searcher who assumes this representation may focus on the rules people tend to have, the factors that promote the acquisition of new rules, and the factors that control whether people recognize that a particular rule is relevant in a given context.

According to an alternative account of logical reasoning ability, however, people do not have logical rules that apply across domains. After all, logical rules do not care about the content of the statements P and Q. As long as a situation has the right form, the logical rules apply. According to one such account, people have a *mental model* of a situation about which they are going to reason (see chap. 9). Mental models are not general schemas of inference but instantiations of particular situations. This account suggests that problems framed in an abstract way (like the Wason selection task) are difficult, because it is difficult to construct models for abstract situations. Thus, a problem with the same structure (an isomorphic problem) may be easier to solve if it is in a domain for which it is easy to construct a model.

This view of representation suggests that the selection task should be tried with different problem contents. As an example, imagine you are working for the security patrol of a college on a Saturday night, and it is your job to make sure that campus bars serve alcohol only to people of the legal drinking age (21 years old in the United States). You enter a bar and see one person you know to be 18 years old, a second you know to be 22 years old, a third person, whom you do not know, holding a beer, and a fourth, unknown to you, drinking club soda. Which people must you check to ensure that the bar is satisfying the rule "If a person has a drink, then he or she is over 21"? College undergraduates given versions of the selection task in familiar domains like this performed quite well. Nearly all knew that only the 18-year-old and the person drinking beer need to be checked. This problem is isomorphic to the task with the cards, but people have much less difficulty with the concrete version (see Johnson-Laird, Legrenzi, & Legrenzi, 1972).

Mental models are not exactly the same as logical rules. Although mental models can be described as having rules, the scope of these rules differs from that of logic. With a particular logical rule, anything with the proper form can be reasoned about. In contrast, the procedures for constructing mental models are domain specific. A person may have rules for reasoning about drinking in bars without having rules for reasoning about genetics or abstract logical forms. For those who have adopted a framework based on logical rules, the content effects discovered in the selection task are difficult to explain. Rips (1994) argued that content effects in this task may reflect people's remembering what happened in their own personal experience and that this personal experience augments but does not replace logical rules. For example, when given the selection task in the context of verifying the rule about the legal age for drinking, people may just recall a situation in which they were in a bar and remember who was asked for identification. In this case, no rules were used at all; the answer to the problem was just remembered. Assuming that reasoning uses logical rules of inference makes it easy to explain logical reasoning abilities at the expense of making content effects more difficult to explain.

People's performance on a psychological task may often be explained in many ways, each of which has a different approach to mental representation. Each way may provide a good account of the phenomenon being studied, but the approaches may differ in their predictions for subsequent studies that should be designed and carried out. Indeed, as I discuss next, adopting particular representational assumptions affects which new questions are most interesting to answer.

WHAT IS A REPRESENTATION?

Mental representation is a critical part of psychological explanation, but it has also been a source of great confusion. Different researchers have used the word *representation* in different ways. Psychologists have used representation in somewhat different ways from other cognitive scientists, such as philosophers and computer scientists, who are interested in representation. To avoid confusion, I offer a broad definition of representation, one that includes all things that cognitive scientists have considered representations, although it may admit some things that people may feel uncomfortable calling representations, or at least uncomfortable thinking of as psychological representations. My definition of representation has four components. The first two components of representation are:

1. **A represented world:** the domain that the representations are about. The represented world may be the world outside the cognitive system or some other set of representations inside the system. That is, one set of representations can be about another set of representations.

2. **A representing world:** the domain that contains the representations. (The terms *represented world* and *representing world* come from a classic paper by Palmer [1978a].)

As an example, consider various representations of the items pictured in the top row of Figure 1.2. These items are the represented world for this example. In this world, there are three objects of interest, an ice cube, a glass of water, and a pot of water on a fire. I can choose to represent many aspects of this world, but for now, I focus on the temperature of the water. This representational decision has consequences. If I represent only

