, and Lichten (1951). They showed that even if considerable noise was added to a speech signal, more predictable messages would continue to be recognized. Generation of more efficient

mental images is analogous to the reduction of power in a perceptual signal. And so long as correct interpretation of the images continues, so will the increase in the efficiency of imagery.

A basic source of redundant information exists in the cooperation between perception and mental imagery. Information provided in perception need not be repeated in imagery (Hayes, 1973). Relatively few theorists have taken seriously the importance of the structure of the environment, and ongoing perceptual processing, to the nature of representation in thinking (Hayes, 1973; Kotovsky et al., 1985; Newell & Simon, 1972; Simon, 1981), but if we are to explain the natural occurrence of mental images, it will be important to have theories of this interaction. For example, when an individual repairs or reassembles a device, there is much information given in perception, including a highly organized set of retrieval cues.

Although there has been relatively little consideration of the cooperation of perception and mental imagery, there are experimental results that point to rich possibilities. Many cognitive phenomena discussed in terms of mental imagery appear to be primarily concerned with the goal directed operation of perceptual organization (e.g., Freyd & Finke, 1984; Pani & Dupree, 1994; Pani et al., in press a; Podgorny & Shepard, 1978).

*Schematic imagery.* Selective visual images at a global level of structure (*schematic* images) often can provide the information needed from images. Representations in which schematic imagery would be common include the following.

A glance at an object generally is sufficient for recognition, and the generation of an image of the object can exploit this (Biederman, 1987, 1990; Hummel & Biederman, 1992; Kosslyn, 1980, 1994). As noted above, object level representation can be useful in the consideration of categories (Jolicoeur et al., 1984; Rosch et al., 1976).

Concepts that initially were learned and applied in an item by item fashion are later organized at a higher level and used rapidly (Book, 1910; Bryan & Harter, 1897, 1899; Chase & Simon, 1973a,b). That is, there is chunking of representation (Anderson, 1983; Miller, 1956; Newell, 1990). A glance at a chess board can tell an expert chess player what the current situation is (Chase & Simon, 1973a,b), and a schematic image is sufficient for representation of the situation in thinking.

The dependence of spatial understanding on simple forms of organization also would promote schematic imagery (Pani, 1993, 1994; Proffitt & Gilden, 1989; Tversky, 1981). Two blobs connected along a vertical line appear to adequately represent what most people know about the geography of the Americas.

Schematic images are useful when there is a need to synthesize a variety of relationships into a unitary organization (Cheng & Simon, 1995; Huttenlocher, 1968; Johnson-Laird, 1983; Koedinger & Anderson, 1990; Larkin & Simon, 1987). Mental imagery in the three term series problems was offered as an example (e.g., Huttenlocher, 1968). Depiction at such an abstract level of analysis can be applied in a wide variety of problems. As a consequence, spatial imagery can be used to organize information in problems that are not intrinsically spatial (e.g., Johnson-Laird, 1983).

It is important to note that many questions that lead to schematic imagery are initially framed in abstract terms. It is not a matter of taking concrete problems and using efficient imagery to solve them. In the three term series problems (e.g., Huttenlocher, 1968), it soon becomes obvious that the problems are not actually about three

people or even about the relations ''taller'' and ''shorter.'' The individual is simply solving puzzles that involve ordinal relations. Although the *diagrammatic* imagery is abstract, it nevertheless provides accurate depictions of concrete examples of the concepts under consideration. As noted above, the work on diagrammatic imagery is consistent with current work in cognitive linguistics (e.g., Johnson, 1987; Lakoff & Johnson, 1980; Langacker, 1988; Talmy, 1988).

*Amodal imagery.* With sufficient perceptual experience, the interpretation of an image may take place without the image (see Baars, 1988). The image has become a redundant intermediary. Some of the attentional and motor action associated with the image may continue, and this is where people observe thinking to take place purely as ''conscious attitudes'' (Titchener, 1909) or perceptual anticipations (Neisser, 1978). I will refer to such representations as *amodal* imagery. Consider, for example, that if an individual attempts to imagine a cube to hang by one corner from a string, much depictive (but schematic) imagery will be required (Hinton, 1979; Pani, Zhou, & Friend, in press). People typically have not consolidated recognition of cubes in that orientation. In contrast, simply to represent ''cube'' in a default orientation will quite often require no such imagery. People ''just know'' they are thinking of a cube.

If an amodal image occurs in the context of an ongoing task, then appropriate propositions also can be generated amodally. For instance, if a person is thinking about following a route that has become familiar, a landmark along the way can be anticipated, the sense of recognition of the landmark can be amodal, and the proposition, ''Here I turn right'' can respond appropriately. Note that amodal imagery may occur simply because a concept is considered over an extended period of time or is repeated in thinking. Much as priming preserves activation specific to a perception (e.g., Jacoby & Dallas, 1981), the benefit of an image remains for a time without the image being explicitly maintained. In these instances of highly contextualized representation, amodal imagery is similar to the use of pronouns in language. The pronoun ''it'' can provide the same information as the phrase ''The Eiffel Tower on a sunny day in March'' in the appropriate context.

*Knowledge and imagery.* Representation of concrete properties of the world becomes embedded within an extended knowledge system, a system recognized to be analytical, hierarchical, categorical, taxonomic, and associative. This embedding permits highly selective depictive imagery. If someone decides to answer the question, ''What shape are a German Shepherd's ears?'', there may be generated a schematic image of the head of the animal, with detail at the ears (Kosslyn, 1980). This is possible, as Kosslyn suggests, because there is conceptual information that disambiguates the images and in general supports the reasoning.

I have purposely simplified the discussion of mental imagery by leaving aside the many issues relating to linguistic representation. However, the interaction of depictive imagery with knowledge clearly points to the importance of a combined use of linguistic representation (including inner speech) and depictive imagery in thinking. For example, many problems that lead to diagrammatic imagery are initially given verbally (e.g., Huttenlocher, 1968; Johnson-Laird, 1983). Without the context provided by these initial statements, the images would be meaningless (and, indeed, would never be generated).

