

Perception of Rotated Forms: A Theory of Information Types

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The present article proposes a theory of form perception in an attempt to understand puzzling problems in mental rotation and in perception of forms rotated in the frontal-parallel plane. According to the theory, it is critical to distinguish four types of information. They result from the orthogonal combination of two binary distinctions: information can be orientation-free or orientation-bound, elementary or conjunctive. The theory provides an explanation as to when and why mental rotation has to be performed. If two forms can be discriminated only on the basis of conjunctive orientation-bound information, mental rotation or some other functionally equivalent strategy is required. Mental rotation is unnecessary if the forms differ in either type of orientation-free information, provided that the difference is actually encoded as such. This explanation along with the proposed distinctions among the four types of information was supported by two mental rotation experiments and three visual search experiments. © 1989 Academic Press, Inc.

When does mental rotation occur and when does it not occur? Why does mental rotation have to be performed in some cases but not in others in order to discriminate between rotated forms? The present paper is addressed to these basic questions as well as to a number of other puzzles generated by the results of previous mental rotation studies. The reason that these problems remain unanswered seems to be that mental rotation has been discussed mostly in the context of mental imagery investigation. Obviously, however, mental rotation has a close bearing on another general problem: perception of rotated forms. If the puzzling problems are examined in the context of form perception, it may be possible to find proper solutions to them. Our understanding of form perception, in turn, may also benefit from close examination of mental rotation findings.

The present article attempts to reconsider the fundamental relation

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between orientation and form perception with respect to relevant findings in both mental rotation and form perception. The resulting theory of form perception provides a powerful tool for solving various problems in mental rotation and in perception of rotated forms. The present article discusses several puzzles to demonstrate how they can be explained by the theory. They are reviewed briefly in the first section. The second section is devoted to the description and discussion of the proposed theory: a theory of information types. In the third section, the initial puzzles are reexamined in the light of this theory. The remaining four sections report experimental findings that support the basic assumptions of that theory.

PUZZLES IN MENTAL ROTATION

Shepard and Metzler (1971) showed their subjects a pair of perspective drawings of three-dimensional objects placed side by side, and asked them to judge as quickly as possible whether the depicted objects were the same or different. In the case of different objects, they were mirror-image "enantiomorphs" of each other. The angular difference between the orientations in which the two objects were portrayed was systematically varied from trial to trial. When the researchers plotted the reaction time against the angular difference, an ascending straight line appeared. This linear function was interpreted as evidence that the subjects "mentally rotated"¹ one of the presented objects to the orientation of the other before making a comparison between them. In the original study by Shepard and Metzler (1971), the orientations of the object were different either in the frontal-parallel plane or in depth; the same results were obtained in both cases. However, the puzzles to be discussed have all emerged from the frontal plane case. Accordingly, the proposed theory is tuned principally to perception of forms rotated in the frontal-parallel plane. It is possible to extend the theory so that it could be applied to perception of forms rotated in three-dimensional space as well (Takano, 1987). The present article, however, will be confined almost exclusively to the discussion of the two dimensional case in which a two-dimensional projection of an object is rotated in the same two-dimensional plane.

Presence and Absence of Mental Rotation

The original findings by Shepard and Metzler (1971) have been replicated with various stimuli and in various conditions (see Shepard & Cooper, 1982). Nevertheless, it is still unclear why mental rotation has to be performed at all. No theory of form perception thus far explains the necessity of mental rotation.

¹ The expression is metaphorical. It simply means that the subjects imagined the rotation of an object.

When a figure is disoriented, its image falls on a new set of retinal receptors. The fact that such figures are easily recognized nevertheless poses serious difficulty for a simple template matching theory of form recognition (see Neisser, 1967). In order to cope with this problem, feature extraction theories have been proposed (Selfridge, 1959; Selfridge & Neisser, 1960; Sutherland, 1969). These theories suggest that recognition may be based on those features that would not be affected by rotation: a capital letter *A* would retain the sharp point and *P* the closed loop after any frontal plane rotation. If a set of such orientation-free features is stored for each form and used for its recognition, form recognition will be released from the disorientation problem. If human form recognition depends entirely on those orientation-free features, however, it is impossible to understand why the orientations of two objects have to be aligned by mental rotation before judging whether they are the same or different (Metzler & Shepard, 1974, pp. 189–192).

The same problem arises in the “object-centered coordinate system” proposed by Marr and Nishihara (1978; also in Marr, 1982). This coordinate system was designed to structure separate orientation-free features into an integrated form. Roughly speaking, the structure of an object is described in terms of various axes assumed in that object and interrelations among those axes. A principal axis is assumed to go through the center of the object, typically along its most elongated dimension. Subsidiary axes correspond to the axes of generalized cones (Binford, 1971), each of which approximates a component of the object. The updown direction, the front direction, and the clockwise direction are defined with regard to the principal axis. That is, the principal axis serves as a basis to construct an entire coordinate system. All the subsidiary axes are located with reference to this coordinate system.² Such a system has an important characteristic which was the very purpose of its development: the structural description of the object remains the same irrespective of the orientation of its principal axis, namely, the orientation of the whole object. This is because the structure is described without making reference to any external framework. It follows that two identical objects have the same description even when they are placed in totally different orientations. A direct comparison of the respective descriptions will suffice to determine whether the two objects are the same or different; again, no mental rotation is needed.

It is indeed possible to include the orientational value of the principal axis in the description of an object when a certain external framework is

² In spite of the assumed modularity of the coordinate system (see Marr & Nishihara, 1978), the *final* reference is made anyway to the principal axis in locating any component of the object.

defined to locate the whole object. However, such an orientational value does not affect the structural description of the object, such as specified relations of the subsidiary axes to the principal axis; the orientational value can simply be ignored when deciding whether the two objects are the same or different (Pinker, 1984). Hence there is no necessity for mental rotation.

Hinton and Parsons (1981) introduced a small modification into the theory of object-centered coordinate system so that this theory could explain the occurrence of mental rotation; they added the assumption that the object-centered coordinate system encodes *handedness* (i.e., information that differentiates between right and left) only when the principal axis of the object is upright. In typical mental rotation experiments, two different objects are mirror images of each other; the sole difference between them lies in the right/left distinction. If this distinction were not available in the representation of a tilted object, the tilt would have to be corrected before the decision on its identity is made. Mental rotation would thus be called for.

However, this modification does not work for all the cases in which mental rotation occurs. In some of the mental rotation experiments (e.g., Shepard & Metzler, 1971), presented objects were both displaced from the upright position: for example, when the angular difference was 60° , the two objects might be in 40° and 100° as well as in 0° and 60° . Nevertheless, the reaction time always corresponded to 60° , not to 140° or 100° . It follows that the subjects in those experiments simply rotated one object into the orientation of the other, instead of rotating both objects until their principal axes became upright. Evidently, the subjects could decide on the *handedness* of the objects while they remained tilted as far as the tilt was identical. This directly contradicts the assumption made by Hinton and Parsons (1981). Furthermore, mental rotation was later found to occur even when the up/down reversal was employed instead of the right/left reversal (Corballis & McLaren, 1984). This finding poses another problem for the modification proposed by Hinton and Parsons (1981). Thus, the occurrence of mental rotation has been left as a puzzle for all existing theories of form perception (Pinker, 1984; Shepard & Cooper, 1982).

Does mental rotation then always have to be conducted to recognize disoriented forms? Rock (1973) suggested a positive answer to this question. Corballis and his associates, however, later found those cases in which disoriented forms were recognized without mental rotation. Corballis, Zbrodoff, Shetzer, and Butler (1978) asked their subjects to judge as quickly as possible whether a presented alphanumeric character was a predetermined target. Though the characters were shown in both normal and backward (mirror-image) versions, the subjects were told to treat both versions equally: mirror-image discrimination was not required. The

results showed little or no rise in reaction time with increasing angular departure from the upright position. It follows that mental rotation did not occur in this experimental setting. Eley (1982) obtained the same results with meaningless nonletter figures when he required his subjects to name them by associated CVCs. Similarly, when subjects were asked to classify presented stimuli into letters and digits, the reaction time was almost constant regardless of angular departure (Corballis & Nagourney, 1978). Mental rotation seemed to be unnecessary in this task as well. Accordingly, any proper explanation of the reason why mental rotation is necessary in some cases must also explain the reason why it is not necessary at all in other cases.

“Orientation-Free” Description with Orientational Terms

Just and Carpenter (1985) attempted to explain the presence and absence of mental rotation without consulting any particular theory of form perception. They maintained that any object could be given both orientation-bound descriptions and orientation-free descriptions; mental rotation is needed when the internal description of the object is orientation-bound, whereas mental rotation is not needed when the description is orientation-free. Just and Carpenter (1985) described a “corridor-walk strategy” to demonstrate that orientation-free descriptions could be formed for the Shepard-Metzler objects (Fig. 1) as well.

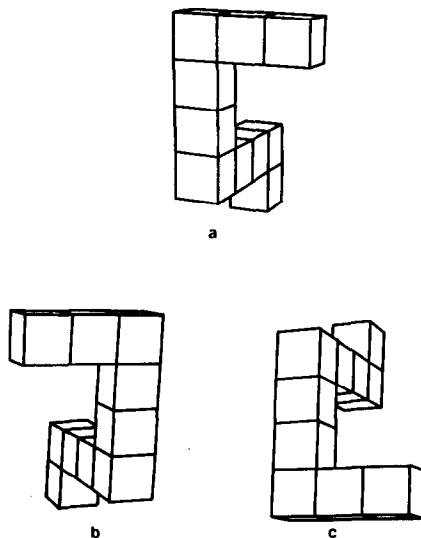


FIG. 1. Samples of the Shepard-Metzler objects. They serve to illustrate the “corridor-walk” strategy in the text.

In this strategy, the object is regarded as a winding corridor. The viewer is supposed to take an imaginary walk in its inside. Take Fig. 1a as an example: if the viewer enters the corridor from the rightmost "opening" of its horizontal "arm," she has to take a down turn first, followed by a right turn and then a left turn. On the other hand, the turns should be "down, *left, right*" in the case of Fig. 1b, the mirror image of Fig. 1a. The difference in turns shows that these two objects are not identical. If this strategy is adopted, it is possible to discriminate mirror images without conducting mental rotation, because the order and types of turns stay invariant after any rotation. For example, if an imaginary walk is taken through Fig. 1c entering the same "opening" and stepping on the same "floors," the turns will be "down, *left, right*," which are identical to those for Fig. 1b. In fact, Fig. 1c is the same as Fig. 1b, not as Fig. 1a.

Although Just and Carpenter (1985) have not presented any formal data concerning the above strategy, it will be easy to confirm the absence of mental rotation by actually trying it. The problem is, however, that the strategy does not seem to be orientation-free. The coding of an object by imaginary turns consists of those terms as *right* and *left*, *up* and *down*, which exactly indicate orientations themselves. It is hard to consider such a coding "orientation-free."³ In fact, for the reader who is looking at Fig. 1c from the outside, the same turns are actually "up, right, up," instead of "down, left, right."

Why is this strategy then able to circumvent mental rotation if it is not orientation-free? This is another puzzle.

"Knowing the Answer Beforehand"

Some of the data in mental rotation experiments suggest that before initiating mental rotation subjects already "know" the answer to the question of whether a tilted stimulus is normal or backward (i.e., mirror-reversed). Corballis and his associates (Corballis & Nagourney, 1978; Corballis et al., 1978) found that subjects needed more time to respond to backward letters than to normal letters in any orientation when mirror-image (normal/backward) discrimination was not required and thus no mental rotation occurred (see the first subsection). It follows that some appropriate information regarding the normal/backward distinction was available to the subjects while a presented letter remained tilted, because those subjects responded without correcting the tilt by mental rotation. If

³ This type of coding cannot be orientation-free because it has to make reference to a certain orientational framework that is consistent with the body of the viewer (i.e., the imaginary walker). On the other hand, the object-centered coordinate system is considered to be orientation-free in that it is independent of any orientational framework that is consistent with the body of any viewer, whether actual or imaginary.

this distinction can be made in a tilted stimulus, however, why do subjects spend extra time and effort to carry out mental rotation when mirror-image discrimination is formally required? Is mental rotation not performed to discriminate between mirror images? There seems to be a contradiction.

Sekiyama (1982) was confronted with a similar paradox while investigating mental rotation of right and left hands. Her subjects behaved as if they first rotated the image of a right hand from its upright position when the drawing of a right hand had been presented, rotating the image of a left hand when the drawing of a left hand had been presented. When Sekiyama (1983) asked her subjects to actually rotate their own hands up to the same orientation as that of a presented drawing, they almost always started to rotate the correct hand without trial and error: they immediately rotated the right hand when the drawing of a right hand had been presented, and vice versa. The same question has to be asked again: Why do subjects perform mental rotation if the answer is already available in advance of mental rotation? How is that answer obtained, if not through mental rotation?

A THEORY OF INFORMATION TYPES

The preceding section has made it clear that two opposite questions have to be answered: How could form perception be independent of orientation and dependent on orientation at the same time? A reasonable way to cope with these conflicting questions is to assume that two different types of information are used in mental representations of forms: information that is indifferent to orientation and information that is sensitive to it. When the former is critical in discriminating rotated forms, form perception will appear to be independent of orientation; when the latter is critical, form perception will appear to be dependent on orientation. In the subsequent discussion, these two types of information will be referred to as "orientation-free information" and "orientation-bound information." If some constituent features of forms are orientation-free (Selfridge, 1959; Selfridge & Neisser, 1960), and if the human visual system actually relies on such orientation-free features, it follows that they must be accessible as separate information units in mental representations of forms. Otherwise, those features could not be consulted individually, and would thus be useless. However, these features must also be conjoined in a particular way to reconstruct a given form as a particular configuration of features. Therefore, both elementary information and conjunctive information are needed to specify individual features and to specify the way of structuring them, respectively.

The necessity of these two sets of distinctions can be shown in another way. As pointed out earlier, if the description of an object is made up

without reference to orientation and if the orientation of that object is attached to the whole description afterward as a parameter value, then the orientation value can simply be ignored in identifying that object. This is because the description of its form stays unchanged whatever value the orientation parameter may take. In order for the orientation to affect the discrimination process, it has to be "woven into" the description of the form. To put it another way, the orientation has to be an indispensable part in describing the form. If the whole object were mentally represented as a single unit, there would be no way for the orientation to be woven into that unitary representation; the only way to include the orientation would be to attach the orientation value to the unitary representation from the outside.⁴ If the whole object is broken down into two or more elements, however, the orientation *can* be incorporated into the inside of the description. In this case, what is incorporated is not the orientation of the whole object but orientational relations among those elements, such as "to-the-right-of," "above," and so on. In other words, the mental representation of an object has first to describe its individual elements and then to conjoin them using orientational terms. The distinction between elementary information and conjunctive information is thus called for. However, spatial relations among figural elements are not confined to those sensitive to orientation: for example, two attached circles remain attached whether one of them is to the right of the other or to the left of it. In order to take both orientational and nonorientational relations into account, the distinction between orientation-bound information and orientation-free information has to be assumed as well.

An orthogonal combination of these two binary distinctions results in four different types of information to be used in mental descriptions of forms (see Fig. 2). As is seen in the following section, the assumption of

⁴ Imagine a contrary case in which the length and orientation of a line are encoded in an integrated manner (see also the discussion at the end of the present subsection). In other words, it is now assumed that both nonorientational factor (i.e., length) and orientational factor constitute an inseparable unitary representation that defines a particular form in an imaginary recognition system. Under this assumption, a change in orientation must result in a corresponding change in the definition of the form, hence a change in its appearance. More concretely, two lines of the same length placed horizontally and vertically, respectively, should have different definitions and look totally different just as a straight line and a curved line of the same length do. This is because the form of a particular line is defined in terms of its orientation as well as its length. It follows from the above assumption that there is no one unitary representation for lines of a certain length in general; instead, there must be many unitary representations corresponding to lines placed in different orientations. Obviously, this assumption does not hold for human form recognition because a line of a certain length is recognized as an identical line in whatever orientation it may appear. It follows that there is an identical unitary representation for lines of that length in different orientations and that orientation is therefore not an inseparable ingredient.