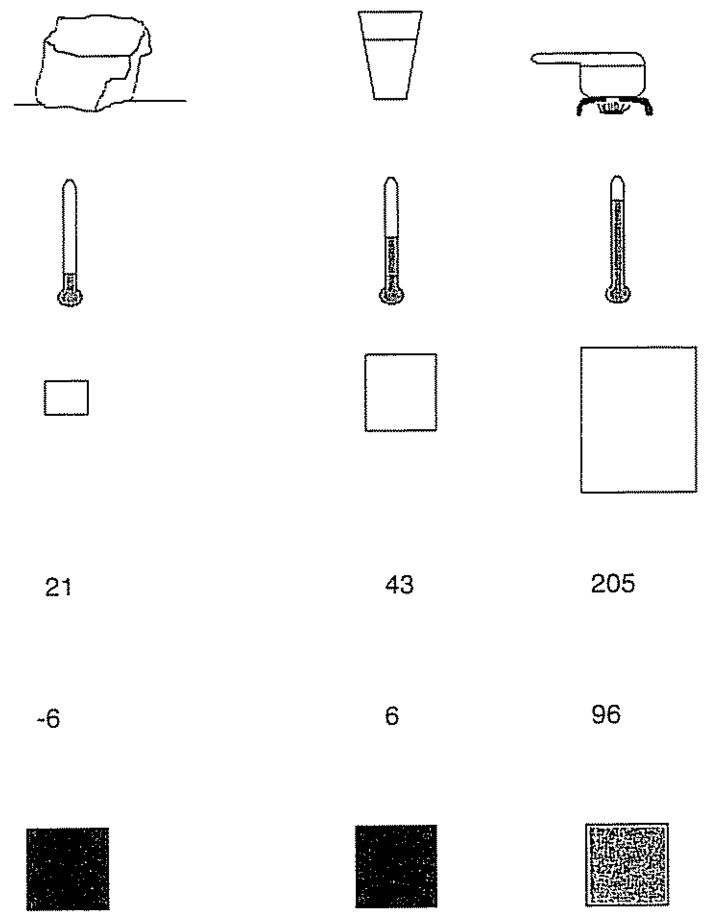


FIG. 1.2. Various ways of representing temperature. The top row depicts water that is frozen, at room temperature, and boiling. The next two rows depict possible analog representations. The two following rows show numerical temperature notations. Finally, the last row depicts temperature with the darkness of the square.

the temperature of the water, all the rest of the information about the situation is lost, including the shape of the ice cube, the size of the glass of water, and the degree of curvature of the handle of the pot. This point is not trivial: In all known representational systems, the representing world loses information about the represented world.

In modern culture, the representation of temperature, as in the second row of Figure 1.2, often appears as the height of mercury in a thermometer.

That is, I can use the height of mercury as a representing world, in which the higher the line of mercury, the greater the temperature. In this representation, however, a few important issues lie buried. First, the height of mercury in a thermometer works as a representation of temperature, because there is a set of rules that determine how the representing world corresponds to the represented world. Thus, the third component of my definition of representation is:

3. **Representing rules:** The representing world is related to the represented world through a set of rules that map elements of the represented world to elements in the representing world. If every element in the represented world is represented by a unique element in the representing world, there is an *isomorphism* between the represented and representing worlds. If two or more elements in the represented world are represented by one element in the representing world, there is a *homomorphism* between the represented and the representing worlds.[1]

As an illustration of this component of the definition, when temperature is represented as the height of mercury in a thermometer, each temperature is reflected by a unique height of mercury. The specific height that the mercury reaches is determined by the circumference of the thermometer as well as by the physical laws that govern the expansion of mercury with changes in temperature. Because each temperature has its own unique height, there is an isomorphism between the temperature in the represented world and the height of mercury in the representing world, but not all representations of temperature need to be isomorphisms. If a digital thermometer that gave readings on the Fahrenheit temperature scale (as in the second row of Figure 1.2) gave readings accurate to only 1 degree, any temperature between, say, 20.5 degrees and 21.4 degrees would be represented as 21 degrees. In this case, the relation between the represented and representing worlds is a homomorphism. When there is a homomorphism between the representing and represented worlds, the representation has lost information about what it is representing.

Another issue that arises with this example is that nothing inherent in a mercury thermometer alone makes it a representation. Since the dawn of time (or soon thereafter), mercury has had the property of expanding and contracting with changes in temperature, but mercury was not always a representation of temperature. For something to be a representation,

[1]There is much debate in philosophy about how physical systems (like minds) have the power to represent things in the external world, but in this book, I am not concerned with solving this problem. Instead, I assume that cognitive systems have the capacity for representation, and I focus on proposals in cognitive science for the nature of these representations.

some process must use the representation for some purpose. In this culture, having been schooled in the use of a thermometer, people can use the column of mercury as a representation of temperature. A vervet monkey who lacks the mathematical skills and cultural upbringing (among other things) to read a thermometer cannot use the column of mercury as a representation of temperature. More broadly, something is a representation only if a process can be used to interpret that representation. In this case, the combination of the thermometer and the person who can read it makes the thermometer a representation. More generally, the fourth component of a representation is:

4. **A process that uses the representation:** It makes no sense to talk about representations in the absence of processes. The combination of the first three components (a represented world, a representing world, and a set of representing rules) creates merely the potential for representation. Only when there is also a process that uses the representation does the system actually represent, and the capabilities of a system are defined only when there is both a representation and a process.