As people master a domain, they develop a taxonomic system of concepts with which to solve problems (Chi et al., 1981). In engineering, a concrete problem about rolling wheels may be transformed into a generic problem about moments of inertia (Proffitt & Gilden, 1989; Proffitt, Kaiser, & Whelan, 1990). On average, depictive imagery will be less prevalent; such superordinate concepts as ''center of gravity'' and ''vehicle'' can be used to make inferences where concrete examples would be quite unnecessary.

There are knowledge domains that are sufficiently complex or variable that no matter how much expertise has been acquired, there remains uncertainty in thinking within the domain. Where those domains incorporate spatiotemporal relationships, depictive mental imagery may never disappear entirely (Koedinger & Anderson, 1990; Shepard, 1978). Chess is an example of an intrinsically spatial domain, and much excellent work has provided information about the representations employed by expert chess players (Binet, 1893/1966; Chase & Simon, 1973a,b; de Groot, 1965). Other spatial domains include the natural sciences (e.g., physics, chemistry, geology, and biology), certain branches of mathematics, navigation (e.g., Lynch, 1960), engineering, architecture, and the visual arts.

On the other hand, there is no reason to believe that any single depiction is a consistently necessary component of conscious mental representation. With the contextual information provided from following the course of a chess game, expert players often move with no conscious representation beyond recognition of the opponent's move. And if a player considers a move before making it, or entertains alternative courses of action, a vanishingly abstract spatial image can facilitate representation of a move. As Binet (1894/1966) pointed out, concrete properties of the game tend to be predictable and need not be imaged. They certainly do not need to be imaged if the player is looking at the board. And again, the player knows at what point the game rests. If in this context it is the queen's bishop that could slash diagonally across the board to a familiar position, a diagonal shift of attention across a virtual space provides an unambiguous representation of the move.

The use of such selective and contextualized representation is a further instance in which there is a close relationship between the function of an image and its structure. The largely amodal, partly gestural, image is not used to facilitate discrimination of the player's pieces from those of the opponent, nor the bishop from other pieces, nor even the particular diagonal over which the bishop moves. That is, very little information is needed for interpretation of the image. The representation is primarily for supporting the formation of propositions. It facilitates asking the question, ''What if I threatened with the bishop?'' or reaching the decision, ''I'll threaten with the bishop.''

## SUMMARY AND CONCLUSION

Mental images are a compelling aspect of conscious experience, and yet they often seem unpredictable. Visual images are depictive, and yet most of what we think about cannot be depicted. And a camera that produced pictures like most visual images would be considered defective. These have been empirical challenges for theories of mental imagery from the beginning of psychological research on the problem. There

is a constellation of theoretical responses to these problems that stem from thinking of mental imagery not just as analog representation, but as a source of information for an active, adaptive, efficient cognitive system.

The initial source of the structure of images is perceptual experience. This gives imagery at least a degree of isomorphism to sensory experience with objects and determines that images will be relevant to most any exercise of cognition. The more that progress in thinking requires the use of representations that were encoded in perceptual experience, the more obviously will imagery incorporate analog representation. As thinking in particular domains becomes analytical, categorical, and more efficiently associative, isomorphism with sensory experience may become tenuous indeed. In many cases, spatial imagery may appear to be no more than an anticipation of virtual objects.

People are not generally aware of the ''low quality'' of depiction in mental images because people are not attempting to depict. They are thinking about objects in an effort to generate potentially useful information; as part of this process, images help in the reference to things. If the reference is effective, and the thinking goes forward, the image was appropriate, no matter how it ''looked.'' Thus, the deviation of images from high-fidelity depiction is closely analogous to the amodal perception of occluded parts of objects. The incidence and the structure of images are appropriate for the environment in which they occur: Images are felt to depend upon the abilities, interests, and needs of the thinking person. That which is not depicted accurately is ''missing'' in the same way that occluded parts of an object happen not to be visible at the moment. The invisibility is attributed to the occlusion and not to the structure of the object. The missing information in imagery is attributed to the lack of a need for it (or to weaknesses of memory).

Development of a more complete adaptationist theory of mental imagery will depend upon further integration of theories of the capacities for mental imagery with theories of behavior, reasoning, and problem solving. For example, what are the ways in which representations based on perceptual experience are given meaning in thinking? A few instances were offered above. A person can image a set of things in order to count them, can image a prototype to consider a category, a context to jog a memory, or a diagram to reason about ordinal relations. But these are isolated demonstrations rather than a general theory of representation and meaning. Of course, such a general theory will depend on a better understanding of how perceptual experiences themselves include meaning (e.g., Freyd, 1987; Gibson, 1979; Proffitt & Bhalla, 1992). What makes an object an obstacle, a tool, or a shelter?

There also must be more complete description of variation in the need for information in thinking. Newell (1990), Laird, Newell, and Rosenbloom (1987), Anderson (e.g., 1983, 1987, 1990, 1993), and Kosslyn (1980) have the most inclusive theories to date. Ultimately, there must be description of a wide variety of influences on mental imagery. These include degrees of perceptual experience (with regard both to the *ability* to generate images and the *need* to generate them), types and amounts of concurrent perceptual information, the nature of behavioral response (e.g., verbal or spatiomotor), levels of conceptual expertise, domains of knowledge, and the information demands of individual tasks. It is striking how much closer we are to such an integrated theory than we were just decades ago.

## ACKNOWLEDGMENTS

I am indebted to William Brewer for much help in the conceptualization and completion of this project. I am grateful also to Bernard Baars, for suggesting important improvements in the paper, and to Carolyn Mervis for much help with earlier drafts. Parts of this paper are based on a master's thesis submitted to the University of Illinois, Urbana-Champaign, in 1984. I thank William Brewer and Jack Adams for their help with the thesis.

## REFERENCES

Anderson, J. R. (1978). Arguments concerning representations for mental imagery. *Psychological Review,* **85,** 249–277.

Anderson, J. R. (1983). *The architecture of cognition.* Cambridge, MA: Harvard Univ. Press.

Anderson, J. R. (1987). Skill acquisition: Compilation of weak-method problem solutions. *Psychological Review,* **94,** 192–210.