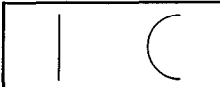

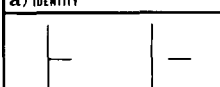

	ORIENTATION-FREE	ORIENTATION-BOUND
ELEMENTARY	 a.) IDENTITY	 b.) ABSOLUTE ORIENTATION
CONJUNCTIVE	 c.) COMBINATION	 d.) RELATIVE ORIENTATION

FIG. 2. Four types of information as defined by the orthogonal combination of two sets of binary distinctions. Each pair of line drawings illustrates a difference in each type of information.

these four information types provides a powerful tool for solving various problems in recognition of rotated forms.

Four Types of Information

In this subsection, the above four types of information will be characterized briefly in an intuitive manner. The next subsection will specify the orientational framework to which orientation-bound information is referred. More detailed theoretical considerations concerning these two distinctions are found in later subsections.

The first type of information concerns the identity of individual elements that constitute a form. This information indicates, for example, whether an element is a straight line or a curve (Fig. 2a). The second type of information specifies the orientations of individual elements: e.g., whether a line is vertical or horizontal (Fig. 2b). The third type is concerned with a way of combining two or more elements without respect to orientation: e.g., whether two lines are attached or detached (Fig. 2c). Finally, the fourth type of information determines the orientational relation between two or more elements: e.g., whether the horizontal line is to the right of the vertical line or to the left of it in Fig. 2d.

The names given to those four types of information (i.e., identity information, absolute orientation information, combination information, and relative orientation information) may not represent their exact contents. This is unavoidable because our natural languages are not equipped with such a conceptual schema. The contents of the four information types should be conceived as outcomes of the combination of the above two binary distinctions. For example, "combination information" is defined as conjunctive information that is orientation-free. Therefore, it includes any relation between elements that is not susceptible to orientation change: distance, parallelism, absolute value of an angle without clockwise/counterclockwise distinction, and so on. Conversely, relative

orientation information includes any spatial relation that is susceptible to orientation change: to-the-right-of, below, 30° clockwise from the top, and so on. The term "relative" was chosen because this information depends on a relation between two or more elements. For example, an element *A* may be "above" another element *B*; but at the same time, it can be "below" a third element *C* that is on the opposite side. The term "absolute" for absolute orientation information was chosen because this information depends directly on a certain orientational framework, which is the *final* frame of reference for determining any orientation. In order for absolute orientation information to be determined, nothing else needs to be consulted. In contrast, relative orientation information needs a relation between two or more elements in addition to such an orientational framework. Incidentally, it has to be stressed that the above instances are all simply based on an intuitive classification. A theoretical discussion about a more precise classification is found in a later subsection.

A form is specified unambiguously if all of its elements and all of their interrelations are specified. The above four information types contain both information about elements and information about their interrelations. It follows that an appropriate combination of the four types of information will determine a unique form. As an illustration, for a capital letter *R*, identity information will specify at least three elements: a long line, a short line, and a loop (and, perhaps, a closure as well; see Treisman & Paterson, 1984). Absolute orientation information will indicate that the long line is vertical, the short line is tilted counterclockwise by a certain amount, and the loop is convex to the right. Combination information specifies the following: one end of the loop connects with one end of the long line, and the other end of the loop touches the center of the long line while an end of the short line joins the same junction. Finally, relative orientation information will indicate that both the loop and the short line are to the right of the long line with the loop above the short line. This verbal description is, of course, not sufficient to recover *R* as it is because of limitations in the precision of verbal depiction. In principle, however, it should be possible to specify precisely any form unambiguously if parameter values with sufficient precision are provided for the above four types of information (e.g., the angle between the long line and the short line).

Specifications given by the four different types of information may be redundant to some extent. For instance, when the angle between the *vertical* long line and the short line in *R* is known, there is no need for absolute orientation information to specify the amount of tilt of the short line. The complete form can still be recovered. Nevertheless, this does not deny the possibility that the same information can be encoded and represented redundantly in different forms by an organism. The safety of

retaining redundant information may be preferred at least in some cases to simple mathematical economy (see Experiment 2).

As already stated, the proposed four types of information can be regarded as consequences of the orthogonal combination of two binary distinctions (see Fig. 2). One binary distinction is made between orientation-bound information and orientation-free information. It is self-evident that absolute orientation information is orientation-bound. For example, if a vertical line is tilted by 30° , the information that the line is vertical will become totally inapplicable. The information that specifies orientational relation among elements (e.g., right or left; above or below) is also orientation-bound. In Fig. 3, 3a is different from 3b only in that the square is to the right of the vertical bar (Fig. 3a) or to the left of it (Fig. 3b). In Fig. 3c, the square is to the right of the bar, just as in Fig. 3a, but Fig. 3c is actually the same as Fig. 3b, not as Fig. 3a. The original relative orientation information in Fig. 3b is not applicable any longer when it has been rotated (Fig. 3c); this clearly shows that relative orientation information is also orientation-bound.

In contrast, identity information is orientation-free. If the horizontal line between the square and the bar in Fig. 3a is replaced by a curve as in Fig. 3d, the difference is preserved as it is, even after a rotation as in Fig. 3e. A curve is a curve; it is not changed to a straight line by any tilt. The same holds true for combination information. The vertical bar and the square which are detached in Fig. 3a have become attached in Fig. 3f. Even though the whole figure is inverted, attached parts remain attached as seen in Fig. 3g.

The other binary distinction is made between elementary information and conjunctive information. Both identity information and absolute orientation information are concerned with single elements such as a line. On the other hand, combination information as well as relative orientation information asserts something about relations among two or more elements.

It must be noted that these distinctions among the four types of information have not been proposed as a general mathematical theory which must be valid in any form perception system. The distinctions, instead, have been proposed as a psychological theory. It is not hard to imagine a nonhuman perceiver who does not make such distinctions. Suppose, for example, that a perceiver is equipped with detectors to encode a line in each specific orientation, but that it is not equipped with circuits to combine these detectors in such a way as to cancel the orientation factor. For such a perceiver, two lines placed in two different orientations would not be seen as an identical element. Instead, they would be treated as two different kinds of element (see also Footnote 4). The proposed theory has been constructed to solve the puzzling problems in *human* form percep-

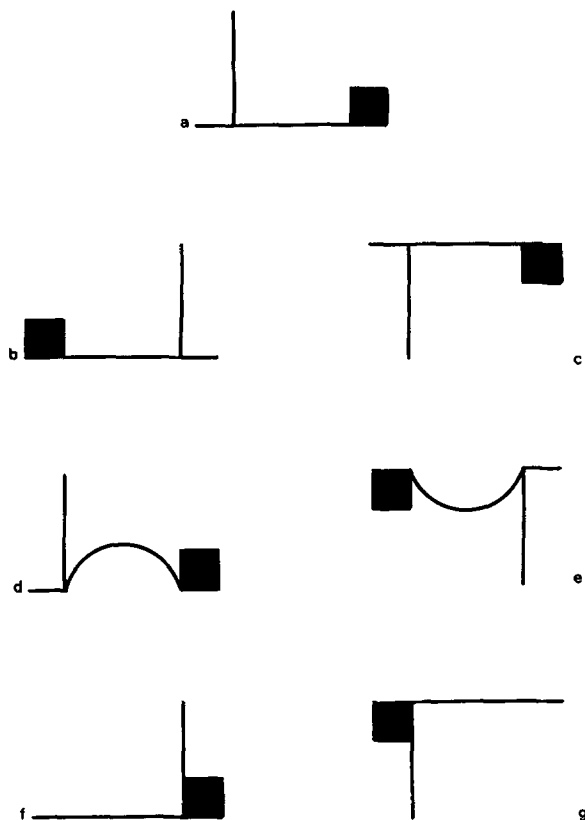


FIG. 3. The effects of orientation change in the frontal plane upon three different types of information. A standard figure is shown in (a). Relative orientation information has been altered in (b); identity information in (d), and combination information in (f). They have been inverted in (c), (e), and (g), respectively. Relative orientation information is shown to be orientation-bound, while both identity information and combination information are shown to be orientation-free. These figures were used in Experiments 1 and 3 as well.

tion, although it seems to be possible to apply the theory to prospective machine vision as well.

Orientational Framework

In order to understand the fact that human form recognition depends, at least to some extent, on the orientation of a form relative to the viewer's body, it seems indispensable to assume a certain kind of egocentric framework in which the perceiver is the origin of all directions. The space defined by such a framework must be three-dimensional in order to explain the fact that mental rotation can be performed in depth (e.g., Humphreys, 1983; Shepard & Metzler, 1971; Steiger & Yuille, 1983; Yuille &

Steiger, 1982), as well as other relevant facts, such as shape constancy, that clearly show that human form perception takes the third dimension into account. The exact way of defining the space depends on how orientations and orientational relations are described in actual mental representations. This is an empirical question and is not explored further in this paper. It seems to be highly probable, however, that humans possess at least three orthogonal, primitive directions as implied by the presence of the corresponding verbal labels in most natural languages (i.e., up-down, right-left, and front-back; though they might be better conceived as three pairs of six directions). These three orthogonal directions are also implied by the intuitive appeal of the Cartesian expression of three-dimensional space.

It is also an empirical question how such a framework is formed. Previous studies (e.g., Howard, 1982; Parker, Poston, & Gullledge, 1983; Rock, 1973; Templeton, 1973) seem to suggest that an orientational framework is constructed on the basis of a weighted combination of at least four factors: a gravitational direction, a retinal direction, a bodily direction, and a direction implied by an environmental framework. These studies also suggest that the weights assigned to the respective factors may vary considerably from one occasion to another. Yet it should be noted that the present theory asserts nothing about the way of constructing the orientational framework. The framework is presupposed as a given to represent forms in relation to itself.

Once an orientational framework is given, absolute orientation information is defined with reference to this framework: e.g., how much a line deviates from the up-down direction. Relative orientation information can also be defined by this orientational framework. In a two-dimensional Cartesian space that is composed of two orthogonal axes, X and Y , the positional relationship between two elements, A and B , can be expressed, for example, as

$$X_A > X_B, \quad (1)$$

where X_A and X_B denote the coordinates of A and B on the axis X . Alternatively, the same relationship can be expressed by, "A is to-the-right-of B," if natural language-like descriptors are preferred. In either case, the expression is meaningful only in a specific orientational framework. Although it is possible to use a neutral descriptor that has no reference to any orientational framework (e.g., "next-to") to describe a certain kind of positional relationship, the difference in direction cannot be expressed by such a descriptor: "A is next-to B" specifies nothing as to whether A is to the right of B or to the left of it. It is not surprising that the difference in direction cannot be defined without an orientational framework: the primary role of an orientational framework is to provide

a basis to discriminate between different directions. As a consequence, the descriptor has to be replaced when the relation between a form and a framework has been altered by a rotation of one or the other. In the case of a rotation of 180 degrees, for example, the inequality (1) has to change into

$$X_A < X_B \quad (2)$$

Similarly, “*A is to-the-right-of B*” is replaced by “*A is to the-left-of B*.” Thus, an orientational framework determines both absolute and relative orientation information in its specific way.

As the defined framework is egocentric, the description of a form based on that framework may be considered as “viewer-centered” in a sense, but not in the sense of Marr (1982). According to Marr (1982), the “viewer” of the viewer-centered description is a physical viewer who is actually viewing an object. The vantage point of the viewer-centered description thus always coincides with that of the physical viewer. On the other hand, the “viewer” for the current egocentric framework of orientation is a hypothetical viewer who takes a certain vantage point in order to construct an internal representation of a form. When the perceived form of an object is compared with its corresponding internal representation, the actual vantage point in perception may well be totally different from the original vantage point from which the internal representation has been formed. Therefore, the description based on the current orientational framework, is not “viewer-centered” in Marr’s sense.⁵

But it is not “object-centered” either. The final reference of the description is made to the orientational framework, not to the principal axis of an object. The framework itself is defined in relation to the *subject* of the description in the representation: if “*A is on the right*,” then *A* is to the right of the subject who represents it in the internal space. The vantage point of such a subject may happen to coincide with that of the physical viewer, but they may be different from each other in many cases as stated above. Accordingly, the description may better be called “subject-centered.” A homunculus is not needed for this “subject.” It seems that the “subject” is best conceived as a set of processors that construct

⁵ The role of the current orientational framework is to provide a basis to construct a *canonical* representation of a perceived object. Accordingly, the current orientational framework is to substitute for the object-centered coordinate system, not the viewer-centered coordinate system. The latter is necessary anyway to construct a percept when an object is actually seen. It is proposed that the percept based on the viewer-centered coordinate system should be transformed into a description based on the current orientational framework instead of a description based on the object-centered coordinate system. Therefore, it *never* occurs that the description based on the current orientational framework is modified every time the viewer changes her position relative to the object.

form representations in the mind. The subject-centered nature of mental representation is even clearer in the transformation of a representation as a mental image. If a viewer mentally "rotates" a cup in front of herself to "see" another view, the newly created vantage point relative to the cup is no longer identical to that of her physical eyes. Conversely, Hinton and Parsons (1981) demonstrated that an orientational framework, instead of an image, could be mentally rotated in the mental rotation paradigm under certain optimal conditions. In this case as well, the vantage point of the mentally rotated framework does not coincide with that of the actual viewer. This subject-centered nature of the orientational framework will play a crucial role in the attempt to explain the "corridor-walk" strategy in the next section.

The subject-centered coordinate system would be able to define any necessary directions; it could substitute for the object-centered coordinate system (Marr & Nishihara, 1978) as a determiner of orientations. Both of them share the same advantage in that they are not bound to a physical vantage point in actual perception. In addition, the subject-centered coordinate system has other advantages that are not shared by the object-centered coordinate system. First, the latter needs a different type of coordinate system that is essentially identical to the proposed subject-centered coordinate system, in order to represent the orientational relationship between a vantage point (whether actual or imaginary) and represented objects. Second, a scene requires as many object-centered coordinate systems as there are objects within it because every such system is intrinsic to an individual object. Only one subject-centered coordinate system will conveniently replace all those object-centered coordinate systems. Third, and above all, the subject-centered coordinate system explains both dependence and independence of form perception on orientation (see the next section), while the object-centered coordinate system fails to explain the dependence part as discussed in the first section.⁶

Types of Transformation

The effects of a 180° rotation in the frontal-parallel plane without any

⁶ It is not impossible for the object-centered coordinate system to explain the occurrence of mental rotation. It suffices to assume that mental rotation is employed to align a viewer-centered coordinate and an object-centered coordinate of a perceived object. However, it follows from this assumption that mental rotation is mandatory whenever a perceived object is disoriented from its canonical orientation. In other words, the absence of mental rotation cannot be explained. Thus, the object-centered coordinate system is able to cope with only one of the presence and the absence of mental rotation whereas the subject-centered coordinate system explains both. Apart from mental rotation, furthermore, the object-centered coordinate system has no basis to account for the influence of orientation change upon the appearance of a form (see Takano, 1987, for more detailed discussion).

translation were examined in Fig. 3. It turned out that the curvature of a line and the distance between two or more figural elements are orientation-free. Other factors (e.g., the length of a line or an angle between two lines) are also unaffected by a frontal plane rotation. It is important, however, to realize that the same orientation-free/bound distinction may not apply to other types of rigid transformations.