The importance of processes when thinking about representations cannot be underestimated (J. R. Anderson, 1978; Palmer, 1978a). In the temperature example, there is no representation until someone can use the thermometer to read off the temperature. In general, it may seem obvious that certain cognitive processes can be explained by a representation, but in many instances two very different kinds of representations can make exactly the same predictions when the right set of processes acts over them.

To demonstrate how the four components of representation interact to create a representation, we return to the temperature example. The rectangles in the third row of Figure 1.2 can also be representations of temperature. For example, the area of each rectangle could be used as a representation of a particular temperature. In this case, comparing two temperatures may involve laying one rectangle on top of another to see which is larger: A larger rectangle corresponds to a higher temperature. Of course, a different set of representing rules and processes completely changes the interpretation of this representation: If the heights of the rectangles are used to represent temperature, pairs of temperatures can be compared by laying the rectangles next to each other. It is easy to generate other possibilities: For example, smaller rectangles can represent higher temperatures. For each possibility, the representing rules and associated processes for interpreting the representation must be configured accordingly.

The representations in the second and third rows of Figure 1.2 depict a continuous quantity with another continuous quantity. Once the length of the line is linked by a representing rule with the temperature of the object, a change in the length of the line can be interpreted as a change in temperature. Using one dimensional quantity to represent another seems to provide some information for free. These representations are often called *analog*, because the representing world has an inherent structure that governs how it operates and the relations between aspects in the representing world are not arbitrary. For example, it is a fact about spaces that if line A is longer than line B and line B is longer than line C, line A is also longer than line C. Length is an appropriate representation for temperature, because temperature has the same transitive structure as length. If temperature did not have a transitive structure, length would not be an appropriate representing world to use for temperature.

Not all representations are analog. The fourth row of Figure 1.2 shows such a representation. In modern culture, people use numerical representations of quantities such as temperature all the time. This representation is very different from those in the second and third rows: Making the numbers taller or shorter does not signal changing the temperature of the objects; only changes in the digits change the representation. Nothing inherent in the scratches of ink requires the number 21 to be larger than the number 20 or smaller than the number 22. Rather, a system of representing rules links the written numerals to the represented world of abstract mathematical quantities. These representations are often called *symbolic* because a convention is established to link all the elements in the representing world. The relation among elements in the representing world is arbitrary and could have occurred in some other way had the representing rules been differently constructed. (The arbitrary, conventionally established use of symbols in mental representation is similar to the use that, for example, allows the symbol Σ to play one role in Greek writing and a different role in mathematical equations.)

For a symbol system like Arabic numerals to be used as the basis of a representation of the represented world of temperature, a set of representing rules must be established between symbols and temperature. First, there must be rules that map the numerals onto numbers, but even after this mapping has been established, there are many possible ways to map the numbers onto temperatures. For example, with the Fahrenheit temperature scale as representing rules, there is a set of correspondences between the represented and representing worlds different from that with the Celsius scale. An infinite number of sets of representing rules can be constructed to map numbers onto temperatures. The same point is true for analog representations (such as using lines to represent temperatures): Different lengths of a line can represent the same degree of temperature change. The particular correspondence between temperature and line length is established by the representing rules.

A particular representation makes some information obvious and other information difficult to extract (Marr, 1982). The length of a column of mercury as a representation of temperature makes it easy to make direct comparisons between pairs of temperatures. A simple procedure of laying two lines next to each other and seeing which extends further accomplishes this task. To compare two numbers, in contrast, extensive knowledge of the system of symbols underlying numbers and an understanding of numerical relationships, must be brought to bear. Not all things are easier to do with the length representation of temperature, though. If a specific value for temperature is required to make a complex calculation, say for understanding a chemical reaction, the length representation is poorly suited as a representation of temperature; for this purpose, the numerical representation may be better.

To summarize, representations have four components. At the heart of a representation is a representing world that is used to represent information in the represented world. The particular representations in this world are bound to the represented world by representing rules that relate aspects of the representing world to aspects of the represented world. The process of representing some world typically produces a loss of information, because information can be used only when there is a procedure for extracting it. I have made a distinction between *analog* representations, for which the relations among elements in the represented world are fixed by the structure of the representational system, and *symbolic* representations, for which the relations among elements in the represented world are arbitrary and must be fixed by convention. Finally, any representational choice makes some information easy to find but may make other information very difficult to determine.

Representations and Cognitive Representations

My working definition of representation is quite broad. For example, according to this definition, a thermostat has representations although a thermostat is not a cognitive system. What exactly constitutes a cognitive system or cognitive representation is a difficult question that has occupied researchers in cognitive science for some time. No satisfactory definition exists that includes all and only things that all researchers are happy calling representations, but I hope to demonstrate the range of things that are good candidates for psychological representations. In this way, I can triangulate on a good definition for cognitive representation.