Anderson, J. R. (1990). *The adaptive character of thought.* Hillsdale, NJ: Erlbaum.

Anderson, J. R. (1993). *Rules of the mind.* Hillsdale, NJ: Erlbaum.

Anderson, J. R., & Bower, G. H. (1973). *Human associative memory.* Washington, DC: Winston.

Angell, J. R. (1897). Thought and imagery. *Philosophical Review,* **6,** 646–651.

Angell, J. R. (1906). Studies in psychology (a review). *Journal of Philosophy, Psychology, and Scientific Methods,* **3,** 637–643.

Angell, J. R. (1907). The province of functional psychology. *Psychological Review,* **14,** 61–91.

Angell, J. R. (1908). *Psychology* (4th ed.). New York: Holt.

Angell, J. R. (1910). Methods for the determination of mental imagery. *Psychological Review Monograph Supplements,* **13** (1, whole No. 53).

Angell, J. R. (1911a). Imageless thought. *Psychological Review,* **18,** 295–303.

Angell, J. R. (1911b). A review of E. B. Titchener's *A textbook of psychology.* New York: Macmillan, 1910, Part II. *Philosophical Review,* **20,** 545–551.

Angell, J. R., & Moore, A. W. (1896). Reaction time: A study in attention and habit. *Psychological Review,* **3,** 245–258.

Arnheim, R. (1969). *Visual thinking.* Berkeley: Univ. of California Press.

Baars, B. J. (1988). *A cognitive theory of consciousness.* New York: Cambridge Univ. Press.

Baddeley, A. D. (1976). *The psychology of memory.* New York: Basic Books.

Baddeley, A. (1990). *Human memory: Theory and practice.* Boston: Allyn & Bacon.

Barratt, P. E. (1953). Imagery and thinking. *Australian Journal of Psychology,* **5,** 154–164.

Berk, L. E. (1994). Why children talk to themselves. *Scientific American,* November, 78–83.

Betts, G. H. (1909). *Teachers College, Columbia University, Contributions to Education: No. 26. The distribution and functions of mental imagery.* New York: Columbia Univ. Press.

Biederman, I. (1987). Recognition by components: A theory of human image understanding. *Psychological Review,* **94,** 115–147.

Biederman, I. (1990). Higher-level vision. In D. N. Osherson, S. M. Kosslyn, & J. M. Hollerbach (Eds.), *Visual cognition and action* (pp. 41–72). Cambridge, MA: MIT Press.

Biederman, I., & Gerhardstein, P. C. (1993). Recognizing depth-rotated objects: Evidence and conditions for three-dimensional viewpoint invariance. *Journal of Experimental Psychology: Human Perception and Performance,* **19,** 1162–1182.

Biederman, I., Mezzanotte, R. J., & Rabinowitz, J. C. (1982). Scene perception: Detecting and judging objects undergoing relational violations. *Cognitive Psychology,* **14,** 143–177.

Binet, A. (1966). Mnemonic virtuosity: A study of chess players (M. L. Simmel & S. B. Barron, Trans.). *Genetic Psychology Monographs,* **74,** 127–162. (Original work published 1893)

Binet, A. (1969). Imageless thought (F. K. Zetland & C. Ellis, Trans.). In R. H. Pollack & M. J. Brenner

(Eds.), *The experimental psychology of Alfred Binet* (pp. 207–221). New York: Springer. (Original work published 1903)

Book, W. F. (1910). On the genesis and development of conscious attitudes (*Bewusstseinslagen*). *Psychological Review,* **17,** 381–398.

Boring, E. G. (1950). *History of experimental psychology* (2nd ed.). New York: Appleton–Century–Crofts.

Boring, E. G., Langfeld, H. S., & Weld, H. P. (1935). *Psychology.* New York: Wiley.

Bower, G. H. (1972). Mental imagery and associative learning. In L. W. Gregg (Ed.), *Cognition in learning and memory* (pp. 51–88). New York: Wiley.

Bransford, J. D., & McCarrell, N. S. (1974). A sketch of a cognitive approach to comprehension: Some thoughts about understanding what it means to comprehend. In W. B. Weimar & D. S. Palermo (Eds.), *Cognition and the symbolic processes* (pp. 1–42). Potomac, MD: Erlbaum.

Brewer, W. F. (1974). The problem of meaning and the interrelations of the higher mental processes. In W. B. Weimar & D. S. Palermo (Eds.), *Cognition and the symbolic processes* (pp. 1–42). Potomac, MD: Erlbaum.

Brewer, W. F., & Pani, J. R. (1983). The structure of human memory. In G. H. Bower (Ed.), *The psychology of learning and motivation: Advances in research and theory* (Vol. 17). New York: Academic Press. Reprinted (1993) in P. E. Morris & M. A. Conway (Eds.), *The psychology of memory-International library of critical writings in psychology.* Gloucester, UK: Edward Elgar.

Brewer, W. F., & Treyens, J. C. (1981). Role of schemata in memory for places. *Cognitive Psychology,* **13,** 207–230.

Brooks, L. R. (1968). Spatial and verbal components of the act of recall. *Canadian Journal of Psychology,* **22,** 349–368.

Brown, R. (1958). *Words and things.* New York: Macmillan Co.

Bryan, W. L., & Harter, N. (1897). Studies in the physiology and psychology of telegraphic language. *Psychological Review,* **4,** 27–53.

Bryan, W. L., & Harter, N. (1899). Studies on the telegraphic language. *Psychological Review,* **6,** 345–375.

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

Calkins, M. W. (1909). The abandonment of sensationalism in psychology. *American Journal of Psychology,* **20,** 269–277.

Carlson, R. A., & Lundy, D. H. (1992). Consistency and restructuring in learning cognitive procedural sequences. *Journal of Experimental Psychology: Learning, Memory, and Cognition,* **18,** 127–141.

Carpenter, P. A., & Eisenberg, P. (1978). Mental rotation and the frame of reference in blind and sighted individuals. *Perception & Psychophysics,* **23,** 117–124.

Chambers, D., & Reisberg, D. (1992). What an image depicts depends on what an image means. *Cognitive Psychology,* **24,** 145–174.