When a figure rotated in depth is projected onto the retinal surface, such parameters as line length and angle will change their values. When a square, for example, is slanted in depth so that its top edge recedes from the viewer, its retinal projection will become a trapezoid. In this case, the parallelism between the two vertical edges of the square is seemingly destroyed. A simple translation within a picture plane could produce a similar distortion: the projection of a square located above the line of sight is essentially a trapezoid. Strictly speaking, therefore, genuine frontal surface transformation has to be defined separately from simple picture plane transformation.⁷ Only when a rigid transformation of an object is made inside a genuine frontal surface does the classification into the proposed four types of information apply as it is. Otherwise, some kind of depth rotation is introduced, and the same classification schema no longer applies. However, it is not meant that the information type theory is entirely invalidated by depth rotation. The classification schema itself remains useful, though the concrete contents of each category (e.g., angle as combination information) have to be reclassified accordingly (Takano, 1987). The purpose of the present paper, however, is to investigate per-

⁷ A genuine frontal surface is defined as a surface in which all the points are the same distance from the eye. As an approximation, it is convenient to imagine a hemisphere; the eye is located at its focus. Imagine further two axes on the inside surface of this hemisphere. These axes are perpendicular to each other, intersecting at the point where the line of sight meets the hemisphere. Although both axes are curved along with the hemisphere, they should look straight for the eye. Whenever the line of sight moves, these imaginary axes are supposed to move together on the inside surface of the hemisphere. A form will *not* suffer from any nonrigid distortion if it moves on the inside surface of the hemisphere, keeping the angle with the line of sight unchanged. Similarly, no distortion will occur if the form is on a tangent plane that touches the hemisphere at the same point where the line of sight meets the hemisphere. Provided that this tangent plane slides along the outside surface of the hemisphere with the given form on it, the retinal image of the form projected from that plane will remain undistorted. This time, the two imaginary axes are assumed on the tangent plane. In both cases, the line of sight is not supposed to shift inside the form because its shift means a change in the angle between the form and the line of sight, namely, a depth rotation. Under these circumstances, if the form changes its orientation only in relation to the two imaginary axes on the hemisphere or on the tangent plane, then a genuine frontal surface rotation will result. The distinction between orientation-free information and orientation-bound information explained in the text is valid, strictly speaking, only in such genuine frontal surface rotation; the distinction can be made solely on the geometrical basis in this case.

ception of forms transformed in a genuine frontal surface; the depth rotation case will not be explored further.

In actual mental rotation experiments, a test figure is rotated in a picture plane, not in a genuine frontal surface. Besides, subjects are free to move their line of sight in that fixed picture plane. As a result, a certain amount of depth rotation is inevitably involved. The test figure, however, usually subtends a visual angle of only several degrees in typical mental rotation experiments. The amount of depth rotation due to eye movements within this range of visual angle will be negligible given the limited acuity of human eyes. Accordingly, it seems to be reasonable to consider an orientation change of a presented test figure in a picture plane as a genuine frontal surface rotation. In the following discussion, the orientation-free/bound distinction in the genuine frontal surface rotation will be invoked to examine those experiments that varied the orientation of a test figure in a picture plane.

The orientation-free/bound distinction in a frontal surface is completely determined in a geometrical manner (see Footnote 7). Therefore, the distinction may be regarded as an objective one. Nevertheless, it is still possible that humans may not encode all of the objectively existing information. If this is the case, the free/bound distinction in mental representations of forms will become an empirical problem. This issue is investigated experimentally in a later section.

Hierarchical Organization

The elementary/conjunctive distinction implies some kind of hierarchical organization because a conjunction of two or more elements has to reside in a "later" or "higher" level in a perceptual system in order to preserve the elements separately from their conjunctions. In general, hierarchical organization is known to give large flexibility to a perceptual system in describing a form (Leeuwenberg, 1971; Palmer, 1975). The elementary/conjunctive distinction provides a case that confirms the necessity of hierarchical organization.

It is also required by multiple encoding of elements. In Fig. 4, a horizontal elongation containing all five geometric figures is perceived although there is no horizontally elongated line "objectively." Some mechanisms proposed for early visual processing may account for perception of such an elongation. Marr (1982; Marr & Hildreth, 1980), for example,



FIG. 4. An instance to demonstrate multiple encoding. A large horizontal elongation is perceived in addition to the individual line segments.

assumed "filters" of various scales to detect line segments. A coarse filter among them will respond to the above horizontal elongation if it is given an array of figures as in Fig. 4. The same elongation will also be detected by Fourier analyzers (Kabrinsky, 1966; Ginsburg, 1973; Wilson & Bergen, 1979). It is highly probable that such an elongation may be treated as a basic element in the perceptual system because it has been detected directly, rather than indirectly through combining smaller elements. On the other hand, finer filters or analyzers will detect many smaller line segments that constitute triangles and rectangles in Fig. 4. Some kind of hierarchical organization is indispensable to relate those smaller elements to the larger one (i.e., the horizontal elongation in this case), both of which are concerned with the same visual stimulus.

Incidentally, the idea of multiple encoding provides a clue as to how the orientation of a whole object is represented in the information type theory. The elongation of an object is detected as a large scale element by a coarse filter or analyzer. The orientation of an element is represented by absolute orientation information. In this case, however, the orientation of the detected element happens to be the orientation of the whole object. Thus, the orientation of an object is represented by absolute orientation information in the framework of the information type theory.

The Basis of the Elementary/Conjunctive Distinction

The assumption of multiple encoding of the same stimulus leads to a reconsideration of the following problem: how should a line between elements and their conjunctions be drawn? Given the possibility of multiple encoding, it is hard to decide what features are actually treated as elements in the human perceptual system.⁸ This cannot be determined

⁸ It is important to specify elements accurately. Otherwise, confusions may arise. For example, Hoffman and Richards (1984) have proposed a method to partition a visual field into its constituent parts. The method itself seems promising. However, they have suggested that it is only the interrelations among parts not the parts themselves that are affected by orientation change. This suggestion seems to be misleading. What they call a "part" is an area that is surrounded by certain boundaries on the surface of an object: e.g., a quadrangular step in a flight of stairs. However, it is well known that the appearance of such a "part," in fact, depends on its orientation. A square, for example, looks like a diamond when it has been tilted by 45° in a picture plane. Such a change in appearance occurs because a square is not really a single part. A square is better conceived as a conjunction of four or five elements: four lines and probably a closure (see Treisman, 1986). It is true that the identity of an element is independent of its orientation. But the identity of a conjunction is not. In order to identify a conjunction, its structural description has to be consulted. This description consists of two different types of information: orientation-free (combination) information and orientation-bound (relative orientation) information. The latter is vulnerable to orientation change. For instance, a pair of two parallel lines of a square has an "above-below" relation while the other pair has a "right-left" relation. After the square has been tilted, these orientational relations do not apply any more. It seems reasonable to assume

simply by examining physical properties of a stimulus. It is logically possible that no conjunction is formed at all. There can be a processing system that extracts every piece of necessary information as a single independent element by multiple encoding in earlier stages of processing, without forming any conjunction in later stages. Such a system may be very inefficient, but it is still possible. Conversely, it is not logically tenable to assume a system that uses conjunctions alone without encoding any elements; the elements to be conjoined must be extracted somewhere in earlier stages of processing.

It is possible, however, that a higher level processor does not have any direct access to those primitive elements. For instance, information extracted by a single cone on the retina does not seem to be directly available to a higher level processor that underlies consciousness. Only conjunctive information based on multiple cones is accessible. In such a case, this conjunctive information must behave as elementary information for that higher level processor. What behaves as conjunctive information for that processor is a conjunction of conjunctions. Therefore, the distinction between elementary and conjunctive information must be made with respect to a particular processor in a particular processing system. In this way, what is elementary information and what is conjunctive information are genuinely empirical questions.

The proposed distinction, elementary/conjunctive, then has to be redefined with reference to some particular processor in the human perceptual system. This is admittedly a difficult task because precise knowledge as to the construction of the system is not available at present. The best candidate for that processor, however, seems to be a hypothetical central processor that contributes to the control of voluntary responses while consulting available visual information. One reason is that this hypothetical processor (or a set of processors, perhaps) is crucial in explaining overt behavior of the whole system (i.e., a human). Another reason is that this processor appears to be critical in understanding our own conscious experience as to the elementary/conjunctive distinction (recall Fig. 3). It is true that the above specification of the processor is somewhat ambiguous. But it excludes a number of irrelevant candidates for elements. For example, information encoded by a single cone will never be referred to

that the change in appearance is caused by such a change in internal description. In this way, a "part" is not orientation-free. What is actually orientation-free in their theory is the proposed procedure to find boundaries surrounding a part: in other words, identification of border lines. It corresponds to identity information in the framework of the information type theory. It is indeed orientation-free. The information type theory and the theory proposed by Hoffman and Richards (1984) could be integrated naturally because the information type theory leaves unanswered the question how to find individual elements. At any rate, the above instance clearly shows the importance of accurate specification of elements.

as an element in the present theory because that information does not seem to be directly accessible for the above-defined central processor. A more precise specification of the processor requires more precise knowledge about the human perceptual system; but more precise knowledge about the human perceptual system seems to require a tentative specification of the critical processor.

Analog/Propositional Problem

The information-type theory would be best expressed by so-called "propositional representation." Nevertheless, the theory does not commit itself to a firm position on the analog/propositional controversy (see Kosslyn, 1980; Pylyshyn, 1984). As discussed elsewhere (Takano, 1981), there is no agreed-upon logical distinction between the two concepts, "analog" and "propositional." Consequently, it is impossible to decide *strictly* whether a given representation is "analog" or "propositional." What could be done would be, at best, to judge whether the given representation would look more similar to certain prototypical "analog" representations or to certain prototypical "propositional" representations. Yet these prototypes in mind may well vary from one psychologist to another. What is more, even a prototypical "analog" representation would be able to behave just like a prototypical "propositional" representation if coupled with appropriate processors (Anderson, 1978).⁹

What the information-type theory requires is simply that form perception has to go through a certain process that would be carried out most easily by prototypical "propositional" representations. The process may be carried out by a set of prototypical "analog" representations and their appropriate processors. In addition, the information type theory does not deny the possibility that "analog" or "holistic" representations may be used elsewhere in the system for different purposes other than form recognition. For example, an image may be "rotated" in an "analogical" or "holistic" fashion, though subsequent matching processes may depend on "propositional" representations.

THE PUZZLES RECONSIDERED

In the preceding section, a theoretical framework of form perception was presented and discussed. We now return to the questions about mental rotation introduced in the first section to see whether the proposed

⁹ Note that Anderson's strong requirement of *real time* mimicking is not indispensable here. A critical point is that both analog representation and propositional representation could always end up with functionally equivalent mechanisms if appropriate additional assumptions were provided. This statement is derived from a more general principle that any limited set of data has an infinite number of possible explanations (see Takano, 1981, for more detailed discussion).

theory is able to provide reasonable answers for them. The answers are straightforward in some cases with direct experimental evidence to be presented in later sections. In other cases, however, the provided explanations need some additional assumptions, and their empirical confirmation is left to future efforts. In any case, the proposed theoretical framework turns out to be a reliable basis for better understanding of various problems concerning perception of rotated forms.¹⁰

Presence and Absence of Mental Rotation

When is mental rotation needed and when is it not needed? In a mental rotation experiment, the difference between a target and a nontarget can be defined unambiguously. What subjects have to do in order to respond correctly is simply to detect this difference, i.e., the information that distinguishes the nontarget from the target. The response should be positive if the information in question is absent, and negative if it is present. The information-type theory predicts that mental rotation will be needed if the above critical information is orientation-bound and that mental rotation will not be needed if the critical information is orientation-free. The reason is that the critical information is immediately interpretable regardless of orientation change if it is orientation-free, whereas the critical information is interpretable only after the orientation of a test figure has been made canonical if that critical information is orientation-bound.

Corballis et al. (1978) confirmed for the first time that there was a case in which no mental rotation occurred. In their study, the subjects had to identify a letter among six well-defined alternatives: *G*, *J*, *R*, 2, 5, and 7. In this set of alternatives, differences in orientation-free information are sufficient to discriminate one from another. There are no pairs of letters that differ only in orientation-bound information, as do the lower-case letter pairs, *b* and *d*; *p* and *q*. In Eley's (1982) study as well, there was no pair of figures that were right-left or up-down reversals of each other. The same holds true for the classification task in Corballis and Nagourney (1978): no Roman characters could be transformed into Arabic numerals by simple mirror reversal. Although the mirror images of the letters were also included in the stimulus sets used in the above two studies by Corballis and his associates, their subjects were not required to discriminate between mirror images; the subjects responded to a letter and its mirror image in the same way. As the critical differences were thus orientation-

¹⁰ In addition to the problems to be discussed below, the information type theory is helpful in understanding the following problems as well: how to know the shorter path of rotation before starting mental rotation (see Takano, 1985); a seeming contradiction between eye movement data (Just & Carpenter, 1976; Carpenter & Just, 1978) and the data (Cooper, 1976) that suggest holistic rotation (see Takano, 1985); and the "Margaret Thatcher illusion" (Thompson, 1980) (see Takano, 1987).

free, the subjects in those experiments did not have to "rotate" the presented stimuli back to their canonical orientations in order to discriminate among them.

On the other hand, the subjects were required mirror-image discrimination in all the experiments where mental rotation was confirmed. Mirror images share all orientation-free information with each other; the only difference between them is relative orientation information (i.e., right or left) as in Figs. 3a and 3b. As relative orientation information is orientation-bound, the corresponding pieces of relative orientation information cannot be directly compared between two figures when they are placed in different orientations. The subjects have either to make the orientations identical by mental rotation, or to circumvent direct comparison of the corresponding pieces of relative orientation information by resorting to some other figure-specific strategies like the "corridor-walk" strategy to be discussed in the next subsection.¹¹

Shepard and Metzler (1971) seem to have been at least partially aware of the above condition for the occurrence of mental rotation when they chose mirror-image nontargets: "The choice of objects that are mirror-images of each other for the 'different' pairs was intended to ensure that the decision as to whether the two objects were the same or different was made only on the basis of global shape and not on the basis of any local features" (Metzler & Shepard, 1974, p. 148). The distinction between "global shape" and "local features," however, is not precise enough to distinguish the cases where mental rotation is necessary from the cases

¹¹ The distinction between clockwise and counterclockwise directions apparently belongs to the category of relative orientation information, for it is concerned with the orientational relationship between two points on the locus of rotational movement. However, no mental rotation is needed to judge whether a given direction is clockwise or counterclockwise, wherever the movement may be proceeding. It may thus appear that the clockwise/counterclockwise distinction constitutes a piece of counterevidence against the proposed explanation of mental rotation. This is not the case, however. Mental rotation may be unnecessary simply because both kinds of transformation (i.e., clockwise rotation and counterclockwise rotation) have already been encoded for each quadrant, probably on the basis of innumerable experiences with clocks. For example, when the locus of a given rotation is convex to the *right*, the rotation is clockwise if it moves *downward* and counterclockwise if *upward*; when the locus is convex to the *left*, these relations are reversed. By memorizing these rules, the clockwise/counterclockwise distinction can be made without resorting to mental rotation, wherever the locus of a movement may be located. In other words, the reason why mental rotation can be omitted is that the outcomes of a rotational movement have been pre-stored in memory. Once the outcomes are available, an actual rotational movement need not be performed any longer to classify an example. The same principle would apply to the Shepard-Metzler objects as well. If the relative orientation information in the description of an object is memorized separately for every quadrant, there will be no need for mental rotation in discriminating it from its mirror-image (see Takano, 1987, for more comprehensive discussion).

where it is unnecessary. A change in "global shape" may be orientation-free and therefore not require mental rotation if it affects only combination information as in Figs. 3a and 3f (see also Experiment 1). Even identity information may sometimes be global, as in the case of Marr's (1982) coarse filter output.