Before we examine the notion of cognitive representations in more detail, however, there is one danger with defining a cognitive system that we must discuss explicitly. There is a strong intuition that a thermostat is not a cognitive system. After all, a thermostat is not that interesting a device. The bimetallic plate changes its shape with the temperature in the room, and at some point the change causes a switch to close and to turn on the heat (or perhaps the air conditioning). Later, the change in temperature in the opposite direction causes the switch to open, and the heat (or air conditioning) stops. Why is this not cognitive?

J. A. Fodor (1986) gave an answer to this question. He argued that the behavior of systems like thermostats is well described, perhaps even best described, by using the principles of physics and chemistry. A bimetallic plate changes its shape because the two metals expand at different rates (a change predicted by laws of physics and chemistry). Thus, although a thermostat has a representation, it is a representation that needs no principles of psychology to be understood, and thus it is not a cognitive representation.[2] This way of distinguishing between cognitive and noncognitive representations seems reasonable. Although the behavior of any representational system can be described by the laws of physics at some level, no interesting generalizations from physics or chemistry can explain how a cognitive system (like a brain or a suitably programmed computer) represents information, and so it is necessary to appeal to other sciences.

An inappropriate answer (in my view) to the question of what makes something a cognitive representation is that a thermostat is a deterministic device. The physics of thermostats is well enough understood to predict their behavior with striking accuracy. A complete psychology may allow predictions of the behavior of humans and other animals with alarming effectiveness as well. I raise this point here, however, because implicit in many discussions of representation is the notion that a cognitive system has an element of free will in it. I do not choose a definition of cognitive system in a way that assumes that there is (or is not) free will.

The Meaning in a Representation

In a cognitive representation, the representation is an internal state; that is, in humans, mental representations are in the head. The nature of the represented world is controversial. Is the represented world in the head, outside the head, or some combination of the two? Cognitive scientists have often assumed that some represented worlds are outside the head and others are inside. In order to look more at what it means for a representation to be about something, we must explore some work in the philosophy of mind.

[2]Actually, Fodor argued that thermostats do not have representations at all and that what makes something a representation is having properties that cannot be explained by the laws of basic sciences (what he called *non-nomic* properties). This position does not explain how a thermostat makes contact with its environment to do something interesting in a way that a rock heating in the sun does not. See Markman and Dietrich (1998) for a more complete discussion of Fodor's view and problems with it.

Philosophers have been concerned with the notion of *intentionality* (Dennett, 1987; Dietrich, 1994; Searle, 1992). Rather than referring to the familiar idea that something may be done with intent or on purpose, the philosophical concept of intentionality refers to what a representation is about. For example, my representation of the computer screen I am looking at is about this computer screen. My belief that chocolate ice cream is good is about chocolate ice cream. My belief that unicorns do not exist is about unicorns. Defining *aboutness*, however, is not straightforward. For my belief about the computer screen, it is enough that there is a computer screen in front of me (barring a very convincing hallucination). Likewise, my belief about chocolate ice cream can refer to instances of chocolate ice cream in the world, particularly those instances I have experienced in the past (that were good). Unicorns are more problematic: There are none, and never were. Thus, it is not enough to assume that representations are about things in the world because not everything represented is in the world (or ever was). Some things may be abstract concepts without good visualizable forms. Finally, even when a representation *is* about something in the outside world, there may be a mismatch between what is in the world and the way I represent it. On a dark foggy night, I may represent something as a black cat, only to find out too late that it is a skunk. A theory of representation must allow such mistakes to occur.

A complete catalog of theories of intentionality in philosophy would take up more room than I have in this chapter (or in this book; see J. A. Fodor, 1981; J. A. Fodor & Lepore, 1992; Stich & Warfield, 1994). To understand representation, it is important to think about how the elements in a representation can mean something. One solution to this problem (discussed again in later chapters) is conceptual role semantics, in which the meaning of a representational element is fixed by its relations to other representational elements. This situation is analogous to a dictionary, in which a word is defined in terms of other words. For example, the glossary of an introductory psychology textbook may define the term *olfaction* as "the sense of smell." This definition is helpful only if there already is a meaning for the phrase "the sense of smell" (and you know what that definition is).

A conceptual role semantics has two problems: First, the meanings of at least some elements in the representation must be known, or none of the elements means anything. The representational elements with known meanings are the *grounded* elements. Without knowing the meanings of any words, it is not helpful to look up words in a dictionary: Everything is gibberish in this case. In the chapters that follow, it is worth thinking about which elements in the representing world may be grounded, and how may the grounding take place?