Chase, W. G., & Clark, H. H. (1972). Mental operations in the comparison of sentences and pictures. In L. W. Gregg (Ed.), *Cognition in learning and memory* (pp. 205–232). New York: Wiley.

Chase, W. G., & Simon, H. A. (1973a). Perception in chess. *Cognitive Psychology,* **4,** 55–81.

Chase, W. G., & Simon, H. A. (1973b). The mind's eye in chess. In W. G. Chase (Ed.), *Visual information processing* (pp. 215–281). New York: Academic Press.

Cheng, P. C.-H., & Simon, H. (1995). Scientific discovery and creative reasoning with diagrams. In S. M. Smith, T. B. Ward, & R. A. Finke (Eds.), *The creative cognition approach* (pp. 205–228). Cambridge, MA: MIT Press.

Chi, M. T. H., Feltovich, P. J., & Glaser, R. (1981). Categorization and representation of physics problems by experts and novices. *Cognitive Science,* **5,** 121–152.

Chomsky, N. (1965). *Aspects of the theory of syntax.* Cambridge, MA: MIT Press.

Clark, H. (1916). Visual imagery and attention: An analytical study. *American Journal of Psychology,* **27,** 461–492.

Clarke, H. M. (1911). Conscious attitudes. *American Journal of Psychology,* **22,** 214–249.

Colvin, S. S. (1909). Methods of determining ideational types. *Psychological Bulletin,* **6,** 223–237.

Colvin, S. S. (1910). A marked case of mimetic ideation. *Psychological Review,* **17,** 260–268.

Comstock, C. (1921). On the relevancy of imagery to the processes of thought. *American Journal of Psychology,* **32,** 196–230.

Cooper, L. A., & Shepard, R. N. (1973). Chronometric studies of the rotation of mental images. In W. G. Chase (Ed.), *Visual information processing* (pp. 75–176). New York: Academic Press.

Corballis, M. C. (1988). Recognition of disoriented shapes. *Psychological Review,* **95,** 115–123.

Crosland, H. R. (1921). A qualitative analysis of the processing of forgetting. *Psychological Review Monograph Supplements,* **22** (1, whole No. 130).

De Groot, A. (1965). *Thought and choice in chess.* The Hague: Mouton.

Dennett, D. C. (1969). *Content and consciousness.* London: Routledge & Kegan Paul.

Dennett, D. C. (1978). Toward a cognitive theory of consciousness. In C. W. Wade (Ed.), *Perception and cognition: Issues in the foundations of psychology—Minnesota studies in the philosophy of science:* (Vol. 9, pp. 201–228). Minneapolis: Univ. of Minnesota Press.

Dewey, J. (1894). The theory of emotion: I. Emotional attitudes. *Psychological Review,* **1,** 553–569.

Dewey, J. (1895). The theory of emotion: II. The significance of emotions. *Psychological Review,* **2,** 13–32.

Dewey, J. (1896). The reflex arc concept in psychology. *Psychological Review,* **3,** 357–370.

Dewey, J. (1897). The psychology of effort. *Philosophical Review,* **6,** 43–56.

Dewey, J. (Ed.). (1903). *Studies in logical theory—The decennial publications:* (2nd Ser., Vol. 11). Chicago: Univ. of Chicago Press.

Dewey, J. (1910). *How we think.* Boston: Heath.

Dewey, J. (1916). *Essays in experimental logic.* Chicago: Univ. of Chicago Press.

Dewey, J. (1933). *How we think* (2nd ed.). Boston: Heath.

Downey, J. (1929). *The creative imagination.* London: Kegan Paul.

Duncker, K. (1945). On problem-solving (L. S. Lees, Trans.). *Psychological Monographs,* **58,** (5, whole No. 270). (Original work published 1935)

Ebbinghaus, H. (1913). *Memory* (H. A. Ruger & C. E. Bussenius, Trans.). New York: Teachers College, Columbia Univ. Press. (Original work published 1885).

Ericsson, K. A., & Simon, H. A. (1984). *Protocol analysis: Verbal reports as data.* Cambridge, MA: MIT Press.

Evans, R. B. (1981). Introduction: The historical context. In W. James, *The principles of psychology* (Vol. 1). Cambridge: Harvard Univ. Press.

Farah, M. J. (1988). Is visual imagery really visual? Overlooked evidence from neuropsychology. *Psychological Review,* **95,** 307–317.

Farah, M. J. (1990). *Visual agnosia.* Cambridge, MA: MIT.

Farah, M. J., Hammond, K. M., Levine, D. N., & Calvanio, R. (1988). Visual and spatial mental imagery: Dissociable systems of representation. *Cognitive Psychology,* **20,** 439–462.

Fernald, M. R. (1912). The diagnosis of mental imagery. *Psychological Review Monograph Supplements,* **14** (1, whole No. 58).

Finke, R. A. (1989). *Principles of mental imagery.* Cambridge, MA: MIT Press.

Finke, R. A. (1990). *Creative imagery: Discoveries and inventions in visualization.* Hillsdale, NJ: Erlbaum.

Fitts, P. M. (1964). Perceptual-motor skill learning. In A. W. Melton (Ed.), *Categories of human learning* (pp. 243–285). New York: Academic Press.

Fisher, S. C. (1916). The process of generalizing abstraction, and its product, the general concept. *Psychological Review Monograph Supplements,* **21** (2, whole No. 90).

Fodor, J. A. (1965). Review of *Language and thought. Modern Language Journal,* **49,** 384–386.

Fodor, J. A. (1975). *The language of thought.* New York: Crowell.

Fodor, J. A., Bever, T. G., & Garrett, M. F. (1974). *The psychology of language.* New York: McGraw–Hill.

Fox, C. (1914). The conditions which arouse mental images in thought. *British Journal of Psychology,* **6,** 420–431.

Freyd, J. J. (1987). Dynamic mental representations. *Psychological Review,* **94,** 427–438.

Freyd, J. J., & Finke, R. A. (1984). Facilitation of length discrimination using real and imagined context frames. *American Journal of Psychology,* **97,** 323–341.