The above counterargument against the global/local distinction is valid for the Shepard-Metzler objects as well. Take one of those objects as a concrete instance (Fig. 1a). According to Sayeki's (1981) analogy, this object can be seen as a sitting human body who extends the right "arm" horizontally. In the case of its mirror-image (Figure 1b), the body extends the left "arm" instead of the right "arm." This difference in relative orientation information is orientation-bound and its detection requires mental rotation when a test figure is disoriented. But now imagine that an "arm" is extended to the *front* in a new nontarget. This modification is "global," just as the modification in which the right "arm" was replaced by the left "arm." However, it creates a change in combination information: the "arm" and the "laps" are pointing in the same direction in this new nontarget while they are extended in different directions in the target. This difference between the target and the nontarget remains intact after any disorientation. Therefore, mental rotation is unnecessary when this new nontarget is used together with the former target (Fig. 1a). It is now clear that the global/local distinction is not a satisfactory criterion for predicting the necessity of mental rotation.¹²

The results of previous mental rotation studies are consistent with the proposed explanation in terms of the information type theory. Mental rotation is confirmed when only relative orientation information is different between targets and their mirror-image nontargets (see Shepard & Cooper, 1982). A seeming exception, however, is found in the study of Cooper and Podgorny (1976). Together with the typical mirror-image nontarget, they also used six non-mirror-image nontargets for each target. These nontargets were created by changing the contour of the target random polygon. Therefore, identity and/or combination changes had to be contained in these nontargets. Nevertheless, reaction time increased linearly with angular departure, indicating that mental rotation had been performed. At first glance, this finding seems to contradict the explanation proposed above. But in fact, their experimental procedure simply forced the subjects to perform mental rotation, irrespective of the types of

¹² It is worth noting that the above difference in combination information is immediately detectable without mental rotation even when a depth rotation is involved. That is, the current explanation of the necessity of mental rotation is valid for both two-dimensional and three-dimensional cases, as far as the Shepard-Metzler objects are concerned (see Takano, 1987, for further discussion). As a matter of fact, almost all mental rotation studies dealing with depth rotation have employed the Shepard-Metzler objects or their variations.

nontarget. On every trial, the subjects were first shown one of the targets in its upright position. Then an arrow was shown in a certain orientation and the subjects were required to prepare the image of the target in that orientation. When the preparation was completed, the subjects pressed a button and the arrow was replaced by a test figure in the same orientation. They were to judge whether it was identical to the prepared image or not. The time between the presentation of the arrow and the completion of the preparation was found to be proportional to angular departure; this was taken as evidence of mental rotation. In this procedure, however, the subjects could not rely solely on the difference in identity of combination information even when such a difference was actually contained in a presented test figure. The subjects always had to prepare for the case in which the mirror-image nontarget might be tested, because they had no prior knowledge as to which type of nontarget would be tested next. The only reasonable preparation in this procedure, therefore, was to rotate the image of the presented target as a whole into the indicated orientation and to keep it intact there for later comparison. Otherwise, it would be impossible to make a correct discrimination when a test figure is the mirror-image nontarget that contains no difference in identity or combination information. The procedure peculiar to this experiment thus prevented the subjects from utilizing identity or combination changes effectively. Therefore, the study by Cooper and Podgorny (1976) does not present any substantial counter-evidence to the present explanation of mental rotation.

Recently, Jolicoeur and Landau (1984) found that error rates in *identification* of alphanumeric characters increased with angular departure from the upright. Jolicoeur (1985) also found that *identification* time had been roughly proportional to angular departure before the subjects experienced sufficient practice, and that the practice effect did not transfer to a novel set of characters. These findings constitute qualifications for the findings by Corballis and Nagourney (1978), Corballis et al. (1978), and Eley (1982) cited earlier. At first glance, they appear to contradict the currently proposed explanation of mental rotation. In actuality, however, they can be given logical explanations by the information type theory combined with a few additional assumptions. It is reasonable to assume that the mental representation of an alphanumeric character is composed of orientation-bound information as well as orientation-free information. Usually, both types of information can be consulted in identifying the character. When the character is disoriented, however, it is orientation-free information alone that can be employed in identification. A higher error rate is then predicted for two reasons. First, the amount of useful information is smaller. Second, the recognition system has to make some

effort to ignore irrelevant orientation-bound information which is automatically encoded and usually consulted. Furthermore, it seems reasonable to assume that some amount of practice is indispensable to tune the recognition system so that it relies only on orientation-free information. Then longer time will be needed for identification before the tuning is complete. Mental rotation may well be carried out from time to time during this initial period. It follows that the overall reaction time will be proportional to angular departure as long as there is insufficient practice. With feature-extraction models such as the pandemonium (Selfridge, 1959) in mind, it appears reasonable to assume that the recognition system is tuned not to orientation-free information in general, but to particular pieces of orientation-free information that are actually contained in a particular character to be identified. If this is the case, then it is predicted that the practice effect in identification time will not transfer to different characters (as actually shown by Jolicoeur, 1985). The same line of explanation seems to apply to the findings that reading inverted letters induces more errors and longer reading time than reading upright letters (e.g., Kolars & Perkins, 1969a, 1969b). The proposed theory thus appears to be capable of explaining the seemingly contradictory findings if it is provided with reasonable additional assumptions for individual cases.

Thus far, the proposed explanation of mental rotation seems to depend only on the distinction between orientation-free information and orientation-bound information. What is the role of the other distinction, elementary versus conjunctive?

To begin with, it is important to note that absolute orientation information is totally useless in explaining the conditions requiring mental rotation. It has already been seen that the orientation of an entire object can be represented by absolute orientation information if its elongation is encoded as a larger-scale element. Now suppose that the orientation of an object is taken as a criterion to discriminate between a target and a nontarget in a typical mental rotation experiment. More concretely, suppose that Fig. 3b is a target and Fig. 3c is a nontarget. The only difference between them is absolute orientation information: the object is upright in Fig. 3b while the otherwise identical object is inverted in Fig. 3c. What if the same object is presented at 90° as a test figure? Is it a target or a nontarget? There is no reasonable answer.

Such a confusion occurs because absolute orientation information serves as an independent variable in a mental rotation experiment. As the value of the independent variable has to be varied, it cannot be used as a stable basis for discrimination; it cannot be used to define the difference between a target and a nontarget. The discriminatory criterion thus has to be set on a dimension separate from absolute orientation information. In

order to explain the presence and absence of mental rotation, the nature of that criterion has to be clarified. In this way, absolute orientation information is irrelevant in order to explain the necessity of mental rotation.

Of course, it would be possible to change absolute orientation information only for an individual element, leaving the orientation of the whole object unaltered. However, such a change cannot occur in isolation; it will always be accompanied by changes in other types of information. Suppose, for example, that the orientation of the vertical bar in Fig. 3a has been changed by 30 degrees in order to create a nontarget. It will be found, however, that the angle between that bar and the horizontal line has also been changed. The angle is considered to belong to combination information, which is orientation-free. Thus, there is no case in which a rotated object must be identified only on the basis of absolute orientation information of individual elements.

It is relative orientation information alone that can be used to define the difference between a target and a nontarget in an experiment where mental rotation is required. Relative orientation information does not constitute the independent variable in a mental rotation experiment; the difference between a target and a nontarget defined in terms of relative orientation information is not invalidated by any change in the value of the independent variable (i.e., rotation of a whole object). At the same time, that difference is affected by the rotation in such a way that it becomes undetectable without correcting the orientation of the whole object. In this way, only relative orientation information in the category of orientation-bound information plays a critical role in explaining the presence and absence of mental rotation, while absolute orientation information does not. What distinguishes relative orientation information from absolute orientation information is the elementary/conjunctive distinction. Therefore, the explanation of mental rotation requires the elementary/conjunctive distinction as well as the orientation-free/bound distinction.

One might suspect from the discussion thus far that the proposed explanation of mental rotation together with its underlying theory is related only to form *recognition*, and not to form *perception* in general. This is not the case, however. It is true that differences in relative orientation information cause a problem only when an object that has once been *perceived* has to be *recognized* later. However, this is simply because disorientation cannot be a problem in the initial encounter with a novel object. What has to be done with a novel object is merely to encode it in its own orientation. There is simply no possibility of orientational discrepancies between the percept and the stored representation, because the latter does not exist. If relative orientation were not encoded at all at the time of the initial perception, there would certainly not be the problem

of disorientation at the time of later recognition; instead, however, there would be no way to discriminate between mirror images. Relative orientation information has to be encoded at the very beginning in perception, whether it later becomes helpful or bothersome. Thus, the explanation of form *recognition* provided by the information type theory makes sense just because the theory applies to form *perception* in the beginning.

"Orientation-Free" Description with Orientational Terms

Given the arguments in the second section on a theory of information types, it is not hard to realize what the "corridor-walk" strategy was actually doing. Figure 1c was coded by three turns, "down, left, right." In relation to the viewer's body, however, the same turns are "up, right, up." In order to get the former set of turns, the subject-centered orientational framework has to be rotated whenever the imaginary walker takes a turn, so that the framework coincides with the walker's body, not with the viewer's body. In this particular instance, three different frameworks were used successively to code the three turns. Every one of those frameworks is different from the orientational framework that is consistent with the viewer's body. The resultant codes depend on such directional terms as down, left, and right. They are not orientation-free; they are bound to the above orientational frameworks centered on the imaginary walker. Although the "corridor-walk" strategy has succeeded in avoiding mental rotation by taking advantage of the subject-centered nature of the orientational framework, the strategy has not succeeded in releasing the descriptions of the objects from orientation per se. It simply replaced mental rotation of an object by rotation of an orientational framework.

Just and Carpenter (1985) seem to have suggested that any pair of figures can be provided with orientation-free descriptions, whenever they have become familiar enough. This suggestion does not seem to be warranted. In principle, differences in relative orientation information like those in mirror images can be described only in reference to a certain orientational framework. Descriptors like "up," "down," "right," and "left" would have no meaning without such a framework. It may be possible to devise a figure-specific strategy to circumvent mental rotation as in the case of the "corridor-walk" strategy as well as the strategy used by Thomas (cited in Metzler & Shepard, 1974). However, such a strategy is simply utilizing relative orientation information in a different manner while assuming a certain orientational framework; the resulting description is not orientation-free at all. A real "orientation-free" description must be defined so that it remains invariant regardless of any change in the relation between an object and an orientational framework.

"Knowing the Answer Beforehand"

The idea that some kinds of information are available to recognize a titled figure in advance of mental rotation makes it possible to understand the problem of "knowing the answer beforehand." The availability of orientation-free information together with some general rules of transformation (to be discussed below) often makes transformed relative orientation information interpretable without rotating back an entire mental image.

If an element *A* is to the right of another element *B* when a certain object that contains *A* and *B* is upright, *A* will be located below *B* when the whole object has been rotated clockwise about 90°. Similarly, *A* will be brought to the left of *B* by a rotation of about 180°, and so forth. These are general rules that could be applied to any configuration of elements. For example, when the back side of a hand is shown in the upright position, the hand is a right hand if its thumb is to the left of the palm; it is a left hand if the thumb is to the right. When the hand is upside down, the orientational relation between the thumb and the palm is reversed. It is not hard to judge, on the basis of orientation-free information, which part is the thumb and which part is the wrist as opposed to the tips of fingers. If subjects are able to utilize such rules, their behavior will look as if they know the very answer as to whether the presented hand is a right hand or a left hand before actually performing mental or physical rotation. For example, if a hand is presented in the upside down position and has its thumb on the right, the rule tells the subjects that the hand is a right hand. Thus, they can start rotating the correct hand or its image without trial and error in such experiments as Sekiyama's (1982, 1983).

If the subjects were fully skilled in the use of these rules, however, they would not have to perform mental rotation at all. As a matter of fact, they do. Therefore, it must be assumed that their ability to apply the rules is too unreliable to be used in a speeded task and that mental rotation is needed for reliable confirmation. Although these additional assumptions seem to be congruent with our intuition, empirical tests are desirable. They are not attempted in this paper. However, it must be stressed that the information-type theory has provided a logical framework for a reasonable explanation of the otherwise paradoxical phenomenon.

The longer reaction time for backward (mirror image) alphanumeric characters (Corballis et al., 1978; Corballis & Nagourney, 1978) may be explained in a similar way. In their studies, the subjects were required to identify a rotated character regardless of whether it was normal or backward. A backward character should not match the representation of its normal version with respect to relative orientation information in the rotated position. Nevertheless, the subjects had to respond to the back-

ward character positively just as to the normal one. If this mismatch in relative orientation information is detected on the basis of the general rules discussed above, a negative signal will be internally generated. The subjects have to do something to suppress this signal before emitting a positive response. This suppression may well cause a slight delay in their reaction.¹³ The result will turn out to be a slightly longer reaction time for a backward character just as observed by the above researchers.

ORIENTATION-FREE AND ORIENTATION-BOUND INFORMATION

In the preceding section, all the puzzles reviewed in the first section have been given reasonable answers within the proposed theory of information types. In the subsequent four sections, the basic assumptions of the information type theory will be submitted to empirical tests. The proposed four different types of information stemmed from the orthogonal combination of two binary distinctions: orientation-free and orientation-bound on the one hand, and elementary and conjunctive on the other. In order to establish the distinctions among the four different types of information, accordingly, each of the two binary distinctions must be confirmed separately. In the first experiment, the mental rotation paradigm will be used to see whether the distinction between orientation-free information and orientation-bound information is actually playing a significant role in human form perception. Experiments 3 through 5 invoke the visual search paradigm to confirm the elementary/conjunctive distinction within each of orientation-free and orientation-bound information. Experiment 2 constitutes a part of the effort to establish the free/bound distinction, but its principal purpose is to investigate the problem of encoding failure.

¹³ There are other possibilities as well. The magnitude of the positive response may have been reduced by the negative signal or the negative signal may have triggered further confirmation, which consumed additional time. At any rate, it must be noted that any such accounts have to presuppose the detection of the mismatch, which is the core of the explanation by the information type theory. Still another type of explanation exists: some of the subjects may have simply memorized the shapes of disoriented characters as in the case of the clockwise/counterclockwise distinction (see Footnote 11). The phenomenon, "knowing the answer beforehand," has been observed only with regard to alphanumeric characters and hands thus far; it is not rare experience to see letters and hands in unusual orientations. It is thus not surprising that subjects may have some memory about disoriented letters or hands. But what are the contents of that memory? They must be the outcomes of applying the above rules of transformation. For example, when a right hand has been rotated by 180°, the thumb is now to the right of the palm; then memorize this relative orientation of the thumb and the palm for later use. It is always true that the memory of the outcome of a certain rules saves its actual application, as far as particular objects memorized are concerned. However, the same principle underlies both memory and application; hence this last explanation is essentially identical to the one proposed in the text.

As stated in the preceding section, mental rotation will *not* be needed to discriminate a tilted target from a tilted nontarget if they differ from each other in orientation-free information. If their difference is only in relative orientation information, mental rotation or other functionally equivalent strategies will have to be employed. As shown in earlier mental rotation studies, the majority of subjects will choose mental rotation in this case because other possible strategies such as “corridor-walk” consume too much time to be employed in a speeded task. Accordingly, reaction time for discrimination is expected to increase with the amount of tilt in the case of the relative orientation difference. By contrast, reaction time should be insensitive to the amount of tilt in the case of the orientation-free difference. The first experiment was designed to test this prediction in an attempt to confirm the distinction between orientation-free and orientation-bound information. Although previous mental rotation studies are in complete agreement with this prediction, none of them tested it systematically. Besides, identity information and combination information have never been examined separately. Thus, to be specific, the present experiment is designed to test the distinction between relative orientation information on the one hand and identity and combination information on the other. Although this experiment attempts to establish the distinction between orientation-free information and orientation-bound information, an absolute orientation change is not included in the definition of the difference between a target and a nontarget. As stated earlier, it is impossible to define that difference in terms of absolute orientation information in a mental rotation experiment. However, absolute orientation information is orientation-bound by definition (recall that a vertical line that has been slanted by 30° is not vertical any more). There seems to be no need for experimental confirmation as to this fact.