The second problem with conceptual role semantics is holism (J. A. Fodor & Lepore, 1992). If representational elements are given meaning by their relations to other representational elements, the meaning of any one element depends on every other representational element. According to this view, two people's concepts of *dog* differ because each knows different things about dogs, and also about the 1986 New York Giants. If the meaning of any concept depends on the meaning of every other concept, then how can people function without accessing all information at all times? If each person's concepts differ from every other person's concepts, because of differences in past experience, communication is impossible: One person's meanings of the concepts used in a discourse must differ radically from another person's concepts on the basis of differences in past experience. The holism problem requires that cognitive systems be able to do some processing without having to make use of every piece of their knowledge for every process. Again, in the chapters that follow, it is worth thinking about how particular representations avoid having to access and use every piece of known information to function.

A final problem that philosophers have often raised in conjunction with discussions about representation concerns how representations are interpreted. If I have a picture of the Grand Canyon, I believe the picture represents the Grand Canyon because of particular color saturation patterns that map onto color saturations that were at the Grand Canyon at the time the picture was taken. When I look at it, because I have the right kind of visual system, I can interpret the picture and extract information from the representation. The problem comes with thinking about cognitive representations. The representing world in a cognitive representation is assumed to be internal to the organism. Who looks at the representation to interpret it? There cannot be another person in my head (a *homunculus*) who looks at my representations, because then who would interpret the representations in the homunculus's head?

Cognitive scientists have generally avoided this conundrum by assuming that the cognitive system is a computational device. That is, the cognitive system has representations, and it also has processes that manipulate the information in these representations, just as a familiar digital computer can have data structures, which can be manipulated by procedures in computer programs. Digital computers are able to carry out algorithms, because they have instructions encoded in them to allow them to follow a program in the same way that a cook follows a recipe.[3]

[3]The ability to follow a program is based on the theoretical concept of a Turing machine. A description of Turing machines is beyond the scope of this chapter; interested readers should consult the description of Turing machines by Johnson-Laird (1988). A clever introduction to Turing machines appeared in Barwise and Etchemendy's work (1993b); they provided a computer program that allows readers to construct Turing machines to solve a variety of problems.

In this section, I have raised two important philosophical issues about representation. The first is intentionality (i.e., what a representation is about): How is the representing world connected to the represented world? The second is computation: There is a danger when positing psychological theories of requiring an intelligent agent to interpret the representations in it. According to the concept of computability derived from Turing machines, a process designed to make use of a representation can be carried out without needing such an intelligent agent.

THREE DIMENSIONS OF VARIATION IN REPRESENTATIONS

How does one representational format differ from another? Are the differences merely a matter of notation, or do actual substantive issues separate the types of representations? Proposals for representations can vary along many dimensions (see also Markman & Dietrich, 1998).[4] As a demonstration that these dimensions of variation are substantive, I consider three: the duration of representational states, the presence of discrete symbols, and the abstractness of representations. In the following section, I discuss some general criteria for deciding that one proposal for representation is better than another.

The first dimension of variation is in the duration of representational states. The definition of representation given here does not require that representational states exist for any particular time. In the case of a mercury thermometer, representational states are instantaneous; the height of the mercury in the thermometer represents the temperature at the moment. Any changes in temperature change the height of the mercury and leave the system without any memory of past states. Representations may also endure for long periods. I can remember the day that my parents and I moved from an apartment to a house when I was about 3 years old (some 28 years before I am writing this). The fact that I have a mental image of the moving truck behind our car means that some representation of this event has endured in my cognitive system for a long time (although my current mental image of this state may reflect only a transient activation of neurons in my brain). Thus, different representational systems may focus on transient or enduring representational states.

A second important dimension of variation is the presence of discrete symbols. Many representational formats assume that discrete elements in the representing world bear some relation to elements in the represented

[4]Markman and Dietrich (1988) actually discussed five dimensions of variation, but three are most central for this discussion.

world. When the relation between these discrete elements and the things they represent in the represented world is arbitrary, these discrete elements are called symbols. Although symbols are common in representational systems (see chaps. 3–9), they are not obligatory. For example, as I discuss in chapter 2, many systems use space as a representation. Space is continuous and hence does not divide the representing world into discrete parts. Thus, symbols are commonly used in representations but are not required.

The issues of duration and symbol use are not trivial and have been the source of some controversy in cognitive science. Indeed, theorists who have focused on representations that exist for only short periods and do not require explicit symbols have considered the possibility that cognitive systems have no representations at all. One example presented by van Gelder (1992; see also Thelen & Smith, 1994) involves Watt's apparatus used as the governor for a steam engine. The mechanism, shown in Figure 1.3, spins around; the faster it spins, the higher the balls on the outside rise. As the balls rise, they close a valve that lets steam flow through the engine; this process reduces the pressure and causes the mechanism to spin more slowly. The decrease in the rate of spin lowers the balls, which causes the valve to open more, thereby increasing the pressure, and so on. This elegant machine keeps steam engines from exploding by keeping pressure in the engine from rising too high.

