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Mental Transformations in the Identification of Left and Right Hands

Lynn A. Cooper
University of California, San Diego

Roger N. Shepard
Stanford University

Subjects determined as rapidly as possible whether each line drawing portrayed a left or a right hand when the drawings were presented in any of four versions (palm or back of either hand) and in any of six orientations in the picture plane. Reaction time varied systematically with orientation and, in the absence of advance information, was over 400 msec longer for the fingers-down orientation. However, when subjects were instructed to imagine a specified (palm or back) view of a specified (left or right) hand in a specified orientation, reaction times to test hands that were consistent with these instructions were short (about 500 msec), independent of orientation, and unaccompanied by errors. It is proposed that subjects determine whether a visually presented hand is left or right by moving a mental "phantom" of one of their own hands into the portrayed position and by then comparing its imagined appearance against the appearance of the externally presented hand.

Human subjects are able to identify a visually presented hand as a left or a right hand even in the absence of extraneous correlated cues (such as wristwatches, wedding rings, or writing instruments) and even though the hand may be presented in any of a vast number of different positions.

The basis for making this identification is not obvious, since the two hands do not differ with respect to any simple visual feature inherent in one hand or the other. Rather, they differ only with respect to the overall structures of the two hands which, as Kant long ago noted, are identical except for a reflection in three-dimensional space (e.g., see Gardner, 1969; Nerlich, 1973). In view of the enormous variety of ways in which either three-dimensional hand can project onto the retina, it seems unlikely that each such two-dimensional projection is identified as right or left by comparison against "right-hand" and "left-hand" templates stored individually for all possible projections.

Our introspections as well as the verbal reports of many of our subjects suggest that this determination is generally made by imagining one's own preferred hand in the position of the visually presented hand and, then, by testing for a match or mismatch between the appearance of the externally presented hand and the internally transformed visual–kinesthetic image of one's own hand. Thus, without having either to preserve or to search through a store of fixed two-dimensional templates corresponding to all possible retinal projections, the desired discrimination may be made more economically by retaining a single internal representation or "phantom" for each hand. This phantom can then be mentally maneuvered into any position, where it can serve as a sort of template for comparison against a visually presented hand. The present experiment is primarily concerned with two empirically testable consequences of this account of the identification of hands.

1. When a hand is presented in just the position in which the subject is expecting

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Requests for reprints should be sent to L. A. Cooper, Department of Psychology, University of California, San Diego, La Jolla, California 92037.

it, the subject need merely compare the external stimulus against his or her previously prepared mental template. Such a comparison should be quite rapid and independent of the correctly anticipated orientation of the test hand (cf. Cooper & Shepard, 1973a, 1973b).

2. However, when the position of the visually presented hand departs from a standard reference position or from some other specifically expected position, a subsequent transformation of the internal representation will be needed before it can be matched against the externally presented hand. In this case, the time to make the left–right determination should increase monotonically with the departure of the test hand from the standard or expected position (cf. Cooper & Shepard, 1973a, 1973b; Shepard & Metzler, 1971).

Our desire to evaluate these proposals has two principal sources: (a) the intrinsic interest of the particular problem of how people identify left and right hands, and (b) the implications of this particular problem for general theoretical arguments concerning the importance of holistic analog operations in human perception and thought recently developed by Shepard (in press), Cooper and Shepard (1973a), and Metzler and Shepard (1974).

Method

Subjects and Stimuli

The eight subjects, five males and three females, were students and staff at Stanford University. All subjects were right-handed.

The four alternative test stimuli, displayed in the 2×2 array in Figure 1, were line drawings of each of the two sides (palm and back) of each of the two opened-out human hands (right and left). On a given experimental trial, any one of these four alternative versions of a human hand could be presented in any one of six equally spaced orientations around a circle in the two-dimensional picture plane. The six possible orientations corresponded to 60° steps (measured clockwise) from the 0° orientation, which was defined as the orientation in which the fingers pointed straight up. This 0° orientation is illustrated for each of the alternative test hands in Figure 1.