A two-dimensional line drawing shown in Fig. 3a was used as a target. Its mirror image (Fig. 3b) served as one of the nontargets, in which only relative orientation (*RO*) information has been changed. In order to create an identity (*I*) information change, a horizontal line in Fig. 3a was replaced by a curved line (Fig. 3d). In order to create a combination (*C*) information change, the vertical bar in the target was moved so that it would touch the filled square (Fig. 3f). This distinction between identity (*I*) information and combination (*C*) information was made intuitively. It is critically important to confirm that identity (*I*) information and combination (*C*) information are *both* orientation-free, in order to verify the theory. Whether the current *I* condition and *C* condition really reflect the *I/C* distinction is empirically examined in Experiment 3 using the same stimuli. The relatively simple stimuli in Fig. 3 were chosen to assure that their critical features would subtend a large enough visual angle when

they were scaled down so that a large number of them could be presented in the same display in Experiment 3.¹⁴

Experiment 1

Method

Subjects. Twenty-four undergraduate students at Cornell University served as *Ss*. Fourteen of them were male and 10 were female. Each *S* was tested individually and paid \$3.00 for participation in a 50-min session.

Stimuli. The figures shown in Fig. 3 were drawn by hand; slides were made from their photocopies. Figure 3a was consistently used as a target for each of three different types of nontarget (Figs. 3b, 3d, and 3f). Two sets of slides were prepared. In one set, each slide contained two figures placed side by side. The left (standard) figure was always the same target figure shown in its upright position as in Fig. 3a. The right (test) figure was either the target or one of the three types of nontarget. It was shown in one of the following six orientations: 0, 60, 120, 180, 240, and 300° clockwise. In the other set of slides, the target on the left was omitted; each slide contained the test figure alone on the right. The test figure in this set of slides was shown together with a red dot indicating the direction of its "top." The dot was placed just above the vertical bar in Figs. 3a, 3b, 3d, and 3f; it remained in the same position relative to the figure, regardless of the orientation of the whole figure. It was expected that the red dot would minimize the time spent in determining the orientation of the test figure, which appears to be proportional to the amount of disorientation (Metzler & Shepard, 1974). Similarly, it was expected that the single presentation would eliminate the time spent in comparing the test figure with the standard target figure. (This time component also appears to be proportional to the amount of disorientation; see Shepard & Metzler, 1988). These measures were taken so that the above two sorts of time would not be confounded with the time due to mental rotation. In each set of slides, half of them presented the target as a test figure while the other half presented the nontarget as a test figure. When the slide was viewed from a distance of 90 cm, each figure subtended a 5° visual angle. In the first set of slides, two figures were in an area of approximately 6° × 15° of visual angle.

Apparatus. The slides were mounted in a random access slide projector (GAF 2000AV), and rear-projected onto a translucent screen. An electronic shutter (Lafayette 43011) was attached to the projector. A response box was placed in front of the subject. It had two keys arranged side by side, each of which was 5 × 5 cm in size. The shutter was opened by *E* to project one of the slides onto the screen; at the same time, a timer (Hunter 120A) started. The pressing of one of the response keys by the *S* closed the shutter and stopped the timer; the pressed key was indicated by one of two lamps on a control box.

Design. One between-*Ss* factor was concerned with the presentation mode: whether a test figure was presented alone or together with the standard figure (the single condition and the double condition). Each *S* was randomly assigned to one of the two groups with the restriction that the proportion of males to females should be equal in both groups. Two other factors were manipulated within *Ss*: three levels of information type and six levels of orientation. There are six possible orders to test the three information types. In each group, two *Ss* were allocated to every possible order.

Procedure. The *S* was seated in a chair with the head fixed in the upright position by a

¹⁴ Results essentially identical to those in the present experiment have been obtained in another experiment using four other targets and their nontargets that are more complex (Takano, 1985).

chinrest, and with the index fingers on the response keys. The *S* was asked to press the key for the preferred hand as quickly as possible if the right-hand figure was the target, irrespective of its orientation, and to press the other key if it was not the target. Both speed and accuracy of response were stressed equally. At the outset of the experiment, the *S* was asked to copy the upright target on a sheet of paper with a pencil. This was to assure that the *Ss* in the single presentation condition would remember the target correctly, though the copying was imposed on the *Ss* in the double presentation condition as well. There were three sessions. Only one of the three nontargets was tested together with the target in each session. At the beginning of each session, one of the nontargets was shown together with the target, and then four practice trials were given using four randomly chosen slides. The *S* was next given twelve practice trials with all twelve slides to be used in that session. Every response was followed by feedback as to its accuracy in these practice blocks. After three warm-up trials with randomly chosen slides, three test blocks of twelve trials each were given. Feedback was provided only in response to the *S*'s request. At the end of the session, the slides on which the *S* had made errors were presented repeatedly in a random order intermixed with other randomly chosen slides until correct responses were obtained. The order of presenting the slides was randomized in each block. The same procedure was repeated in the remaining two sessions with different nontargets, except that the first practice block of four trials was omitted. On each trial, the *E* first asked, "Ready?," and the *S* responded orally if prepared. Then a slide was projected, and the timer started. As soon as the *S* pressed either key, the figure(s) disappeared and the timer stopped. The reaction time was recorded in milliseconds together with the response made.

Results

Every slide was tested three times for each *S*. A median RT was used in the subsequent analyses in order to avoid the effects of extraordinarily short or long latencies. The means calculated across *Ss* have been plotted in Fig. 5 against the angular departure from the upright direction. The 0° RTs have been plotted twice for 0° and 360°. There are three different functions in each panel of the positive response. The same target figure could produce these different functions because it could have very different meaning according to what nontarget was coupled with it in a particular experimental session. In the case of the *RO* (relative orientation) change, the functions attest to the occurrence of mental rotation, with the longest RTs at 180°. The functions for the *I* (identity) and *C* (combination) changes were almost flat, except for the two functions for the positive response in the *C* condition; they show very slight influences of angular departure.

The median RTs were submitted to a three-way multivariate analysis of variance (MANOVA).¹⁵ The analysis was conducted separately for the positive and negative response data. In the case of the positive response, the presentation mode (single versus double) made no difference either in

¹⁵ Although there was only one dependent variable, MANOVA was used to treat the within-*Ss* factors adequately. The following *F*-values are based on Rao's (1952) approximation; their corresponding degrees of freedom are all hypothetical values, except for the main effect of the between-*Ss* factor.

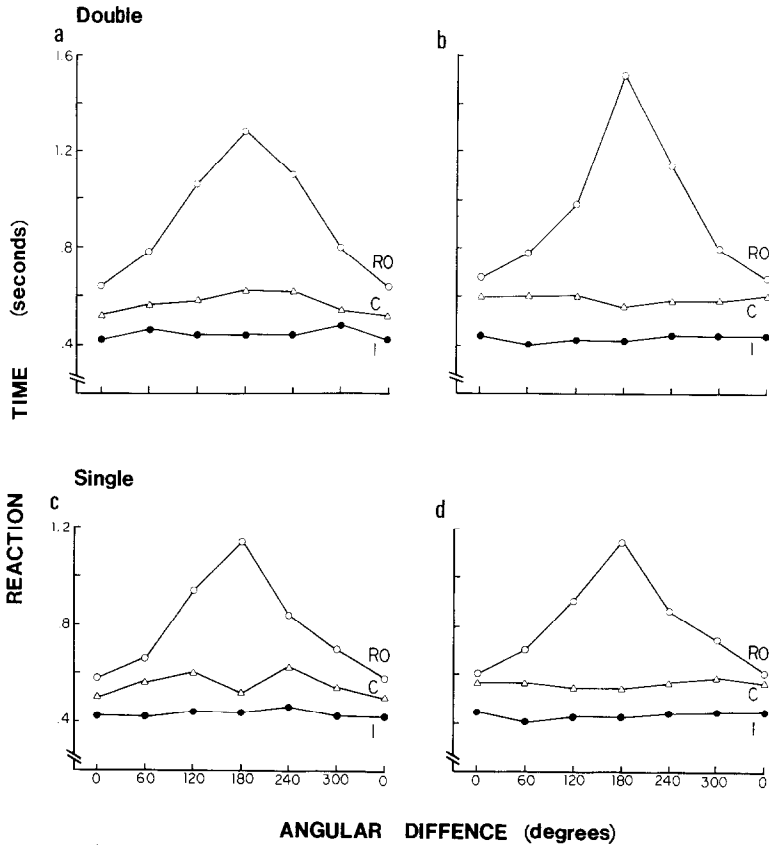


FIG. 5. Results of Experiment 1: Mean reaction time as a function of the orientation of a test figure. The upper graphs (a and b) show the results in the double presentation condition; the lower graphs (c and d) show the results in the single presentation condition. The left graphs (a and c) show the results for the positive response; the right graphs (b and d) show the results for the negative response. The open circles show the results in the RO condition; the triangles show the results in the C condition; the filled circles show the results in the I condition.

the main effect or in the interactions. Of primary concern is the interaction between the information type and the orientation. It was highly significant [$F(10,13) = 8.305, p < .001$]. The main effects were also significant ($p < .001$): $F(2,21) = 75.065$ for the information type, and $F(5,18) = 15.203$ for the orientation. A one-way MANOVA was conducted to see the effects of orientation for each combination of the information types and the presentation modes. For the single presentation, the orientation effect was significant in the RO condition [$F(5,7) = 10.387, p < .005$], and not significant in the I [$F(5,7) = 2.914$] or the C [$F(5,7) = 1.800$] condi-

tion. The same holds true for the double presentation: $F(5,7) = 8.282$ ($p < .01$) in the *RO*, $F(5,7) = 2.699$ in the *I*, and $F(5,7) = 2.381$ in the *C* conditions. The above mentioned slight influence of the orientation on RT for the positive response in the *C* condition was thus not reliable statistically in either presentation mode.

The negative response generated exactly the same pattern of results. In a three-way MANOVA, only the type-by-orientation interaction and their respective main effects were significant ($p < .001$): $F(10,13) = 7.084$ for the interaction, $F(2,21) = 56.946$ for the information type, and $F(5,18) = 9.537$ for the orientation. Only the *RO* condition showed significant orientation effects in one-way MANOVAs: $F(5,7) = 8.446$ ($p < .01$) in the single presentation condition, and $F(5,7) = 13.151$ ($p < .005$) in the double presentation condition.

The slopes in the linear regressions of RT on angular difference are presented in Table 1. (The angles, 240 and 300 degrees were converted into 120 and 60 degrees, respectively.) For the *RO* condition, the slopes were substantial and significant in every case. In contrast, half of the slopes for the *I* and *C* conditions were negative and all the absolute values were close to zero.

The error rates seem to reflect difficulty of judgment to some extent: 4.05% in the *RO*, 2.55% in the *C*, and 1.74% in the *I* conditions. It is clear that flat functions in the *C* and *I* conditions were not due to a speed-accuracy tradeoff. The overall error rate was 2.78%. The error rates had no correlation with the orientation or the presentation mode.

Discussion

The overall pattern of results is very clear in the predicted direction.

TABLE 1
Slopes of the RT-Angle Functions in Experiment 1

Response	Type	Presentation mode	
		Double	Single
Positive	RO	3.76***	3.17***
	I	.06	.18
	C	.55	.35
Negative	RO	4.65***	3.00***
	I	-.03	-.00
	C	-.20	-.11

Note. RO, Relative orientation change condition; I, identity change condition; C, combination change condition. The orientations 240° and 300° have been converted into 120° and 60°, respectively, in order to calculate linear regression slopes.

*** $p < .001$.

The RT increased with angular departure only when the nontarget alternative was a mirror image in which only the relative orientation (*RO*) information was different from that in the target. The increase of RT suggests that mental rotation was a predominant strategy as usual. Though the RT-angle functions were not strictly linear, this nonlinearity does not seem to question the occurrence of mental rotation because the functions are not always linear in typical mental rotation experiments (Cooper & Shepard, 1973; Hock & Tromley, 1978). The functions in this experiment are monotonically increasing up to 180° and then monotonically decreasing up to 360°. This seems to provide a reasonable basis to infer that mental rotation had to be performed in the *RO* condition.

In contrast, when there was a difference either in identity (*I*) information or in combination (*C*) information between the target and the nontarget, the angular departure did not produce any systematic change in RT, just as predicted by the theory. Although the slopes of the RT-angle functions (Table 1) were not precisely zero, none of them was statistically significant. It is unrealistic to expect exactly zero slopes because measurement errors are unavoidable. In the *I* and *C* conditions, half of the linear regression slopes were negative with the other half positive, which is in accordance with the chance expectation when the true slope is zero. It thus seems to be safe to conclude that mental rotation was unnecessary in both *I* and *C* conditions,¹⁶ while it was indispensable in the *RO* condition.

The single presentation combined with the red dot had little effect on the slopes in any condition as shown by the insignificant interaction between the presentation mode and the orientation. The absence of significant effects of the single presentation combined with the red dot seems to show that both comparison time and detection time are negligible when figures are as simple as those in the present experiment.

In conclusion, the findings in the present experiment attest to the fol-

¹⁶ Should the positive slopes in the *I* and *C* conditions be regarded as the evidence of very fast mental rotation? The answer seems to be negative. The estimated "rate of mental rotation" is 1818° per second in the slowest case (i.e., *C* change, positive response, and double presentation), and 16,667° per second in the fastest case (i.e., *I* change, positive response, and double presentation). By contrast, the "rate" is only about 60° per second in the case of the Shepard-Metzler objects (Metzler & Shepard, 1974), from 154 to 800° per second according to individual *Ss* in the case of familiar alphanumeric characters (Cooper & Shepard, 1973). Even when one of the Shepard-Metzler objects was familiarized by regarding it as a human body (Sayeki, 1981), the "rate" was only 1000° per second. The "rates" obtained in the present experiment seem too large to be considered as results of mental rotation. Would the notion of mental rotation have been accepted if the "mental rotation rate" had been of the order of thousands of degrees per second in the first place? Furthermore, the negative slopes in the present experiment are totally uninterpretable in terms of mental rotation.

lowing facts: First, the human visual system actually takes advantage of the difference between orientation-free information and orientation-bound information, as is valid in the frontal surface. Second, relative orientation information is actually encoded as orientation-bound information. Finally, at least one of identity information and combination information is orientation-free. Though *both* of them may well be orientation-free as formulated in the theory, it is possible that only one of them was tested in this experiment because the distinction between identity and combination was made only on an intuitive ground. The distinction is an empirical one as discussed before; both the *C* change and the *I* change assumed here may have been *I* changes in actuality, or, alternatively, both of them may have been *C* changes. The free/bound distinction in the information type theory cannot be fully established until *both* identity information and combination information are confirmed to be orientation-free. This problem is investigated in Experiment 3.

ENCODING REDUNDANT INFORMATION

This section presents another attempt to establish the distinction between combination information and relative orientation information. The primary concern here, however, is how figures are actually encoded by subjects in terms of these two types of information.