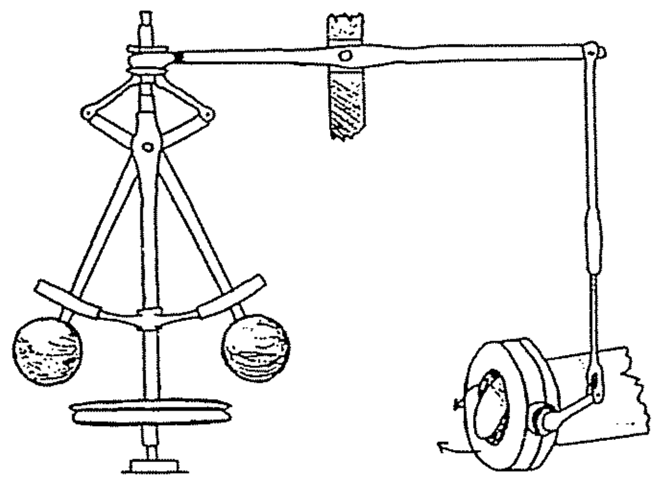


FIG. 1.3. Diagram of Watt's steam engine governor. From *Dynamic Systems Approach*, by E. Thelen and L. B. Smith (1994). Copyright © 1994 by MIT Press. Reprinted with permission.

STRUCTURE IN MENTAL IMAGERY AND MENTAL MODELS

One of the fiercest battles about representation in cognitive science was fought over mental imagery. Just to ground the phenomenon of interest, answer the following three questions.

Who was president of the United States during the Civil War? (6.1)

How many windows were in the front face of the house you lived in when you were 10 years old? (6.2)

Which is higher, the top of a collie's head or the bottom of a horse's tail? (6.3)

All three questions seem answerable, but Question 1 is qualitatively different from the other two. Answering "Abraham Lincoln" requires accessing a stored fact that one was likely to have been told (perhaps many times). In contrast, answering Questions 2 and 3 probably does not involve accessing stored answers. One may never have pondered these questions before. Many who answer these questions report using mental imagery. For Question 2, they may form a mental image of the house they lived in at the age of 10 and then count the windows in the image, or they may take a mental tour of the house and count the windows in each room. For Question 3, people often imagine a collie and a horse standing side by side and compare the height of the top of the dog's head to the height of the bottom of the horse's tail.

This self-report of the utility of mental imagery has spurred numerous investigations of people's ability to use and manipulate mental images. As discussed in chapter 2, early researchers of imagery examined whether people can carry out the same transformations on mental images as they can on real images, such as rotating or stretching them. Shepard, Metzler, and Cooper (Cooper, 1975; Metzler & Shepard, 1974; Shepard & Cooper, 1982) presented subjects with pairs of two- and three-dimensional objects and asked them to make same–different judgments. On some same trials, identical objects were rotated slightly either in the plane of the image or in depth. The time to respond to these items was linearly related to the difference in orientation. Regression lines fitted to these data yielded a slope of about 2 milliseconds per degree of rotation. The data suggested that people carry out these same–different judgments by mentally rotating the objects to a common orientation before comparing them.

In another classic set of studies, Kosslyn, Ball, and Reiser (1978) had people learn a map of a fictitious island. After learning this map, the investigators asked people to imagine the map and to travel from one landmark to another. Scanning times for this mental map were longer for objects far apart on the map than for objects near together, a result suggesting that mental scanning involves traversing the region between landmarks. Zooming in on the map so that its mental image was large yielded longer scanning times than did zooming out on the map so that its mental image was small. These data suggest that mental images are like real images in many ways.

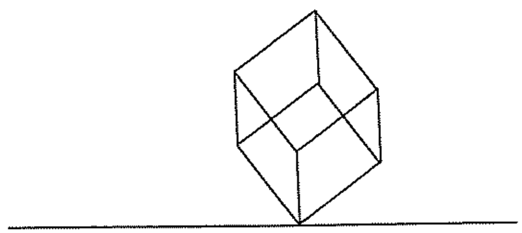
The debate that raged in cognitive science involved determining in what way a mental image resembled a real image. On one side, there was ample evidence that mental images could be transformed like real images and that they contained some amount of metric information (that is, information about the distances between points in the image). On the other side was the problem that if a mental image was simply a copy of a real image, there would need to be some process that could "see" the mental image and process it. Otherwise, there is a danger of an infinite regress of images: There would have to be a homunculus looking at the internal image, and the homunculus would have an image in his or her head, and there would be a homunculus to read that image, and so on. Furthermore, not all tasks that can be done with real images can also be done with mental images. For example, it is not possible to count the stripes on a mental image of a tiger, even though the stripes on a real image can be counted (Pylyshyn, 1981).