In addition to the four test stimuli, a thumbless outline of the hand (illustrated at the right in Figure 1) was used whenever advance information concerning the picture-plane orientation of the upcoming test stimulus was to be provided. Since this partial outline included the wrist and four fingers, the rotational position in which it appeared furnished complete information regarding the orientation of the ensuing test stimulus. However, since the thumb and all of the internal markings that differentiate the palm from the back were omitted, and since the thumbless outline was constructed as completely symmetrical about the natural axis of the hand, the advance orientation cue provided no information as to *which* of the four possible alternative test stimuli would appear in that orientation. (In order to be consistent with this thumbless outline, all four drawings of complete hands were constructed, with a small distortion of the appearance of real hands, so that with the exception of the thumb, each picture was exactly symmetric. Thus, the "little finger" was depicted as identical in size to the opposite index finger.)

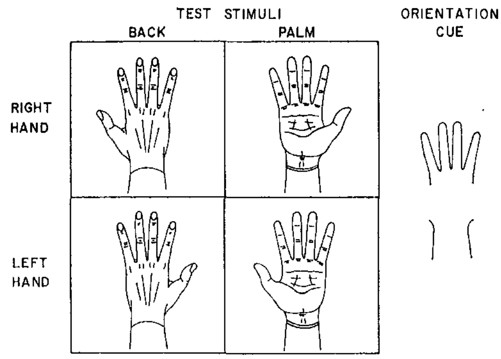

FIGURE 1. The four alternative hand versions that could appear as test stimuli are exhibited in the 2×2 array in the 0° orientation. (The partial outline used to indicate only the orientation of the upcoming test stimulus is illustrated at the right.)

Structure of Individual Trials

All of the visual stimuli were presented in an Iconix three-field tachistoscope. On each trial the subject was required to determine, as quickly as possible, whether the visually presented test stimulus represented a right hand or a left hand, regardless of which side of the hand (palm or back) was portrayed and regardless of its orientation in the picture plane. "Right-hand" responses were signaled by pushing a right-hand button, and "left-hand" responses were signaled by pushing a left-hand button. The reaction time recorded on each trial was always the time from the onset of the actual test stimulus to the first depression of one of the response buttons. Each test stimulus remained illuminated until the subject had made such a response.

The onset of the test stimulus coincided either with the offset of a 2,000-msec blank warning field (if no advance orientation cue was provided), or with the offset of a 2,000-msec field containing the thumbless outline used as an advance orientation cue. In the latter case, the advance cue and the ensuing test stimulus always appeared in the same picture-plane orientation.

The sequence of visual stimuli appeared centered in a white circular field with a black surround. The luminance of the circular field was about 68.5 cd, and it subtended a visual angle of 4°. The test hands and the thumbless orientation cue subtended an angle of about 1.5°.

The Six Experimental Conditions

When the presentation of the test stimulus was not to be preceded by any advance orientation cue, the subject was instructed simply to determine as rapidly as possible whether the test stimulus was a right hand or a left hand—regardless of the position in which the test hand might appear. However, when the test presentation was to be preceded by the thumbless outline, the subject was first given one of five different instructions on how to use that cue in preparing for the ensuing stimulus. These five alternative instructions, together with the "no advance information" condition, constitute the full set of six experimental conditions.

In four of the five advance-information conditions, the subject was given explicit instructions on the strategy to be used in preparing for the upcoming test stimulus. Specifically, he was asked to imagine one particular version of a human hand in the orientation designated by the thumbless outline during the 2,000-msec advance-information interval. For example, in one such condition, the subject was instructed to imagine the back of the right hand superimposed on the thumbless outline during its 2,000-msec duration. Similarly, in the three other "imagery instruction" conditions, the subject was requested to imagine the palm of the right hand, the palm of the left hand, or the back of the left hand in the designated orientation. Regardless of the specific instruction given to the subject, in all four of these conditions the actual test stimulus could be any one of the four alternative versions of a human hand (always appearing in the orientation indicated by the thumbless outline). Thus, in each of these four separate imagery instruction conditions, the probability that the specific version of a hand that the subject was requested to imagine in advance would be identical to the actual test stimulus, when presented, was only .25.