In the preceding section, a mirror image of a whole figure was used to create the relative orientation (*RO*) information change. An *RO* change could also be created by partial transformation instead of such global transformation. In Fig. 6b, for example, only the upper "hook" part of Fig. 6a has been "flipped" into the mirror-image, resulting in an *RO* change (i.e., the "opening" on the left of the "hook" has been moved to

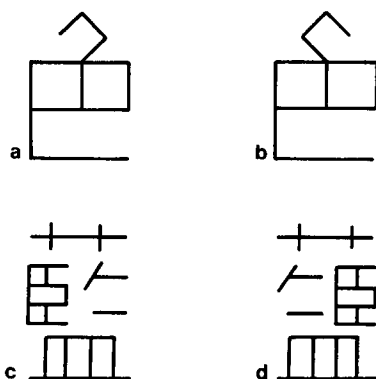


FIG. 6. A partial change in relative orientation information (a to b; c to d) is always accompanied by change(s) in orientation-free information. The figures (a, b, c) and their mirror-images (not d), were used in Experiment 2.

the right). Figure 6d was generated by exchanging the positions of two components in the middle of Fig. 6c. This transposition also induces an *RO* change (i.e., the right-hand component in Fig. 6c is on the left in Fig. 6d, and vice versa). Nonetheless, such partial transformations of *RO* were not adopted in Experiment 1 because they are always accompanied by orientation-free information change(s). In Fig. 6b, for example, the upper and lower "openings" are on the same side of the figure but they are on the opposite sides in Fig. 6a. This difference between the same side and the opposite sides remains unaffected after any orientation change of the whole figure. It is thus orientation-free; at the same time, it is concerned with relationship between two separate elements. Therefore, it should be classified as combination information. The difference between Fig. 6c and 6d can also be regarded as an orientation-free combination change: the T-like component in the middle of Fig. 6c is pointing outside while it is pointing inside toward the block-like component in Fig. 6d. There are exceptions to the above principle. If the middle part of Fig. 6c is "flipped" into the mirror-image instead of being transposed as in Fig. 6d, this "flipping" does not produce any orientation-free change. As the top and bottom unchanged parts of Figure 6c are both symmetric, the "flipping" of the middle asymmetric part results in the mirror-image of the whole figure, where *RO* information alone is different when compared with Fig. 6c. Except for such special cases, however, partial *RO* change is usually accompanied by certain orientation-free information change.

A question arises here: Is mental rotation necessary or unnecessary when *RO* has been changed only partly in a nontarget? The answer seems to be: It depends on how that change is encoded by *Ss*. If it is encoded as a change in *RO* information which is susceptible to disorientation, *Ss* will have to resort to mental rotation or some other functionally equivalent strategies. If it is encoded as a change in orientation-free information, the difference will be directly detectable without mental rotation irrespective of disorientation. Is it possible that *Ss* do not encode a combination change that is objectively present in a given figure? As stated in the second section, the four types of information often provide redundant descriptions. Consequently, a figure can be fully described without encoding all available information. In Fig. 6b, for example, the description based on *RO* information, "the upper opening is to the right and the lower opening is to the right," implies "both openings are to the same side," which is a description based on *C* information. Thus, Fig. 6b can be described in its entirety without representing the *C* information explicitly. It seems fully possible that overlapping information is left unencoded.

This possibility is important because it implies a case in which the prediction of the information type theory may not be actualized. According to the theory, mental rotation is expected when *RO* information alone

is different between two figures to be discriminated. Although the existing data are in complete agreement with this prediction, there is room for violations, theoretically speaking. If subjects fail to encode an orientation-free difference that is objectively present, mental rotation may have to be invoked to distinguish the figures on the basis of encoded *RO* differences. The next experiment was designed to investigate the possibility of this encoding failure.

Experiment 2

Figure 6a was used as a target and Fig. 6b as its nontarget in a typical mental rotation setting. According to the above reasoning, it was predicted that the orientation of a test figure should not affect RT if the *Ss* notice and encode the *C* change between the target and nontarget. On the other hand, when the *Ss* fail to notice the *C* change and encode the difference as an *RO* change, RT should increase with angular disparity because mental rotation should be needed as in typical mental rotation experiments. It is possible, however, that the *Ss* may notice the *C* change in the middle of the experiment because the same figure has to be presented repeatedly in the mental rotation paradigm. In the hope of assuring that the *Ss* might not become aware of the *C* change spontaneously, Fig. 6c and its mirror-image (*not* Fig. 6d) were presented to the *Ss* as a second pair of target and nontarget. This mirror-image pair was expected to work as a context to bias the *Ss* so that they would be inclined to encode the difference between Figs. 6a and 6b as an *RO* change. Of primary interest is the first pair of figures (Figs. 6a and 6b) which will be referred to as "critical figures," while the second pair (Fig. 6c and its mirror-image) will be referred to as "noncritical figures" because they are not directly related to the purpose of the current experiment.

Method

Subjects. The *Ss* were 20 Cornell undergraduate students, 4 males and 16 females. They were randomly assigned to two groups (the Inst group and the No-Inst group) with the constraint that the proportion of males to females should be identical in either group. Three dollars were paid for participation in a 40-min session.

Stimuli. Two sets of slides for the critical figures and one set of slides for the noncritical figures were prepared based on the same procedure as in Experiment 1. In both sets of slides for the critical figures, a test figure was presented in one of the following six orientations: 0, 60, 120, 180, 240, and 300°. Each of the first set of slides always contained the target figure in its upright position (as seen in Fig. 6a) on the left of the display field in addition to a test figure on the right. Each of the second set of slides contained a test figure alone on the right. A red dot was placed just above the "hook" part of the test figure in this set of slides; the dot always occupied the same relative position to the figure regardless of its orientation. The purpose of the single presentation and the red dot was the same as that in the preceding experiment. Each slide of the noncritical figures contained both the standard target figure on

the left and a test figure on the right. The test figure was presented in one of only three orientations (i.e., 0, 90, and 180°) to prevent an experimental session from being too long.

Design. Each *S* was tested individually in an experimental session, which consisted of three distinct subsessions. In the first subsession (Session 1), the *S* was tested in the double-presentation mental rotation paradigm with the first set of slides of the critical figures and with the slides of the noncritical figures. The *C* change described above was explained for one group of *Ss* (the Inst group) after Session 1. The other group of *Ss* (the No-Inst group) were not given this critical instruction. The functions relating RT to angular departure would be compared between these two groups, both before and after this critical instruction (or its corresponding dummy instruction in the case of the No-Inst group). The second subsession (Session 2) was devoted to practice with the same set of slides for the non-critical figures but with the second set of (single-presentation) slides for the critical figures. In the third sub-session (Session 3), the *S* was tested with the same sets of slides as in Session 2. In addition to a between-*Ss* factor (Inst versus No-Inst), there were two within-*Ss* factors: the sessions before and after the critical instruction, and the orientation with six levels.

Procedure. The same apparatus as in Experiment 1 was used. In Session 1, the noncritical figures were shown first with a standard mental rotation instruction as in the preceding experiment, and it was explicitly pointed out that the target and the nontarget were mirror images of each other. Next, when the critical figure was introduced in the instruction, the *S* was simply asked whether or not the difference between the target and the nontarget was clear enough. After this initial instruction, the *S* practiced in a block of 18 trials, in which every slide was shown once; the two kinds of figures were intermixed. Feedback as to accuracy was provided on error trials. Two test blocks of 18 trials each followed, with feedback given only upon the *S*'s request. Error trials were reassessed at the end of the last block as in Experiment 1 but only for the critical figures, with randomly mixed filler slides consisting of both kinds of figures. The order of presenting the slides was randomized in each block. Before Session 2, both groups of *Ss* were shown the single-presentation slides of the critical figures with the red dots, and asked to learn the critical figures well during the following practice session because the left-hand standard figure would be omitted in the last test session. They were also told to become accustomed to the use of the red dot as a cue to the orientation of a test figure. While looking at the same slides, the *Ss* in the Inst group were informed of the *C* change and told to "become skilled" in utilizing this change during the following practice session (the critical instruction). The *Ss* in the No-Inst group were not given this critical instruction. Session 2 was composed of two practice blocks of eighteen trials each without reassessment trials. What the *S* was required to do in a trial was the same as in Session 1. Session 3 was a test session which also consisted of two blocks of 18 trials each. Error trials for the critical figures were reassessed. Every block in every session showed each slide once according to a random order. At the end of the whole experimental session, the *Ss* were asked to report what strategies they had used in each session to decide on whether a test figure was one of the targets or not. The rest of the procedure was common to that in Experiment 1.

Results

Although measures had been taken to make it hard to find the *C* change spontaneously, 3 out of the 10 *Ss* in the No-Inst group reported that they had discovered it during Session 2. No *S* found it during Session 1 in either group.

Every slide was shown twice in each test session. The mean of the two RT values was used for the subsequent analyses. The RTs averaged

across the *Ss* for each test session have been plotted against angular departure in Fig. 7. In Session 1, typical mental rotation functions emerged in both groups. In Session 3, however, the functions for the Inst group became nearly flat, whereas the functions for the No-Inst group remained virtually unchanged with distinct peaks at 180° though their intercepts were reduced appreciably. This pattern of results is essentially identical for both response categories.

A three-way MANOVA was first applied to the positive response data. The session and the orientation had significant ($p < .001$) main effects [$F(1,18) = 20.722$ and $F(5,14) = 21.932$, respectively], while the group did not [$F(1,18) < 1$]. Of primary concern is the triple interaction among the group, the session, and the orientation. This interaction tests whether the presence of the critical instruction caused the flattening of the function; it was insignificant, however [$F(5,14) = 1.495$]. This may be due to too few degrees of freedom. Fortunately, the same triple interaction could be tested by a univariate ANOVA which has greater statistical power, because the sphericity assumption was not violated [$\chi^2(10) = 6.322$, $p > .70$]. The triple interaction was significant according to the ANOVA test [$F(5,90) = 3.020$, $p < .05$]. Among the double interactions, only the session-by-orientation interaction was significant [$F(5,14) = 7.491$, $p < .001$], which means that the slope of the RT-angle function was steeper in Session 1. The other double interactions were not significant.

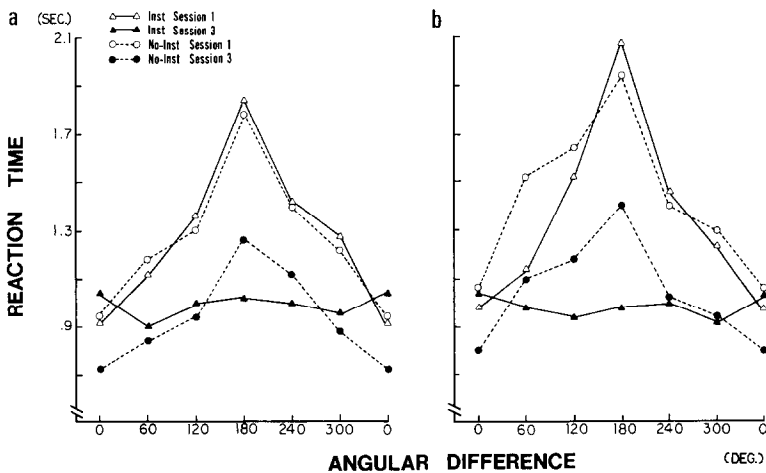


FIG. 7. Results of Experiment 2: Mean reaction time as a function of the orientation of a test figure. (a) The results for the positive response; (b) the results for the negative response. The solid lines show the results for the Inst group; the dotted lines show the results for the No-Inst group. The open circles and open triangles show the results in Session 1; the filled circles and filled triangles show the results in Session 3.

A three-way MANOVA for the negative response generated similar results. The important difference was that the triple interaction of primary concern was significant [$F(5,14) = 3.300, p < .05$]. The main effects were significant ($p < .001$) for the session [$F(1,18) = 30.244$] and for the orientation [$F(5,14) = 13.980$], while insignificant for the group [$F(1,18) < 1$]. Two double interactions were significant: the session-by-orientation [$F(5,14) = 6.884, p < .005$] and the group-by-orientation [$F(5,14) = 3.808, p < .05$]. The latter means that the slope of the RT-angle function was steeper for the No-Inst group.

The effects of orientation were tested separately for each curve in Fig. 7 by a one-way MANOVA. In the case of the positive response, orientation had significant effects for the No-Inst group in both sessions: $F(5,5) = 12.842$ ($p < .01$) in Session 1, and $F(5,5) = 8.774$ ($p < .05$) in Session 3. In contrast, orientation was significant only in Session 1 for the Inst group [$F(5,5) = 15.340, p < .005$]. Although the orientation effect approached significance in Session 3 [$F(5,5) = 4.366, .05 < p < .10$], the shape of the curve was quite different from that of mental rotation as seen in Fig. 7. Similar results emerged from the negative response. For the No-Inst group: $F(5,5) = 7.967$ ($p < .05$) in Session 1, and $F(5,5) = 14.736$ ($p < .005$) in Session 3. For the Inst group: $F(5,5) = 7.909$ ($p < .05$) in Session 1, and $F(5,5) = 1.523$ ($p > .30$) in Session 3.

Error trials were not reassessed for the noncritical figures, and their RTs were not submitted to statistical analyses. When all the correct RTs were averaged for each session, however, a clear pattern of mental rotation emerged: 1593, 1876, and 2432 ms for 0, 90, and 180° in Session 1; 1120, 1363, and 1818 ms in Session 3. Essentially the same monotonically increasing functions were obtained for both groups and for both response categories.

The mean error rate for the critical figures was 3.23%. The error rate was slightly higher at 180° (6.88%) but not very different for the other orientations.

Discussion

All the *Ss* in both groups reported mental rotation in Session 1. The RT-angle functions revealed the typical mental rotation pattern in both groups and in both response categories, supporting the reports of the *Ss*. The use of mental rotation implies that the *Ss* did not encode the orientation-free *C* change in spite of its objective presence. It is indeed logically possible that the *Ss* simply did not utilize the *C* change though they had encoded it. This seems unlikely, however, because the *Ss* were required to respond as fast as possible, and they could have responded even faster if they had utilized the orientation-free difference (see the results in Experiment 1). The implication that the *Ss* failed to encode the *C* change

is surprising given that there were only two kinds of figures repeatedly presented and that the *C* change had been introduced into the simpler figure in a fairly obvious manner.

After the *Ss* in the Inst group were informed of the *C* change, they were able to respond to the tilted test figures as fast as to the upright ones as shown by insignificant orientation effects in one-way MANOVA. The combined effects of the single presentation and the red dot in Session 3 should not be responsible for this change. These combined effects had to be present in the No-Inst group as well. The Session 3 RT-angle functions for this group retained the same mental rotation pattern as in Session 1. The fact that 3 out of the 10 *Ss* in the No-Inst group spontaneously found the *C* change during Session 2 may have reduced the overall difference between the two groups with respect to the slope change between Sessions 1 and 3. Nevertheless, the relevant triple interactions were statistically reliable. It thus seems to be clear that the flattening of the functions for the Inst group in Session 3 was caused by the use of the orientation-free difference as predicted in the beginning.

There was an unexpected difference between the Inst group and the No-Inst group: the intercepts of the RT-angle functions were not lower in Session 3 for the Inst group as opposed to the No-Inst group. There are two possible explanations. First, the *Ss* in the Inst group had to change their initial strategy (i.e., mental rotation) to the designated *C* change strategy. As a result, the cumulative effect of practice had to be much smaller in the Inst group than in the No-Inst group where at least seven *Ss*, who did not notice the *C* change, continued to use the same mental rotation strategy throughout the experimental session. It seems highly probable that the smaller amount of practice prevented the *Ss* in the Inst group from responding to the upright test figures in Session 3 more quickly than in Session 1. Second, the particular *C* change used in the current experiment may have needed longer time to be encoded than the particular *RO* change used in the current experiment.

Whatever the cause of the unchanged intercepts may be, they do not seem to counter the principal findings in this experiment (i.e., the effects of the encoded orientation-free difference). If the flattened function had been located above the peak of its corresponding mental rotation function in Session 1, artificial delay of the response in Session 3 due to demand characteristics would have to be suspected as a cause of the flattening. In actuality, however, the figures in all the orientations in Session 3 were judged as fast as the upright figures in Session 1 in the case of the Inst group. Logically, a flat function with the same intercept could still be generated by artificial delay in the following manner: the function is lowered as a whole by the practice effects, and then artificial delay is added so that the function becomes flat. However, in order for artificial delay to

create the flatness, the delay must be inversely proportional to the RT between 0 and 180° while directly proportional to the RT between 180 and 360°. In the present experiment, there is no reason to suspect such elaborated delay in response. What is more, in the No-Inst group, the RT for the inverted (180°) figure in Session 3 was much longer than the RT for the upright (0°) figure in Session 1, in either response category. It is implied that the practice effects were not large enough to make the 180° RT in Session 3 identical to (or lower than) the 0° RT in Session 1, in the case of the Inst group as well. This contradicts the above hypothetical reasoning in terms of artificial delay. In any case, it is improbable that the flattening of the functions was created by artificial delay due to demand characteristics.