Galton, F. (1883). *Inquiries into human faculty and its development.* London: Macmillan & Co.

Garner, W. R., Hake, H. W., & Eriksen, C. W. (1956). Operationism and the concept of perception. *Psychological Review,* **53,** 317–329.

Gibson, J. J. (1941). A critical review of the concept of set in contemporary experimental psychology. *Psychological Review,* **38,** 781–817.

Ginsburg, H., & Opper, S. (1969). Piaget's theory of intellectual development. Englewood Cliffs, NJ: Prentice–Hall.

Goodman, N. (1976). *Languages of art* (2nd ed.). Indianapolis: Hackett.

Goodman, N. (1982). On thoughts without words. *Cognition,* **12,** 211–217.

Gore, W. C. (1903). Image and idea in logic. In J. Dewey (Ed.), *Studies in logical theory—The decennial publications* (2nd Ser., Vol. 11, pp. 184–202). Chicago: Univ. of Chicago Press.

Graf, P., & Masson, M. E. J. (1993). *Implicit memory: New directions in cognition, development, and neuropsychology.* Hilldale, NJ: Erlbaum.

Griffitts, C. H. (1927). Individual differences in imagery. *Psychological Review Monograph Supplements,* **37** (3, whole No. 172).

Haber, R. N. (1966). The nature of the effect of set on perception. *Psychological Review,* **73,** 335–351.

Hampson, P. J., & Morris, P. E. (1983). *Imagery and consciousness.* New York: Academic Press.

Hayes, J. R. (1973). On the function of visual imagery in elementary mathematics. In W. G. Chase (Ed.), *Visual information processing* (pp. 177–214). New York: Academic Press.

Hayes, J. R., & Simon, H. A. (1977). Psychological differences among problem isomorphs. In N. J. Castellan, D. B. Pisoni, & G. R. Potts (Eds.), *Cognitive theory.* (Vol. 2, pp. 21–41). Hillsdale, NJ: Erlbaum.

Hebb, D. O. (1968). Concerning imagery. *Psychological Review,* **75,** 466–477.

Heidbreder, E. (1933). *Seven psychologies.* New York: Appleton–Century.

Hilgard, E. R. (1956). *Theories of learning* (2nd ed.). New York: Appleton–Century–Crofts.

Hilgard, E. R., & Bower, G. H. (1966). *Theories of learning* (3rd ed.). New York: Appleton–Century–Crofts.

Hinton, G. (1979). Some demonstrations of the effects of structural descriptions in mental imagery. *Cognitive Science,* **3,** 231–250.

Hintzman, D. L., O'Dell, C. S., & Arndt, D. R. (1981). Orientation in cognitive maps. *Cognitive Psychology,* **13,** 149–206.

Hochberg, J. (1986). Representation of motion and space in video and cinematic displays. In K. R. Boff, L. Kaufman, & J. P. Thomas (Eds.), *Handbook of perception and human performance. Vol. 1: Sensory processes and perception* (p. 22). New York: Wiley.

Hoernle, R. F. A. (1907). Image, idea and meaning. *Mind,* N. S., **16,** 70–100.

Hollingworth, H. L. (1911). Vicarious functioning of irrelevant imagery. *Journal of Philosophy, Psychology, and Scientific Methods,* **8,** 688–692.

Hollingworth, H. L. (1926). *The psychology of thought.* New York: Appleton.

Hollingworth, H. L. (1928). *Psychology: Its facts and principles.* New York: Appleton.

Horne, P. V. (1993). The nature of imagery. *Cognition and Consciousness,* **2,** 58–82.

Hummel, J. E., & Biederman, I. (1992). Dynamic binding in a neural network for shape recognition. *Psychological Review,* **99,** 480–517.

Humphrey, G. (1951). *Thinking: An introduction to its experimental psychology.* London: Methuen.

Huttenlocher, J. (1968). Constructing spatial images: A strategy in reasoning. *Psychological Review,* **75,** 550–560.

Huttenlocher, J. (1973). Language and thought. In G. A. Miller (Ed.), *Communication, language, and meaning* (pp. 172–184). New York: Basic Books.

Huxley, T. H. (1879). *Hume.* New York: Harper.

Jacoby, L. L., & Dallas, M. (1981). On the relationship between autobiographical memory and perceptual learning. *Journal of Experimental Psychology: General,* **3,** 306–340.

James, W. (1975). *The meaning of truth.* Cambridge: Harvard Univ. Press. (Original work published 1909).

James, W. (1975). *Pragmatism.* Cambridge: Harvard Univ. Press. (Original work published 1907)

James, W. (1976). *Essays in radical empiricism.* Cambridge: Harvard Univ. Press. (Original work published 1912)

James, W. (1981). *The principles of psychology* (2 Vols.). Cambridge: Harvard Univ. Press. (Original work published 1890).

Johnson, M. (1987). *The body in the mind.* Chicago: Univ. of Chicago Press.

Johnson-Laird, P. N. (1983). *Mental models: Towards a cognitive science of language, inference, and consciousness.* Cambridge, MA: Harvard Univ. Press.

Jolicoeur, P., Gluck, M. A., & Kosslyn, S. M. (1984). Pictures and names: Making the connection. *Cognitive Psychology,* **16,** 243–275.

Joseph, J. E., & Proffitt, D. R. (1994, November). *Perceptual and conceptual processing of color in object recognition.* Poster presented at the annual meeting of the Psychonomic Society, St. Louis, MO.

Judd, C. H. (1907). *Psychology.* New York: Scribner's.

Just, M. A., & Carpenter, P. A. (1976). Eye fixations and cognitive processes. *Cognitive Psychology,* **8,** 441–480.

Kahneman, D. (1973). *Attention and effort.* Englewood Cliffs, NJ: Prentice–Hall.

Kahneman, D., Slovic, P., & Tversky, A. (1982). *Judgment under uncertainty: Heuristics and biases.* New York: Cambridge Univ. Press.

Kaushall, P., & Parsons, L. M. (1981). Optical information and practice in the discrimination of 3-D mirror-reflected objects. *Perception,* **10,** 545–562.