In the fifth advance-information condition, no specific strategy instructions were provided. The subject was simply encouraged to make use of the orientation cue in whatever way possible, but to try not to imagine any *specific* version of a hand during the 2,000-msec duration of the thumbless outline.

General Experimental Design

A within-subject factorial design was used such that each of the eight subjects saw each of the four alternative hand versions (back and palm of the right and left hands) in each of the six orientations (0°–300° in 60° steps) under each of the six experimental conditions. Thus, 144 experimental trials per subject were required to obtain one observation for each cell of the design.

Following an initial practice session consisting of 36 trials, each subject participated in two experimental sessions. The trials were blocked by conditions such that within each session six blocks were completed. Each within-session block corresponded to one of the six experimental conditions. Within each of these six blocks, 12 experimental trials—selected randomly from the complete set of 24 trials for each condition—were presented. The order of conditions within a session was balanced over subjects and over the two sessions.

Trials on which errors were made were later retaken in order to obtain for each subject an errorless reaction time for each combination of test-hand alternative, orientation, and experimental condition.

RESULTS

Reaction Time as a Function of the Relationship Between the Imagined and Presented Hands

Mean reaction times averaged over all eight subjects and over all four versions of the test hand are displayed in Figure 2. The filled circles and solid lines were obtained by also averaging over all six orientations in the picture plane. The open circles and dashed lines (which will be considered later) were obtained by averaging only over the 0° and ±60° orientations. Each of the four data points connected by line segments represents a particular relationship between the hand that the subject had been instructed to imagine and the hand that was actually presented.

For the first or leftmost point ("same side, same hand"), the imagined and presented hands were identical with respect to hand identity, side, and orientation. For the second point ("same side, other hand"), the imagined and presented hands differed only with respect to hand identity. That is, although the presented hand showed the same (palm or back) side in the same (picture-plane) orientation as the imagined hand, the thumb appeared on the opposite side. Thus, the (left–right) identity of the presented hand was opposite to that imagined. For the third point ("other side, other hand"), the presented and imagined hands differed with respect to both hand identity and side. In this case the thumb position and the entire outline of the presented hand agreed with what was imagined, but the internal markings that distinguish the palm from the back differed. For the last point ("other side, same hand"), the presented hand and the imagined hand differed with respect to both thumb position and palm–back markings. These two discrepancies resulted in a presented hand that was the same in left–right identity as the imagined hand—only displayed as flipped over to the other side.

At the right in Figure 2 are the corresponding pairs of points for the two remaining conditions in which no specific imagery instructions were given. The higher points represent the condition in which no advance information was provided, and the lower points represent the condition in which the orientation cue was provided and the subject was requested to use that cue without imagining either hand in the indicated orientation. As before, the filled points are averaged over all six orientations, and the open points are averaged over just the upright orientation and $\pm 60°$ from upright.

As these group data indicate, subjects responded quite rapidly whenever the presented hand was identical to the hand imagined in advance. An additional 200 msec were required (to make the opposite response) when the same side of the opposite hand was presented instead. Still another 200 msec were required when the opposite side of *either* the same or the opposite hand was presented. Mean reaction times in this last case approximated the reaction times when *no* information as to hand, side, or orientation was provided in advance.

Statistical tests indicate that all pairwise differences among the mean reaction times connected by solid lines in Figure 2 are reliable, with the exception of the differences between the last two points on the right, labeled "other side, other hand" and "other side, same hand." (In performing the *t* tests, a conservative modification of the Newman–Keuls procedure for multiple comparisons was used. See Winer, 1971, p. 197.) Values of the Studentized range statistic (q), with 3 steps between means and 7 degrees of freedom, for differences between the means for the first and second points and for differences between the means for the second and third points were 8.98 and 7.66, respectively (for both comparisons, $p < .01$). For the comparison between means for the third and fourth of these four connected points, $q(3, 7) = 1.7$, $p > .10$.