In summary, there are four major findings in the current experiment. First, it was demonstrated again that the distinction between combination (orientation-free) information and relative orientation (orientation-bound) information is valid in the human visual system. Second, another kind of combination information that was different from the one used in Experiment 1 was proved to be orientation-free. Third, relative orientation change was proved to be orientation-bound not only in global mirror-image reversal but also in partial reflection, as long as its concomitant combination changes were not detected. Finally, and most importantly, it was found that the prediction of the information-type theory as to the presence and absence of mental rotation might be violated in some cases. However, it must be stressed that these exceptional cases are expected not because the theory has a flaw, but because its prediction could sometimes be overridden by a different factor (i.e., encoding failure). Accordingly, when a test of the above prediction is intended, it has to be confirmed that the difference in orientation-free information has been actually encoded as such by the subjects.

IDENTITY AND COMBINATION

The preceding two sections were devoted to experimental confirmation of the proposed distinction between orientation-free information and orientation-bound information. In this section and the next, empirical tests will be conducted to confirm the other distinction: elementary versus conjunctive. The distinction itself has already been established (see Treisman, 1986). In order to verify the basic assumptions of the information type theory, however, the elementary/conjunctive distinction has to be established within each of the two categories: orientation-free information and orientation-bound information. Experiment 1 had confirmed that two kinds of information were orientation-free: zero curvature versus nonzero curvature, and zero distance versus nonzero distance (see Figs. 3a, 3d, and 3f). They were assumed to be elementary (i.e., identity) in-

formation and conjunctive (i.e., combination) information, respectively. The purpose of the following experiment is to verify this assumption, using exactly the same figures as in Experiment 1.

Neisser (1967) distinguished initial preattentive parallel processes from later attentive serial processes in visual information processing. Recently, Treisman and her associates (Treisman, Sykes, & Gelade, 1977; Treisman & Gelade, 1980; Treisman & Schmidt, 1982; Treisman & Paterson, 1984) have shown in a series of experiments that elementary features of a figure are processed preattentively and in parallel while conjunctive features have to be processed attentively in a sequential manner. In their visual search experiments, the *Ss* were required to detect a prespecified target among similar distractors. When the difference between the target and the nontarget distractor was defined in terms of a single elementary feature (e.g., a color as in the case of a pink "O" among purple "O"s and brown "O"s), the number of nontargets did not affect the time to detect the target among them. This indicated that all the presented figures were examined in parallel. On the other hand, when the difference was defined by a conjunction of two single features (e.g., a pink "O" among pink "N"s and green "O"s), the search time increased linearly with the number of presented figures. The figures appeared to be examined serially. When the target was absent, the reaction time in the conjunction condition increased linearly with the number of presented figures, which suggested that the *Ss* had conducted a serial exhaustive search. In the case of this target absent condition, the linear slope was steeper than that for the target present condition. This was interpreted to suggest that the *Ss* detected the target on average in the middle of the search when it was present and emitted the response without examining all the remaining figures. When no target was shown, the reaction time increased in the elementary condition as well, though the increase was much smaller than that in the conjunctive condition. This was interpreted as follows: when the *Ss* did not detect the target by the parallel search, they tended to examine some figures serially for further confirmation, but they did not examine all the figures exhaustively.

These researchers also found that the above difference in visual search function was accompanied by corresponding differences in two other experimental paradigms. First, illusory conjunctions were formed based on separate single features when attention was diverted, whereas illusory single features were perceived much less frequently in the same setting. Second, the difference in single features mediated texture segregation, whereas the difference in conjunctions did not. Accordingly, the initial distinction between elementary features and their conjunctions in their visual search experiments is considered to have sufficient empirical validity, though it was made on a priori grounds in the first place. Given

such convergent evidence, it seems reasonable to use the difference in visual search function in a converse manner to determine whether a certain feature is a single element or a conjunction of two or more elements (Treisman, 1986). The following experiment attempts to differentiate between identity (elementary) information and combination (conjunctive) information by taking advantage of the above findings concerning the visual search paradigm.

Experiment 3

Method

Subjects. Ten undergraduate students at Cornell University, two males and eight females, served as *Ss*. Each *S* was tested individually and paid \$3.00 for participation in a 40-min session.

Design. Three variables were manipulated within *Ss*. One variable was the supposed type of information change, identity or combination. The second variable was the display size (i.e., the number of figures shown at the same time). This variable had four levels: 1, 5, 15, and 30 figures per display. Finally, half the displays contained the target; the other half did not. The displays were shown in four blocks: two for the identity condition and two for the combination condition. The identity blocks and the combination blocks alternated in the ABAB order. An identity block was given first to half of the *Ss*; a combination block was given first to the other half of the *Ss*. The assignment was made randomly with the constraint that the male/female ratio be identical in both order groups. The reason that the presentation order was not counterbalanced (as it would be in the sequence ABBA) was to minimize memory effects in the second presentation of the same displays.

Stimuli. Figure 3a was used as a nontarget distractor. Figure 3d was used as a target for identity information change, and Fig. 3f for combination information change. Both changes have already been confirmed to be orientation-free in Experiment 1. (Note that the roles of these figures as "target" and "nontarget" have been reversed in this experiment compared with Experiment 1.) Either 1, 5, 15, or 30 intersections were randomly chosen from the 494 possible intersections of an imaginary 19×26 grid on condition that no figures overlapped one another when their photocopies were put on those intersections. All the photocopies were set in the same upright position. A slide was made from this configuration of the figures. For each combination of the information type, the display size, and the presence or absence of the target, four slides were prepared. A total of 64 slides were produced. When the target was present, only one target was shown in a slide. The location of the target was decided randomly with the constraint that it had to appear once in each quadrant of the whole display. The same constraint was imposed when only one nontarget was shown. When the display size was equal to or more than five, a further constraint was imposed so that the figures were scattered over an area of more than 11×11 intersections. These slides were used in the test blocks. An additional set of sixteen slides, one for each combination of the above three conditions, were made for practice trials in the same way. An individual figure subtended $1.2^\circ \times 1.6^\circ$ of visual angle when seen from 70 cm distance. The figures were shown in an area of $11^\circ \times 16^\circ$. Examples of these displays are presented in Fig. 8.

Procedure. The same apparatus was used as in the previous experiments, including the chinrest. In the first block, the *Ss* were first shown the target and the appropriate nontarget; they were told to press the key for the preferred hand whenever they saw the target irrespective of its location, and the other key otherwise. Both speed and accuracy were equally stressed. Then they were tested with eight practice slides in a random order, in which they experienced once each combination of the positive/negative response and the display size.

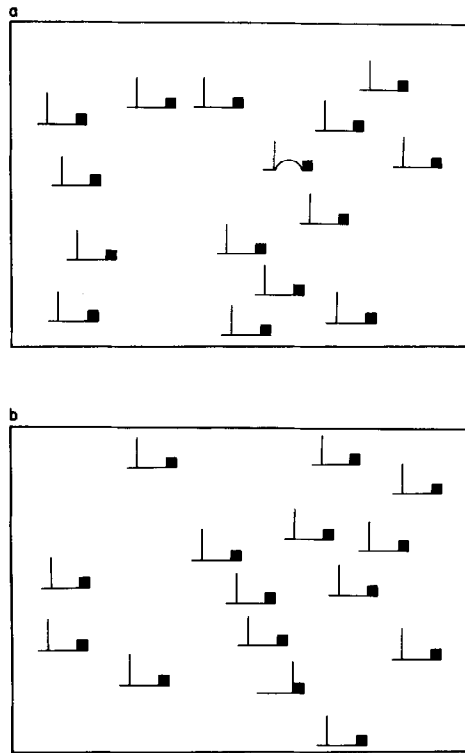


FIG. 8. Samples of the displays (size, 15) used in Experiment 3: (a) contains the identity change target while (b) contains the combination change target.

Feedback was provided for every response as to its accuracy. After four warm-up trials with randomly chosen practice slides, 32 test trials were given. Feedback was provided at the *S*'s request and in any case if errors were made consecutively on three or more slides of the same display size in the same response category. All the error trials were reassessed at the end of the block together with dummy slides randomly intermixed. In the second block, the other target was used in the same organization of the practice, warm-up, and test trials. These two blocks were repeated in the same order without the initial eight practice trials for the second time. The organization of each trial was identical to that in Experiment 1.

Results

Eight observations were obtained from one *S* for each display size in each information type condition. They were averaged for the subsequent analyses. The positive response data and the negative response data were analyzed separately by statistical tests. Figure 9 summarizes the results. According to the studies by Treisman and her associates, in the case of the positive response, RT should show linear increase with display size if the difference between the target and the nontarget is conjunctive, while

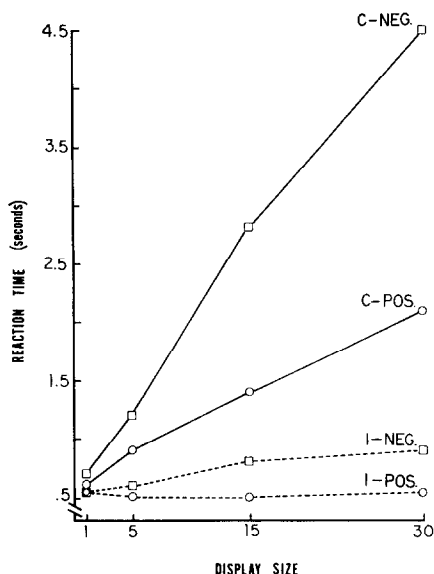


FIG. 9. Results of Experiment 3: Mean reaction time as a function of the display size. The solid lines show the results in the combination condition; the dotted lines show the results in the identity condition. The squares show the results for negative responses; the circles show the results for positive responses.

RT should remain the same if the difference is elementary. The functions for the positive response in Fig. 9 revealed exactly the predicted pattern. In the case of the supposed identity (*I*) change, the slope of the function was only 1.08 ms per figure, which was comparable to 2.76 and 1.32 ms in Treisman et al. (1977). The polynomial regression showed a significant trend only for the quadratic component [$F(1,9) = 11.572$, $p < .01$], with the linear component insignificant [$F(1,9) = 4.630$, $.05 < p < .10$]. In contrast, the slope for the supposed combination (*C*) change was much larger: 50.75 ms per figure. Only the linear trend was significant in this condition [$F(1,9) = 47.985$, $p < .001$]. A three-way MANOVA for the positive response data detected no main effect or interactions concerning the test order. But both main effects for the information type and the display size were significant [$F(1,8) = 114.700$ ($p < .001$), and $F(3,6) = 22.069$ ($p < .001$), respectively]. Their interaction was also highly significant [$F(3,6) = 39.024$, $p < .001$].

A three-way MANOVA for the negative response data showed a pattern of results that was consistent with the one in Treisman et al. (1977). The test order had no effect. The main effects and the interaction were all reliable for the type and the display size: $F(1,8) = 39.009$ ($p < .001$) for the type, $F(3,6) = 21.125$ ($p < .001$) for the size, and $F(3,6) = 20.254$ (p

< .005) for the type-by-size. Both types of information had substantial slopes: 12.84 ms for the *I* change and 132.01 ms for the *C* change. In the former case, both linear and quadratic components were significant [$F(1,9) = 17.152$ ($p < .005$), and $F(1,9) = 18.857$ ($p < .005$), respectively]. In the latter case, the linear, quadratic, and cubic components were all significant [$F(1,9) = 32.335$ ($p < .001$), $F(1,9) = 6.909$ ($p < .05$), and $F(1,9) = 8.023$ ($p < .05$) in that order].

The mean error rate was 2.89%. The number of errors did not correlate with the information type or the display size except that it was especially small for the display size 5 (0.63%).

Discussion

In the case of the positive response, the difference between the assumed information types was very obvious in the predicted direction. The negligible slope for the *I* change agrees with the notion of parallel processing; the linear slope for the *C* change with the notion of serial processing. The former suggests that the difference between a straight line and a curve is elementary, which agrees with the previous findings by Treisman et al. (1977) and Treisman and Gelade (1980). The linear slope for the *C* change condition suggests that the employed change was conjunctive as expected.

The present results differ from Treisman et al. (1977) results in that the non-linear components were significant for the negative response in the *C* condition. Treisman et al. (1977) considered the linearity of the negative response function as evidence of serial exhaustive search. However, a slight response bias in some *Ss* could make nonlinear components significant. For example, after inspecting many nontargets in a given display, some *Ss* may be inclined to curtail the search to emit a quick negative response. This being the case, the function will be negatively accelerated as in Fig. 9 with significant nonlinear components. Thus, the small deviation from linearity does not seem to question the overall validity of the assumed serial exhaustive search.

What is more, the above deviation does not throw any doubt on the obvious difference in the positive response slopes, which is of primary concern in the current experiment. This difference suggests that the assumed combination information had to be processed in parallel, whereas the assumed combination information had to be processed serially. Given the findings by Treisman and her associates cited above, it follows that the assumed identity information was actually elementary while the assumed combination information was actually conjunctive. As both kinds of information employed in the current experiment have already been proved to be orientation-free, it seems to be justified to make the distinction between identity information and combination information within the

category of orientation-free information, as far as the human visual system is concerned. It is true that the distinction was confirmed only for a limited set of figures. However, the employed difference between zero curvature and nonzero curvature as well as between zero distance and nonzero distance seems to play an important role in the discrimination of most shapes. In addition, there is no reason to doubt that the human visual system takes advantage of the same distinction with respect to other figural features as well in performing the task of form perception.

ABSOLUTE ORIENTATION AND RELATIVE ORIENTATION

Relative orientation (*RO*) information was proved to be orientation-bound in Experiments 1 and 2. As stated previously, it is self-evident that absolute orientation (*AO*) information is also orientation-bound. The distinction between these two types of orientation-bound information, however, has not been tested yet. Theoretically, it is not impossible that *RO* information may be encoded as elementary information just like *AO* information. Imagine a simple template matching model, for example, where Fig. 3a drawn on a transparency serves as a template. This template is put on every given figure; the figure is judged to be identical to Fig. 3a if it matches the template. (The size of figures are assumed to be invariant for simplicity.) Figure 3b is not identical to Fig. 3a because it does not match the template due to the right-left reversal. Here, the difference in *RO* information is not encoded as a conjunction of the square and the vertical bar. It is encoded by the whole template together with the square and the bar in an integrated manner. In other words, the *RO* information is one of the characteristics of a single element (i.e., the whole figure in this case). This characteristic is susceptible to orientation change. Thus, there is no difference between *AO* information and *RO* information in such a representation. The following experiment employs the visual search paradigm again in order to examine the reality of the *AO/RO* distinction in the human visual system.