Keller, F. S. (1973). *The definition of psychology* (2nd ed.). Englewood Cliffs, NJ: Prentice–Hall.

Kerr, N. H. (1983). The role of vision in ''visual imagery'' experiments: Evidence from the congenitally blind. *Journal of Experimental Psychology: General,* **112,** 265–277.

Koedinger, K. R., & Anderson, J. R. (1990). Abstract planning and perceptual chunks: Elements of expertise in geometry. *Cognitive Science,* **14,** 511–550.

Kohler, W. (1929). *Gestalt psychology.* New York: Liveright.

Kolers, P. A. (1983). Perception and representation. *Annual Review of Psychology,* **34,** 129–166.

Kolers, P. A., & Smythe, W. E. (1979). Images, symbols and skills. *Canadian Journal of Psychology,* **33,** 158–184.

Kosslyn, S. M. (1975). Information representation in visual images. *Cognitive Psychology,* **7,** 341–370.

Kosslyn, S. M. (1980). *Image and mind.* Cambridge: Harvard Univ. Press.

Kosslyn, S. M. (1981). The medium and the message in mental imagery: A theory. *Psychological Review,* **88,** 46–66.

Kosslyn, S. M. (1994). *Image and brain.* Cambridge, MA: MIT Press.

Kosslyn, S. M., & Jolicoeur, P. (1980). A theory-based approach to the study of individual differences in mental imagery. In R. E. Snow, P. A. Federico, & W. E. Montague (Eds.), *Aptitude, learning,*

*and instruction: Cognitive process analysis of learning and problem solving* (Vol. 2, pp. 139–176). Hillsdale, NJ: Erlbaum.

Kosslyn, S. M., Murphy, G. L., Bemesderfer, M. E., & Feinstein, K. J. (1977). Category and continuum in mental comparisons. *Journal of Experimental Psychology: General,* **106,** 341–375.

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

Kotovsky, K., Hayes, J. R., & Simon, H. A. (1985). Why are some problems hard? Evidence from Tower of Hanoi. *Cognitive Psychology,* **17,** 248–294.

Kuhlmann, F. (1906). On the analysis of the memory consciousness: A study in the mental imagery and memory of meaningless visual forms. *Psychological Review,* **13,** 316–348.

Kuhlmann, F. (1907). On the analysis of the memory consciousness for pictures of familiar objects. *American Journal of Psychology,* **18,** 389–420.

Kuhlmann, F. (1909). On the analysis of auditory memory consciousness. *American Journal of Psychology,* **20,** 194–218.

Ladd, G. T. (1894). *Psychology: Descriptive and explanatory.* New York: Scribner's.

Laird, J. E., Newell, A., & Rosenbloom, P. S. (1987). Soar: An architecture for general intelligence. *Artificial Intelligence,* **33,** 1–64.

Lakoff, G., & Johnson, M. (1980). *Metaphors we live by.* Chicago: Univ. of Chicago Press.

Langacker, R. W. (1988). Toward a coherent and comprehensive linguistic theory. In B. Rudzka-Ostyn (Ed.), *Topics in cognitive linguistics* (pp. 1–161). Philadelphia: Benjamins.

Langfeld, H. S. (1916). Concerning the image. *Psychological Review,* **23,** 180–189.

Larkin, J. H., & Simon, H. (1987). Why a diagram is (sometimes) worth ten thousand words. *Cognitive Science,* **11,** 65–99.

Lenat, D. B. (1977). Automated theory formation in mathematics. *Proceedings of the Fifth International Joint Conference on Artificial Intelligence,* pp. 833–842.

Loomis, J. M., Da Silva, J. A., Fujita, N., & Fukusima, S. S. (1992). Visual space perception and visually directed action. *Journal of Experimental Psychology: Human Perception and Performance,* **18,** 906–921.

Lorenz, C., & Neisser, U. (1985). Factors of imagery and event recall. *Memory & Cognition,* **13,** 494–500.

Lynch, K. (1960). *The image of the city.* Cambridge, MA: MIT Press.

MacDougall, R. (1911). The system of habits and the system of ideas. *Psychological Review,* **18,** 324–335.

MacLennen, S. F. (1902). The image and the idea. *Psychological Review,* **9,** 69–79.

Mandler, J. M., & Mandler, G. (1964). *Thinking: From association to gestalt.* New York: Wiley.

Mangan, B. (1993). Taking phenomenology seriously: The ''fringe'' and its implications for cognitive research. *Cognition and Consciousness,* **2,** 89–108.

Marmor, G. S., & Zabeck, L. A. (1976). Mental rotation by the blind: Does mental rotation depend on visual imagery? *Journal of Experimental Psychology: Human Perception and Performance,* **2,** 515–521.

Marr, D., & Nishihara, H. K. (1978). Representation and recognition of the spatial organization of three-dimensional shapes. *Proceedings of the Royal Society of London, Biological,* **200,** 269–294.

Mervis, C. B., & Rosch, E. (1981). Categorization of natural objects. *Annual Review of Psychology,* **32,** 89–115.

Miller, G. A. (1956). The magical number seven, plus or minus two: Some limits on our capacity for processing information. *Psychological Review,* **63,** 81–97.

Miller, G. A., Heise, G. A., & Lichten, W. (1951). The intelligibility of speech as a function of the context of the text materials. *Journal of Experimental Psychology,* **41,** 329–335.

Mowrer, O. H. (1960). *Learning theory and the symbolic processes.* New York: Wiley.

Navon, D. (1977). Forest before trees: The precedence of global features in visual perception. *Cognitive Psychology,* **9,** 353–383.

Neisser, U. (1967). *Cognitive psychology.* New York: Appleton–Century–Crofts.

Neisser, U. (1970). Visual imagery as process and as experience. In. J. S. Antrobus (Ed.), *Cognition and affect.* Boston: Little, Brown.

Neisser, U. (1976). *Cognition and reality: Principles and implications of cognitive psychology.* San Francisco: Freeman.

Neisser, U. (1978). Perceiving, anticipating, and imagining. In C. W. Wade (Ed.), *Perception and cognition: Issues in the foundations of psychology—Minnesota studies in the philosophy of science:* (Vol. 9, pp. 89–105). Minneapolis: Univ. of Minnesota Press.