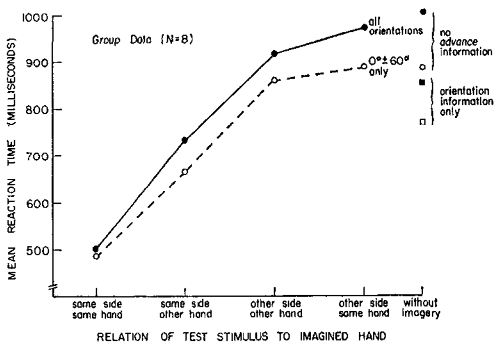

FIGURE 2. Mean reaction time for each of the four possible relationships between the hand the subject was instructed to imagine and the hand actually presented as the test stimulus (connected points). (Mean reaction times for the two conditions in which no specific hand was to be imagined are displayed as separate points at the right. The filled circles plot averages over all six orientations, while the open circles plot averages over only the more upright orientations of $0° \pm 60°$.)

The same pattern emerged consistently in the data of each of the eight individual subjects. For every subject the first three of the four connected points (cf. Figure 2) increased monotonically and approximately linearly. However, five of the eight subjects exhibited an appreciable increase in reaction time from the third to the fourth points, while three subjects exhibited a reversal for these last two points. As we shall suggest below, these two groups of subjects may have used somewhat different strategies.

Reaction Time as a Function of Test-Stimulus Orientation under Different Instructions

Figure 3 presents mean reaction time as a function of orientation of the test stimulus

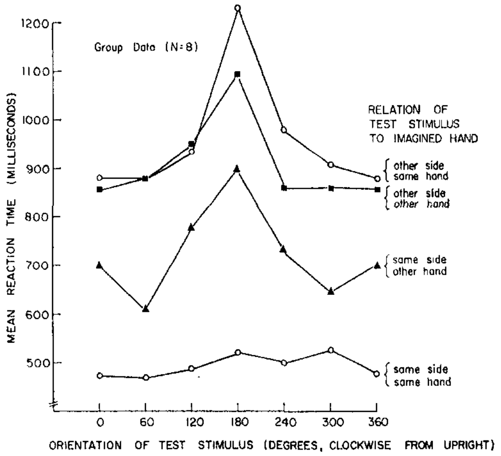

FIGURE 3. Mean reaction time plotted as a function of test-stimulus orientation, expressed as degrees of clockwise rotation from the 0° (fingers pointing up) position. (The four separate functions correspond to the possible relationships between the imagined hand and the test hand.)

(expressed in degrees of clockwise rotation from the orientation in which the fingers point straight up) for the four imagery instruction conditions. The four separate reaction time functions correspond to the four possible relationships between the imagined stimulus and the actual test stimulus distinguished in Figure 2. The plotted points are averages, within the four types of relationships between the imagined hand and the test hand, taken over the eight subjects, the four imagery instruction conditions, and the four specific palm–back and left–right test-stimulus combinations. All of the points plotted in Figure 3 are independent, with the exception of the points at 360°, which are duplicates of the points at 0°.

The differences among the overall heights of the four reaction time functions correspond to the differences among the mean reaction times plotted in Figure 2. Our concern now is with comparisons among the shapes of these four functions. For all of the cases in which the imagined stimulus and the test stimulus differ in some way, reaction time generally increases as the orientation of the test stimulus departs from the 0° (fingers up) orientation. The reaction time increase is particularly marked as the maximum departure is approached at the completely inverted (fingers down) orientation of 180°. (The only noticeable deviation from this monotone relationship is the elevation of the 0° point above the ± 60° points for the case in which the imagined and the test stimulus represent the same side of different hands.) In striking contrast, when the imagined hand and the presented hand are identical in all respects, the function relating reaction time and test-stimulus orientation is virtually flat.

With respect to both its flat shape and its low absolute level (of only about 500 msec), this reaction time function is reminiscent of the function obtained by Cooper and Shepard (1973a, 1973b) when subjects were informed sufficiently in advance as to the identity and the orientation of an upcoming rotated letter or numeral. As in that previous experiment, we conclude here that subjects prepared for the upcoming test hand by imagining the appropriate hand version rotated into the indicated orientation. If the test hand, when presented, was identical to the imagined hand, then subjects could rapidly indicate that the two representations matched, regardless of the picture-plane orientation of the test hand.