Experiment 4

The line drawing shown in Fig. 10a was used as a nontarget distractor. In the case of the *AO* change, the bar was slanted by 60° clockwise as in Fig. 10b. In the case of the *RO* change, the filled circle was to the right of the vertical bar instead of the left (Fig. 10c). The circle was used to assure that the difference between Figs. 10a and 10b would not contain any difference in identity (i.e., orientation-free elementary) information. If a horizontal straight line had been used instead of the circle, for example, slanting the vertical bar in Fig. 10a would have produced not only the absolute orientation change of the bar but also the change in the angle between the bar and the horizontal line. Though an angle was considered

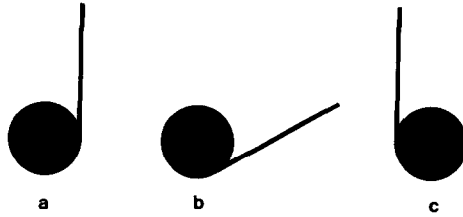


FIG. 10. The stimulus figures used in Experiment 4: the nontarget distractor (a), the absolute orientation change target (b), and the relative orientation change target (c).

as combination information in the previous intuitive classification, it has not been verified yet; an angle may be a kind of identity information. If this is the case, the *Ss* will be able to respond to orientation-free elementary information instead of orientation-bound elementary information in Fig. 10b; the distinction between *AO* information and *RO* information will not be tested. By using the circle in Fig. 10, only orientation-bound information could be manipulated in the category of elementary information. On the other hand, it has already been confirmed by a number of mental rotation experiments including Experiment 1 in the present paper that the difference between mirror images like Figs. 10a and 10c is orientation-bound. If the difference in positive response function between Figs. 10b and 10c follows the expected pattern as in the preceding experiment, therefore, the elementary/conjunctive distinction can be made between *AO* information and *RO* information in the category of orientation-bound information.

Method

Subjects. Ten Cornell undergraduates served as *Ss* and were paid \$3.00 for participation in a 40-min individual session. Two were male and eight were female. None of them had taken part in Experiment 3.

Stimuli. The figures in Fig. 10 were used to make display slides through the same procedure as in Experiment 3. Each figure approximately subtended a $0.5^\circ \times 1.2^\circ$ visual angle.

Procedure. The procedure was the same as that in Experiment 3.

Results

Mean RTs are plotted in Fig. 11. The critical comparison concerns the slopes for positive responses: The slope for the *AO* change was negligible (2.61 ms per figure), whereas the slope for the *RO* change was substantial (31.23 ms per figure). According to polynomial regression, both linear and quadratic components were significant for the *AO* change [$F(1,9) = 9.261$, ($p < .05$), and $F(1,9) = 6.780$ ($p < .05$), respectively]. In contrast, only the linear component was significant for the *RO* change [$F(1,9) = 55.850$, $p < .001$]. This pattern of results is essentially identical to those in Experiment 3 and Treisman et al. (1977). A three-way MANOVA

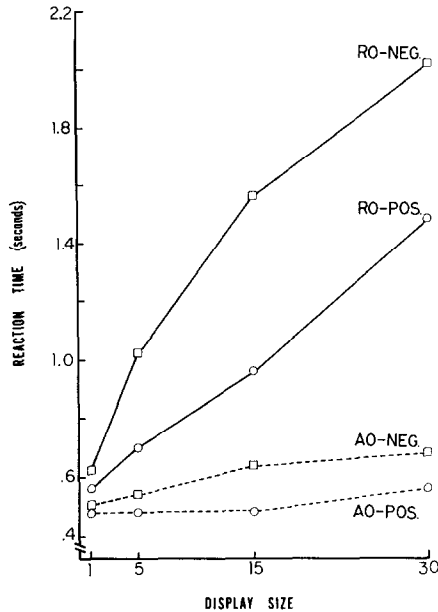


FIG. 11. Results of Experiment 4: Mean reaction time as a function of the display size. The solid lines show the results in the RO condition; the dotted lines show the results in the AO condition. The circles show the results for the positive response; the squares show the results for the negative response.

showed no effects concerning the test order. The information type and the display size as well as their interaction were all statistically reliable [$F(1,8) = 40.509$ ($p < .001$), $F(3,6) = 51.102$ ($p < .001$), and $F(3,6) = 18.836$ ($p < .005$)].

In the case of the negative response, the slope for the AO change was 6.16 ms per figure and that for the RO change was 46.50 ms per figure. Both linear and quadratic trends were significant for both information types: $F(1,9) = 49.431$ ($p < .001$) and $F(1,9) = 7.434$ ($p < .05$) in the AO condition, and $F(1,9) = 52.693$ ($p < .001$) and $F(1,9) = 11.637$ ($p < .01$) in the RO condition. A MANOVA gave consistent results: only the main effects of the type and the size as well as their interaction were significant [$F(1,8) = 55.399$ ($p < .001$), $F(3,6) = 13.216$ ($p < .005$), and $F(3,6) = 12.854$ ($p < .005$)].

The error rates were very low with an overall mean of 0.78%; they had no correlation with the information type or the display size.

Discussion

The results mostly confirmed the predictions. Although the slope for the AO change in the case of positive responses was slightly larger than

that in Experiment 3 (2.61 ms as opposed to 1.08 ms), its magnitude was well within the range of slopes in Treisman et al. (1977): 1.32 through 2.76 ms. Besides, the influence of the display size on RT could not be accounted for by the linear trend alone. In contrast, only the linear component was significant in the case of the positive responses to the *RO* change.

The quadratic component for the negative responses to the *RO* change was significant in this experiment as well. The negative acceleration in the corresponding curve (Fig. 11) is more conspicuous here than in the preceding experiment. The *Ss* in the present experiment may not have been patient enough to examine all the nontargets one by one when there were many of them. When the *RO* target was present in a display of size 30, it was detected in 1475 ms on the average, with the standard deviation 682 ms. Therefore, when the *Ss* could not find the target after about 2.5 s of search, it would be fairly safe to emit a negative response by curtailing the search. Granting that some *Ss* actually adopted this strategy from time to time, the average search time could be shorter than when exhaustive search was always carried out by all the *Ss*, without appreciable rise in the error rate. The reason is as follows: When the search is curtailed, the emitted response becomes a false negative response through a probabilistic process. In other words, the emitted response is not always a false negative response; it may be a correct rejection. Theoretically speaking, there can be no false negative response at all in the extreme case. Thus, the error rate could remain low when the above strategy is applied on some trials. On the other hand, the curtailed search always contributes to the reduction of search time. This is not a probabilistic process but a deterministic one. The reduction of search time on some trials necessarily results in the reduction of average search time. In this way, it is not unreasonable that the search time function for the negative response is negatively accelerated without appreciable rise in the error rate as in the current experiment. At any rate, the clear difference between the *AO* slope and the *RO* slope for positive responses appears to present fairly strong evidence for the elementary/conjunctive distinction within orientation-bound information. It thus seems to be justified to conclude that the human visual system actually takes advantage of the distinction between absolute orientation information and relative orientation information.

Experiment 5

The preceding two experiments provided an empirical basis for making the distinction between elementary and conjunctive information for both orientation-free and orientation-bound information. However, an alternative explanation is possible for the results in both experiments. In either

experiment, the *Ss* had to process at least two elements in the case of the conjunction change while they only had to process a single critical element in the case of the element change. In Experiment 3, the subjects could ignore vertical bars and squares in order to discriminate a curve from straight lines. The same holds true for Experiment 4, in which the *Ss* could ignore the circles in order to discriminate a slanted line from vertical lines. By contrast, two components (i.e., the vertical bar and the square in Experiment 3; the line and the circle in Experiment 4) had to be processed in order to detect a conjunction change. In other words, the encoding load in the conjunction condition was twice as much as that in the element condition. It may be argued that such differential difficulty caused the difference in the slope of the visual search function. In order to examine this same possibility, Treisman and Gelade (1980) used a disjunctive target in their elementary condition: their *Ss* were required to respond positively to "S or blue." Thus, they were forced to process both relevant featural dimensions. Under this condition, they obtained positive response slopes (2.5 ms for "S" and 3.8 ms for "blue") comparable to those in the case of the *single* feature detection. These results constitute counter-evidence against the above alternative account. Nonetheless, it is still possible to argue that interference between figural elements (e.g., a vertical line and a circle as in Experiment 4) may be much stronger than interference between a figural element (e.g., a curved line) and a nonfigural element (e.g., blue) that Treisman and Gelade (1980) tested. Both Experiments 3 and 4 employed conjunctions of figural elements. Accordingly, it seems to be desirable to test this possibility before drawing a definite conclusion from the above two experiments. This last experiment compares the conjunction condition with the element condition where a disjunctive target is defined in terms of two different *figural* elements.

Method

Subjects. The *Ss* were 10 undergraduate students at Cornell University, three males and seven females. Each *S* was paid \$3.00 for participation in a 40-min individual session. No *Ss* had taken part in Experiment 3 or 4.

Stimuli. The nontarget, the conjunctive target, and one of the elementary targets were the same as in Experiment 3 (see Figs. 12a, 12b, and 12c, respectively). The other elementary target was a figure in which the vertical bar of the nontarget (Fig. 12a) had been slanted by 45 degrees clockwise (see Fig. 12d). That is, one of the disjunctive elementary targets contained an identity change and the other an absolute orientation change; but both changes were supposed to be elementary. In the *AO* target, the angles between the bar and the horizontal line were also changed by tilting the bar. But even if the *Ss* tried to utilize this angle change, they still had to process two or more elements (i.e., a curve and a non-right angle) to find the disjunctively defined elementary targets. If an angle is a kind of combination information, the *Ss* will process the slant rather than the non-right angle because it should require a shorter time to process a property of a single component. At any rate, the change in angle does not present any problem for the purpose of this experiment. A set of

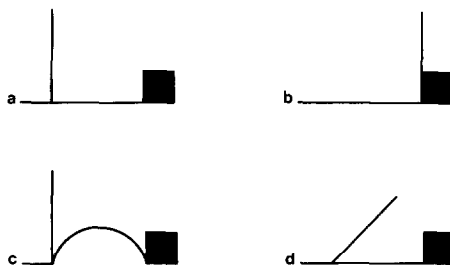


FIG. 12. The stimulus figures used in Experiment 5: the nontarget distractor (a), the conjunction change target (b), and the element change targets (c and d).

new slides (both positive and negative displays) were prepared for the new elementary target through the same procedure as in Experiment 3. The same number of slides were newly produced for the conjunctive target as well in order to equate the number of slides for the conjunctive target with the number of slides for the elementary targets. As a result, twice as many slides were used as in the previous visual search experiments. The practice slides were also doubled in the same way, including the new elementary target. No slide contained the two elementary targets together.

Procedure. The procedure in Experiment 3 was followed except for the following modifications. First, the practice block consisted of 16 trials instead of 8. Second, the whole experimental session consisted of two blocks instead of four, but the total number of trials remained the same because each session was composed of 64 trials, not 32 trials. Each slide was tested only once instead of twice. Third, in both practice and test blocks, the two elementary targets were intermixed to be presented in random orders. The *Ss* were asked to respond positively whenever they saw *either* of the two elementary targets. Finally, two males and three females were tested first with the conjunction target and then with the elementary targets, and vice versa for the rest of the *Ss*.

Results

A three-way MANOVA for the elementary condition did not show any significant effects of the two different elementary targets. Accordingly, they were combined for the subsequent analyses. The mean RTs were plotted against display size in Fig. 13. The overall pattern was exactly the same as in Experiments 3 and 4. In the case of the positive response, the slope for the combined elementary target was -0.01 ms per figure. This virtually zero slope was a consequence of combining the positive slope for the identity change target (1.79 ms) and the negative slope for the absolute orientation change target (-1.82 ms). The slope for the conjunctive target was 54.82 ms per figure. The polynomial regression revealed no significant trend in the elementary condition, whereas only a linear component was highly significant in the conjunctive condition [$F(1,9) = 42.200$, $p < .001$]. A three-way MANOVA showed no significant effects of the test order, while the information type, the display size, and their interaction were all statistically reliable: $F(1,8) = 85.609$ ($p < .001$), $F(3,6) = 13.943$ ($p < .005$), and $F(3,6) = 22.008$ ($p < .001$), respectively.

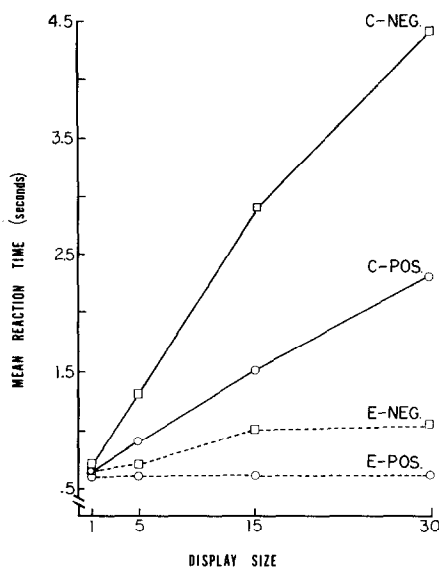


FIG. 13. Results of Experiment 5: Mean reaction time as a function of the display size. The solid lines show the results in the conjunction condition; the dotted lines show the results in the element condition. The circles show the results for the positive response; the squares show the results for the negative response.

In the case of negative responses, the slope for the element condition was 16.88 ms per figure; that for the conjunction condition was 129.94 ms per figure. According to polynomial regression, both linear and quadratic components were significant in the element condition [$F(1,9) = 11.696$ ($p < .01$), and $F(1,9) = 31.254$ ($p < .001$)], as well as in the conjunction condition [$F(1,9) = 65.304$ ($p < .001$), and $F(1,9) = 39.641$ ($p < .001$)]. A MANOVA presented consistent results: $F(1,8) = 96.929$ ($p < .001$) for the information type, $F(3,6) = 86.887$ ($p < .001$) for the display size, and $F(3,6) = 34.914$ ($p < .001$) for their interaction, with no effects of the test order.

The error rate was comparable for every display size except for fewer errors in the display size five (0.94%) as in Experiment 3. The mean error rate was 2.89%.

Discussion

The above results clearly indicate that the *Ss* did not suffer from extra difficulty induced by the presence of the additional elementary target. The critical pattern of the results in Experiments 3 and 4 was precisely replicated. In the current experiment, the difference between the elementary target and the nontarget distractor was defined by a different *figural* el-

ement for either elementary target. The *Ss* could not predict which of the figural elements would be critical on a particular trial, due to the randomized presentation. Therefore, the *Ss* had to check at least two figural elements for each figure in the display in the element condition just as in the case of the conjunction condition. Nevertheless, the positive response slope for the element condition did not become identical to that for the conjunction condition. In light of these results, the explanation in terms of the number of critical features to be checked seems to be inappropriate in understanding the results in Experiments 3 and 4. Consequently, it is now justified to take the results in those experiments as indicating the validity of the elementary/conjunctive distinction in both orientation-free and orientation-bound information.

CONCLUSION

The basic assumptions of the information type theory (i.e., the four distinct types of information used by the human visual system to represent spatial forms) have gained empirical support in the present series of experiments. The distinction between orientation-free information and orientation-bound information was established in Experiments 1 and 2. These experiments employed the occurrence of mental rotation as an index of orientation-bound information difference, and the nonoccurrence of mental rotation as an index of orientation-free information difference. Although absolute orientation information was not included in either experiment, it is orientation-bound by definition as discussed earlier. Experiment 3 confirmed the distinction between elementary information and conjunctive information within the formerly established category of orientation-free information. As a result, the proposed distinction between identity information and combination information was confirmed. This experiment employed the difference in visual search rate as an index of the elementary/conjunctive distinction. The same index was used in Experiment 4 to establish the same distinction within the category of orientation-bound information. The results supported the proposed distinction between absolute orientation information and relative orientation information. An alternative explanation of the results in Experiments 3 and 4 was tested and rejected in Experiment 5. Thus, an empirical basis was provided for all the four information types as consequences of combining the proposed two binary distinctions.

The other assumptions in the theory (e.g., the subject-centered nature of an orientational framework) are supported by the logical synthesis of related past studies as discussed in the second section. The theory now seems qualified to be used in disentangling various confusions in the fields of mental rotation and form perception as was done in the third section (see also Footnote 10). Note that Experiments 1 and 2 also served as

successful empirical tests for the proposed explanation as to the presence and absence of mental rotation based on the information type theory. However, Experiment 2 warns that the prediction of the information type theory may sometimes be overridden by failure to encode conjunctive orientation-free information. When the theory is applied, therefore, it is important to ensure the absence of this confounding factor.

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