Neisser, U. (Ed.). (1987). *Concepts and conceptual development: Ecological and intellectual factors in categorization.* New York: Cambridge Univ. Press.

Neisser, U. (1994). Multiple systems: A new approach to cognitive theory. *European Journal of Psychology,* **6,** 225–241.

Neisser, U., & Kerr, N. (1973). Spatial and mnemonic properties of visual images. *Cognitive Psychology,* **5,** 138–150.

Newell, A. (1990). *Unified theories of cognition.* Cambridge, MA: Harvard Univ. Press.

Newell, A., & Simon, H. A. (1972). *Human problem solving.* Englewood Cliffs, NJ: Prentice–Hall.

Ogden, R. M. (1911). Imageless thought: Resume and critique. *Psychological Bulletin,* **8,** 183–197.

Ogden, R. M. (1923). The phenomenon of meaning. *American Journal of Psychology,* **34,** 223–230.

Okabe, T. (1910). An experimental study of belief. *American Journal of Psychology,* **21,** 563–596.

Osgood, C. E. (1953). *Method and theory in experimental psychology.* New York: Oxford Univ. Press.

Paivio, A. (1969). Mental imagery in associative learning and memory. *Psychological Review,* **76,** 241–263.

Paivio, A. (1971). *Imagery and verbal processes.* New York: Holt, Rinehart & Winston.

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

Palmer, S. E. (1975b). The effects of contextual scenes on the identification of objects. *Memory & Cognition,* **3,** 519–526. Palmer, S. E. (1977).

Palmer, S. E. (1977). Hierarchical structure in perceptual representation. *Cognitive Psychology,* **3,** 441–474.

Palmer, S. E. (1978). Fundamental aspects of cognitive representation. In E. Rosch & B. B. Lloyd (Eds.), *Cognition and categorization* (pp. 259–303). Hillsdale, NJ: Erlbaum.

Pani, J. R. (1982, November). *A functionalist approach to mental imagery*. Paper presented at the annual meeting of the Psychonomic Society, Minneapolis, MN.

Pani, J. R. (1993). Limits on the comprehension of rotational motion: Mental imagery of rotations with oblique components. *Perception,* **22,** 785–808.

Pani, J. R. (1994). The generalized cone in human spatial organization. In C. W. Tyler (Ed.), Theoretical issues in symmetry perception [Special Issue]. *Spatial Vision,* **8,** 491–502.

Pani, J. R., & Depree, D. (1994). Spatial reference systems in the comprehension of rotational motion. *Perception,* **23,** 929–946.

Pani, J. R., Jeffres, J. A., Shippey, G., & Schwartz, K. (in press, a). Imagining projective transformations: Aligned orientations in spatial organization. *Cognitive Psychology.*

Pani, J. R., William, C. T., & Shippey, G. (in press, b). Determinants of the perception of rotational motion: Orientation of the motion to the object and to the environment. *Journal of Experimental Psychology: Human Perception and Performance.*

Pani, J. R., Zhou, H., & Friend, S. M. (in press). Perceiving and imagining Plato's Solids: The generalized cylinder in spatial organization of 3D structures. *Visual Cognition.*

Piattelli-Palmarini, M. (1994). *Inevitable illusions: How mistakes of reason rule our minds.* (M. Piattelli-Palmarini & K. Botsford, Trans.) New York: Wiley. (Original work published 1991)

Pinker, S. (1984). Visual cognition: An introduction. *Cognition,* **18,** 1–63.

Podgorny, P., & Shepard, R. N. (1978). Functional representations common to visual perception and imagination. *Journal of Experimental Psychology: Human Perception and Performance,* **4,** 21–35.

Proffitt, D. R., & Bhalla, M. (1992, November). *Perceiving the slope of natural terrains.* Paper presented at the annual meeting of the Psychonomic Society, St. Louis, MO.

Proffitt, D. R., & Gilden, D. L. (1989). Understanding natural dynamics. *Journal of Experimental Psychology: Human Perception and Performance,* **15,** 385–393.

Proffitt, D. R., Kaiser, M. K., & Whelan, S. M. (1990). Understanding wheel dynamics. *Cognitive Psychology,* **22,** 342–373.

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

Pylyshyn, Z. W. (1978). Imagery and artificial intelligence. In C. W. Wade (Ed.), *Perception and cognition: Issues in the foundations of psychology—Minnesota studies in the philosophy of science:* (Vol. 9, pp. 19–55). Minneapolis: Univ. of Minnesota Press.

Pylyshyn, Z. W. (1981). The imagery debate: Analogue media versus tacit knowledge. *Psychological Review,* **88,** 16–45.

Pylyshyn, Z. W. (1984). *Computation and cognition: Toward a foundation for cognitive science.* Cambridge, MA: MIT Press.

Rahn, C. (1913). The relation of sensation to other categories in contemporary psychology. *Psychological Review Monograph Supplements,* **16** (1, whole No. 67).

Reed, H. B. (1918a). Associative aids: II. Their relation to practice and the transfer of training. *Psychological Review,* **25,** 257–285.

Reed, H. B. (1918b). Associative aids: III: Their relation to the theory of thought and to methodology in psychology. *Psychological Review,* **25,** 378–401.

Reed, S. K. (1974). Structural descriptions and the limitations of visual images. *Memory and Cognition,* **2,** 329–336.

Rieser, J. J. (1989). Access to knowledge of spatial structure at novel points of observation. *Journal of Experimental Psychology: Learning, Memory, and Cognition,* **15,** 1157–1165.

Rieser, J. J. (1993, November). *Imagery and action: Knowing how objects look when they are moved by hand without vision.* Paper presented at the annual meeting of the Psychonomic Society, Washington, DC.

Richardson, A. (1969). *Mental imagery.* London: Routledge & Kegan Paul.

Roediger, H. L. III, & Srinivas, K. (1993). Specificity of operations in perceptual priming. In P. Graf & M. E. J. Masson (Eds.), *Implicit memory: New directions in cognition, development, and neuropsychology.* Hilldale, NJ: Erlbaum.