Proposals for the representations used in mental imagery have begun to resemble proposals for the representations of visual objects (Hinton, 1979; Kosslyn, 1994; Tye, 1991). Indeed, Kosslyn (1994) suggested that the visual system used mental images to assist in object recognition. For example, an activated mental image can help fill in obscured details from the visual world. On this view, it should be no surprise that mental images use the same kinds of representations as do visual object representations. Kosslyn further pointed out that one reason why people may not be able to carry out all the same operations on mental images that they can on visual images is that some operations on real images require multiple fixations. Multiple fixations are not possible on mental images, because the mental image is processed in visual buffers that are used to facilitate the integration of visual information from different fixations. Counting the stripes on a tiger requires scanning across the tiger, making a number of successive eye fixations, and counting the stripes along the way. The mental image cannot be similarly scanned, because the image is processed in areas of cortex far down the line from the retina.

In addition to arguments that mental images can play a role in object recognition, there are also demonstrations of imagery phenomena compatible with the presence of structure in mental imagery. Hinton (1979) produced a compelling example: He asked people to hold a finger about 1 foot off the surface of a table and then to imagine a cube with one corner touching the finger and the diagonally opposite corner touching the table at the point of the table directly below the finger in the air. The imagined cube should appear to be standing on its corner. Then Hinton asked people to point to the other corners of the cube. Whoever is unfamiliar with this example should try to accomplish it.

It is quite difficult to do this task correctly. A picture of a wire-frame cube standing on its edge is shown in Figure 6.11A. Many people point to only four corners in the air, even though there are six more corners of the cube (in addition to the ones touching the table and the finger). People often put these four corners on the same plane arranged in a square. As shown in Figure 6.11A, the remaining six corners are not in the same plane, but are arranged in a shape like a crown. Hinton suggested that people have difficulty with this task because of the way their representations of the cube are structured. The default structure is as a pair of squares separated by edges. Hinton repeated the cube task by asking people to imagine a cube on a table in front of them with one face pointing at them. Then they were to imagine tilting the cube away from them so that it rested on its back edge, with the diagonal edge vertically above it (as in Figure 6.11B). When asked to point to the corners of the cube in this task, people had no difficulty. This

(A)



(B)

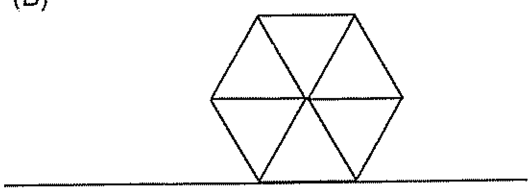


FIG. 6.11. A: Cube resting on one point with the diagonal point directly above it; B: Cube resting on one edge.

finding is compatible with the default structure. A second possible representation that people can generate is as two tripods extending from opposite corners, where each tripod is rotated by 60 degrees, and the alternating legs of the two tripods are connected to form the remaining edges of the cube. This structure requires keeping track of more edges than does the double square representation and hence is more difficult to process. Of central importance for this discussion is simply that mental images do appear to have structure and that different ways of structuring an image can change the relative ease of processing the image.

As previously discussed, researchers have suggested that visual object representations contain information about relations among parts as well as metric data that encode specific information about distance and geometric properties. Likewise, there is some evidence that mental images have information about both structural and metric properties. If mental images had information only about parts and relations among parts, it would be very difficult to form a mental image and then find emergent properties of the image. In contrast to this prediction, Finke, Pinker, and Farah (1989) gave people simple descriptions such as this:

> Imagine a capital letter H. Rotate the figure 90 degrees to the right. Now place a triangle at the top, with its base equal in width to that of the figure. What is it? (6.4)

With descriptions of this type, on nearly 50% of trials on which they were able to do the correct transformation, people interpreted this item as a tree. These identifications required a different segmentation of the object into parts than was given in the initial description. Thus, people's ability to interpret these mental images as pictures suggests that some amount of metric information was also incorporated into the images.

It is unclear how visual representations and mental images preserve metric information. One possibility is that images involve some kind of array representation, in which the image is stored as a two-dimensional array of pixels with filled points distinguished from empty points (see the discussion of Knapp & Anderson's, 1984, model in chap. 2). Ullman's (1984, 1996) image alignment mechanism involves this kind of array representation. Kosslyn (1994), who also suggested that metric spatial relations are important to visual processing, was vague about the way metric information is represented.