In Figure 4 mean reaction time (over subjects and test-hand versions) is plotted as a function of orientation of the test stimulus for the two experimental conditions in which subjects were given no specific instructions as to how to use the thumbless orientation cue (if it was presented at all). In both conditions, reaction times are (a) generally longer than in the case of the imagery instruction conditions, and (b) markedly dependent on orientation.

From Figure 4 we see that when *no* information is provided in advance of the presentation of the test stimulus, reaction time increases rapidly as that test stimulus approaches the completely inverted, 180° orientation. When information concerning the orientation of the upcoming test hand is provided, but the subject does not know *which* concrete stimulus to expect, mean reaction times are some 100–150 msec faster than in the no-advance-information condition at all orientations alike. These new results provide further support for two of our earlier (Cooper & Shepard, 1973a) conclusions: (a) Subjects *cannot* effectively prepare for a rotated stimulus by "mentally rotating" only an abstract frame of reference. (b) The presentation of advance information concerning only orientation reduces total reaction time by an amount that would otherwise be needed to determine the orientation of the test stimulus itself *before* any further processing, such as mental rotation, can be initiated.

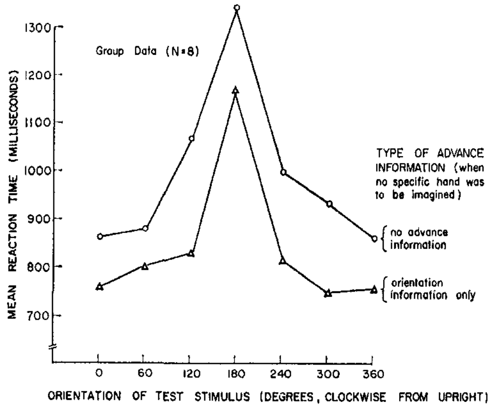

FIGURE 4. Mean reaction time plotted as a function of test-stimulus orientation for the conditions in which no advance information or only orientation information was provided.

Errors

All trials on which errors were made were retaken during the experimental sessions; nonetheless, errors were recorded. Error rates were low, ranging from 2.1% to 9.2% for individual subjects, with an average error rate of 5.6%. In addition, error rates correlated positively with mean reaction times. It is noteworthy that no errors were made by any one of the eight subjects on those trials in which the hand version that the subject had been instructed to imagine in advance corresponded to the hand version that was presented as the actual test stimulus.

Discussion

Evidence that Identification is Based on an Internal Analog Transformation

The above results confirm the two testable consequences initially derived from our notion of how subjects determine the left–right identity of a visually presented hand. (a) When subjects were given complete, veridical information as to the version and orientation of the to-be-presented hand, they responded rapidly and entirely without error regardless of the designated orientation. The uniform speed and accuracy of these responses suggests that they were based on the outcome of a holistic template-like comparison between an internally readied representation and the ensuing external stimulus. (b) When the advance information was either incomplete or nonveridical, reaction times were 200–700 msec slower, and they depended systematically on both the orientation of the test hand and the relation of the test hand to the imagined hand. This finding is consonant with the notion that, in order to achieve a match and hence identification, an internal representation of the corresponding hand had to be transformed from some standard, canonical position into the palm–back and picture-plane orientation actually presented—with more extensive transformations requiring more time.

If there is one "canonical" orientation shared by all subjects, then our results suggest that it is the orientation with the fingers pointing upward. This is certainly consistent with the fact that in either viewing or displaying one's own hands (as in presenting a finger count), one generally tends to hold the hands with the fingers pointing up. However, in view of both the relative flatness of the reaction time functions in the vicinity of 0° and the fact that one often views or displays the hands in positions tilted somewhat from the 0° orientation, it is quite possible that subjects could have canonical internal representations corresponding to different, somewhat tilted orientations.