Rosch, E. (1978). Principles of categorization. In E. Rosch & B. B. Lloyd (Eds.), *Cognition and categorization* (pp. 27–48). Hillsdale, NJ: Erlbaum.

Rosch, E., Mervis, C. B., Gray, W., Johnson, D., & Boyes-Braem, P. (1976). Basic objects in natural categories. *Cognitive Psychology,* **8,** 382–439.

Rowe, E. C. (1910). Voluntary movement. *American Journal of Psychology,* **21,** 513–562.

Schiller, F. C. S. (1920). The meaning of meaning. *Mind,* N. S., **29,** 385–397.

Schwartz, B., & Reisberg, D. (1991). *Learning and memory.* New York: Norton.

Schwartz, R. (1981). Imagery—There's more to it than meets the eye. In N. Block (Ed.), *Imagery* (pp. 109–130). Cambridge, MA: MIT Press.

Shepard, R. N. (1966). Learning and recall as organization and search. *Journal of Verbal Learning and Verbal Behavior,* **5,** 201–204.

Shepard, R. N. (1975). Form, formation, and transformation of internal representations. In R. Solso

(Ed.), *Information processing and cognition: The Loyola Symposium* (pp. 87–122). Hillsdale, NJ: Erlbaum.

Shepard, R. N. (1978). The mental image. *American Psychologist,* **33,** 125–137.

Shepard, R. N. (1984). Ecological constraints on internal representation: Resonant kinematics of perceiving, imaging, thinking, and dreaming. *Psychological Review,* **91,** 417–447.

Shepard, R. N. (1994). Perceptual-cognitive universals as reflections of the world. *Psychonomic Bulletin and Review,* **1,** 2–28.

Shepard, R. N., & Feng, C. (1972). A chronometric study of mental paper folding. *Cognitive Psychology,* **3,** 228–243.

Shepard, R. N., & Metzler, J. (1971). Mental rotation of three-dimensional objects. *Science,* **171,** 701–703.

Siegler, R. S., & Shrager, J. (1984). Strategy choices in addition and subtraction: How do children know what to do? In C. Sophian (Ed.), *Origins of cognitive skills* (pp. 229–293). Hillsdale, NJ: Erlbaum.

Simon, H. A. (1981). *The sciences of the artificial.* Cambridge, MA: MIT Press.

Skinner, B. F. (1953). *Science and human behavior.* New York: Macmillan Co.

Slee, J. A. (1980). Individual differences in visual imagery ability and the retrieval of visual appearances. *Journal of Mental Imagery,* **4,** 93–113.

Smith, E. E., & Medin, D. L. (1981). *Categories and concepts.* Cambridge: Harvard Univ. Press.

Spencer, H. (1881). *The principles of psychology* (2 Vols., 3rd ed.). London: Williams and Norgate.

Staats, A. W. (1961). Verbal habit families, concepts, and the operant conditioning of word classes. *Psychological Review,* **68,** 190–204.

Stout, G. F. (1898). Reply to Professor Angell's criticism of Analytic psychology. *Philosophical Review,* **7,** 72–76.

Stout, C. F. (1902–1903). Mr. Bradley's theory of judgment. *Proceedings of the Aristotelian Society,* N. S., **3,** 1–28.

Takano, Y. (1989). Perception of rotated forms: A theory of information types. *Cognitive Psychology,* **21,** 1–59.

Talmy, L. (1988). The relation of grammar to cognition. In B. Rudzka-Ostyn (Ed.), *Topics in cognitive linguistics* (pp. 165–205). Philadelphia: Benjamins.

Tarr, M. J., & Pinker, S. (1989). Mental rotation and orientation dependence in shape recognition. *Cognitive Psychology,* **21,** 233–283.

Thorndike, E. L. (1907). The function of mental images. *Journal of Philosophy, Psychology, and Scientific Methods,* **4,** 324–327.

Titchener, E. B. (1898). The postulates of a structural psychology. *Philosophical Review,* **7,** 449–465.

Titchener, E. B. (1901). *Experimental psychology: A manual of laboratory practice* (Vol. 1, parts 1, 2). New York: Macmillan Co.

Titchener, E. B. (1909). *Lectures on the experimental psychology of the thought processes.* New York: Macmillan Co.

Titchener, E. B. (1911). *A text-book of psychology.* New York: Macmillan Co.

Titchener, E. B. (1912). Description vs. Statement of meaning. *American Journal of Psychology,* **23,** 165–182.

Titchener, E. B. (1915). *A beginner's psychology.* New York: Macmillan Co.

Titchener, E. B. (1929). *Systematic psychology: Prolegomena.* New York: Macmillan Co.

Tulving, E., & Thomson, D. M. (1973). Encoding specificity and retrieval processes in episodic memory. Psychological Review, **80,** 352–373.

Tversky, B. (1981). Distortions in memory for maps. *Cognitive Psychology,* **13,** 407–433.

Washburn, M. F. (1915). *Movement and mental imagery.* Boston: Houghton Mifflin.

Watson, J. B. (1913). Psychology as the behaviorist views it. *Psychological Review,* **20,** 158–177.

Watson, J. B. (1914). *Behavior: An Introduction to comparative psychology.* New York: Holt.

Watson, J. B. (1919). *Psychology from the standpoint of a behaviorist.* Philadelphia: Lippincott.

Watt, H. J. (1911). A review of E. B. Titchener's lectures on the experimental psychology of the thought processes. *Mind,* N. S., **20,** 108–112.

Werner, H., & Kaplan, B. (1963). *Symbol formation: An organismic-developmental approach to the psychology of language and the expression of thought.* New York: Wiley.

Winch, W. H. (1908). The function of images. *Journal of Philosophy, Psychology, and Scientific Methods,* **5,** 337–352.

Woodworth, R. S. (1906). Imageless thought. *Journal of Philosophy, Psychology, and Scientific Methods,* **3,** 701–708.

Woodworth, R. S. (1915). A revision of imageless thought. *Psychological Review,* **22,** 1–27.

Woodworth, R. S. (1938). *Experimental psychology.* New York: Holt.

Received October 31, 1994