The potential problem with array representations of metric information is that processes operating over them must be defined. An array does preserve geometric relations like angles between lines and contains more precise information about the relative location of elements in an image than is contained in general categorical relations like *beside* or *near.* Some process must actually calculate the angle between the lines or determine the relative distances between elements for an array representation to be useful.

Defining processes that operate successfully on arrays has proved difficult. One reason for this difficulty is that arrays are limited in their spatial resolution, and transformations of objects in arrays tend to lose information. The processes that transform images in an array have to reason about the behavior of each element (pixel) independently, rather than use a higher level description of the object being transformed. Figure 6.12 illustrates the problems with local transformations. In this figure, I rotated a square in a computer drawing package through 180 degrees in 12 unequal steps. The 90- and 180-degree rotations are marked on the figure. Each of these rotations is no longer a clear square; the lines become progressively more diffuse with successive rotations. To get a computer drawing package to make smooth rotations of figures requires a mathematical description of the object as a square rather than a pixel representation of it. Because of this difficulty in transforming images, it has been difficult to provide accounts of phenomena like mental rotation by using array representations.

One issue that I have ignored in this discussion is the status of the mental image itself. When many people have performed tasks that involve mental imagery, they have reported having a conscious experience similar to the experience of looking at objects in the world (although perhaps

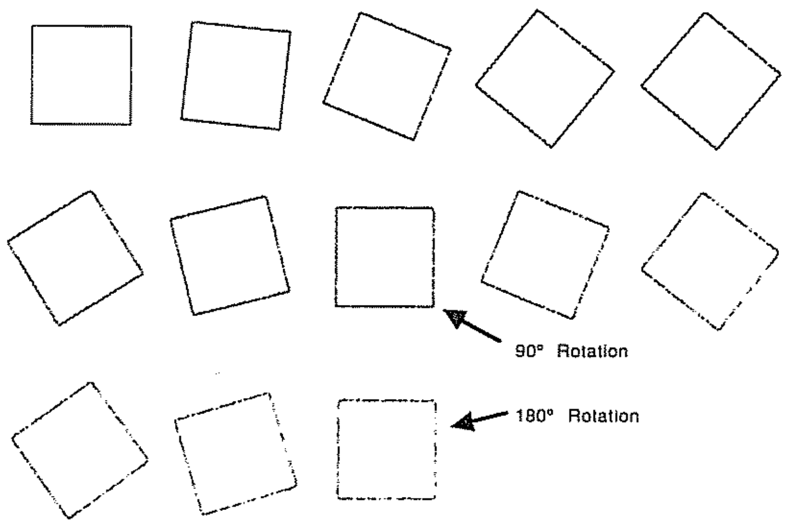


FIG. 6.12. Successive rotations of an array representation of a square. The 90° and 180° rotations of the square marked on the figure are no longer clear squares like the original.

not as rich). Some have argued that the conscious experience of the mental image is crucial to the use of imagery; others have argued that the experience occurs as a byproduct of the processing done while performing imagery tasks. Although this debate is interesting (and is captured in many references cited in this section), it is not relevant to the representational issues at hand. Mental images have representations, and these representations are quite similar to those required by the visual system for other tasks. This observation provides no way of resolving the importance of the conscious experience of mental images.

To summarize, mental images are not simply pictures in the head; they use the same kinds of representations that were proposed in discussions of visual objects. Mental imagery seems to rely on structural representations in which parts are bound together by relations. The particular structure used to represent an item determines what mental transforms are easy and difficult to do on the image. Despite the centrality of structured representations in imagery, some information about geometric properties, which allow the creative use of imagery to find emergent perceptual properties, must also be preserved.

VISUAL REPRESENTATION AND LANGUAGE

There is often a tension between perception and language. The common adage "A picture is worth a thousand words" attests to the difficulty of giving precise descriptions that capture the essential aspects of visual information in language. Nonetheless, there is an important relationship between visual representation and language. People can talk about space, and indeed notions of space seem to pervade language use. Language may direct attention to aspects of visual scenes that are likely to be important. In this section, I examine two places in which visual information and spatial language interact. First, I discuss the use of spatial language in general and then explore the use of spatial models to interpret discourse about scenes with a spatial extent.

Spatial Language

Although there are many ways to talk about space, an intriguing aspect of language is the system of spatial prepositions. Prepositions are a class of words that specify relations among elements in sentences. Most languages have only a small number of prepositions (particularly relative to the number of nouns and verbs), and so they are easy to study exhaustively. For this reason, authorities have intensively studied preposition systems of a variety of languages, and other work has contrasted the prepositions used