Nevertheless, identification time increased sharply for all subjects as the presented hand approached the 180° orientation in which the fingers point straight down.[1] Some subjects emphasized the kinesthetic component of their mental imagery in this task and claimed that the marked increase in reaction time at this orientation was due to the physical awkwardness of positioning one's own (right or left) hand in that inverted orientation—even though the positioning is performed only mentally. The increase may also be attributable to the related fact that we less frequently see our own physical hands in this rather awkward position. In any case, since subjects *can* prepare in advance for a hand presentation at any such inverted orientation under appropriate conditions (cf. Figure 3), the dependence of reaction time on orientation in the *absence* of appropriate advance information presumably reflects two facts: (a) We do not ordinarily expect to be presented with hands in inverted positions. (b) Extra effort and time are required to prepare for a rapid match against a hand in an "awkward" orientation.

A Proposed Information-Processing Model

The data from this one experiment are not sufficient to determine the precise sequence of internal processes that underlie the determination of the left–right identity of a visually presented hand. Nevertheless, these data do provide additional support for a notion to which we have been led in our previous studies. Specifically, in order to determine the identity of one of two "isomeric" objects (which differ only in global structure), subjects carry out mental analogs of spatial transformations on mental analogs of those objects until a holistic match is attained between the externally presented object and a mentally transformed internal representation.

We wish to apply one model based on these general principles to the major features of the data presented in Figures 2 and 3. In so doing, we must make some rather tentative specifications. We propose that, on a trial in which the subject is asked to imagine a particular side of a particular hand in the predesignated orientation, he proceeds through the following self-terminating sequence of steps:

1. Following the instruction to imagine a particular side of a particular hand in a particular orientation, the subject prepares for the upcoming test stimulus by first imagining the designated hand moved into the designated position (of side and picture-plane orientation), and by then readying his corresponding physical hand to respond if the imagined hand matches the ensuing test hand.

2. Immediately upon its external onset, the test stimulus is compared in a holistic, template-like fashion with the preparatory mental image. If the two representations match, the prereadied response is executed and the recorded reaction time (of about 500 msec) is the sum of (a) the time to process the test stimulus and detect the match and (b) the time to execute the response.

3. If the attempted match fails, an internal representation of the opposite (nondesignated) hand is mentally moved into the designated position (of side and orientation), and response readiness is switched to the corresponding (nondesignated) physical hand.

4. As before, a holistic comparison is attempted between the mentally transformed internal representation and the external stimulus. If a match is achieved, the currently readied response is executed. The *additional* 200 msec (at 0°)–400 msec (at 180°) in the recorded reaction time is the sum of (a) the time to carry out the mental positioning (200 msec at 180°), (b) the time to switch control to the opposite hand (about 100 msec according to Cooper & Shepard, 1973a), and (c) the time to complete the holistic comparison.

5. If this second attempted match fails, the current internal representation (i.e., the image of the nondesignated hand) is men-

[1] This reaction time increase, shown in Figure 4, is markedly nonlinear, in contrast to the strikingly linear reaction time functions obtained in other studies of mental rotation (cf. Cooper, in press; Shepard & Feng, 1972; Shepard & Metzler, 1971). Factors contributing to such nonlinearity in the case of familiar stimuli with a preferred "upright" orientation are discussed by Cooper and Shepard (1973a).

tally flipped over to its opposite (palm or back) side.

6. A third holistic comparison is then made between this previously rotated and, now, flipped representation of the nondesignated hand and the external test stimulus. If a match results, the readied response (still of the nondesignated physical hand) is executed. The additional 200 msec in the recorded reaction time is the sum of (a) the time to carry out the mental flip and (b) the time to complete this third holistic comparison.

7. If this last attempted match fails, then by elimination, readiness is switched to the originally designated hand before executing the "same hand" response.

This process model provides a satisfactory account of the major features of the data displayed in Figures 2 and 3. However, as mentioned above, for three of the eight subjects reaction times to the opposite side of the opposite hand (from that imagined) were *longer* than reaction times to the opposite side of the same hand (i.e., the third and fourth points plotted in Figure 2 were reversed for these subjects). We might speculate that these subjects retained, in some state of secondary readiness, the prepositioned representation of the designated hand (from Step 1) during the subsequent transformation and comparison involving the opposite hand (Steps 3 and 4). They might then be able to use that representation of the originally designated hand in performing the flip and comparison of Steps 5 and 6. This proposal, though highly speculative, would produce the observed reversal in reaction time of the last two points for these three subjects.

In any case, the first four of the seven steps proposed above are strongly suggested by the data for all eight of the subjects. The flat shape and low height of the bottom function in Figure 3 establish that subjects first attempted a holistic match with a representation of the predesignated hand that had been mentally maneuvered into the predesignated position. The peaked shape and intermediate height of the next higher function indicates that subjects next attempted a match with a representation of the opposite, nondesignated hand that had *not* previously been mentally maneuvered into the designated position.

Concluding Observations

The last three of the seven steps proposed are much less certain than the first four—particularly in view of the inter–subject differences. Other more quantitative details also remain uncertain. For example, is the time required to complete a mental flip from one side to the other of an imagined hand at all dependent on the orientation of that hand in the picture plane? The approximate parallelism of all but the bottommost curve in Figure 3 suggests that any such dependence is relatively slight.

A related quantitative question concerns the curves plotted in Figure 2. The shape of the solid curves is potentially misleading, as the plotted points are averages over all six picture-plane orientations. For, recall that reaction time varied markedly with orientation in the case of the three points on the right in Figure 2, but was essentially flat in the case of the point on the left (cf. Figure 3). Since reaction time was approximately flat in the $-60°$ to $+60°$ range around the normal, upright orientation for all curves in Figures 3 and 4, the dashed line (with open points) in Figure 2 is largely free of this artifact. The effect of this correction is to lower all except the first point by 50–100 msec. Thus, the shape of the curve is changed very little; however, the increase exhibited by the first three points becomes, if anything, even more linear.

Whether this linearity is theoretically significant or coincidental is not yet known. In terms of the tentatively proposed model, the time required to rotate the image of a hand from the upright to the inverted orientation (included in the difference between the first two points in Figure 2) approximately equals the time to flip the image from one side to the other (included in the difference between the second two points). Certainly both operations amount to 180° rotations about some axis in three-dimensional space (cf. Shepard & Metzler, 1971).

One of our intents in reporting this experiment has been to make plausible the claim that identification of "isomeric" objects is accomplished by a sequence of analog mental transformations and holistic matches. Alternatively, one might consider a "two-stage" or "dual-process" model in which failure of the initial holistic match (Step 1) is followed by a series of local tests against individual features rather than by holistic operations throughout (cf. Bamber, 1969; Sekuler & Abrams, 1968; Silverman, 1973; Smith & Nielson, 1970). In the present case, such individual features would include palm-versus-back markings, position of the thumb, etc. However, any account based on local feature tests has difficulty explaining the strong dependence of reaction time on test-stimulus orientation exhibited in all but the bottommost curve in Figure 3. (One might argue that individual features take longer to detect when they appear in the unfamiliar, upside-down orientation. But this argument is difficult to reconcile with both the approximate parallelism of the obtained curves and with the introspective impression that discrimination of palm-versus-back markings should not increase in difficulty with departure from the upright position.) It may be that with more extensive practice in distinguishing left from right versions of unadorned hands, subjects could learn to achieve the discrimination by a series of feature tests. However, in the case of the present experiment, such an interpretation seems unlikely.

In conclusion, we interpret our results as supporting the notion that subjects determine the left–right identity of a presented hand by first imagining one of their own hands moved into the position of the presented hand, and then testing for a match or mismatch. Only the general analog and holistic character of these operations are dictated by this sort of model. The precise sequence of these operations under any given condition has been inferred entirely from the obtained data. In particular, the specification (in Steps 3 and 4 above) that a failure of the first holistic match is always followed by a test with the same side of the opposite hand *before* a test with the opposite side of the same hand was determined solely by the outcome of the empirical data—not by any requirement of a theory based on analog transformations and holistic matches. Thus, a remaining question of interest is whether subjects could be induced, by means of appropriate instructions and/or practice, to perform some of these operations in a quite different order.

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